

ABSTRACT

Title of Dissertation: EXPERIMENTAL INVESTIGATION OF
FORCE TRANSIENTS DURING
GUST ENCOUNTERS

Hulya Biler
Doctor of Philosophy, 2021

Dissertation Directed by: Professor Anya R. Jones
Department of Aerospace Engineering

The small size and low speed of Micro Air Vehicles make them vulnerable to wind gusts such that sustaining controlled flight becomes a challenge in the unsteady environments. A better understanding of the gust flow is crucial to develop models capable of predicting unsteady forcing. Therefore, this study aims to improve understanding of fundamental flow physics behind the unsteady force production during gust encounters. The bulk of the results presented here were obtained experimentally for a flat plate passing through a transverse gust created in a water towing tank and found to have a sine-squared velocity profile. The effects of 4 different parameters, namely angle of attack, gust ratio, effective angle of attack, and aspect ratio, were explored. A wide investigation range was used for each parameter. The forces increased significantly from their steady-state values during the encounter. 2D flowfields showed the formation and shedding of vortices from the leading and trailing edges of the wing. The flow was found to stay nominally two-dimensional until the forces peak. Only thereafter, spanwise variations were

observed in the 3D flowfields. The accuracy and limitations of Küssner's model were evaluated by comparing the sine-squared and top-hat transverse gusts (the latter experiments performed by collaborators). The gradients in the transverse velocity profile were found to significantly affect the force response such that sharper gradients cause higher nonlinearities. Küssner's model was found to provide accurate predictions for the sine-squared gust even when the flow is highly nonlinear, whereas it failed to do so for the top-hat gust. A momentum flux-based normalization was proposed and found to scale the responses of different velocity profiles as long as the response can be predicted by Küssner's model. The effect of gust type on the unsteady forcing was examined by comparing the sine-squared transverse and vortex gusts (the latter experiments performed by collaborators). The results showed that both gust encounters result in large transients in the lift. The increase in the lift force and the leading-edge vortex strength for the transverse gust was found to be steeper than the vortex gust. A flowfield-based force prediction method was proposed and found to be effective for low-to-moderate effective angles of attack.

EXPERIMENTAL INVESTIGATION OF FORCE TRANSIENTS DURING GUST ENCOUNTERS

by

Hulya Biler

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2021

Advisory Committee:

Professor Anya Jones, Chair/Advisor

Professor Alison Flatau

Professor Kenneth Yu

Professor Anubhav Datta

Professor Kenneth Kiger, Dean's Representative

© Copyright by
Hulya Biler
2021

Dedication

To my grandma, Perihan Biler, I love you, and I miss you every day. Thank you for making me who I am. Also, to all women who are fighting patriarchy every day in their own unique and beautiful way.

Acknowledgments

First and foremost, I would like to express my sincere appreciation to my advisor, Dr. Anya Jones. It is safe to say that working with her has changed the course of my life. There is too much that I have learned from Dr. Jones, both as a researcher and as a person. Perhaps the most important thing that she has taught me unknowingly is the ability to ask myself “What would Anya do?” and once I know the answer to that question, no problem seems too hard to tackle. Her calm attitude, problem solving skills, patience, acceptance, and support has always been inspiring, and for that, I am forever grateful.

Of course, I also would like to thank my labmates Jonathan Lefebvre, Luke Smith, Girguis Sedky, and Zachary Smith for making my time at UMD memorable and fun. It remains a mystery how they survived all my nagging about laser alignment. Also, a huge thanks go to Drs. Camli Badrya, Gino Perrotta, Field Manar, Peter Mancini, André Bauknecht, and Andrew Lind for sharing their knowledge and wisdom. I also would like to thank Dr. Okşan Çetiner for the support she provided. In addition, I am deeply grateful to Seyhan Gül, who always kindly offered his friendship and intellectual support.

Throughout my doctoral studies, I had the unique opportunity to collaborate with outstanding researchers from all over the world. Thank you to Ignacio Andreu

and Dr. Holger Babinsky for providing the experimental data on top-hat gust and Murat Sarıtaş and Dr. Okşan Çetiner for sharing the vortex gust data, which was within the scope of Murat Sarıtaş' doctoral studies. Also, thanks to Dr. Camli Badrya for providing the CFD data for this dissertation. The contribution of these collaborations to this dissertation is undeniable. In addition, the current work was supported in part by the U.S. Air Force Office of Scientific Research under grant FA9550-16-1-0508 and the National Science Foundation under grant no. 1553970. I also would like to acknowledge the University of Maryland for the Ann G. Wylie dissertation fellowship.

I am incredibly grateful to my favorite historian, Gamze Yavuzer. She is also very likely to be the only historian who has an in-depth understanding of gust encounters. There is no possible way that I would have completed this dissertation without her support. Without any doubt, she is the best thing that the U.S. has brought to my life. Another special thanks go to Baturalp Büyükkates for always calming me down and making me laugh. I cannot imagine the last five years without him. I am immensely grateful to my wildy intelligent best friends, Elçin Kızılkaya and Gözde Çelebi. It is impossible to describe the value they have added to my life. I would like to thank them for always being there for me and holding my hand through it all.

Finally, I would like to thank my mom and dad, who are without a doubt the strongest people I know. The resilience they have shown towards life has always been inspiring. Thank you for loving me no matter what I do. I couldn't have asked for better parents. In addition, a huge thanks to my family, Murat Pat, Evren

Karaca, Nuri Biler, who always supported me throughout my education. A special thanks to my auntie, Hülya Kumbasar, for being the kindest. I am so glad that my stubborn father named me after you.

Table of Contents

Dedication	ii
Acknowledgements	iii
List of Tables	ix
List of Figures	x
1 Introduction	1
1.1 Motivation	1
1.2 Problem Statement	5
1.3 Background	7
1.3.1 Categorization of Wind Gusts	7
1.3.2 Canonical Discrete Gust Types	9
1.3.3 Thin Airfoil Theory	11
1.3.3.1 Steady Thin Airfoil Theory	11
1.3.3.2 Quasi-steady Thin Airfoil Theory	14
1.3.4 Unsteady Models	16
1.3.4.1 Wagner’s Model	17
1.3.4.2 Küssner’s Model	19
1.3.5 Studies on Canonical Discrete Gust Types	22
1.3.5.1 Longitudinal Gust Encounters	22
1.3.5.2 Transverse Gust Encounters	23
1.3.5.3 Vortex Gust Encounters	27
1.3.6 Studies on Gust Mitigation	30
1.4 Present Work	31
1.5 Dissertation Outline	33
2 Methodology	34
2.1 Facility	34
2.2 Test Models	36
2.3 Transverse Gust	38
2.3.1 Gust Generator System	38

2.3.2	Gust Characterization Procedure	39
2.3.3	Streamwise Velocity Profile and Pump Operating Range . . .	41
2.3.4	Spanwise Velocity Profile	43
2.3.5	Flow Unsteadiness	45
2.4	Kinematics and Defining Parameters	47
2.5	Force Measurements	50
2.6	Flowfield Measurements	53
2.6.1	Particle Image Velocimetry	54
2.6.2	Circulation Measurements	57
2.6.3	Dye-flow Visualization	59
2.7	Chapter Summary	62
3	Methodology of Collaborators	63
3.1	Transverse Gust	64
3.1.1	Sine-squared Transverse Gust Computational Methodology . .	64
3.1.1.1	Flow Solver	65
3.1.1.2	Computational Domain	66
3.1.2	Top-hat Transverse Gust Experimental Methodology	68
3.1.2.1	Facility and Test Model	68
3.1.2.2	Gust System and Its Characterization	70
3.1.2.3	Force Measurements	71
3.1.2.4	Flowfield Measurements	71
3.2	Vortex Gust Experimental Methodology	72
3.2.1	Facility and Test Model	72
3.2.2	Gust System and Its Characterization	74
3.2.3	Force Measurements	76
3.2.4	Flowfield Measurements	76
3.3	Chapter Summary	77
4	The Unsteady Aerodynamics of Sine-squared Transverse Gust Encounters . .	79
4.1	Variations in Angle of Attack	80
4.1.1	Trends of Forces, Flowfields, and Circulation Production . . .	80
4.1.1.1	Lift and Drag	80
4.1.1.2	Flowfields	83
4.1.1.3	Circulation Production	89
4.1.2	A Detailed Investigation of Force Transients	90
4.1.2.1	Behavior of Force Maximum	92
4.1.2.2	Behavior of Force Minimum	94
4.1.2.3	Behavior of Force Secondary Maximum	95
4.1.3	Exposed Projected Area Normalization	96
4.2	Variations in Gust Ratio	99
4.2.1	Trends of Forces, Flowfields, and Circulation Production . . .	99
4.2.1.1	Lift and Drag	99
4.2.1.2	Flowfields	101
4.2.1.3	Circulation Production	105

4.2.2	A Detailed Investigation of Force Transients	106
4.2.2.1	Behavior of Force Maximum	107
4.2.2.2	Behavior of Force Minimum	109
4.2.2.3	Behavior of Force Secondary Maximum	110
4.2.3	Gust Ratio Normalization	111
4.3	Maximum Effective Angle of Attack and Lift	117
4.4	Drag Coefficients at Low Angles of Attack	121
4.5	Three-dimensional Effects	125
4.5.1	Trends in Three-dimensional Flowfields	126
4.5.2	Variations in Aspect Ratio	131
4.5.2.1	Lift and Drag	131
4.5.2.2	Three-dimensional Flowfields	133
4.6	Chapter Summary	137
5	Comparison of Transverse Gust Velocity Profiles and Evaluation of Küssner's Model	140
5.1	Comparison of Sine-squared and Top-hat Transverse Gusts	141
5.1.1	Force Comparison	143
5.1.2	Flowfield Comparison	144
5.1.3	Circulation Comparison	148
5.2	Accuracy and Limitations of Küssner's Model	149
5.3	Momentum Flux-based Normalization	154
5.4	Chapter Summary	158
6	Comparison of Gust Types and Flowfield-based Force Prediction Method	161
6.1	Vortex Gust	162
6.2	Comparison of Sine-squared Transverse and Vortex Gust Encounters	167
6.2.1	Force and Flowfield Comparison	169
6.2.2	Circulation Comparison	172
6.3	Flowfield-based Force Prediction	174
6.4	Chapter Summary	179
7	Conclusions	182
7.1	Summary and Conclusions	182
7.2	Original Contributions	188
7.3	Suggestions for Future Work	189
	Bibliography	192

List of Tables

1.1	Cruising speed of several natural flyers and airspeed of various weather conditions, taken from Ref. [18]	3
2.1	The test models used for sine-squared transverse gust encounters. . .	37
2.2	Coefficients of variation of the peak gust velocity and the gust width from various spanwise locations.	44
2.3	Coefficients of variation of the peak gust velocity and the gust width from instantaneous measurements.	46
2.4	Motion profile parameters for the test models used in the experiments.	48
2.5	Test matrix for the sine-squared gust encounter experiments.	50
3.1	Computational parameters.	66
3.2	Test matrix for the top-hat gust encounter experiments.	69
3.3	Test matrix for vortex gust encounters.	74
4.1	Steady-state lift and drag coefficients for various angles of attack. . .	92
4.2	Coefficients of variation of the maximum gust ratio normalized lift coefficient for various angles of attack.	115
4.3	Coefficients of variation of the maximum normalized drag coefficient for various angles of attack.	117
6.1	Comparison between the sine-squared transverse gust and the vortex gust.	169

List of Figures

1.1	The mass and flight speed of natural flyers and human-made aircraft, adapted from Ref. [5].	2
1.2	The Black Widow fixed wing MAV, the MAVSTAR coaxial twin-rotor rotary wing MAV, and the hummingbird flapping wing MAV, taken from Refs. [6–8].	2
1.3	Sketch of transverse gust encounters.	6
1.4	Sketches of various canonical discrete gust profiles.	8
1.5	Sketches of canonical discrete gust types.	10
1.6	Vortex sheet placement, taken from [57].	12
1.7	Pitching and plunging airfoils and the velocity perturbations caused by the airfoil’s motion, taken from Ref. [58].	14
1.8	Wagner’s function for a step change.	18
1.9	Analogy between the transverse gust encounter and a broken-line airfoil, adapted from Ref. [60].	20
1.10	Küssner’s function for an infinitely long sharp-edged gust.	21
1.11	Investigation of a flat plate at 0° angle of attack encountering sine-squared transverse gust of various widths: a) velocity profiles, b) computational and analytical lift coefficients, and c) maximum lift coefficients, taken from Ref. [85].	25
1.12	Investigation of a flat plate at 0° angle of attack encountering vortex gust of various incoming positions: a) velocity profile, b) path of the vortex gust , and c) experimental lift coefficients, taken from Ref. [90].	29
2.1	Experimental setup and wing installation mechanism.	35
2.2	Gust generation system.	38
2.3	Spanwise gust characterization locations shown on wing 1 (5 cm chord, 20 cm span).	40
2.4	Sine-squared gust characterization for the highest pump speed at the centerline of the wing.	41
2.5	Linear fit to both peak gust velocity and gust width.	42
2.6	Characterized gust velocity profile for different pump speeds and spanwise locations.	44

2.7	Average gust velocity profiles and standard deviations (Stdev) of instantaneous flowfields in both the peak gust velocity and the gust width for different pump speeds at the centerline.	45
2.8	Fast Fourier Transform of instantaneous measured velocities for different pump speeds at the centerline shown on a logarithmic scale.	46
2.9	Towing velocity of wing 2 and a sample gust velocity profile of 0.13 m/s corresponding to a gust ratio of 0.5.	47
2.10	Raw, ensemble averaged, and filtered lift coefficients for $GR = 1, \alpha = 0^\circ$ case of wing 2 experiments.	51
2.11	Lift coefficients from filtered individual runs, and ensemble average for $GR = 0.5, \alpha = 0^\circ$ case of wing 2 experiments.	53
2.12	Sketch of the PIV setup used for sine-squared gust encounter experiments.	54
2.13	PIV sensitivity study based on the non-dimensional leading-edge vortex strength for $GR = 1, \alpha = 0^\circ$ case.	56
2.14	Vorticity contours at $t^* = 1.8$ for $GR = 1, \alpha = 0^\circ$ case.	57
2.15	Nondimensional circulation of $GR = 1, \alpha = 0^\circ$ case calculated from both the segmentation and the threshold methods.	59
2.16	Nondimensional circulation of $GR = 1, \alpha = 0^\circ$ case calculated from both the segmentation and the threshold methods.	59
2.17	Location of the ports placed on the bottom surface of the wings tested.	61
3.1	Computational domain: Cartesian background mesh and body-fitted O-O mesh from Ref. [80].	67
3.2	Setup of the top-hat gust from Ref. [114].	68
3.3	Measured gust velocities and fit for the top-hat gust from Ref. [81].	70
3.4	Experimental setup for vortex gust encounter experiments from Ref. [90].	73
3.5	Measured gust velocities and Lamb-Oseen Vortex fit from Ref. [90].	74
4.1	Lift and drag coefficients for various angles of attack at a gust ratio of 0.5, circles on this plot corresponds to flowfields in Figure 4.2.	81
4.2	Flowfields for various angles of attack at a gust ratio of 0.5.	85
4.3	Nondimensional circulation for various angles of attack at a gust ratio of 0.5.	89
4.4	Lift and drag coefficients for various angles of attack at a gust ratio of 0.26.	91
4.5	Maximum lift and drag coefficients versus angle of attack for various gust ratios.	93
4.6	Minimum lift and drag coefficients versus angle of attack for various gust ratios.	94
4.7	Secondary peak lift and drag coefficients versus angle of attack for various gust ratios.	95
4.8	Sketch that shows gust-exposed and freestream-projected area of the wing.	97

4.9	The gust-exposed and freestream-projected normalized lift and drag coefficients for various angles of attack at a gust ratio of 0.26.	98
4.10	Lift and drag coefficients for various gust ratios at 0° angle of attack, circles on this plot corresponds to flowfields in Figures 4.11–4.14.	100
4.11	Flowfields at $t^* = 1$ for gust ratios of 0.5 to 1.5.	102
4.12	Flowfields at $t^* = 1.8$ for gust ratios of 0.5 to 1.5.	103
4.13	Flowfields at $t^* = 2.5$ for gust ratios of 0.5 to 1.5.	104
4.14	Flowfields at $t^* = 3.6$ for gust ratios of 0.5 to 1.5.	104
4.15	Nondimensional circulation for gust ratios at 0° angle of attack.	105
4.16	Lift and drag coefficients for low-amplitude (0.08 to 0.32) gust ratios at 30° angle of attack.	106
4.17	Maximum lift and drag coefficients versus gust ratio for angles of attack of 0° to 45°	108
4.18	Minimum lift and drag coefficients versus gust ratio for angles of attack of 0° to 45°	109
4.19	Secondary maximum lift and drag coefficients versus gust ratio for angles of attack of 0° to 45°	110
4.20	Gust ratio normalized lift and drag coefficients for various gust ratios at 0° angle of attack.	112
4.21	Maximum gust ratio normalized lift coefficient for various angles of attack (top plot) and corresponding gust ratio normalized lift histories.	114
4.22	Maximum gust ratio normalized drag coefficient for various angles of attack (top plot) and corresponding normalized drag histories.	116
4.23	Sketch of a wing towing through a sine-squared gust, and three instances that show the gust velocity distribution along the wing.	118
4.24	Maximum lift coefficients with similar maximum mid-chord effective angle of attack for different wings.	119
4.25	Maximum lift coefficients versus maximum mid-chord effective angle of attack for cases where $\alpha \leq 10^\circ$ and $\alpha_{\text{eff,max}} \leq 40^\circ$. The colors shown in this plot corresponds to the same cases displayed in Figure 4.24.	119
4.26	Experimental (solid lines) and computational (dashed lines) tangential coefficients of a flat plate at angles of attack of 0° , 5° , and 10° , and gust ratios of 0.26, 0.16, 0.08, respectively. Computational skin friction contours on the upper surface at $t^* = 2.5$, computational vorticity contours at midspan, and the computational chordwise skin friction coefficients (at midspan).	122
4.27	Experimental drag coefficients for a flat plate at 0° angle of attack encountering the sine-squared gust of various strengths. Experiments performed using wings 1 and 2 are represented with solid and dashed lines, respectively.	125
4.28	(a) Lift coefficient (circles on which corresponds to flowfields shown in (b)), and (b) the three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 0° angle of attack case of wing 2 (aspect ratio of 4).	127

4.29	(a) Lift coefficient (circles on which corresponds to flowfields shown in (b)), and (b) the three-dimensional experimental flowfields (top view) for a 1 gust ratio and 0° angle of attack case of wing 2 (aspect ratio of 4).	128
4.30	(a) Lift coefficient (circles on which corresponds to flowfields shown in (b)), and (b) the three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 20° angle of attack case of wing 2 (aspect ratio of 4).	130
4.31	Lift and drag coefficients of aspect ratio 4, 6, and 8 wings for a 0.5 gust ratio and 0° angle of attack case, circles on this plot corresponds to flowfields shown in Figure 4.33.	132
4.32	Lift and drag coefficients of aspect ratio 4, 6, and 8 wings for a 0.5 gust ratio and 20° angle of attack case, circles on this plot corresponds to flowfields shown in Figure 4.34.	133
4.33	Three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 0° angle of attack case for wing 4 (aspect ratio of 8). . . .	134
4.34	Three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 20° angle of attack case for wing 4 (aspect ratio of 8). . . .	136
5.1	Gust characterization flowfields and gust velocity profiles for both the sine-squared and top-hat gusts.	142
5.2	Lift and gust ratio normalized lift coefficients for gust ratios ranging from 0.5 to 1.5 at 0° angle of attack for both the sine-squared (solid lines) and top-hat (dashed lines) gusts, circles on this plot corresponds to flowfields in Figures 5.3 and 5.4.	143
5.3	Flowfields for both the sine-squared (solid box) and top-hat (dashed box) gusts at a gust ratio of 0.5.	145
5.4	Flowfields for both the sine-squared (solid box) and top-hat (dashed box) gusts at a gust ratio of 1.	147
5.5	Nondimensional circulation for both the sine-squared (shown with a circle symbol) and top-hat (shown with a star symbol) gusts.	148
5.6	Gust ratio normalized lift coefficient from the Küssner's convolution for the sine-squared, top-hat, and sharp-edged gusts.	151
5.7	Gust ratio normalized measured lift coefficients and Küssner's convolution for the sine-squared and top-hat gusts.	152
5.8	Momentum associated with the sine-squared gust (the purple area) and the corresponding sharp-edged gust.	155
5.9	Gust momentum normalized Küssner's convolutions for the sine-squared ($K = 0.61$), top-hat ($K = 0.91$), and sharp-edged ($K = 1$) gusts.	156
5.10	The maximum lift coefficient versus the width-to-chord ratio based on the Küssner's model.	157

5.11	Gust momentum normalized Küssner's convolution (for the sine-squared, top-hat, and sharp-edged gusts) and measured lift coefficients (for the sine-squared and top-hat gusts) with a gust width correction.	158
6.1	Path that vortex gust follows when the test model is at 0° angle of attack.	163
6.2	Lift coefficient and experimental flowfields during vortex gust encounters for a flat plate at 0° angle of attack, circles on Figure 6.2(a) corresponds to flowfields in Figure 6.2(b).	164
6.3	Nondimensional circulation shed from the leading edge for a flat plate at 0° angle of attack.	166
6.4	Longitudinal and transverse velocity profiles for both the sine-squared transverse and vortex gusts.	170
6.5	Lift histories during sine-squared transverse and vortex gust encounters for the $GR = 1, \alpha = 0^\circ$ case.	170
6.6	Nondimensional circulation shed from the leading edge during transverse and vortex gust encounters for the $GR = 1, \alpha = 0^\circ$ case.	173
6.7	The lines upstream of the leading-edge that are used to compute the average velocities, which are displayed on the vorticity contours for both the sine-squared transverse and vortex gusts.	176
6.8	Lift coefficient from force measurements (solid lines) and gust-induced angle of attack (dashed lines) for both gust types.	176
6.9	Lift coefficients from force measurements (solid lines) and predictions (dashed lines) for both gust types.	178

Chapter 1: Introduction

1.1 Motivation

Beginning with the first successful flight by the Wright brothers over a century ago, wind gusts have been known to cause loss of stability and control in flight and occasionally structural failure. Since then, developments in the aerospace industry have mainly focused on producing large aircraft that are capable of undertaking missions such as transport and surveillance. These large aircraft generally operate in a high Reynolds number flow regime, as shown in Figure 1.1. The effects of wind gusts on these vehicles have been investigated thoroughly in the literature to ensure a safe flight [1–4].

The focus has now shifted towards smaller vehicles such as Unmanned Air Vehicles (UAVs), Micro Air Vehicles (MAVs), and Nano Air Vehicles (NAVs) since these vehicles showcase a wide range of applicability varying from military, which includes local reconnaissance, detection of intruders, hostage rescues, and border patrol, to commercial, which includes search and rescue, air sampling, field research, drug delivery, and environmental monitoring [6, 9, 10]. Biological flyers have inspired the production of these vehicles. Some of the MAVs and NAVs may be as small as insects and would fit into the palm of one’s hand [9, 11–13]. Various concepts have

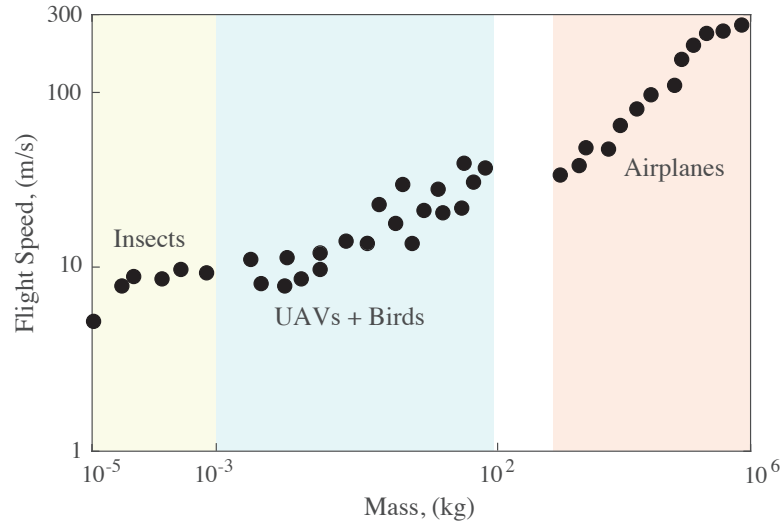


Figure 1.1: The mass and flight speed of natural flyers and human-made aircraft, adapted from Ref. [5].

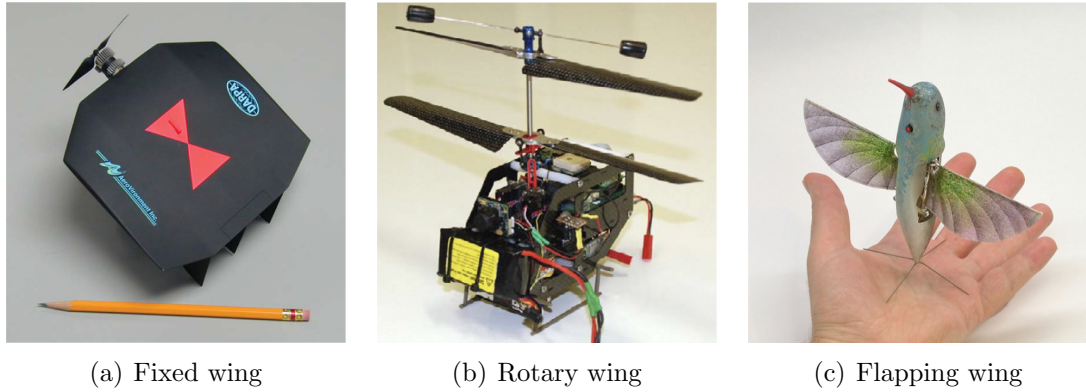


Figure 1.2: The Black Widow fixed wing MAV, the MAVSTAR coaxial twin-rotor rotary wing MAV, and the hummingbird flapping wing MAV, taken from Refs. [6–8].

been proposed for the design of MAVs, which are a fixed wing, rotary wing, and flapping wing [9, 10, 14–16] as can be seen in Figure 1.2. The MAVs' wingspans generally vary from 7.4 to 15 cm and they operate at very low speeds between 10 and 15 m/s (see Figure 1.1), which corresponds to Reynolds numbers between 20,000 and 50,000. Moreover, they are expected to operate in the range of several kilometers [6, 9, 17].

Table 1.1: Cruising speed of several natural flyers and airspeed of various weather conditions, taken from Ref. [18]

Airspeed	Wind Speed, (m/s)	Cruising Speed of
Light air	0.5-1	Butterflies, damselflies
Light breeze	2-3	Gnats, flies, dragonflies
Gentle breeze	4-5	Human-powered airplanes
Moderate breeze	6-8	Bees, wasps, beetles
Fresh breeze	9-11	Sparrows, starlings, swallows
Strong breeze	11-13	Crows, gulls, falcons
Near gale	14-17	Plovers, knots, godwits
Gale	18-21	Swans, ducks, geese
Strong gale	21-22	Sailplanes
Storm	25-28	Home-built aircraft
Violent Storm	29-32	Diving hawks
Hurricane	>32	Diving falcons

The small size and low speed of MAVs bring them numerous advantages. They can operate covertly, resemble a natural flyer to the human eye, can avoid radar detection systems, and are significantly cheaper to manufacture compared to large aircraft [9]. Although the resemblance to natural flyers is an asset for MAVs, achieving a steady flight in the unsteady environments that natural flyers operate in presents significant challenges for these human-made vehicles [10, 19–22]. One of these challenges is the aerodynamics of the vehicle [23]. Since MAVs operate at low Reynolds numbers, the flow is dominated mainly by viscous effects, which causes boundary layer separation, reduced lift-to-drag ratio, and reduced propeller efficiency [9]. Therefore, in order for an MAV to sustain controlled flight, an extensive research on leading-edge vortex formation, spanwise flow structures, and force transients experienced in low Reynolds numbers regime is required [10]. Moreover, the environment that these vehicles operate in also brings profound challenges. MAVs generally operate at very low altitudes, which is well within

the atmospheric boundary layer [24]. The atmospheric boundary layer is defined as the region that is 5 kilometers above the ground level and mostly dominated by a turbulent flow regime [13, 20, 24, 25]. The turbulence intensities are higher closer to the ground due to the friction the surface of the Earth presents [13, 17]. The terrain is another factor that dictates the operational environment of MAVs [13, 17]. The International Organization of Standardization (ISO) classified the effective terrain roughness, and 8 classes were established based on the obstacle height and separation of the landscape, which are sea, smooth, open, roughly open, rough, very rough, skimming, and chaotic. MAVs are generally expected to operate in the “roughness zone”, which is defined as the region where the wake of the local obstacles are significant. Landscapes in the “roughness zone”, such as high rise city centers, contain large turbulence intensities as high as 50% induced by the vortex shedding from the buildings [10, 13, 17, 20, 21, 24, 26, 27]. On the other hand, in a suburban landscape, the turbulence intensities were found to be around 15% [28]. This turbulence poses extreme danger to these vehicles’ stability and brings considerable control problems [13]. Another environmental factor that affects the flight of MAVs is the weather [29, 30]. Table 1.1 provides the airspeed for various weather conditions ranging from light air to hurricane and the cruising speed of various natural flyers and human-made vehicles. The unsteadiness of the flow can be quantified by the gust ratio parameter, which is the ratio of the wind speed to cruising speed. As can be seen from Table 1.1, even the existence of a gentle breeze might give rise to gust ratios around 1 for small human-made vehicles such as MAVs, whereas a gentle breeze only causes a gust ratio around 0.14 for a home-built aircraft [18]. Thus, it is

evident that the insects, small birds, and MAVs are more prone to remain grounded due to weather conditions. Large aircraft, on the other hand, can operate in more severe weather conditions [17]. Moreover, MAVs might be carried along with local currents and lose complete control due to their small size [13].

Deepening the fundamental understanding of the flow physics of gust encounters will provide valuable information for developing aerodynamic models that can quickly predict the unsteady forcing for an extensive range of disturbances. Such a model can be incorporated into an on-board flight controller to enhance the safety and broaden the operational envelope of these vehicles in gusty environments. A better understanding of the flow physics of gust encounters will also allow for developments in other areas such as naval applications, where an aircraft is required to land in a ship with a large airwake [31–33], rotorcraft applications, where a blade may interact with earlier shed tip vortices from an upstream blade [34–36], and wind turbines, where the efficiency of the turbine is affected by the wakes of upstream turbines [37, 38].

1.2 Problem Statement

The current work aims to improve the understanding of fundamental flow physics behind gust encounters. To achieve this, a simplified configuration is chosen for the current study, where a transverse gust and a test model will be used. Figure 1.3 shows a simple sketch of this configuration. A jet system is used to produce a sine-squared transverse gust, which represents a physical gust that a

vehicle would encounter during a real flight [39]. The gust generator system is designed to allow for an investigation of gusts of various strengths. Moreover, a flat plate wing is chosen as the test model not only to ensure consistency between the current work and previous work on pitching, surging, and plunging wings [40–43] but also to achieve a more direct comparison with linearized models such as Küssner’s model.

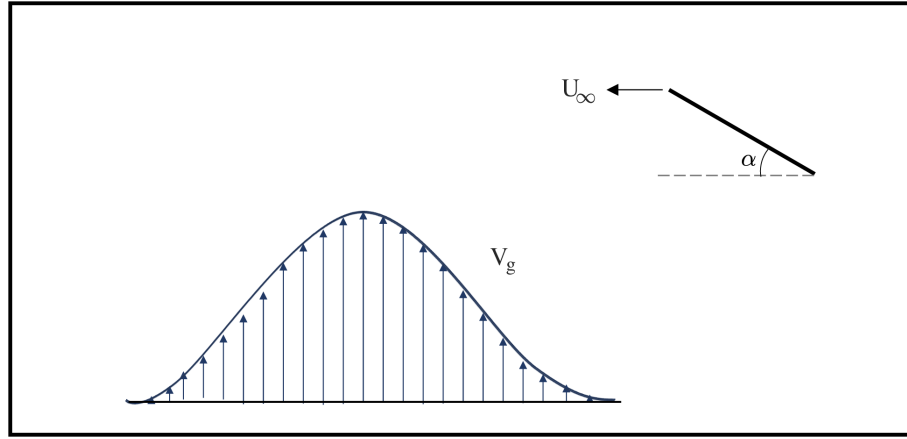


Figure 1.3: Sketch of transverse gust encounters.

Using this configuration, the current dissertation aims to answer the following questions, thereby addressing gaps in the literature:

1. What are the force transients experienced during gust encounters?
2. Which flow structures, both two and three-dimensional, are responsible for these transients?
3. Which method(s) can be used to predict the response to the transverse gust encounters accurately?

1.3 Background

In this section, the reader will find a literature review pertaining to the gust flow and gust encounters.

1.3.1 Categorization of Wind Gusts

In an attempt to understand the turbulent wind and its effects on the response of an aircraft to ensure a safe flight, modelling the gust loads has been an interest in the aerospace industry since 1915 [44]. However, before modelling the gust loads, it is essential to categorize them. There are two categories established in the literature, which are continuous turbulence and discrete gusts [45]. Since the atmospheric disturbances consist of both types [45], Etkin [46] argues that the wind models should include both the discrete gusts and the continuous turbulence.

The continuous turbulence models assume the lifting surface to be a linear system and use a statistical representation for the continuous gust velocity profiles. Therefore, the continuous gusts can be defined as the gusts that are sufficiently represented by Gaussian models. Loads of an aircraft are derived using the Power spectral density (PSD) method, which represents the average variation of energy. The Von Kármán spectrum and Dryden spectrum are the two forms of PSD and the most commonly used models for the continuous gusts [45].

On the other hand, discrete gusts are defined as the rare extreme excursions that occur in continuous turbulence. Unlike the continuous turbulence, discrete gusts are not adequately represented by Gaussian models [46]. The discrete gust

phenomenon can also be described as the ordered structures embedded in a random background, causing abrupt changes in the speed of air being encountered [47, 48]. Arguing that the larger disturbances exist as discrete gusts, researchers took on a mission to model discrete gusts to allow for the analysis of these extreme fluctuations [49, 50]. The discrete gust models require the knowledge of gust magnitude V , shape, width w , gradient distance H , the distance that the gust profile reaches to a maximum, and the probability of occurrence [50].

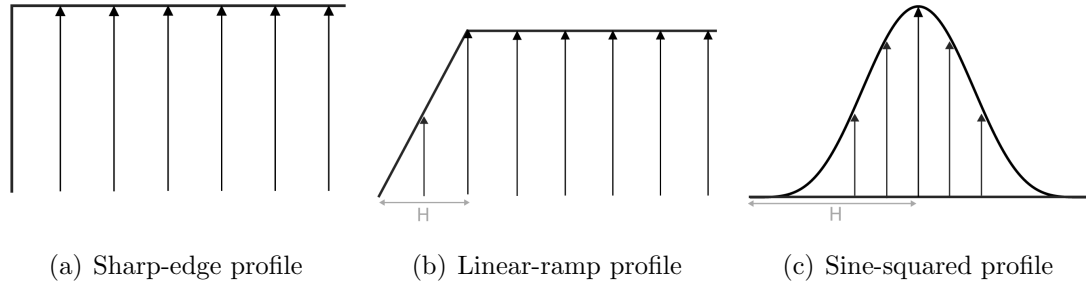


Figure 1.4: Sketches of various canonical discrete gust profiles.

The discrete gust shape can vary. However, there are canonical gust shapes that are established in the literature. The most prevalent shapes are the sharp-edge, linear-ramp, and one-minus-cosine. Be that as it may, there are other shapes discussed, such as sinusoidal and graded gusts [45, 51]. Rhode and Lundquist defined the first discrete gust model in 1931 as the sharp-edged [52] as shown in Figure 1.4(a). This canonical shape is still in use, especially for the response analysis. However, the sharp-edge gust models are not included in the Airworthiness Requirements. In the late 1930s, the linear-ramp gust concept was introduced. As can be seen in Figure 1.4(b), the gust amplitude increases linearly with the gradient distance [45]. Later on in 1953, one-minus-cosine (also known as versine or sine-squared) was

chosen to represent a more physical gust [39], see Figure 1.4(c). Even the current requirements and regulations use this canonical gust shape [53].

Lastly, statistical discrete gust (SDG) models were developed to derive the response of an aircraft in statistical terms [54]. SDG models include the non-Gaussian characteristics of wind gusts. The SDG model uses the “worst-case” approach to assess the response of an aircraft. In a pool that contains various gust amplitudes and gradient distances, the one with the most dramatic effects on the aircraft response is chosen to evaluate the response using this model [45].

Furthermore, even though one of the main causes of wind gusts is the aforementioned atmospheric turbulence as described in section 1.1, it is not the only one. The gust might be caused by an aircraft. A helicopter blade interacting with earlier shed tip vortices from an upstream blade during forward flight, and an aircraft flying through another aircraft’s wake, an aircraft landing on a ship encountering the wake caused by the ship’s superstructure may all be considered examples of wind gusts.

1.3.2 Canonical Discrete Gust Types

This section seeks to introduce the canonical discrete gust types in terms of directionality. The gust experienced in an actual flight is inherently three-dimensional and particularly complicated. To simplify the problem, most studies have focused on two-dimensional gusts, which have been categorized into three types: longitudinal, transverse, and vortex [55, 56]. Longitudinal gusts cause

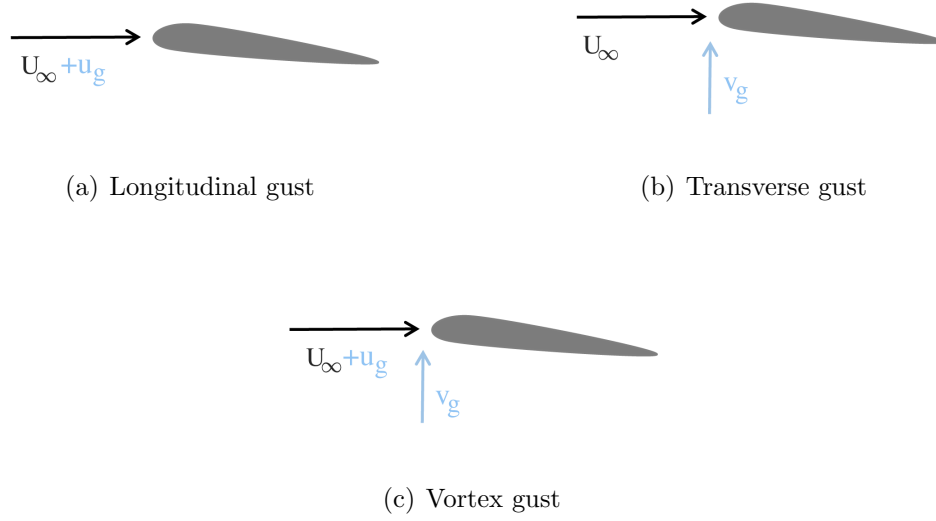


Figure 1.5: Sketches of canonical discrete gust types.

streamwise perturbations in the flow, as illustrated in Figure 1.5(a). Transverse gusts can be defined as fluctuations in the stream-normal direction and displayed in Figure 1.5(b). Lastly, Figure 1.5(c) shows a sketch for the vortex gust, which causes both streamwise and stream-normal fluctuations in the flow. Please note here that lateral gust is another gust type, which causes perturbations in the spanwise direction and is not discussed herein since the flow, in that case, is not two-dimensional [45]. All gust types introduce changes in the dynamic pressure. Before discussing the previous experimental and computational work that has been done on these gust types (see section 1.3.5), an overview of pertaining steady and unsteady impulse methods will be given.

1.3.3 Thin Airfoil Theory

This section seeks to provide information on the steady and quasi-steady thin airfoils theory to provide a baseline for the unsteady models discussed in section 1.3.4. Both theories neglect contributions from the vorticity in the wake, assuming that the starting vortex is sufficiently far from the wing and the contribution from the wake is small compared to the bound vorticity of the airfoil. In addition, the theories only focus on the circulatory force, arguing that the contributions from the non-circulatory force are negligible. Moreover, the flow is assumed to be attached.

1.3.3.1 Steady Thin Airfoil Theory

This section will initiate the discussion on the thin airfoil theory by introducing the steady thin airfoil theory, which is derived by Max Munk, Birnbaum and Glauert in the 1920s [57]. The flow is assumed to be steady, incompressible, and inviscid and the body is assumed to be thin and has an infinite span (i.e., airfoil). In this theory, the camber line of a thin airfoil is replaced by a vortex sheet whose strength (see Figure 1.6(a)), γ , is defined in terms of the tangential velocities immediately above (u_1) and below (u_2) the vortex sheet. Mathematically, vortex sheet strength is defined as: $\gamma = u_1 - u_2$. There are two boundary conditions for this steady flow. One of these is the “no flow through the camber line” boundary condition, also known as the no-penetration condition. The second one is given by the Kutta condition, which essentially requires the flow to leave the trailing edge smoothly independent

of the trailing edge's shape, which can be sharp or cusped. Mathematically, the Kutta condition states that the vortex sheet strength at the trailing edge is zero ($\gamma(TE) = 0$).

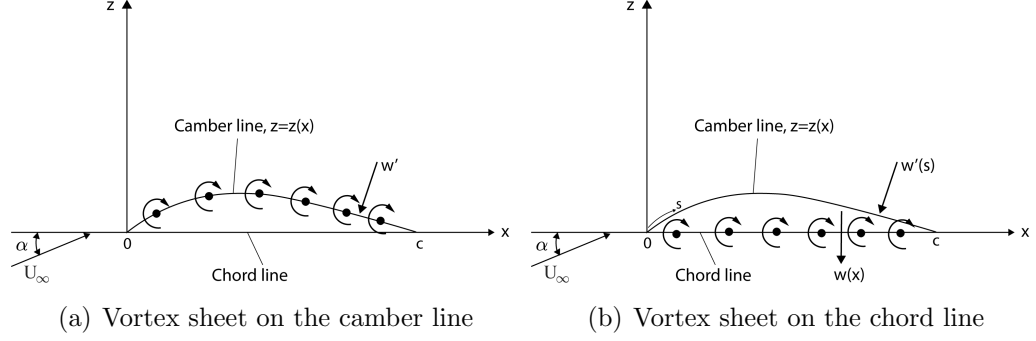


Figure 1.6: Vortex sheet placement, taken from [57].

The fundamental equation of the airfoil theory is based on the no-penetration boundary condition, which makes the camber line a streamline of the flow. Therefore, the total velocity through the camber line is zero. There are two contributions to this boundary condition, one of them is from the freestream ($U_{\infty,n}$), and the other one is from the vortex sheet induced velocities ($w'(s)$). Therefore, the equation can be written as:

$$U_{\infty,n} + w'(s) = 0, \quad (1.1)$$

The normal velocity contribution that comes from the vortex sheet $w'(s)$ is calculated from a vortex sheet that is placed on the chord line, arguing that the airfoil is thin and the camber line and chord line are close to each other ($w'(s) \approx w(x)$), see Figure 1.6(b). Even though the calculation is done for the vortex sheet placed on the chord line, please note that the strength of the vortex sheet is calculated such that

the camber line (not the chord line) is a streamline of the flow. After calculating the above-mentioned normal velocity contributions, the vortex sheet strength can be found using the Kutta condition and is given for symmetric airfoils as:

$$\gamma(x) = -2\alpha U_\infty \frac{(x + c/2)^2}{\sqrt{(c/2 - x)}}, \quad (1.2)$$

where α is a small angle of attack, c is the chord length, and x is the distance from mid-chord such that $x = -c/2$ is the leading edge and $x = c/2$ is the trailing edge. Using this vortex sheet strength, the circulation can be calculated easily using the definition of circulation:

$$\Gamma = \int_{-c/2}^{c/2} \gamma(x) dx = \pi\alpha c U_\infty. \quad (1.3)$$

By substituting this circulation into the Kutta-Joukowski theorem, the lift force per unit span (L') can be found as:

$$L' = \rho U_\infty \Gamma = c\pi\alpha U_\infty. \quad (1.4)$$

Therefore, the lift coefficient becomes

$$C_l = \frac{L'}{0.5\rho U_\infty^2 c} = 2\pi\alpha. \quad (1.5)$$

As can be seen from equations 1.4 and 1.5, the lift force depends on both the freestream velocity and the angle of attack, whereas the lift coefficient is only a function of the angle of attack. This theory is applicable to thin airfoils at small

angles of attack since when the angle of attack is large, the flow separates, and the attached flow assumption is not valid.

1.3.3.2 Quasi-steady Thin Airfoil Theory

Unlike the steady thin airfoil theory, in quasi-steady thin airfoil theory, the body oscillations are accounted for. However, the time history of motion is assumed to have no effect on the airloads. In other words, the present is assumed to be not affected by the past or the future. Therefore, the forces are derived from the steady thin airfoil theory assuming that the flow reaches to steady-state immediately after the changes in the velocity or the angle of attack. The theory also assumes that the wake effects and the non-circulatory forces (e.g., added mass) are negligible.

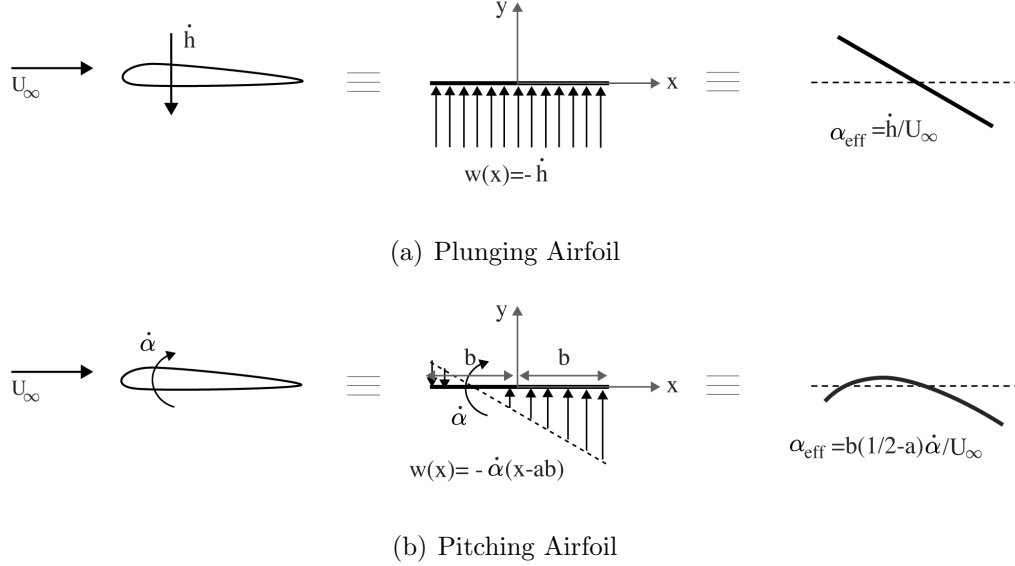


Figure 1.7: Pitching and plunging airfoils and the velocity perturbations caused by the airfoil's motion, taken from Ref. [58].

Leishman [58] divides the oscillation motion into two. The first motion is the plunge, where the airfoil can be modelled as a flat plate with uniform velocity

perturbations along the chord, as can be seen from Figure 1.7(a). Therefore, a plunging motion of the thin airfoil induces a constant effective angle of attack. Therefore, plunging is essentially the same as increasing the geometric angle of attack. The second motion is pitching, where the airfoil can be modelled as a flat plate with non-uniform velocity perturbations along the chord. The non-uniform velocity perturbations cause the flat plate to experience different effective angles of attack along its chord. Therefore, it creates a virtual camber. In other words, the airloads caused by pitching motion are the same as an airfoil with a corresponding camber, as can be seen from Figure 1.7(b). The lift coefficient that arises from both motions can be found using:

$$C_l = 2\pi \left[\alpha + \frac{\dot{h}}{U_\infty} + b \left(\frac{1}{2} - a \right) \frac{\dot{\alpha}}{U_\infty} \right], \quad (1.6)$$

where α is the geometric angle of attack, $\dot{h}$ is the plunge velocity, a is the distance of the pitching axis from the mid-chord in chords, and $\dot{\alpha}$ is pitch rate. Therefore, in equation 1.6, the first term gives the steady-state lift coefficient, the second term is the contribution from plunging, and lastly, the third term is the contribution from the pitching.

The limitations of the quasi-steady thin airfoil theory are primarily rooted in the assumptions of the steady thin airfoil theory. Therefore, the quasi-steady thin airfoil theory assumes that all vorticity in the flow comes from the bound vorticity, the time history of the flow does not affect the airloads, and the flow is attached. Overall, this theory neglects two key contributions, which are the non-circulatory

effects and the wake effects.

1.3.4 Unsteady Models

This section seeks to describe the unsteady models that are used to predict the response of a thin airfoil. The unsteady models differ from the steady and quasi-steady models by incorporating the wake and non-circulatory effects to their analysis. An overview of the unsteady attached models used in the literature is given below.

1. **Theodorsen** provides the unsteady aerodynamic solution in the frequency domain for a harmonically oscillating thin airfoil [59].
2. **Sears** provides the unsteady aerodynamic solution in the frequency domain for a thin airfoil encountering sinusoidal transverse gust [60].
3. **Atassi** provides the unsteady aerodynamic solution in the frequency domain by expending Sears's model to include longitudinal disturbances [61].
4. **Greenberg** provides the unsteady aerodynamic solution in the frequency domain for an oscillating freestream or thin airfoil [62].
5. **Wagner** provides the unsteady aerodynamic solution in the time domain for a step-change in the flow conditions [63].
6. **Küssner** provides the unsteady aerodynamic solution in the time domain for a thin airfoil encountering a sharp-edged transverse gust with an infinite gust width [64].

7. **Miles** provides the unsteady aerodynamic solution in the time domain for a thin airfoil encountering a convecting (in-plane) transverse sharp-edged gust [65].

All of the above-mentioned models assume that the flow is attached, two dimensional, incompressible, inviscid, and the disturbances are small. As described in section 1.2, this work focuses on the response of a flat plate wing encountering a sine-squared transverse gust. Therefore, the effects of the physical gust used in this study can be modeled the best using Küssner’s model, which is described in more detail in section 1.3.4.2. However, before that, Wagner’s model will be discussed in section 1.3.4.1 to provide a base for the Küssner’s model.

1.3.4.1 Wagner’s Model

Wagner’s model [63] is applicable to two typical problems. The first of which is an airfoil at a small angle of attack accelerating. The second one is an airfoil experiencing a step-change in the angle of attack. Therefore, it is the most plausible to define Wagner’s model as a tool that can be used to find the unsteady force production in the time domain for the step changes in either acceleration or angle of attack. Wagner’s model uses the Kutta condition, as does the thin airfoil theory. However, unlike the thin airfoil theory, the circulation is allowed to be shed from the trailing edge in this unsteady model. The shedding occurs at such a rate that the vortex sheet strength at the trailing edge is always zero, thereby satisfying the boundary condition. As established by Kelvin’s circulation theorem, the total

circulation is conserved [66]. Thus, the circulation shed into the wake alters the bound circulation and causes a lift deficiency. Wagner's model assumes the flow is two dimensional, incompressible, and inviscid, and the angles are small. Moreover, the trailing wake is assumed to not deflect from the horizontal axis. The lift coefficient for this model is given by

$$C_l = \frac{\pi c}{2U_\infty} \delta(t) + 2\pi\alpha\phi(t^*), \quad (1.7)$$

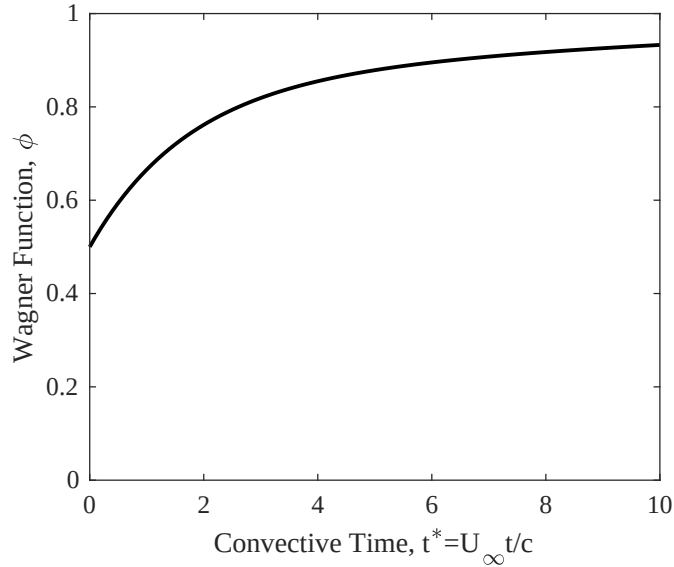


Figure 1.8: Wagner's function for a step change.

where the $\delta(t)$ is the Dirac delta function and represents the step change and $\phi(t^*)$ is the Wagner function. The first term in equation 1.7 is the non-circulatory force (i.e., added mass that occurs due to the step change), and the second term is the circulatory force. Wagner's function can be approximated as [67]:

$$\phi(t^*) \approx 1 - 0.165e^{-0.091t^*} - 0.335e^{-0.6t^*}, \quad (1.8)$$

where t^* is the chords traveled by the airfoil. Figure 1.8 displays the Wagner’s function. As can be seen from this figure, at $t^* = 0$, where the step change occurs, the value of Wagner’s function is 0.5. This jump from 0 to 0.5 is caused by the acceleration (added mass). The value of the Wagner’s function asymptotes to 1 as $t^* \rightarrow \infty$, where the lift coefficient approximates to $2\pi\alpha$ (i.e., the steady-state value). Wagner’s model accounts for the vorticity shed into the wake, added mass, and bound vorticity. However, it neglects the viscous forces that arise in low Reynolds numbers, where the flow is prone to separation.

1.3.4.2 Küssner’s Model

Küssner’s model [64] is a linear analytical model to predict the lift force for a flat plate encountering a sharp-edged transverse gust with infinite gust width. Küssner’s model, just like any other linearized model, comes with quite strict assumptions. The flow is assumed to be two dimensional, incompressible and inviscid. Küssner’s model uses the superposition principle to analyze this potential flow. The lift coefficient consists of three parts, and is given in Ref. [60] as $C_l = C_{l_0} + C_{l_1} + C_{l_2}$.

- (a) C_{l_0} , this term is calculated according to thin airfoil theory, and no wake effects are included in these calculations. Therefore, this is a quasi-steady quantity.
- (b) C_{l_1} , this term is called “apparent mass” in Ref. [60] . However, Corkery proved recently that there is no apparent mass in the physical flow since there is no acceleration associated with the wing. This contribution was rather assigned

to the existence of a gust shear layer [68].

- (c) C_{l_2} , this term is the one that depends strictly on the vorticity distribution in the trailing wake.

The model calculates these lift contributions based on the gust encounter's analogy to a broken-line airfoil as shown in Figure 1.9. The broken-line airfoil is based on the principle that the gust velocities cause an increase in the effective angle of attack of a wing. Therefore, the bound vorticity distribution during the gust encounter is calculated based on the gust-induced effective angle of attack. The details of the derivation can be found in Refs. [60], [64].

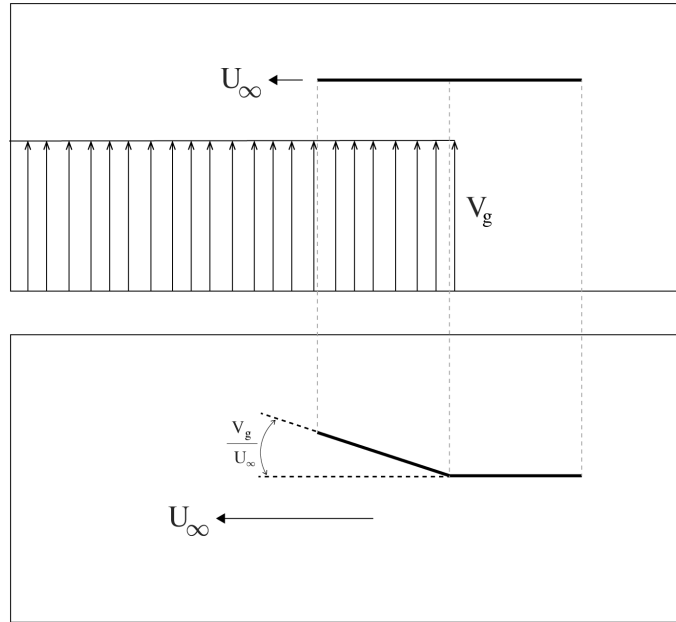


Figure 1.9: Analogy between the transverse gust encounter and a broken-line airfoil, adapted from Ref. [60].

The resulting lift coefficient is written in the following format

$$C_l = 2\pi \frac{V}{U_\infty} \psi(t^*), \quad (1.9)$$

where t^* is the number of chord-lengths the wing has travelled, V is the gust velocity, and $\psi(t^*)$ is the Küssner function, which is generally replaced by the exponential approximation given by [69]

$$\psi(t^*) \approx 1 - 0.5e^{-0.26t^*} - 0.5e^{-2t^*}, \quad (1.10)$$

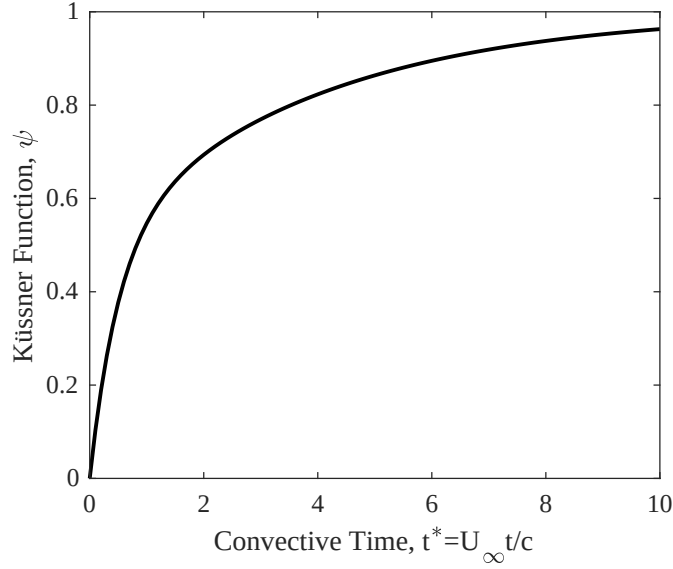


Figure 1.10: Küssner's function for an infinitely long sharp-edged gust.

which is displayed in Figure 1.10. Although the Küssner model is for an infinitely long sharp-edged gust, the Duhamel superposition integral can be used to find the lift response to any arbitrary transverse gust profile [58], given by

$$C_l = \frac{2\pi}{U_\infty} \left(V_g(0) \psi(t^*) + \int_0^{t^*} \frac{dV_g(\sigma)}{dt} \psi(t^* - \sigma) d\sigma \right), \quad (1.11)$$

where σ is a dummy integration variable, $\psi(t^*)$ is defined with equation 1.10 and V_g is the gust velocity profile. The limitations and accuracy of the Küssner model will

be assessed in chapter 5 for various velocity profiles using the convolution provided above.

1.3.5 Studies on Canonical Discrete Gust Types

Two-dimensional gust types were described in section 1.3.2. This section provides the studies that have been made for different gust types, namely longitudinal, transverse, and vortex gusts.

1.3.5.1 Longitudinal Gust Encounters

Longitudinal gusts have been extensively investigated in the past [70–73]. This type of gust can be created by oscillating the freestream or the test model [72]. While it is relatively easy to obtain the streamwise gust by adjusting the towing speed/acceleration in a water tank [74, 75], it can also be created in an unsteady wind tunnel or a low-speed wind tunnel by oscillating the freestream [76]. Since the perturbations occur in the same direction as the freestream for this gust type, no change in the effective angle of attack is observed during the encounter. For example, Granlund et al. [72] examined the response of an airfoil to a low-amplitude longitudinal gust. In this study, both wind and water tunnels were used to create a longitudinal gust over a wing. In the wind tunnel, an unsteady pressure gradient was used to oscillate the freestream flow, whereas in the water tunnel, the wing was driven in a sinusoidal modulation while submerged in a steady freestream flow. They concluded that both the “oscillating model” and “oscillating freestream” approaches

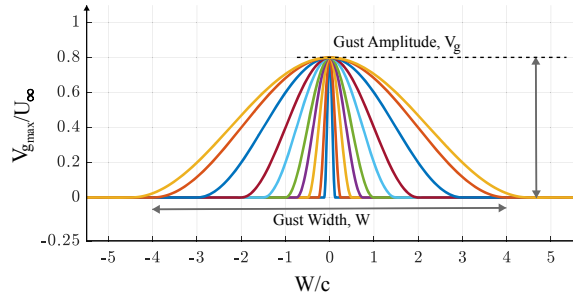
can be used to investigate gust response for low-amplitude longitudinal gusts over a wide range of reduced frequencies. Furthermore, in an attempt to predict the gust response, Greenberg’s theory [62] was used and the predictions were compared with the experimental data obtained in both facilities. At attached flow conditions, the forces showed good agreement with classical theory by undergoing weak amplitude changes depending on the reduced frequency, whereas a high dependency on reduced frequencies due to large leading edge vortex shedding was observed in the separated flow region. Greenberg’s theory was found to be inadequate to predict the forces at high reduced frequencies since the attached inviscid flow assumption is inapplicable in this region. A similar result was found in a separate study by Kirk et al. [77], where a sinusoidally surging flow was investigated for various amplitudes and frequencies, the results showed good agreement with Greenberg’s theory for the attached flow region.

1.3.5.2 Transverse Gust Encounters

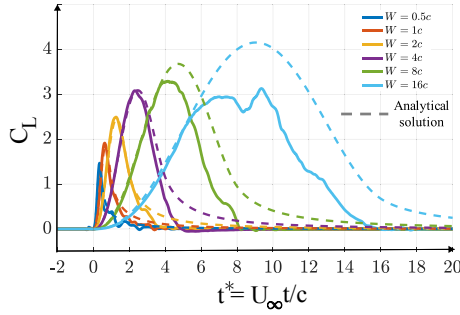
Compared to longitudinal gusts, transverse gusts are harder to create. Even though early researchers were able to achieve low to moderate gust ratios (i.e., the ratio of the gust velocity to the freestream, GR) using closed-jet systems in wind tunnels [78, 79], there was little or no research performed for high-amplitude transverse gust encounters until recently. With growing interest in MAVs, high-amplitude transverse gusts became the focus of attention and have recently been created experimentally using jet systems in water tanks by several research

groups [40, 80, 81]. For example, Holmes [79] generated a transverse gust in a wind tunnel using a closed jet system with time-varying sinusoidal tunnel walls and achieved transverse gust ratios between 0.05 and 0.095. After an investigation of pressure fluctuations on the trailing edge caused by viscous effects, Holmes concluded that the limited separation region that formed due to the extremely small gust ratios achieved allowed for a valid comparison with Kemp’s theory [82] which presents a prediction for fluctuating lift due to non-convecting transverse gust presence. In a separate study, Kuethe [78] also created a transverse gust in a wind tunnel by using an open jet that consisted of a motor and a propeller by which he achieved a gust ratio of 0.24. He also found that lift measurements compared well with analytical theory, this time the two-dimensional theory of Von Kármán and Sears [83]. More recently, Perrotta and Jones [40] constructed a system to produce high-amplitude transverse gusts in a water-filled towing tank using a vertically oriented water jet. In this setup, this gust generation system was able to create only one gust velocity because of hardware limitations. The gust ratio was therefore adjusted by changing the towing velocity of the wing. Using this setup, they were able to achieve gust ratios greater than 1.0. The local increase in the dynamic pressure caused by the gust resulted in large force transients due to the shedding of leading and trailing edge vortices. A semi-empirical quasi-steady analysis was undertaken and results showed agreement while the wing was in the gust, but failed to predict the gust recovery phase. Finally, in another study, by Corkery et al. [81, 84], a top-hat gust was generated in a water tank by using a unique design of a cross-flow test rig. As in the previous work, large force transients caused by the formation and shedding

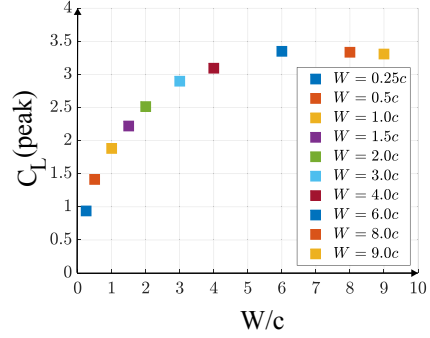
of vortices were observed in strong gusts (with a gust ratio of 1). They found that Küssner's theory [64] showed satisfactory agreement during the wing entry for the $GR \leq 0.5$ cases, whereas significant discrepancies between the theory and measurement were observed for larger gust ratios. For all gust ratios investigated ($0.2 \leq GR \leq 1$), the theory failed to predict the lift response of the encounter when the wing became fully immersed in the gust.



(a) Various gust widths



(b) Computational and analytical lift coefficients



(c) Maximum lift coefficients

Figure 1.11: Investigation of a flat plate at 0° angle of attack encountering sine-squared transverse gust of various widths: a) velocity profiles, b) computational and analytical lift coefficients, and c) maximum lift coefficients, taken from Ref. [85].

On the other hand, in recent computational studies, where the high-amplitude gust encounters were examined. The gust was created by either introducing a source term to the unsteady models such as the split velocity method and field velocity

method [80, 86] or implementing jet boundary conditions [87, 88]. The results of both computational methods were compared with experimental data and found to yield physical responses. Badrya et al. [85] modeled the physical sine-squared transverse gust used in the current study. The lift response of a flat plate wing was investigated for the gust widths shown in Figure 1.11(a) by applying the split velocity method with a source term. Two angles of attack, namely 0° and 45° , were used. For the cases where the angle of attack is 0° , the Küssner's model was found to accurately predict the maximum lift up to the width-to-chord ratio of 4 as shown in Figure 1.11(b). The maximum lift coefficient was found to asymptotically increase with increasing gust width, which is displayed in Figure 1.11(c) for the $\alpha = 0^\circ$ case. In a separate computational study [87, 88], the aforementioned top-hat gust was simulated using a jet boundary condition method. The study showed that the maximum lift coefficient increases as the gust ratio increases. Moreover, it showed that the non-circulatory force experienced during gust encounters are independent of the gust ratio.

The studies proved that the transverse gust encounters cause significant transients in the lift force. However, the effect of the transverse gust encounter on the drag force was often neglected. Moreover, a thorough parametric study was not performed for this gust type. One of the main aims of the current work is to address these gaps in the literature.

1.3.5.3 Vortex Gust Encounters

Vortex gusts can be created experimentally either by pitching and/or heaving an upstream plate, [89–91] or by an upstream bluff body such as rotating cylinder [89, 92, 93]. For instance, Engin et al. [89] created a vortex gust by pitching a flat plate wing upstream of a test model in a water channel. In this study, they concluded that vortex gust encounters cause dramatic force transients. The parametric study they performed on the angle of attack showed that the forces exhibit self-similarity. The effects of gust ratio on the forcing were not investigated in this study, arguing that the gust generation process is complicated using a pitching gust generator plate. The same experimental setup and vortex generation system was used in a separate study by Biler et al. [90]. Figure 1.12(a) displays the vortex gust and the perturbations it causes in both longitudinal and transverse directions. The best fit to the measured perturbations was found to be the Lamb–Oseen vortex model [94]. In this study, the vertical offset, Δy , between the centerline of the gust generator plate and the test model when both are at 0° was varied to investigate the effects of the incoming vortex position (i.e., the path that vortex follows). Figure 1.12(b) shows the vortex core positions during the encounters for three different vertical offsets. The authors concluded that for a flat plate at 0° angle of attack, changing the vertical positioning of the incoming gust causes minor effects at almost every point in the lift response, which consists of a local maximum, a global minimum, and a secondary maximum (see Figure 1.12(c)). Moreover, they found that the transients in the lift force follow the same trends as the effective angle

of attack. In another experimental study by Hufstedler et al. [91], a novel vortex gust generation method was introduced, where the gust generator plate heaves across a water tunnel and swiftly changes its direction and resides at the edge of the tunnel. This heaving vortex gust generation method was compared with a pitching vortex gust generation method. The resulting flowfields and forces were also compared for two methods, and the authors concluded that the heaving method is more efficient in creating an isolated vortex since the wake of the gust generator plate does not interact with the test model downstream and cause unintentional force transients. On the other hand, they also noted that the pitching method results in a more spatially compact vortex gust. Rockwood et al. [95] used a rotating cylinder, which has a one-diameter long attached plate, to create the vortex gust in a water tunnel. Using this setup, Von Kármán vortex streets with various oscillation frequencies (different than the natural frequency of the stationary cylinder) were achieved. This setup was found to annihilate the shedding of any unintentional vortex from the gust generator. Moreover, unlike the heaving and pitching gust generator plates, the vortex strength was found to be altered easily by changing the actuation parameters.

Most of the computational studies performed on vortex gusts model the isolated vortex using the Taylor vortex profile. Even though the computations require experimental validation, the computational studies offer significant advantages for this gust type since as explained before, it is very challenging to create a free vortex gust experimentally without having the effect of an upstream body on the response of the test model. Previous studies by the collaboration between the Air Force Research Laboratory and Embry-Riddle Aeronautical University [96–98]

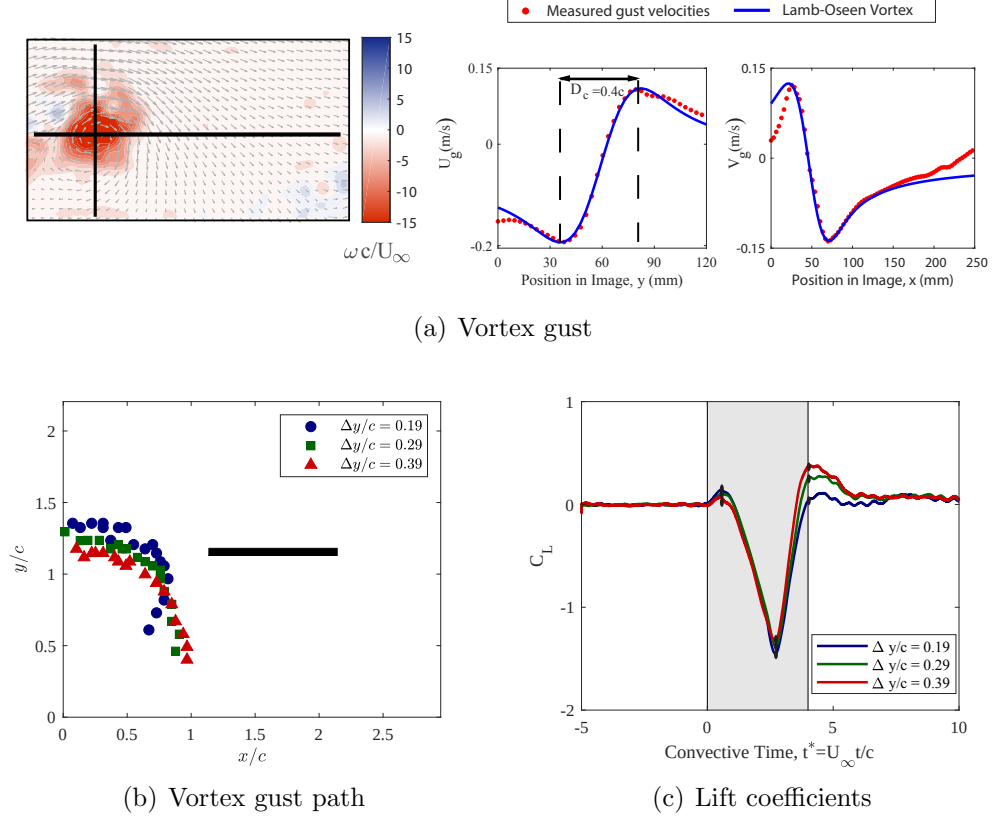


Figure 1.12: Investigation of a flat plate at 0° angle of attack encountering vortex gust of various incoming positions: a) velocity profile, b) path of the vortex gust , and c) experimental lift coefficients, taken from Ref. [90].

paved the way for an overall investigation of vortex gust encounters by Nyguen et al. [99], where the effect of various parameters on the response of an SD7003 airfoil encountering a vortex gust was explored. The study was performed using high-fidelity Navier-Stokes simulations, and the vortex gust was prescribed to have a Taylor vortex velocity profile. The effects of the parameters such as rotation direction of the vortex, incoming vortex path, vortex size, and vortex strength were investigated. The results showed that the lift response includes multiple peaks and is highly nonlinear. While the high-amplitude vortex gust encounters were found to impact the global extrema, the low-amplitude vortex gust encounters were found

to have a dramatic effect on the recovery portion. Increasing the vortex size was found to increase the lift extrema. Moreover, the incoming path of the vortex was found to have a minor effect on the lift transients. The counterclockwise rotating vortex was found to have a more profound effect on the lift force compared to a clockwise rotating vortex. In a separate study by Barnes et al., [100], implicit large eddy simulations (ILES) was used to model the interaction between a Taylor vortex gust and a NACA0012 airfoil. In this study, three different initial vertical positions of the gust were examined. The one whose core is aligned with the leading edge of the wing was found to cause the largest transients in the lift.

1.3.6 Studies on Gust Mitigation

The end goal of this body of gust studies is to mitigate the effects of a wing-gust encounter. To do so, researchers have also attempted to capture the effects of the different types of gusts on a wing using a well-investigated motion profile, e.g., pitching, plunging, surging, or a combination of these. Results have shown that it is possible to replicate streamwise gusts by surging [72], but a close analogy has not been found for transverse or vortex gusts [101–103]. Instead of recreating the gust, well-known motion profiles have been used to mitigate the effect of the gust [104–107]. For example, Andreu and Babinsky were able to achieve 95% gust mitigation for large-amplitude top-hat gust encounters by using a hybrid model that not only maintains zero mean effective angle of attack but also captures the added mass and shed vorticity [104]. In a separate study, a Goman Khrabrov (GK)

model based on effective angle of attack was used to mitigate the effects of a large-amplitude sine-squared transverse gust. By designing a controller based on this model, a reduction in lift coefficient up to 90.43% was achieved [107]. No mitigation model has been shown to work on different types of gusts. To develop such a model, a comparison of different gust velocity profiles and gust types should be thoroughly explored. However, there have not been many comparisons of different gust types and velocity profiles. The current study aims to address this gap in the literature.

1.4 Present Work

The current work aims to improve the understanding of gust encounters, especially on the sine-squared transverse gust encounters. By doing so, it will pave the way for novel controllers to be built, thereby expanding the operational envelopes of MAVs. In this study, a new fluid gust system was designed, constructed, and characterized. Forces, two dimensional and three-dimensional flowfields were experimentally obtained for the sine-squared transverse gust encounters. The results were compared to a convolution of Küssner’s function. Along with the research performed independently, collaborations were done with the University of Cambridge (UC), where the top-hat transverse gust encounters are investigated, and the Istanbul Technical University (ITU), where vortex gust encounters are investigated, allowing for a comparison of different velocity profiles and gust types. The objectives of the current work are

1. to expand the existing understanding behind sine-squared gust encounters

by exploring the force (both lift and drag) transients, wake features (both two- and three-dimensional), and circulation production for a large range of disturbances.

2. to perform a parametric study on the sine-squared gust encounters. The parameters investigated include gust ratio, angle of attack, effective angle of attack, and aspect ratio. This thorough analysis will allow for novel normalization methods to be developed.
3. to introduce and assess the applicability of normalization methods to scale the responses of various angles of attack, gust ratio, effective angles of attack, and transverse velocity profiles.
4. to evaluate the accuracy and limitations of Küssner's model and identify the effect of transverse gust velocity profile by comparing the sine-squared (UMD) and the top-hat (UC) gusts. This step will allow for a thorough investigation of the model.
5. to compare different gust types, the sine-squared transverse (UMD) and the vortex (ITU) gusts, in terms of lift force, flowfields, and circulation production. This comparison will improve the overall understanding of the flow physics behind gust encounters, which has not been done before.
6. to determine the relationship between the effective angle of attack and the lift force and to propose a flowfield-based force prediction method for both the sine-squared transverse (UMD) and the vortex (ITU) gusts.

1.5 Dissertation Outline

The details of the design and characterization of the gust fluid system and the experimental setup used to collect the force, flowfield, and circulation measurements for the sine-squared transverse gust experiments are given in chapter 2. Chapter 3 provides the experimental and numerical methods utilized by collaborators for the top-hat transverse gust experiments (UC), the vortex gust experiments (ITU), and the sine-squared transverse gust simulations (UMD). Chapter 4 details the trends on the forces, flowfields, and circulation production, elucidates the flow physics behind the force transients, and provides a parametric study for the sine-squared gust encounters. Chapter 5 evaluates the accuracy and limitations of Küssner’s model and explores the effect of transverse gust velocity profile by comparing the sine-squared (UMD) and top-hat (UC) transverse gusts. In chapter 6, a comparison between the sine-squared transverse gust (UMD) and the vortex gusts is given. In addition, this chapter introduces a flowfield-based force prediction method and investigates the relationship between the effective angle of attack and lift force. Lastly, chapter 7 summarizes the current work, lists the original contributions, and provides suggestions for future work.

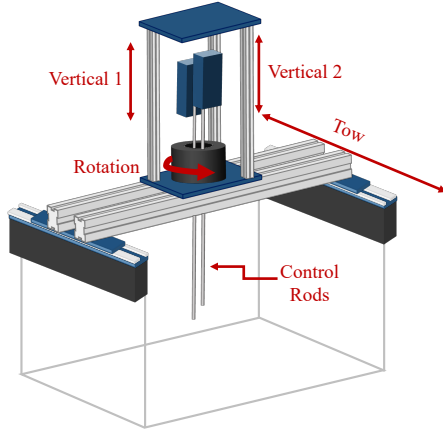
Chapter 2: Methodology

This dissertation aims to deepen the understanding of fundamental flow physics behind unsteady force production during gust encounters. This chapter will outline the experimental data acquisition equipment and techniques used to investigate sine-squared transverse gust encounters, which produced the bulk of the results presented in this dissertation. The reader will also find the design and characterization of a new fluid gust system, and the errors associated with the measurement techniques utilized. All in all, the methods described here will produce a comprehensive database for the sine-squared gust encounters.

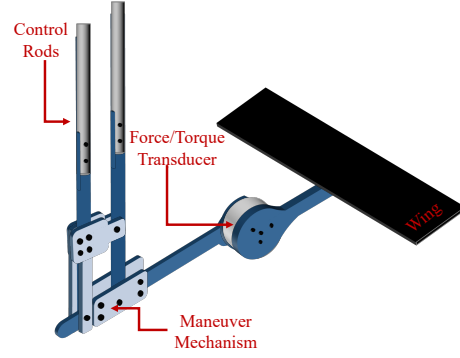
2.1 Facility

The University of Maryland free surface water towing tank, shown in Figure 2.1, was used to perform the experiments presented in this dissertation. The dimensions of the tank are 7 m long, 1.5 m wide, and 1 m deep. The towing tank has steel frames that hold glass walls, thereby allowing optical access for particle image velocimetry (PIV).

A 4 degree-of-freedom (DOF) model motion control system, shown in Figure 2.1(a), allows for streamwise, stream-normal, rotating, and pitching motions.



(a) Sketch of towing tank cross-section



(b) Wing mount

Figure 2.1: Experimental setup and wing installation mechanism.

The motor assembly consists of 2 independent parallel vertical brushless linear motors (H2W BLDC-04) that drive pitching and plunging motions. Actuating the motors in phase produces a plunging motion and/or ensures that the test model tows at the desired depth; actuating the rods out of phase produces a pitching motion and/or ensures that the test model is at the desired angle of attack. These motors are directly connected to the control rods visible in Figure 2.1(a). The motion system also includes a brushless rotary stage that allows for continuous rotation (not used for the tests presented in this dissertation), and two brushless linear motors (H2W BLDC-08) that drive streamwise translation along the length of the tank to generate the freestream velocity. A multi-axis Galil DMC 4153 is used as the motion controller for the entire motion control system, along with magnetic encoders to provide motor positions. The error in the motion, i.e. the difference between the commanded and actual motor positions, was found to be less than 1 mm, which corresponds to a maximum of 0.08% error in the streamwise direction.

Using water as the operating fluid instead of air offers considerable advantages. For the same Reynolds number ($Re_{air} = Re_{water}$) and test model, the model velocities in water are 0.066 of the ones in air ($U_{water} = \frac{\nu_{water}}{\nu_{air}} U_{air}$, where ν is the kinematic viscosity and U is the freestream). Since the experiments performed in any Newtonian fluid at an equivalent Reynolds number would yield the same force coefficient ($C_F = \frac{F}{0.5\rho U^2 cb}$, where F is the force, ρ is the density, c is the chord length, and b is the span), a model in water experiences 3.6 times greater forces than the one in air ($F_{water} = \frac{\rho_{water}}{\rho_{air}} \left(\frac{U_{water}}{U_{air}} \right)^2 F_{air}$). Furthermore, using water advances the ability to investigate unsteady flows using PIV since the density matching of the seeding particles and water is generally better [108]. Moreover, water grants the most accessible and safest form of flow visualization technique, dye-flow visualization [109]. Accelerating the test model using the towing tank also brings numerous conveniences. Firstly, accelerating the fluid creates a pressure gradient on the model, and therefore causes buoyancy-like forces, whereas accelerating the test model does not. In addition, turbulence levels in the towing tank are extremely low vis-à-vis wind and water tunnels. Please note that the turbulence levels of the towing tank used for this dissertation will be discussed in section 2.4 along with the settling time.

2.2 Test Models

The wing was mounted on the mechanism shown in Figure 2.1(b) and connected to the linear motors mounted on the forcing carriage via control rods.

This mounting configuration allowed for a clear separation between the wing and the control rods.

Three different test models, all of which were simple flat plates, were used for the force measurement experiments presented in this dissertation. This geometry was chosen to reduce the geometric complexity, to be consistent with previous work on pitching, surging, and plunging wings (e.g., [40–43]), and to provide a more direct comparison with unsteady thin airfoil theory and Küssner’s model. The first test model (wing 1) was a brass flat plate of aspect ratio 4 (5 cm chord, 20 cm span) and a 0.03 thickness-to-chord ratio. Brass was selected because of its corrosion-resistant nature. The second (wing 2), third (wing 3), and fourth (wing 4) test models were 4.3% thick aluminum flat plates of aspect ratio 4 (3 in chord, 12 in span), aspect ratio of 6 (3 in chord, 18 in span), and aspect ratio of 8 (3 in chord, 24 in span), respectively. These wings were primed and coated to improve the corrosion resistance of aluminum. For the time-resolved PIV experiments, a glass flat plate of the same dimensions as wing 2 was used to avoid a laser shadow in the field of view. The dimensions of the test models used are tabulated in Table 2.1.

Table 2.1: The test models used for sine-squared transverse gust encounters.

Test Model Name	Dimensions	Gust Manifold Coverage	Width-to-chord
Wing 1	$c = 5\text{ cm}, b = 20\text{ cm}, \mathcal{R} = 4$	$4.6\,b$	4
Wing 2	$c = 3\text{ in}, b = 12\text{ in}, \mathcal{R} = 4$	$3\,b$	2.6
Wing 3	$c = 3\text{ in}, b = 18\text{ in}, \mathcal{R} = 6$	$2\,b$	2.6
Wing 4	$c = 3\text{ in}, b = 24\text{ in}, \mathcal{R} = 8$	$1.5\,b$	2.6

2.3 Transverse Gust

The transverse gust was created physically in the water-filled towing tank, described in section 2.1, using a vertically oriented jet system. The following subsections describe the gust generation system, gust characterization, and the unsteadiness in the gust.

2.3.1 Gust Generator System

Building on previous work [40], the fluid gust system was redesigned and reconstructed. In order to improve the previous design and allow for a broader range of gust ratio investigation, a variable speed pump was used. In this new setup, gust ratio can be controlled via the gust velocity, so the towing speed can be selected to obtain a better signal-to-noise ratio for the force measurements, thereby allowing the gust ratio variations to be independent of Reynolds number.

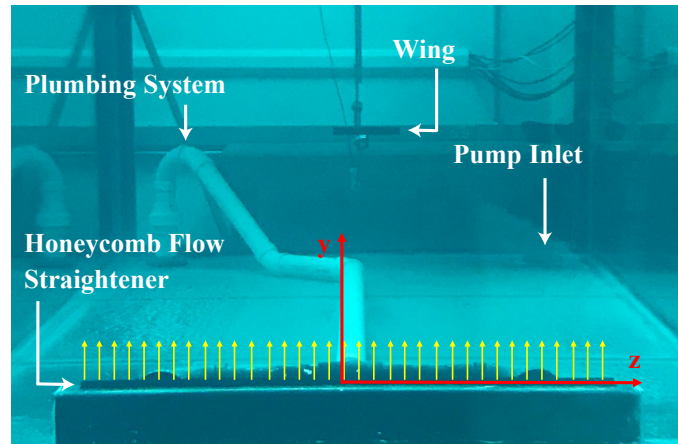


Figure 2.2: Gust generation system.

Figure 2.2 shows the gust generation system, which consisted of a swimming

pool pump (Hayward TriStar SP3202VSP), plumbing system made of PVC pipe, plenum, and a honeycomb flow straightener (36×0.5 inch) with an individual cell width of $1/8$ inch. The gust system manifold covers approximately 4.6, 3, 2, and 1.5 times the wing spans and leaves approximately 14, 8, 6, and 4 chords uncovered by the wing in spanwise direction for wings 1, 2, 3, and 4, respectively. The values of the gust system manifold coverage for different wings are also given in Table 2.1. The water is drawn from an inlet located at the bottom of the tank to the pump, which forces water through the plumbing system and flow straightener. As mentioned before, the water pump can operate over a range of different speeds, which allowed for a wide range of gust velocities. The honeycomb section was used not only to reduce the streamwise waviness of the gust but also to break down any large turbulent eddies in the flow. Please see section 2.3.5 for a more detailed analysis on the flow unsteadiness.

2.3.2 Gust Characterization Procedure

The resulting gust flow was characterized for 13 pump speeds and 4 spanwise locations using time-resolved PIV without the test model installed in the setup. Gust characterization was performed twice at each spanwise location to investigate the repeatability of the resulting flow which will be discussed in section 2.3.3. Figure 2.3 shows these different spanwise locations along wing 1: 1 chord-length off center towards the left (location 1), the spanwise center of the wing (location 2), 1 chord-length off center towards the right (location 3), and 2 chord-lengths off center

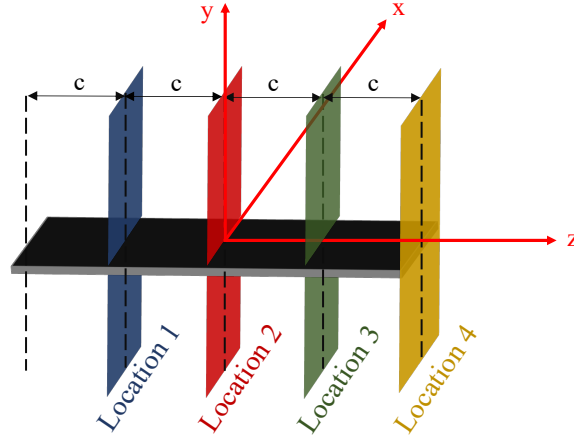


Figure 2.3: Spanwise gust characterization locations shown on wing 1 (5 cm chord, 20 cm span).

towards the right (location 4). In this PIV setup, a Nd:YLF laser (Litron LDY304, 30 mJ/pulse, 10 kHz max) was used as a light source. The flow was seeded with class IV soda lime spheres of $37\text{ }\mu\text{m}$ diameter. A Phantom v311 (1 MP) was used to record the images. Post-processing was performed in the LaVision software DaVis using multi-pass cross-correlation. The interrogation regions were 64×64 px for the first pass and 32×32 px for the second pass. Interrogation regions were overlapped by 50%. A local median filter was then applied to replace vectors if the difference to the averaged value was bigger than 2 standard deviations of its neighbors. 2,000 PIV images were acquired at 0.2 kHz and mean velocity fields were obtained at a distance 15 inches (approximately 8 chord lengths for wing 1 and 5 chord lengths for wings 2, 3, and 4) above the bottom of the water tank to the center of the region of interest (where the wing tows through). Maximum PIV uncertainty for the gust characterization was found to be 0.2%

2.3.3 Streamwise Velocity Profile and Pump Operating Range

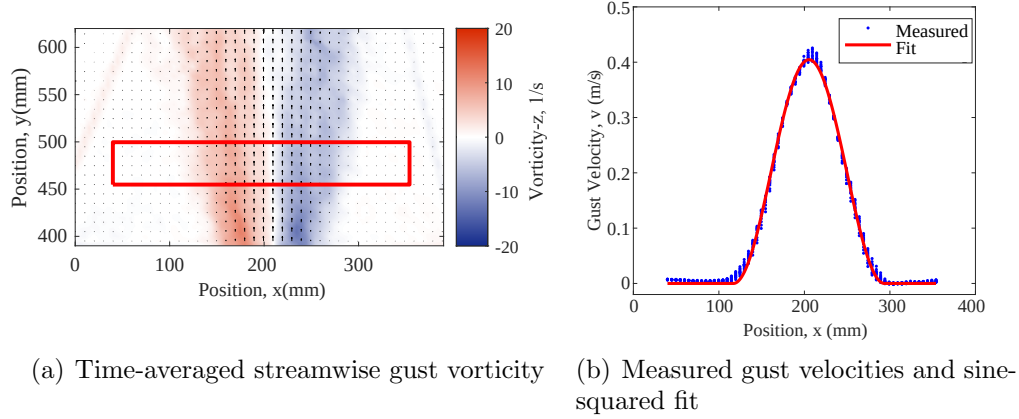


Figure 2.4: Sine-squared gust characterization for the highest pump speed at the centerline of the wing.

In order to characterize the mean streamwise velocity profile, time-averaged flowfields were analyzed for various pump speeds and spanwise locations. Figure 2.4(a) shows the time-averaged gust vorticity for the highest pump speed at the centerline of the wing (location 2). As can be seen from this figure, the shear layer covers the entire width of the gust, meaning the bulk of the gust flow is rotational. Here, the x and y axes represent the horizontal (streamwise) and vertical (stream-normal) positions, respectively. The red rectangle in this figure represents the region of interest. The mean measured velocities in the direction normal to the freestream (i.e., vertical) were extracted from this region and shown in Figure 2.4(b) along with the best fit to experimental data, which is found to be a sine-squared profile and given by: $V(x) = V_p \sin^2(\frac{\pi x}{w})$ where V_p represents the peak gust velocity, x represents the streamwise position, and w represents the gust width as calculated

based on the points where fluid velocity is zero.

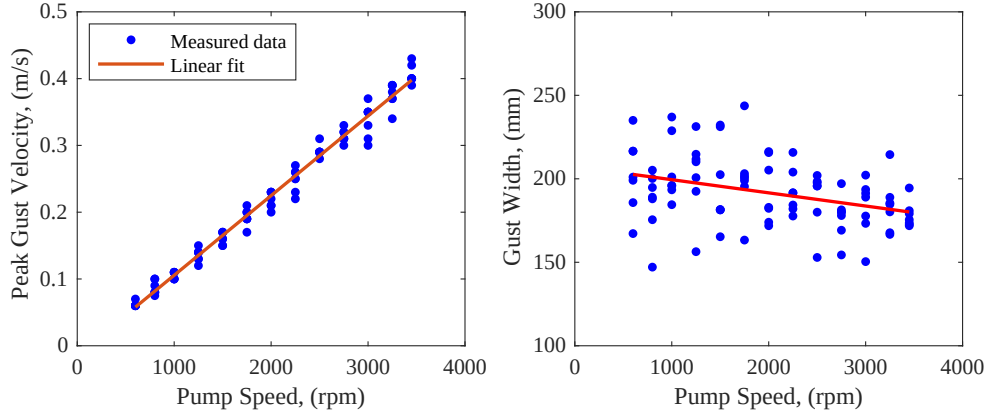


Figure 2.5: Linear fit to both peak gust velocity and gust width.

As mentioned earlier, gust characterization was performed for 13 pump speeds and twice for each spanwise location by fitting a sine-squared velocity profile to the time-averaged data. In an attempt to specify the pump operating range, two defining parameters of the sine-squared profile, namely peak gust velocity and gust width, were extracted from the time-averaged measurements for each case. The peak gust velocity was found to have a linear dependency on pump speed, as shown in Figure 2.5. The equation of this fit was found to be $y = 1.19 \cdot 10^{-4}x - 0.014$, where x represents the pump speed, and y represents the peak gust velocity. Moreover, the peak gust velocity was found to be repeatable for each spanwise location. The current setup was found to allow for a wide range of peak gust velocities between 0.06 m/s and 0.4 m/s. The gust width, on the other hand, does not fit any obvious function. In order to simplify the parameter space, the mean of the gust width was used, which was found to be 198 mm with a standard deviation of 22 mm or coefficient of variation 11%. Therefore, the ratio of the width of the gust to the

chord (w/c) was approximated to be 4 for wing 1 and 2.6 for wings 2, 3 and 4, which are tabulated in Table 2.1.

2.3.4 Spanwise Velocity Profile

The uniformity of spanwise velocity was qualitatively examined and confirmed using dye-flow visualization. To quantify this conclusion, the mean streamwise velocity profiles calculated based on the time-averaged flowfields of various spanwise locations (shown in Figure 2.3) were compared for 3 different pump speeds. Since the resulting gust flow is analogous to a jet, it oscillates with a longer period causing it to wave side to side. Even though a honeycomb section was used to eliminate the meandering effect, the gust is still somewhat wavy, which causes misalignments in the start position of the velocity profiles. The maximum offset between the sine-squared fits of different spanwise locations investigated here was found to be 20 mm, which corresponds to 0.1 convective times (i.e., chord lengths traveled by the wing) for wing 1, and 0.26 convective times for wings 2, 3 and 4. In Figure 2.6, the peaks of the velocity profiles were aligned to eliminate this offset and, therefore, the waviness effect for easier comparison of the shape and magnitude of the profile. Please note that this alignment does not cause any misinterpretation of the spanwise distribution of the gust since the experiments performed for different spanwise locations were not simultaneous. As can be seen from Figure 2.6, the agreement of the profile between different spanwise locations becomes better as the pump speed increases. The standard deviations and coefficients of variation of spanwise locations for different

pump speeds, tabulated in Table 2.2, confirms the aforementioned conclusion. The coefficients of variation of both the peak gust velocity and the gust width decrease with increasing pump speed, likely because more significant pressure in the gust generator system results in a steadier spanwise planar gust. Note that the variations in the gust width are more significant than the variations in the peak gust velocity. Overall, the system produced an approximately spanwise planar gust.

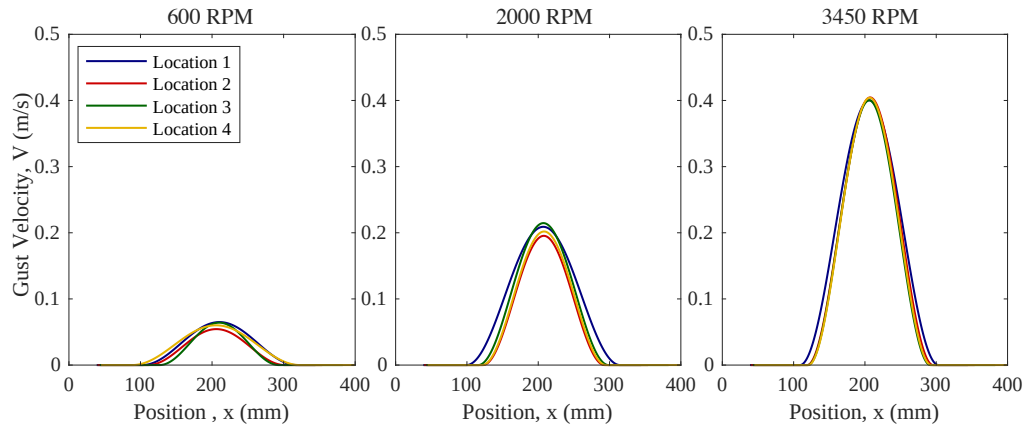


Figure 2.6: Characterized gust velocity profile for different pump speeds and spanwise locations.

Table 2.2: Coefficients of variation of the peak gust velocity and the gust width from various spanwise locations.

Parameter	Pump, (RPM)	Mean $\pm$ Stdev	Coefficient of Variation (%)
V_p , (m/s)	600	0.061 ± 0.005	7.9
	2000	0.205 ± 0.008	4.1
	3450	0.402 ± 0.002	0.6
w , (mm)	600	202.7 ± 29.5	14.6
	2000	185.8 ± 20.5	11.1
	3450	178.9 ± 10.6	5.9

2.3.5 Flow Unsteadiness

So far, time-averaged measurements have been considered. To further the characterization of the transverse gust, the gust unsteadiness will be the primary focus of this section. With this objective in mind, the average gust velocities and gust widths were obtained from instantaneous flowfields by fitting a sine-squared function at the centerline for 3 different pump speeds. The averaged profiles are shown in Figure 2.7, where the errorbars in gust width and peak gust velocity represent one standard deviation. The values of the peak gust velocity and the gust width coefficients of variation are given in Table 2.3. The maximum coefficients of variation found based on the instantaneous measurements were 30% and 24% in the peak gust velocity and the gust width, respectively.

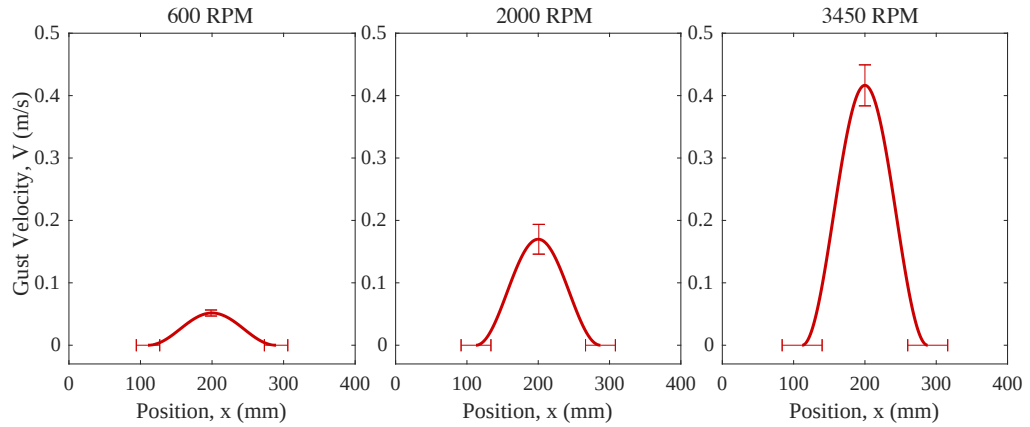


Figure 2.7: Average gust velocity profiles and standard deviations (Stdev) of instantaneous flowfields in both the peak gust velocity and the gust width for different pump speeds at the centerline.

Since the resulting gust flow is a planar jet, it is expected to be fully developed for $y/D \geq 4$, where y is the distance from the nozzle to the characterized height and

Table 2.3: Coefficients of variation of the peak gust velocity and the gust width from instantaneous measurements.

Parameter	Pump, (RPM)	Mean $\pm$ Stdev	Coefficient of Variation (%)
V_p , (m/s)	600	0.052 ± 0.009	17.3
	2000	0.159 ± 0.048	30.1
	3450	0.414 ± 0.066	15
w , (mm)	600	178.97 ± 32.74	18.3
	2000	174.53 ± 41.86	23.9
	3450	176.14 ± 28.03	15.9

D is the nozzle width [110]. In the current experiments, the gust was characterized at $y/D = 15/0.5 = 30$, and the flowfields obtained show the fully-developed canonical sine-squared profile. Fluctuation intensity within the gust can be defined as: $\sqrt{v'^2}/v$, where v' is velocity fluctuation and v is the mean velocity in the planar jet direction. Fluctuation intensities of the characterized gust at $y/D = 30$ were found to be near 0.3, while previous work [111] has reported fluctuation intensities nearer to 0.23 at $y/D = 20$.

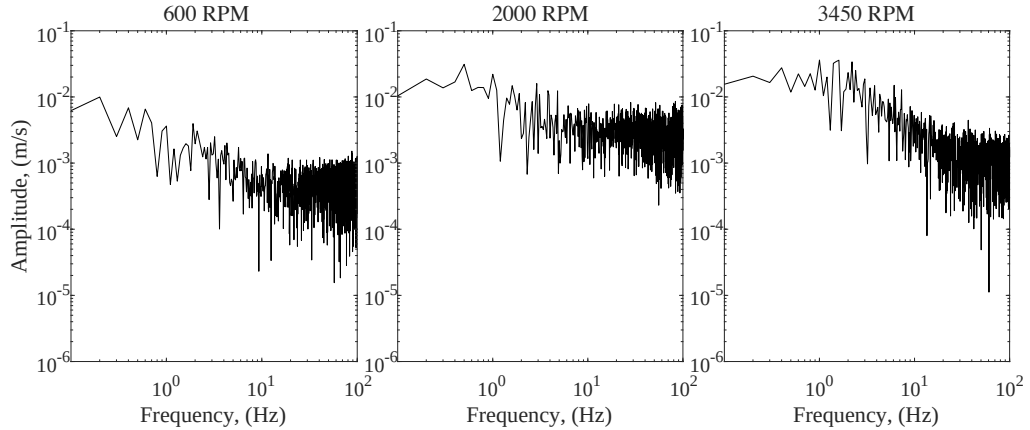


Figure 2.8: Fast Fourier Transform of instantaneous measured velocities for different pump speeds at the centerline shown on a logarithmic scale.

In order to examine the frequency content of the resulting flow, the measured velocities were extracted from the instantaneous flowfields for 3 different pump

speeds at the centerline for a position ($x = 214$ mm, $y = 480$ mm), where the gust velocity is maximum. A Fast Fourier Transform was then applied to the “signal” of extracted measured velocities. Figure 2.8 shows the amplitude versus frequency of these cases on a logarithmic scale. The pump speeds examined were 600 rpm, 2000 rpm, and 3450 rpm, corresponding to 10 Hz, 33 Hz, and 57.5 Hz, respectively. It can be seen that the dominant frequency content is relatively broadband at less than 10 Hz, and there are no dominant frequencies associated with the pump speed.

2.4 Kinematics and Defining Parameters

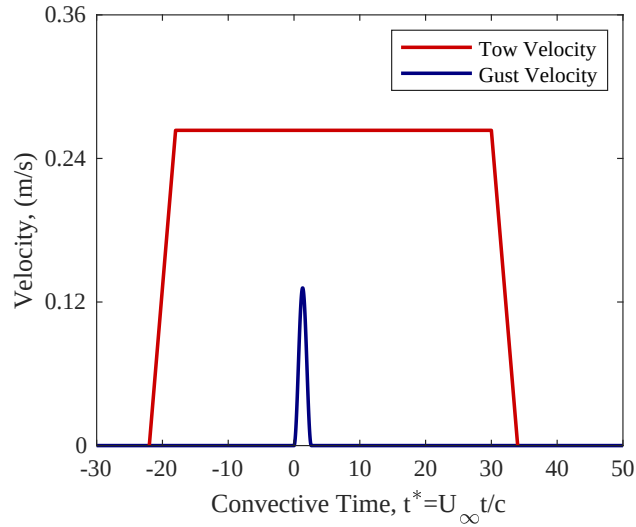


Figure 2.9: Towing velocity of wing 2 and a sample gust velocity profile of 0.13 m/s corresponding to a gust ratio of 0.5.

The working premise is simple; a model is mounted to the actuated carriage that tows the length of the tank. The test model was fixed to a constant angle of attack for each case before the motion began. Then, it was accelerated for some time, traveled with a constant freestream speed, encountered the gust, and decelerated

to a stop past the gust. Therefore, the towing velocity profile can be divided into three regions: acceleration, constant velocity, and deceleration. In order to provide a smooth transition between these regions, not to mention to avoid damaging the motor system, the Hermite Spline function consists of linear segments with 8th order polynomials used at the corners of the profile. For more details, please see Ref. [112]. The lengths of the towing velocity regions are given in chords in Table 2.4. Since the position of the gust generator is fixed in the setup, the test models with different chord lengths require different parameters for the trapezoidal towing profile. Sufficient travel distances were provided before and after the wing enters and exits the gust to ensure that the flow around the wing reaches the steady-state. Figure 2.9 shows this trapezoidal towing velocity profile, as well as the velocity of the gust encountered for a case where the gust ratio is 0.5. Here, the x axis represents the convective time (i.e., the chord lengths traveled by the wing), and $t^* = 0$ was defined as the time at which the leading edge of the wing enters the gust. The gust shown here has a streamwise sine-squared profile as characterized in the previous section.

Table 2.4: Motion profile parameters for the test models used in the experiments.

	Acceleration Region, (chords)	Constant Velocity Region, (chords)			Deceleration Region, (chords)	Total travel, (m)
		Before the Gust	Gust	After the Gust		
Wing 1 (chord= 5 cm)	6	44	4	22	6	4.1
Wings 2, 3, and 4 (chord= 3 in)	4	18	2.6	27.4	4	4.2

Reynolds number, therefore the freestream speed, was selected based on the

hardware limitations and force measurement sensitivities. Various combinations of gust ratio, $GR = \frac{V_p}{U_\infty}$, and angle of attack are investigated in this dissertation. Table 2.5 shows the test matrix for the sine-squared gust encounter experiments. Wing 1 was used to examine the effect of the encounter on the forces using a large sweep of low-amplitude gusts and angles of attack. These force measurement experiments were performed at a constant Reynolds number of $Re = \rho U_\infty c / \mu = 40,000$. Flowfields were obtained only for the $GR = 0.08$ & $\alpha = 10^\circ$, $GR = 0.16$ & $\alpha = 5^\circ$, and $GR = 0.26$ & $\alpha = 0^\circ$ cases via computations (whose methods will be discussed in 3.1.1). On the other hand, wing 2 was used to investigate the effects of large-amplitude gust encounters. These experiments were performed at a lower Reynolds number of 20,000 to allow for higher gust ratios in the setup. Force and PIV measurements were obtained for every case shown in the second row of Table 2.5. Dye-flow visualization experiments, however, were carried out only for gust ratios of 0.5 and 1, and angles of attack of $\alpha = 0^\circ$ and $\alpha = 20^\circ$. Wings 3 and 4 were used for force measurement experiments to explore the effects of aspect ratio. Dye-flow visualization experiments were also performed using wing 4 to investigate the three-dimensionality of gust encounters. All cases were repeated several times based on the measurement technique's sensitivity. Please note that the sensitivity analyses will be discussed in the sections pertinent to the measurement technique. A total of 299 measurements were taken for the work presented here.

In order to determine a suitable wait time between the runs, PIV measurements were taken. 100 images were acquired at 0.2 kHz and post-processed with the same parameters mentioned in section 2.3.2. Velocity obtained from mean

velocity flowfields for the highest towing and pump speeds was found to be around $7.17 \times 10^{-4} \pm 4.34 \times 10^{-4}$, which corresponds to the 0.27% of the lowest freestream velocity used, after 5 minutes were allowed to pass. Therefore, 5 and 10 minutes were allowed to pass between each run for low and large-amplitude gust encounters, respectively, to ensure that the previous motion did not create any recirculation in the tank.

Table 2.5: Test matrix for the sine-squared gust encounter experiments.

Test Model	Reynolds Number	Freestream, (m/s)	Width to chord	Gust Ratio	Angle of Attack, (deg)
Wing 1 ($\mathcal{R} = 4$)	40,000	0.8032	4	0.08, 0.12, 0.16, 0.24, 0.26, 0.32	0°, 5°, 10°, 15°, 20°, 30°, 45°
Wing 2 ($\mathcal{R} = 4$)	20,000	0.2635	2.6	0.5, 0.75, 1, 1.5	0°, 10°, 20°
Wing 3 ($\mathcal{R} = 6$)	20,000	0.2635	2.6	0.5, 1	0°, 20°
Wing 4 ($\mathcal{R} = 8$)	20,000	0.2635	2.6	0.5, 1	0°, 20°

2.5 Force Measurements

A 6 degree-of-freedom force balance (submergible ATI Mini-40 with a range of ± 40 N and a resolution of 0.01 N) was used to measure forces on the test model. The force balance was mounted to the setup as shown in Figure 2.1(b). All experiments were sampled at 1 kHz. Data was transferred from the force balance to the computer via a wireless network. If more than five percent of the data packets were lost during this transfer, the run was repeated. The manufacturer’s calibration was used to convert the internal strain readings to the wing-fixed forces.

All of the cases were repeated 5 times, synchronized, filtered, and ensemble-

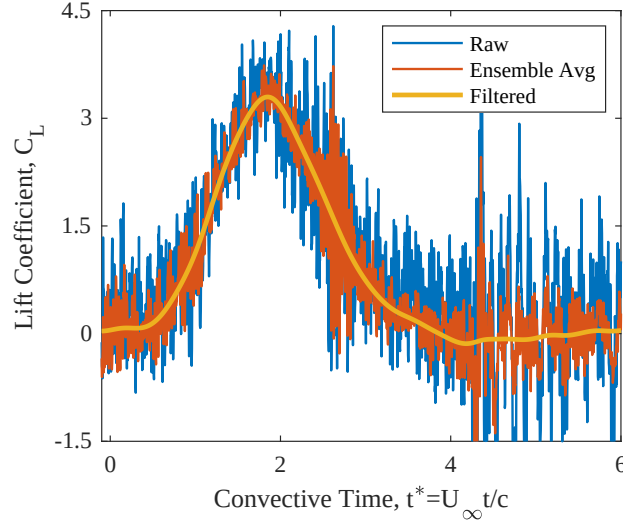


Figure 2.10: Raw, ensemble averaged, and filtered lift coefficients for $GR = 1$, $\alpha = 0^\circ$ case of wing 2 experiments.

averaged. The average forces were calculated when the wing was stationary and subtracted from the measurements to remove the contributions from gravity and buoyancy forces. The mean normal and axial forces were then converted to lift and drag components and non-dimensionalized by the dynamic pressure and the wing area. Since the data collection device and wing kinematics controller operates at different internal clocks, the measurements and kinematics needed to be synchronized. To achieve that, the side force measured was cross-correlated with the expected side force based on the transducer's depth, and the resulting correction time was used to align the clocks. Please refer to Ref. [113] for more information. Fast Fourier Transform was performed for all cases to reveal the frequency content of the measurements, and the dominant frequencies were found to be 10, 20, and 120 Hz (for experiments performed with wing 1), 10, 35, and 110 Hz (for experiments performed with wing 2), and lastly, 12, 38, and 110 Hz (for experiments performed

with wing 3). The periods of the gust encounters ($T_{gust} = w/U_{\infty}$) for low-amplitude and large-amplitude cases were found to be 0.2 s (corresponding to a frequency of 4 Hz) and 0.75 s (corresponding to a frequency of 1.3 Hz), respectively. To remove mechanical and electrical vibrations and measurement noise in the data, 10 Hz and 5 Hz low-pass Butterworth filters were applied to the experiments carried out with wing 1, and wings 2, 3, and 4. Figure 2.10 shows the raw, ensemble-averaged, and filtered lift coefficients for $GR = 1, \alpha = 0^\circ$ case. As can be seen from this figure, the low-pass filter preferred reduces the vibrations and noise without truncating the peak and distorting the response. Figure 2.11 shows filtered lift coefficients from 8 individual runs and their ensemble average for a case of $GR = 0.5, \alpha = 0^\circ$. Even though the characterized gust has fairly significant unsteadiness attached to it (as discussed in section 2.3.5), the lift coefficients from different runs are quite similar. Standard deviations of the lift force coefficients were 0.0886 and 0.1057 for 8 and 5 runs ensemble-averaged, respectively. These standard deviations correspond to 6.1% and 7.3% percentage uncertainty. Furthermore, peak lift coefficient obtained from ensemble averaging 5 runs introduces only 0.56% error compared to ensemble average of 8 runs. In order to make the work feasible, every case was repeated 5 times.

The uncertainty of force measurements on repeated experiments was calculated for a region where the wing has not yet interacted with the gust ($-10 \leq t^* \leq 0$) and travels at a constant speed. From this analysis, standard deviations of the normal force coefficients were found to range from 0.014 to 0.023, which corresponds to a percent uncertainty of 1.3% to 5.8% for the angles of attack between 5 and 45

degrees for experiments with wing 1 while they were found to vary between 0.02 and 0.05 for experiments with wing 2, 0.03 and 0.07 for experiments with wing 3, and lastly for the experiments with wing 4, standard deviations range between 0.04 and 0.07. Please note that since the Reynolds number for the experiments performed using wing 1 ($Re = 40,000$) is significantly higher than those performed using other wings ($Re = 20,000$), the wing 1 experiments result in a better signal-to-noise ratio, thereby lower standard deviations.

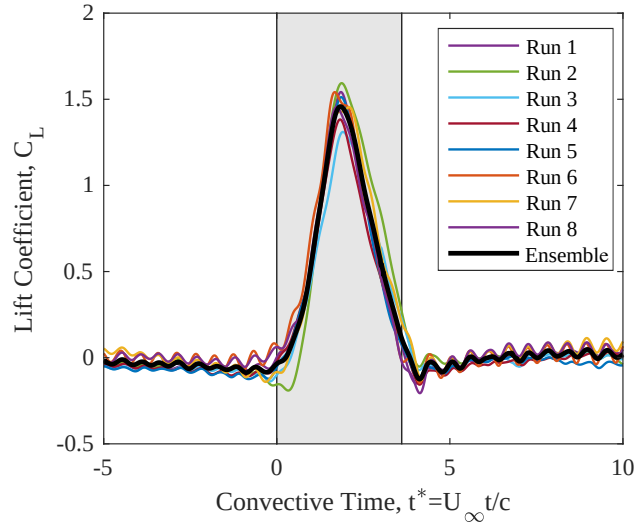


Figure 2.11: Lift coefficients from filtered individual runs, and ensemble average for $GR = 0.5, \alpha = 0^\circ$ case of wing 2 experiments.

2.6 Flowfield Measurements

Flowfields provide illuminating insight into the force transients. This section discusses the methods used to obtain the flowfields, namely PIV and dye-flow visualization, along with methods to calculate the circulation production when a strong shear layer is present.

2.6.1 Particle Image Velocimetry

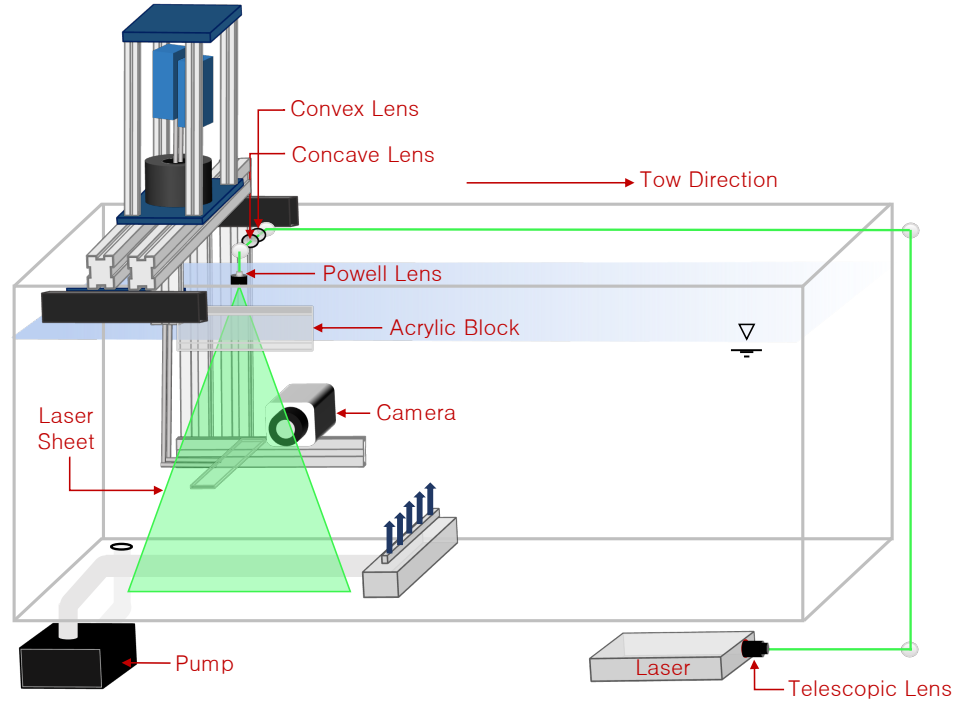


Figure 2.12: Sketch of the PIV setup used for sine-squared gust encounter experiments.

Time-resolved PIV experiments were performed for wing 2 encountering the sine-squared gust. To acquire the images, a 4 MP (Phantom v641) camera was used with an 85 mm Nikon lens. The water was seeded with class IV soda lime glass spheres (diameter of $37 \mu\text{m}$), and the flow was illuminated by an Nd:YLF laser (Litron LDY 304, 30 mJ/pulse, 10 kHz max). Figure 2.12 shows a sketch of this setup.

During these experiments, both the laser sheet and the camera were towed with the wing to allow for a wide investigation range. The camera was placed on an L-shaped structure that is connected to the carriage. Thus, it easily accompanied the wing. Towing the laser sheet, however, was not as effortless since it needed to be

aligned perfectly through the whole tank. The laser was positioned underneath the towing tank and directed towards the carriage by a set of stationary mirrors. Please note that a telescopic lens was mounted on the laser head not only to counteract the fact that the laser beam diverges as it travels but also to achieve an appropriate beam thickness throughout the investigation region. As the beam reached a set of mirrors placed on the carriage, it was redirected along the spanwise direction (from the edge towards the center of the carriage). Then, it passed through convex ($f = 150\text{ mm}$) and concave ($f = 100\text{ mm}$) lenses, respectively. The distance between these lenses was adjusted so that the focal point lies on the wing and allows for a very thin laser sheet in the region of interest. Then, the beam was redirected towards a Powell lens. Since the laser sheet needed to cover the whole region captured by the camera, the fan angle of the Powell lens was selected to be 30° . To annihilate the distortion of the laser sheet due to medium change (air to water), an acrylic block was installed in and towed with the wing, carriage, mirrors, and lenses. The laser sheet illuminated 1 chord-length off mid-span where the images were captured to provide nominally two dimensional flowfields for the aspect ratio 4 wing. Note that images could not be acquired at the mid-span since the support structure does not allow for a such configuration of the optics.

The PIV images were acquired at 0.7 kHz for convective times between -6 and 15. 4250 images were recorded for each case. DaVis v8.1 was used as the processing software. Firstly, a sliding background was subtracted from the acquired images to increase the signal-to-noise ratio of the measurements. Then, the images were cross-correlated using a decreasing interrogation window size from 24×24 to $16 \times 16\text{ px}$.

50% and 75% region overlaps were allowed for the first and second passes. The resulting field of view was 24×16 cm, and the wing was positioned in the image such that approximately 1.1 and 1.2 chords were allowed upstream and downstream of it, respectively. The spatial resolution was 0.1 mm per pixel (772 pixels per chord-length), and the temporal resolution was 202 images per convective time. Final vector spacing was 0.79 mm (96.46 vectors per chord-length). The maximum uncertainty in the velocity measurements was found to be 0.2%.

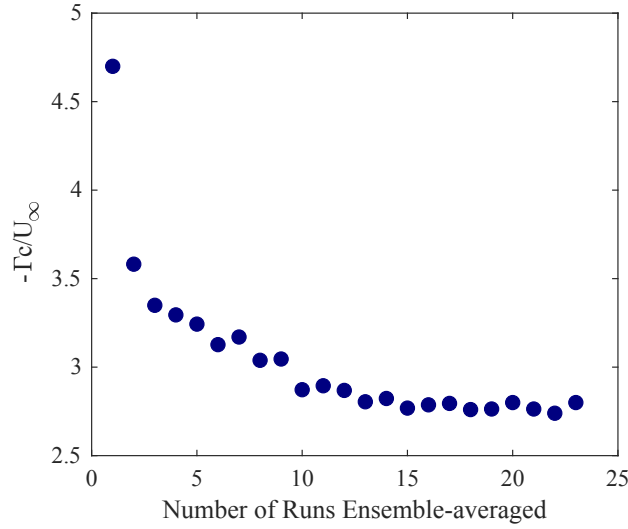


Figure 2.13: PIV sensitivity study based on the non-dimensional leading-edge vortex strength for $GR = 1$, $\alpha = 0^\circ$ case.

A sensitivity study was performed to determine the number of runs to ensemble average. 23 runs of $GR = 1$, $\alpha = 0^\circ$ case were acquired. Since the gust meanders as discussed in section 2.3.4, the sensitivity study was carried out for the leading-edge vortex strength rather than the circulation in the whole PIV flowfield. The procedure followed to calculate the leading-edge vortex strength is detailed in section 2.6.2. Figure 2.13 shows the non-dimensional circulation of the leading edge vortex for

various number of runs ensemble-averaged at $t^* = 1.8$. As can be seen from this figure, the circulation approaches to a constant value as the number of runs increases. To make the work feasible, the cut-off value for number of runs ensemble-averaged were selected to be 8 which corresponds to 8% error for $GR = 1, \alpha = 0^\circ$ case discussed here.

2.6.2 Circulation Measurements

The aim of this section is to introduce a method that can accurately compute the circulation shed from the leading edge based on the experimental flowfields. This is a particularly challenging task since the sine-squared transverse gust introduces a continuous shear layer that consists of positive and negative vorticity regions as described in section 2.3.3.

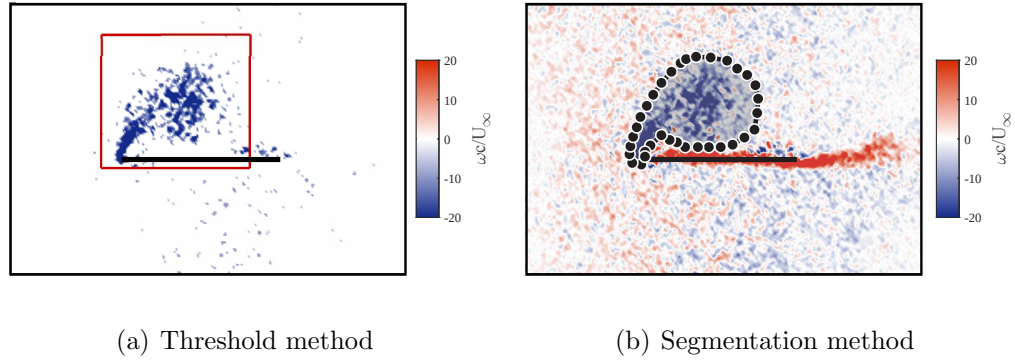


Figure 2.14: Vorticity contours at $t^* = 1.8$ for $GR = 1, \alpha = 0^\circ$ case.

Two methods that are appropriate for this task directly derive from the definition of vortex strength, in other words, its circulation (sum of the vorticity enclosed in the vortex) and given by $\Gamma = \int_A \omega dA$. The first method is the threshold method, where a stationary rectangular box was drawn near the wing,

shown in Figure 2.14(a), and the vorticity in it was calculated. A threshold was then set to remove any vorticity that is greater than -30 to eliminate to avoid any miscalculations due to the gust shear layer. The second method is the segmentation method, where the leading-edge vortex was manually isolated from the gust shear layer using an arbitrary polygon, as shown in Figure 2.14(b). Since the leading-edge vortex contains negative vorticity and a part of the gust shear layer is positive, a threshold was used to remove any positive vorticity to improve the calculations. The vorticity was then integrated around the polygon area, and the strength of the leading-edge vortex was found. The resulting circulation from both the threshold and the segmentation methods were nondimensionalized by the freestream velocity and chord. Figure 2.15 shows these nondimensional circulations for the $GR = 1, \alpha = 0^\circ$ case. As can be seen from this figure, these methods yield similar results early on. However, as the wing moves towards the center of the gust, the circulations calculated from these two methods start to differ. These differences are attributed to the fact that the vortex diffuses and threshold method eliminates some of the vorticity that was originally belonged to the leading-edge vortex. This issue can be addressed by increasing the threshold value. However, the increased threshold value causes the gust shear layer to reappear in the box and thus the method to fail. To conclude, the best method was determined to be the segmentation method, and it was used to calculate the leading-edge vortex strength for the sine-squared gust encounters. Please note that the measurements were down-sampled to 70 Hz to make the manual work feasible.

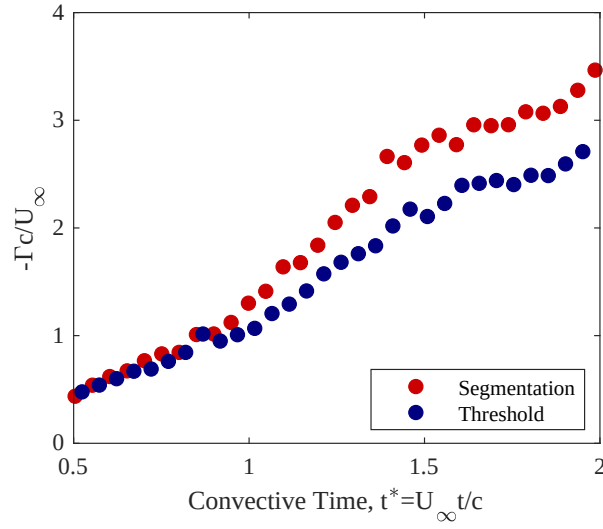


Figure 2.15: Nondimensional circulation of $GR = 1, \alpha = 0^\circ$ case calculated from both the segmentation and the threshold methods.

2.6.3 Dye-flow Visualization

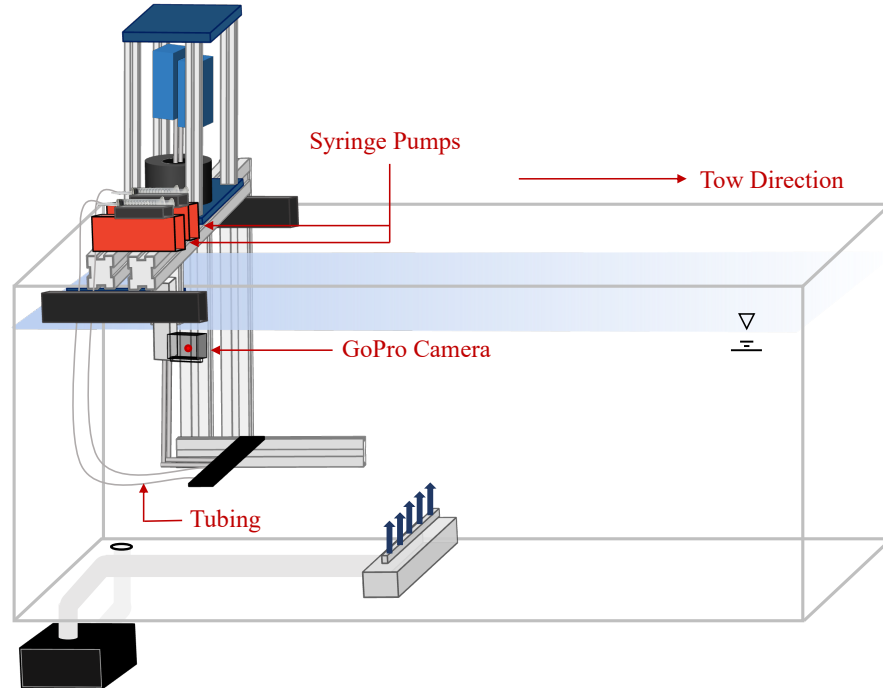


Figure 2.16: Nondimensional circulation of $GR = 1, \alpha = 0^\circ$ case calculated from both the segmentation and the threshold methods.

Dye-flow visualization experiments were performed for aspect ratios of 4 and 8 wings to investigate the three-dimensional effects during large-amplitude sine-squared gust encounters. The mixture used for these experiments consisted of green dye, milk, ethyl alcohol, and water (from the tank). Milk is frequently used in dye-flow visualization mixtures since its high reflective quality creates crisper flow images. Moreover, the high fat content of milk allows for coherent filaments to form in high shear flows by retarding diffusion. Although the soy variety has a longer shelf life, soy milk was found to curdle faster once mixed with ethyl alcohol. Since the curdled milk impairs the quality of the flow, whole milk was preferred for the current study. The ethyl alcohol was then added to the mixture to attenuate the density difference between the water and milk. A combination of 100 ml milk, 10 ml dye, and 17 ml ethyl alcohol was found to result in a neutrally buoyant mixture. Please note that the exact amount of each element depends entirely on its density. Since the purity of each element is expected to change between different brands, the proportions provided here does not guarantee a neutrally buoyant mixture and requires some trial and error for different setups. Lastly, the neutrally buoyant mixture was diluted with 35 ml of water from the tank. By doing so, the temperature differences between the mixture and the operating fluid were minimized.

The resulting mixture was filled into two MonoJect 60 ml syringes, and the air bubbles were removed. Then, the syringes were placed into two identical syringe pumps (NE-300 Just Infusion), which forced the mixture through the tubing (Tygon R-3603) to the ports positioned at the bottom surface of the wing. The tubes were selected to have a very small inner diameter, 0.76 mm, to minimize the disturbance

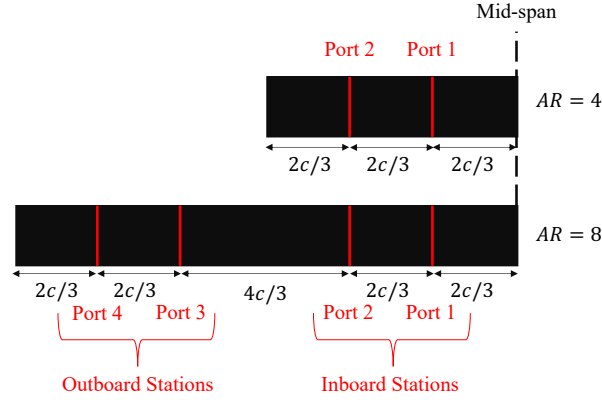


Figure 2.17: Location of the ports placed on the bottom surface of the wings tested.

they might cause to the flow. The exit velocity of the mixture should be selected to match the flow velocity nominally. This, however, was not always achievable since the flow examined is unsteady. A GoPro Hero7 was used to acquire the images and was positioned on the carriage to allow a top view of the test model. The syringe pumps and camera were towed with the wing to allow for a broad investigation range. Figure 2.16 shows a sketch of the setup for this configuration. The flow was illuminated by stationary halogen lights, and the glass walls of the tank were covered with black contact paper to avoid the issues that the light reflection might cause. Figure 2.17 shows the location of the ports for two test models used for this study. The tubes were oriented in the chordwise direction and located approximately 4 mm behind the leading edge to reduce disturbance. Two equally spaced ports were used for the $\mathcal{R} = 4$ wing. Since the current hardware allows the use of only two ports at a time, the experiments performed for $\mathcal{R} = 8$ wing were divided into two sets: inboard and outboard, as shown in Figure 2.17. The images acquired from inboard and outboard stations were later stitched together. Each case was repeated 5 times,

and only the dominant features from all sets were discussed in section [4.5](#).

2.7 Chapter Summary

This chapter has described the methods used for the sine-squared gust encounter experiments. The fluid gust system was redesigned and reconstructed to achieve a wider range of gust ratios independent of Reynolds number. The resulting flow was characterized to have a streamwise sine-squared and spanwise planar velocity profile. Several flat plates were used as the test models for this study. Force and PIV measurements were acquired for a wing passing through the characterized gust at a constant speed. Various combinations of gust ratio and angle of attack were investigated. The resulting flowfields were used not only to identify the dominant flow structures that cause the force transients but also to calculate the circulation shed from the leading edge. Moreover, dye-flow visualization experiments were performed to provide insight into the three-dimensional nature of the flow. The results obtained using the techniques described here are presented in the following chapters.

Chapter 3: Methodology of Collaborators

This chapter details the methods and equipment used by our collaborators to investigate the unsteady response of wings in gust encounters. These collaborations capitalized on the capabilities of each facility, producing different transverse gust velocity profiles and gust types to establish a comprehensive knowledge of the fundamental flow physics of gust encounters. Section [3.1.1](#) describes the computational methods used by collaborators at the University of Maryland to simulate the sine-squared gust encounter experiments detailed in chapter [2](#). These simulations provide valuable information on skin friction coefficient, which is hard to measure experimentally, whereas the experiments offer a unique data set to validate these simulations. Overall, this collaboration helps to extend the knowledge on the unsteady force production during sine-squared transverse gust encounters. The experimental methods employed by collaborators at the University of Cambridge to generate and study top-hat transverse gust velocity profile are discussed in sections [3.1.2](#). Although the bulk of the results shown in this dissertation are from the sine-squared transverse gust encounters, where the effects of significant parameters, such as gust ratio and angle of attack, are explored. Comparing the top-hat and sine-squared transverse gusts allows for an

investigation of the effect of transverse gust velocity profiles and the limitations of analytical models, which cannot be studied thoroughly using just one transverse gust profile. Lastly, the experimental procedures followed by collaborators at the Istanbul Technical University to investigate vortex gust are documented in section 3.2. This collaboration enables the generalization of the conclusions for different gust types and therefore paves the way for development of gust mitigation models that can work on different gusts. Please note that since this dissertation includes results from various experimental and numerical studies, providing the precise details of each method is not possible. Therefore, this chapter only provides relevant information pertaining to the methods of each work. The readers are referred to Refs. [80,90,114] for the exact details of the methods described here.

3.1 Transverse Gust

The methods of both experimental and computational studies on transverse gust encounters are discussed in this section. Section 3.1.1 details the computational methods that were used to recreate the sine-squared gust experiments described in chapter 2, whereas section 3.1.2 describes the experimental techniques used to investigate a different transverse velocity profile, namely the top-hat gust.

3.1.1 Sine-squared Transverse Gust Computational Methodology

The previous chapter outlined the methods and equipment used to perform sine-squared transverse gust encounters. Even though the force, PIV, and dye-flow

visualization experiments provide a unique data set to improve the understanding of sine-squared transverse gust encounters, the Computational Fluid Dynamics (CFD) simulations allow the extraction of information that is difficult to measure experimentally, such as skin friction coefficient. In this section, the computational methods used to simulate the physical flow described in chapter 2 will be discussed. The readers are encouraged to refer to Ref. [80] for the details of these dynamically scaled numerical simulations performed by our collaborators at the University of Maryland.

3.1.1.1 Flow Solver

A 3D unsteady Navier-Stokes (NS) solver, OVERTURNS, was selected to examine the sine-squared gust encounters since it allows the study of highly unsteady and viscous flows. This flow solver was developed at the University of Maryland [115,116], and is a structured, overset, open-source code. The field velocity method (FVM) with a gust source term was used to simulate the sine-squared gust characterized in chapter 2. The FVM assigns the gust velocities to the relevant grid points [2, 117, 118]. One drawback of this method is that it does not capture the effect of the wing's presence on the gust. To account for these wing-gust coupling effects, a source term was derived and added to the FVM. The derivation of this source term can be found in Refs. [80, 119].

Inviscid terms of the Navier-Stokes equations were computed using a third-order spatial scheme (MUSCL) with Roe-Turkel flux difference splitting, whilst

viscous terms were computed using the second-order central scheme. To remove the factorization and linearization errors and recover time accuracy for unsteady computations, implicit dual time-stepping with ten sub-iterations per time step was used. Low-Mach preconditioning was also incorporated into OVERTURNS to ensure convergence and accuracy of the flow field at very low Mach numbers $O(10^{-2})$. The computational parameters are given in Table 3.1. The simulations were performed to match the Reynolds number, wing kinematics, and gust width of the low-amplitude sine-squared gust encounter experiments on wing 1 described in section 2.4. The computational test matrix consisted of three cases, which are GR=0.09, $\alpha = 10^\circ$, GR=0.18, $\alpha = 5^\circ$, and GR=0.27, $\alpha = 0^\circ$.

Table 3.1: Computational parameters.

OVERTURNS Solver options	
Number of grids	2
Total timesteps	10000
Flow	viscous, Re=40,000
Mach number	0.034
Aspect ratio	4
Time-step size	0.25
Newton sub-iterations	10
Pseudo time step	0.1
Spatial scheme	MUSCL 3rd order
Temporal scheme	2nd order backward
Processors (parallel execution)	14

3.1.1.2 Computational Domain

Figure 3.1 shows the overset grid system used for this study, which consists of a body-fitted mesh and a cartesian background mesh. Using two separate meshes

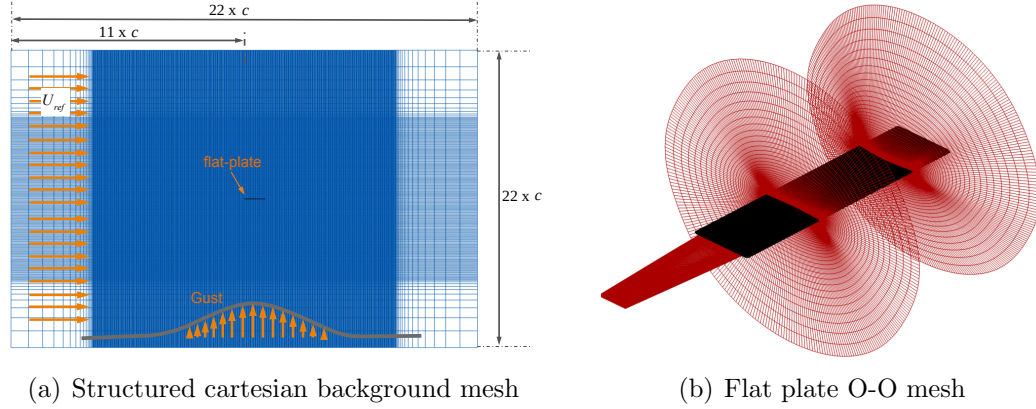


Figure 3.1: Computational domain: Cartesian background mesh and body-fitted O-O mesh from Ref. [80].

with different grid spacing allowed a thorough examination of the flow. While a very fine body-fitted O-O mesh surrounded the wing to resolve the boundary layer fully, a coarser cartesian background mesh captured the far-field flow features. The grid spacing of the body-fitted mesh was chosen such that it was clustered around the leading and trailing edges to capture the vortex shedding. The dimensions of the background mesh were selected to match the physical towing tank setup described in section 2.1. 2.8 million mesh points ($305 \times 101 \times 82$) were used for the body fitted O-O mesh, whilst 16.5 million mesh points were used for the background mesh. Overall, a total of 19.3 million mesh points ($156 \times 603 \times 175$) were used for this study. Please note that the flat plate wing remained stationary, and a far-field boundary condition was implemented for the freestream flow in these simulations. A grid sensitivity study was performed to assess the suitability of the selected mesh, which can be seen in Ref. [80] along with validation of simulations.

3.1.2 Top-hat Transverse Gust Experimental Methodology

In order to explore the effect of gust velocity profile, the author has collaborated with researchers at the University of Cambridge through the NATO-AVT-282 task group on the unsteady aerodynamic response of rigid wings in gust encounters. In this section, the reader will find the techniques and equipment used to generate the top-hat gust as well as the methods used for the force, PIV, and circulation measurements. Please refer to previous work by the author and collaborators [114] for more details on the experimental methods used for this study.

3.1.2.1 Facility and Test Model

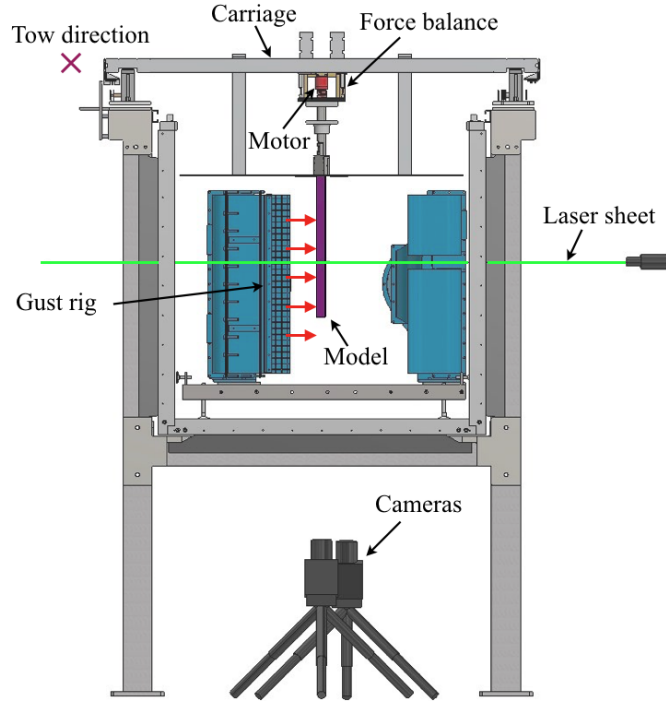


Figure 3.2: Setup of the top-hat gust from Ref. [114].

The facility used for top-hat gust encounter experiments was the $9\text{ m} \times 1\text{ m} \times$

1 m water-filled towing tank at the University of Cambridge. The cross-section of the setup can be seen in Figure 3.2. Similar to the setup used for sine-squared and trapezoidal gust experiments, described in section 2.1, the freestream (tow velocity) was created by model motion. A linear quadrature encoder was used to measure the carriage kinematics with 1 mm resolution. The error in the motion was found to be in the order of 0.01 mm. A glass flat plate with a 12 cm chord, a 48 cm span, and a 0.04 thickness-to-chord ratio was used for these experiments. The test model was mounted vertically on the mechanism, and an endplate was located at the top of the wing. Therefore, the free surface acts as a symmetry plane and the effective aspect ratio of the test model is 8. All experiments that will be shown in this dissertation were performed at a Reynolds number of 30,000, corresponding to a constant freestream speed of $U_\infty = 0.24 \text{ m/s}$. The defining parameters of the top-hat gust experiments are shown in Table 3.2. Please note that both the gust ratio and angle of attack were selected to match with the parameters from the high-amplitude sine-squared gust encounters, discussed in section 2.4. Please refer to Ref. [114] for more details.

Table 3.2: Test matrix for the top-hat gust encounter experiments.

Gust Ratio	Angle of Attack, (deg)
0.50	0°, 10°, 20°
0.75	0°
1	0°
1.5	0°

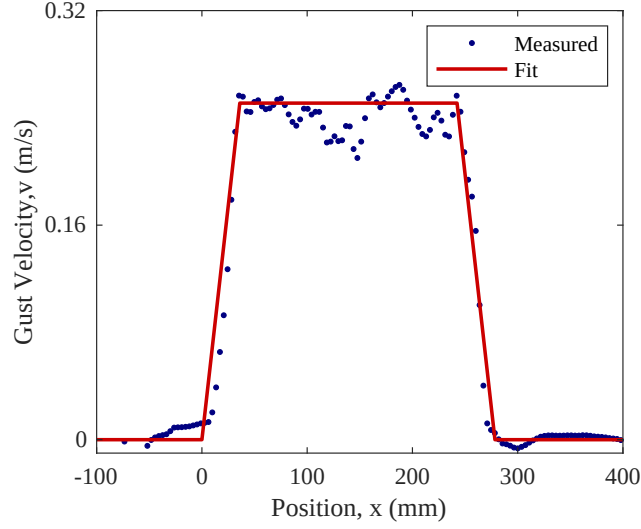


Figure 3.3: Measured gust velocities and fit for the top-hat gust from Ref. [81].

3.1.2.2 Gust System and Its Characterization

The gust rig, shown in Figure 3.2, was constructed to allow for a cross-flow in the stream-normal (transverse) direction. A 2.2 kW 3-phase variable speed pump was used to generate the gust. Time-resolved PIV was used to characterize the resulting flow, which was found to have a streamwise top-hat, spanwise planar velocity profile. Figure 3.3 illustrates the measured velocities and the streamwise best fit. The peak velocity was found to be linearly dependent on the pump speed. The equation of this fit was found to be $y = 4.61 \cdot 10^{-4}x - 7.83 \cdot 10^{-3}$, where y and x represent the peak gust velocity of the fit and pump speed, respectively. The mean gust width was found to be 24 cm, corresponding to a width-to-chord ratio of 2. Unlike the shear layer of the sine-squared gust, the top-hat gust's shear layer was confined in a small region on the edges over a width of 0.3 chords. The details of the gust characterization can be found from Refs. [81, 84].

3.1.2.3 Force Measurements

A 2 degree-of-freedom force balance (with a range of ± 50 N and a resolution of 0.01 N) was used to measure the streamwise and stream-normal forces on the wing, which were sampled at 3 kHz. All cases were ensemble-averaged over 5 runs. The mean normal and axial forces were then converted to lift and drag components and non-dimensionalized based on the towing speed, the dynamic pressure, and the wing area. A low-pass filter was then applied to the measurements. The cut-off frequency of this filter was selected to be 18 Hz to remove the large-amplitude noise at 20 Hz. Refs. [84, 114] contain a detailed analysis of the force measurements.

3.1.2.4 Flowfield Measurements

Time-resolved PIV was also used for top-hat gust encounter experiments to provide additional insight into the forces. Two cameras (with a resolution of 1280×800 px) were used to capture the PIV flow images at the wing midspan as shown in Figure 3.2. A high speed Nd:YLF 527 nm pulsed 2 mm laser sheet at 0.4 kHz was used to illuminate flow. The flow was seeded using titanium dioxide particles with a diameter of $45 \mu\text{m}$. A programmable PTU-X timing unit was used to synchronize the acquired images from both cameras, which were then stitched together using DaVis. All cases were repeated 5 times and ensemble-averaged. The final flowfield spatial and temporal resolutions were 0.3 mm per pixel and 200 images per convective time, respectively.

Since the shear layers in the top-hat gust are contained in a thin layer, as

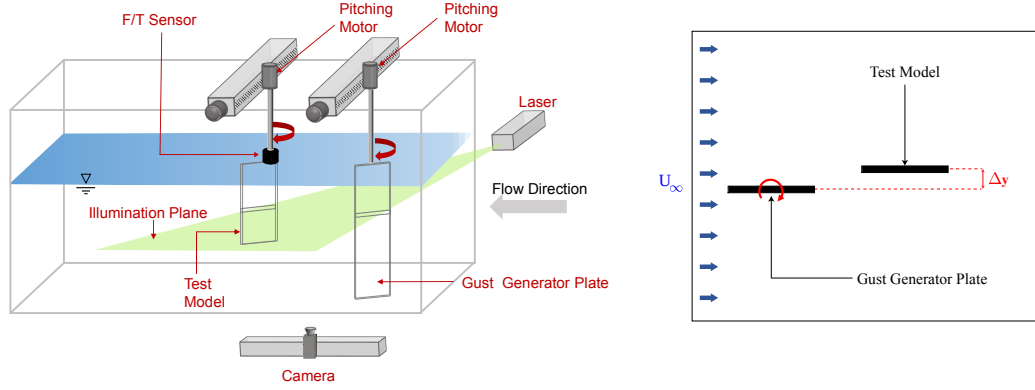
described in section 3.1.2.2, the vortex strength calculations were simple compared to the sine-squared gust, and performed by integrating the vorticity in the whole flowfield. The calculated vorticity was then split into positive and negative parts to differentiate the leading and trailing edge vortices. A manual mask, in other words the segmentation method, was only used when the wing was interacting with the gust shear layers.

3.2 Vortex Gust Experimental Methodology

The previous section provided the methods used to investigate different transverse gust velocity profiles. In this section, the reader will find the techniques used for a different gust type, namely the vortex gust, which was experimentally investigated by collaborators at the Istanbul Technical University.

3.2.1 Facility and Test Model

The free surface water channel located at the Istanbul Technical University (ITU) was used for the vortex gust encounter experiments. A gust generator plate, an aspect ratio 4 (10cm chord, 40cm span) Plexiglass flat plate, was mounted vertically in a cantilevered structure inside the water channel and underwent a clockwise half turn about its mid-chord to produce the vortex gust. Since the free surface acts as a symmetry plane, the effective aspect ratio of the gust generator plate corresponds to 8. The aforementioned motion of the gust generator plate continues for exactly 4 convective times. Please note here that immediately after the motion



(a) Sketch of the water channel

(b) Vertical offset between the test model and gust generator plate

Figure 3.4: Experimental setup for vortex gust encounter experiments from Ref. [90].

began, a positive vortex was shed from the trailing edge of the gust generator plate, which has not been characterized as a part of the vortex gust. Since this positive vortex is relatively weak and distant from the test model compared to the vortex gust shed later in the motion cycle, it is highly unlikely for it to have any profound effect on the results discussed here.

An aspect ratio 2 (10 cm chord, 20 cm) 5% thick flat plate wing was placed approximately 60 mm downstream of the gust generator plate, where 60 mm is the distance between the leading edge of the wing and the trailing edge of the gust generator. Therefore, the effective aspect ratio of the test model corresponds to 4. The test model was also placed at some vertical offset, Δy , from the gust generator plate, as shown in Figure 3.4(b). This vertical offset was adjusted by changing the stream-normal position of the gust generator plate rather than the test model to allow for the same field of view for flowfield measurements. The experiments were performed at a Reynolds number of 10,000 and a freestream speed of 0.1 m/s. The

test matrix for the vortex gust is given in Table 3.3.

Table 3.3: Test matrix for vortex gust encounters.

Vertical offset ($\Delta y/c$)	Angle of Attack, (deg)
0.19	0, 5, 10, 15, 20, 30, 45
0.29	0, 5, 10, 15, 20, 30, 45
0.39	0, 5, 10, 15, 20, 30, 45

3.2.2 Gust System and Its Characterization

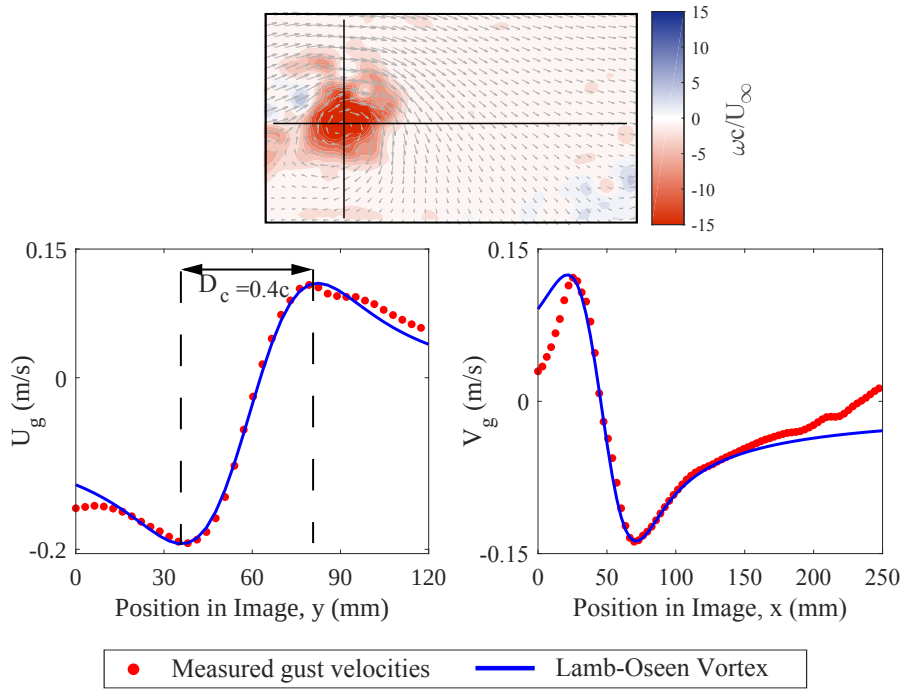


Figure 3.5: Measured gust velocities and Lamb-Oseen Vortex fit from Ref. [90].

The vortex gust was shed 1.5 convective times after the motion of the gust generator plate started. The characterization was performed when the vortex gust reached the location where the test model would be installed. Figure 3.5 shows the vortex gust at this instant (3 convective times after the motion of the gust generator started). Please note that the colorbar has been flipped to make the

visual comparison with the sine-squared transverse gust. The intersection of the perpendicular lines shown on the vortex gust corresponds to the vortex core, and the measured transverse and longitudinal velocities were extracted from these lines. The best fit to the data was found to be the Lamb-Oseen vortex model [94] and is given by $V = \frac{1}{1-e^{-1}} V_{rc} \frac{1-e^{-\bar{r}^2}}{\bar{r}}$ and $U = \frac{1}{1-e^{-1}} U_{rc} \frac{1-e^{-\bar{r}^2}}{\bar{r}}$, where $\bar{r} = r/r_c$ for the vertical and horizontal disturbances, respectively. Thus, the defining parameters of the vortex gust are amplitude (U_{rc} and V_{rc}), core size/radius (r_c), and the distance from the vortex core (r). The freestream was subtracted from the measured longitudinal velocities to obtain only the perturbations. Based on the Lamb-Oseen vortex model, the vortex core size was found to be approximately 20 mm, and the gust width was defined as the vortex core diameter ($w = 2r_c = D_c$), which corresponds to a width-to-chord ratio of 0.4. The gust ratio was found to be $U_g/U_\infty \approx V_g/U_\infty \approx 1$. Please note here that the gust ratio variations were not possible for the vortex gust, unlike the transverse gusts discussed in this dissertation. Therefore, all the cases shown in Table 3.3 have a gust ratio of 1. It should, however, be kept in mind that the characterized parameters change as the vortex convects downstream due to the deformations it undergoes. The variations in the streamwise and transverse velocities were found to be $\tilde{u} = \pm 0.1$ m/s and $\tilde{v} = \pm 0.125$ m/s, respectively. Please see Refs. [89, 90] for more details.

3.2.3 Force Measurements

A 6 degree-of-freedom submersible ATI Nano-17 IP68 was used to measure the forces on the test model. The sensor was connected to the vertical cantilevered mounting beam of the test model, as shown in Figure 3.4(a). A Kollmorgen/Danaher Motion servo motor was used to achieve the pitch motion of the gust generator plate, and connected to a computer via a ServoSTAR digital servo amplifier. A Labview Virtual Instrument (VI) generated the signal for the motor motion profile. Synchronization was achieved using a National Instruments PCI-6601 timer. Forces were acquired at 1 kHz. The estimated uncertainty in the force coefficients was found to be less than 0.034 for the cases discussed here. An adjacent averaging smoothing with 200 points was used to filter the measured instantaneous forces on the wing [90].

3.2.4 Flowfield Measurements

Time-resolved PIV was used to obtain instantaneous flowfields around and in the near wake of the test model. A dual cavity Nd:Yag laser (max 120 mJ/pulse) was used to illuminate polyamide seeding particles (PSP) with a mean diameter of $50\text{ }\mu\text{m}$. The flow images were recorded using a 10-bit camera with 1600×1200 px resolution. The setup used for these experiments can be seen from Figure 3.4(a). The PIV acquisition rate was set to 8 Hz, and the acquired images were cross-correlated using a 16×16 px interrogation window with 50% overlap in each direction. The maximum PIV uncertainty was found to be 0.2%.

Even though the vortex gust does not introduce a continuous shear layer, the threshold method, described in section 2.6.2, miscalculates the strength of the leading-edge vortex since it accounts for the positive vortex (the same sign as the leading-edge vortex) shed by the gust generator. Instead, the segmentation method was used to calculate the leading-edge vortex strength after removing any negative vorticity in the identified region since the vortex gust contains negative vorticity, while the leading-edge vortex is positive.

3.3 Chapter Summary

This chapter outlined the methods used to analyze transverse and vortex gust encounters by collaborators. These collaborations allowed for a unique opportunity to compare different transverse velocity profiles and types and help generalize the conclusions to build profound knowledge of gust encounters. The field velocity method with the source term was implemented in the three-dimensional Navier–Stokes solver OVERTURNS to simulate the sine-squared gust encounters, which allowed computation of the skin friction coefficients. The experimental methods utilized for the trapezoidal and top-hat transverse gusts were also described in this chapter. The results obtained using these methods enabled us to investigate the effects of velocity gradients by comparing sine-squared, trapezoidal, and top-hat transverse profiles, which will be discussed in chapter 5. The trapezoidal gust was generated in the towing tank at the University of Maryland using a novel gust generator design. Since the same experimental facility and test model were used

for both sine-squared (described in the previous chapter) and trapezoidal transverse gust experiments, many differences due to the setup were avoided. The top-hat gust was generated in a different towing tank at the University of Cambridge using a unique gust rig design. The vortex gust, on the other hand, was created in a water channel at ITU by clockwise half-rotation of an upstream gust generator plate and characterized by the Lamb-Oseen fit. Force, PIV, and circulation measurements were acquired for all cases discussed here. The parameters of each campaign were selected to match those from the sine-squared gust encounter experiments to allow for direct comparisons between different gusts.

Chapter 4: The Unsteady Aerodynamics of Sine-squared Transverse Gust Encounters

The reader is reminded that one of the main aims of this dissertation is to improve the understanding of the flow physics behind sine-squared transverse gust encounters. To achieve this, the trends of forces, flowfields, and circulation production that arise from a flat plate at various angles of attack encountering sine-squared transverse gust of different strengths are established. The effects of the gust ratio and angle of attack on both the force transients and force peaks are explored using a unique data set, which includes both low and high-amplitude disturbances. Moreover, two novel normalization methods are introduced to scale the forces resulting from various angles of attack and gust ratios. In an attempt to narrow down the parameter space, the effective angle of attack and its relation with the lift force are explored. Furthermore, the flow mechanisms that cause a negative drag peak are examined. Lastly, trends in the three-dimensional flowfields are detailed, and the effects of aspect ratio variations on the force and flowfield transients are discussed. The results shown in this chapter will not only enhance knowledge of the unsteady aerodynamics of sine-squared gust encounters, but also provide a basis for the comparison of different transverse gust velocity profiles and

gust types.

4.1 Variations in Angle of Attack

The current section seeks to explore the effects of angle of attack on both low-amplitude and high-amplitude sine-squared gust encounters. To this end, firstly, the trends of forces, flowfields, and circulation production will be established. Then, a detailed analysis of the force transients will be presented. Lastly, a novel normalization method will be introduced, which can be used to attenuate the differences that arise due to the variations in the angle of attack.

4.1.1 Trends of Forces, Flowfields, and Circulation Production

In this section, the reader will find the trends of forces, flowfields, and circulation production, the results of which will establish a baseline for the sine-squared gust encounters of various angles of attack. Please note here that the results shown in the following subsections are from experiments performed using wing 2 (3 in chord, 12 in span).

4.1.1.1 Lift and Drag

Figure 4.1 shows the force histories of wing 2 for various angles of attack at a gust ratio of 0.5. In both Figures 4.1(a) and 4.1(b), the x -axis shows the convective time, $t^* = \frac{U_\infty t}{c}$, i.e., the number of chord lengths traveled by the wing. $t^* = 0$ was defined as the time at which the leading edge of the wing enters the gust. The

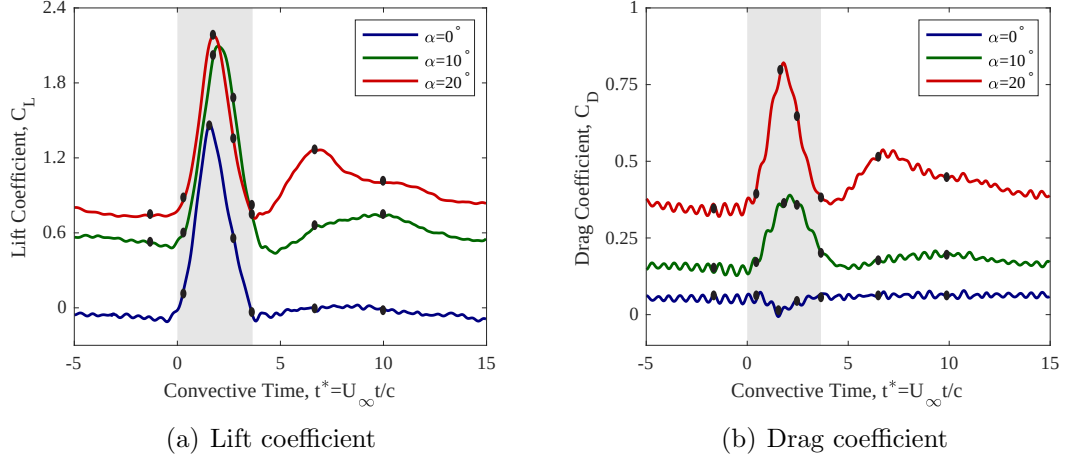


Figure 4.1: Lift and drag coefficients for various angles of attack at a gust ratio of 0.5, circles on this plot corresponds to flowfields in Figure 4.2.

trailing edge of the wing exits the gust $t^* = 3.6$ when the test model is at 0° angle of attack since the width-to-chord ratio (of wing 2) is 2.6 (see section 2.4). However, at non-zero angles of attack, the trailing edge of the wing exits the gust at subtly different times since the gust exposed area of the wing decreases with increasing angle of attack. These exit times are 3.6 and 3.5 convective times for $\alpha = 10^\circ$, 20° , respectively. The wing/gust overlap for $\alpha = 0^\circ$ is highlighted with a grey box in Figures 4.1, 4.10, and 4.28–4.32, where the results from high-amplitude gust encounters (experiments performed using wing 2) are discussed.

Figure 4.1(a) shows the lift coefficients for the above-mentioned cases. As can be seen from this figure, before the wing encounters the gust ($-5 \leq t^* \leq 0$), the lift coefficients are at their steady-state values, which are approximately -0.06, 0.57, and 0.78 for angles of attack 0° , 10° , 20° , respectively. As the wing enters the gust, the lift coefficient starts to increase from the steady-state value and reaches a maximum (peak) when the mid-chord of the wing is approximately at the middle of the gust (at

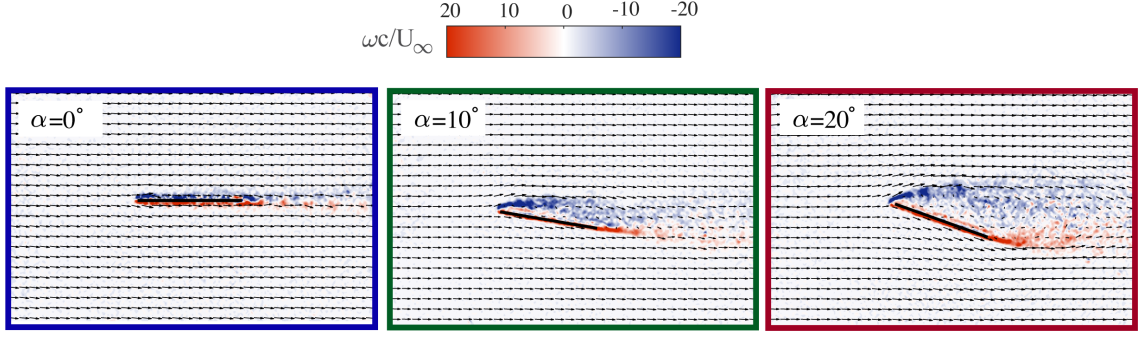
$t^* = 1.8$). Please note that this maximum value is experienced at slightly different convective times for different cases. There are two predominant factors causing these variations in time. Firstly, as the angle of attack changes, the time at which the mid-chord is at the center of the gust also changes. Secondly, the gust meanders, as discussed in section 2.3.4, and therefore introduces minor uncertainties in the convective time calculations. For the tested range here ($0^\circ \leq \alpha \leq 20^\circ$), increasing the angle of attack was found to increase the value of the maximum lift. A wider angle of attack range and their effects on the force coefficients will be discussed in section 4.1.2. After the wing passes through the strongest part of the gust, the lift coefficient starts to decrease. Immediately after the wing at 0° angle of attack fully exits the gust (at $t^* = 3.6$), the lift coefficient reverts to its steady-state value. On the other hand, in the cases where $\alpha > 0^\circ$, the lift coefficient experiences a local minimum around the same instant (at $t^* \approx 3.6$). This local minimum is followed by a secondary maximum in lift coefficient, which is experienced around $t^* = 6.5$ and $t^* = 10$ for $\alpha = 10^\circ$ and $\alpha = 20^\circ$, respectively. The increase in the lift coefficient after the exit for $\alpha = 20^\circ$ is steeper than the one for $\alpha = 10^\circ$. It can be concluded that the recovery from the gust encounter persists for longer for cases where $\alpha > 0^\circ$. All cases investigated here reverts to the steady-state values after 15 convective times.

The drag coefficients are also at their steady-state values before the wing enters the gust ($-5 \leq t^* \leq 0$), as shown in Figure 4.1(b). These values are 0.05, 0.16, and 0.36 for angles of attack 0° , 10° , and 20° , respectively. Increasing the angle of attack causes the steady-state drag coefficient to increase since the flow sees a larger cross-

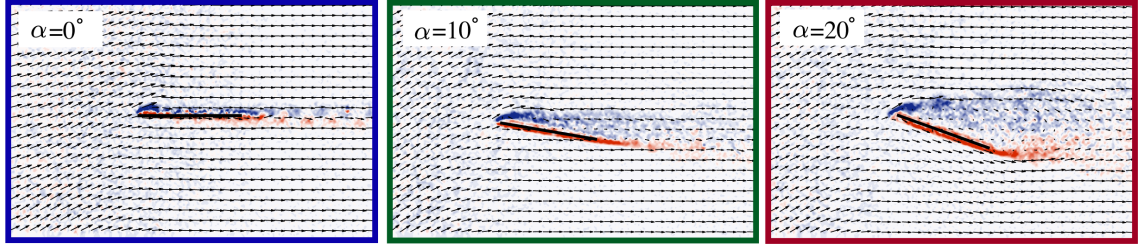
section in the streamwise direction at larger angles of attack. After the wing at 0° angle of attack enters the gust ($t^* \geq 0$), the drag coefficient decreases from its steady-state value and experiences a minimum when the wing is centered in the gust (at $t^* = 1.8$). On the other hand, for larger angles of attack ($\alpha > 0^\circ$), the drag coefficient experiences a maximum, again when the wing is centered in the gust (at $t^* = 1.8$). The value of this maximum drag coefficient increases as the angle of attack increases since the vortex formation and wake effects play a more prominent role in form drag production at larger angles of attack. An in-depth discussion of the drag coefficient and why it exhibits a negative peak at 0° angle of attack will be provided in section 4.4. Similar to the lift response, the drag force reverts to steady state right after the wing exits the gust at $t^* = 3.6$ for $\alpha = 0^\circ$. For $\alpha = 10^\circ$, there are also no dominant peaks visible during the recovery phase, unlike its lift response. On the other hand, for $\alpha = 20^\circ$, the drag force experiences a local minimum at $t^* = 3.6$ and a secondary maximum at $t^* = 6.5$. The drag coefficients from all cases were also found to reach the steady-state values around 15 convective times. The flowfields provided in the following section will highlight the force transients presented here.

4.1.1.2 Flowfields

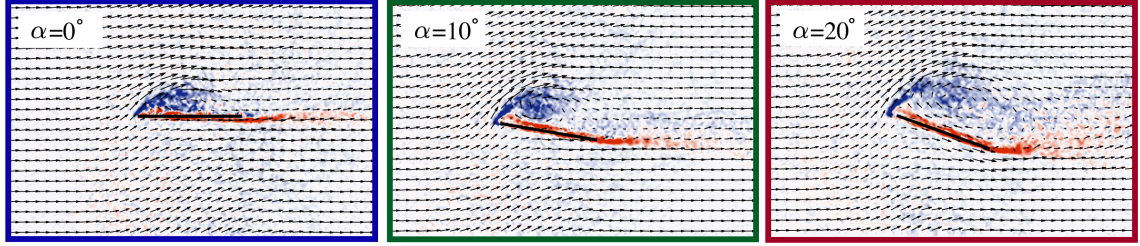
Figure 4.2 shows the flowfields at several convective times ($t^* = -1, 0.5, 1.8, 2.5, 3.6, 6.5, 10$) for angles of attack $0^\circ, 10^\circ, 20^\circ$, which corresponds to the circles marked in Figure 4.1. The flowfields are color-coded to match the forces.



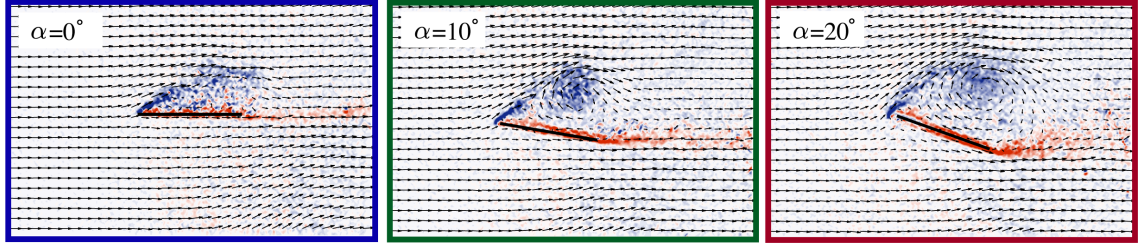
(a) Flowfields at $t^* = -1$ for angles of attack 0° , 10° , 20°



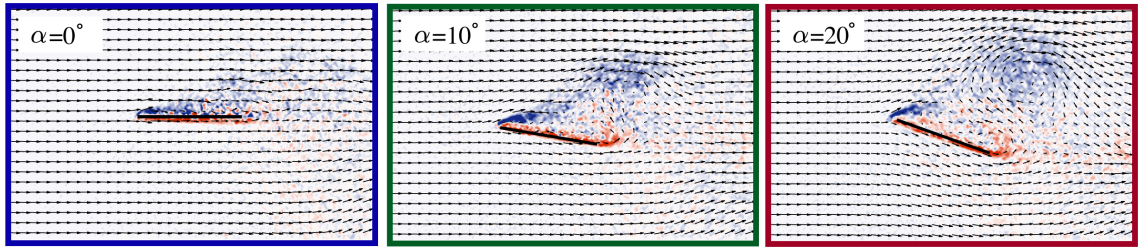
(b) Flowfields at $t^* = 0.5$ for angles of attack 0° , 10° , 20°



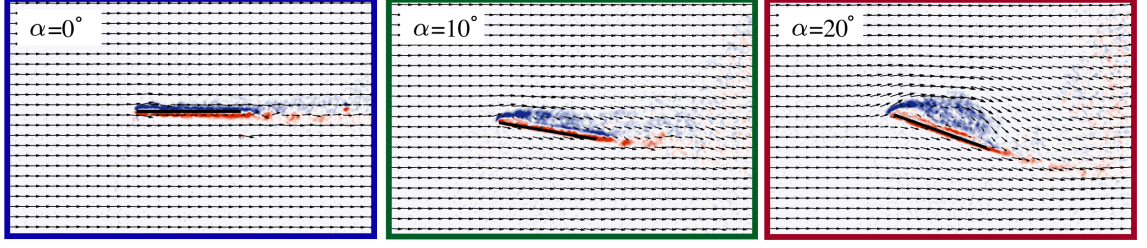
(c) Flowfields at $t^* = 1.8$ for angles of attack 0° , 10° , 20°



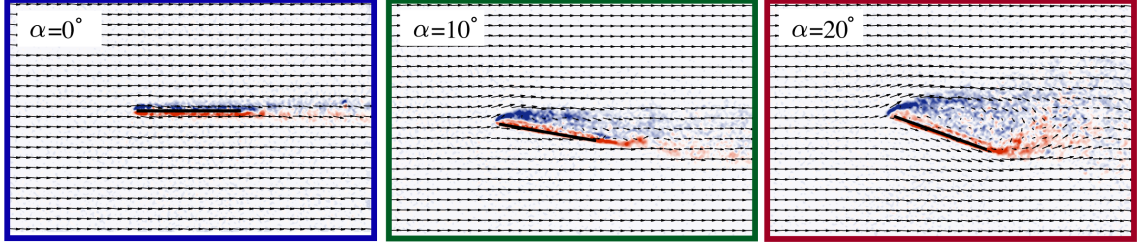
(d) Flowfields at $t^* = 2.5$ for angles of attack 0° , 10° , 20°



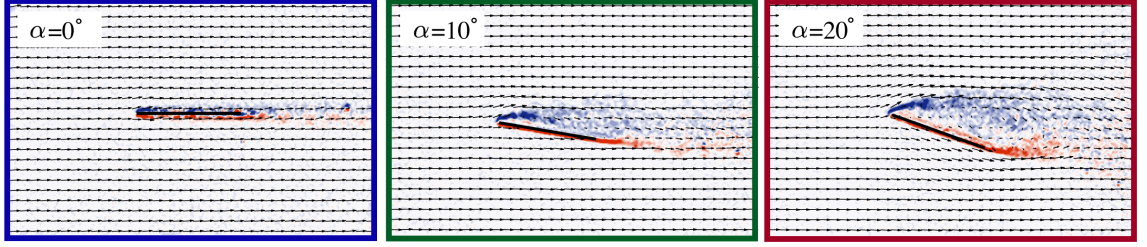
(e) Flowfields at $t^* = 3.6$ for angles of attack 0° , 10° , 20°



(f) Flowfields at $t^* = 6.5$ for angles of attack 0° , 10° , 20°



(g) Flowfields at $t^* = 10$ for angles of attack 0° , 10° , 20°



(h) Flowfields at $t^* = 15$ for angles of attack 0° , 10° , 20°

Figure 4.2: Flowfields for various angles of attack at a gust ratio of 0.5.

Figure 4.2(a) displays the PIV measurements at $t^* = -1$, where the wing has not yet interacted with the gust. At this instant, the flow is at a steady state. For $\alpha = 0^\circ$, the positive and negative vorticity shown in red and blue colors, respectively, are enclosed in the boundary layer. The vortex shedding is periodic, and the Von Kármán street is visible. For $\alpha = 10^\circ$ and $\alpha = 20^\circ$ cases, the flow is separated from the sharp leading edge. Therefore, a large wake is formed immediately behind the flat plate.

At $t^* = -0.5$, when only half of the wing is immersed in the gust, the negative vorticity separates from the leading edge and thickens on the upper surface of the

wing as shown in Figure 4.2(b). Moreover, the flow rolls into a leading-edge vortex, which is not yet quite strong. There is no distinguishable deflection in the trailing wake for any case.

As mentioned before, the forces experience extrema at $t^* = 1.8$, when the wing is fully immersed and approximately centered in the gust. Figure 4.2(c) shows the flowfield measurements at this instant. The leading-edge vortex builds up strength between $0.5 \leq t^* \leq 1.8$. This strong leading-edge vortex causes a low-pressure region and therefore creates a suction force normal to the wing surface, which explains why the above-mentioned lift maxima occur. This normal suction force contributes to the drag coefficient when angle of attack is larger than 0° . For more details on the physical mechanism that causes the drag transients, please refer to section 4.4. Moreover, as seen qualitatively in these flowfields, the strength of this leading-edge vortex increases as the angle of attack increases in the same vein as the force peaks. Please note that the circulation shed from the leading edge is quantified in the following section. The vortex is larger and away from the surface of the wing for higher angles of attack. Furthermore, the vortex core advects toward the trailing edge as the angle of attack increases. These cores are approximately 0.2, 0.4, and 0.7 chords away from the leading edge for angles of attack 0° , 10° , 20° , respectively. For all cases displayed here, a secondary flow forms on the upper surface of the wing due to the separation of positive vorticity from the boundary layer. The strong leading-edge vortices generate a reverse flow region on the wing. The trailing wake stays planar for $\alpha = 0^\circ$, whereas it is slightly deflected when $\alpha > 0^\circ$.

The flowfields at $t^* = 2.5$ are given in Figure 4.2(d). At this instant, the wing

has moved past the strongest portion of the gust but is still fully immersed, and the forces have started to recover from their extrema. For $\alpha = 0^\circ$ case, the leading-edge vortex bursts since it was in close proximity to the wing surface. It seems the most plausible that this is the origin of the force transients discussed earlier. Furthermore, the flowfield looks quite turbulent, which indicates that the three-dimensional effects dominate the flow at this time. The reader is encouraged to review section 4.5 for more details on the three-dimensionality of the sine-squared gust encounters. The trailing wake stays planar, notwithstanding the strong vertical gust velocities. For $\alpha > 0^\circ$ cases, the leading-edge vortex is larger vis-à-vis $t^* = 1.8$. However, it is less concentrated and further away from the wing surface. Moreover, the leading-edge vortex seems to continue inducing a reverse flow region on the wing. The vortex core is located at approximately $0.75c$ and trailing-edge for angles of attack $\alpha = 10^\circ$ and $\alpha = 20^\circ$, respectively. In addition, the deflection of the wake perpetuates, and the secondary separation is still visible for both cases.

Figure 4.2(e) displays the flowfields at $t^* = 3.6$, where the trailing edge of the wing exits the gust and the recovery phase begins. There is no dominant structure visible for $\alpha = 0^\circ$; instead, the flow on the upper surface of the wing looks turbulent. For $\alpha > 0^\circ$ cases, the leading-edge vortex has shed and advected behind the wing. Note that the shed leading-edge vortex for $\alpha = 20^\circ$ is further away from the wing than the one for $\alpha = 10^\circ$. Furthermore, this shed leading-edge vortex induces a trailing edge vortex for both $\alpha = 10^\circ$ and $\alpha = 20^\circ$ cases, which is presumably the reason why the forces experience a minimum at this instant. The strength of this trailing edge vortex increases with increasing angle of attack as does the “dip” in

the forces.

Figure 4.2(f) shows the flowfields at $t^* = 6.5$, which corresponds to 2.9 convective times after the wing has exited the gust. The flowfield for the wing at 0° angle of attack reverts to steady state condition, as do the forces. The earlier shed trailing edge vortex induces a secondary leading-edge vortex for both $\alpha = 10^\circ$ and $\alpha = 20^\circ$ cases. The secondary leading-edge vortex just starts to roll up for $\alpha = 10^\circ$ case at this instant and causes a subtle increase in the forces. On the other hand, for 20° case, a well-defined secondary leading-edge vortex is visible on the upper surface of the wing, which is weaker and closer to the surface than the “primary” leading-edge vortex displayed in Figure 4.2(c). This secondary vortex is thought to produce the steep secondary force maxima for $\alpha = 20^\circ$ detailed in the previous section. The wake seems quite planar at this instant.

Lastly, the flowfields at $t^* = 10$, 6.4 convective times after the wing exits the gust, are displayed in Figure 4.2(g). A weak secondary leading-edge vortex is present on the upper surface of the wing, and a slight wake deflection is visible for $\alpha = 10^\circ$ case. The aforementioned secondary leading-edge vortex for $\alpha = 20^\circ$ is now less concentrated and more towards the trailing edge of the wing compared to $t^* = 6.5$. A weak trailing edge vortex is induced at this moment, which causes the forces to decrease for the $\alpha = 20^\circ$ case.

Figure 4.2(h) displays the flowfields at $t^* = 15$. As can be seen from this plot, all flowfields revert to steady state in the same vein as the forces. The wakes look similar to those before the encounter at $t^* = -1$ (see Figure 4.2(a)).

4.1.1.3 Circulation Production

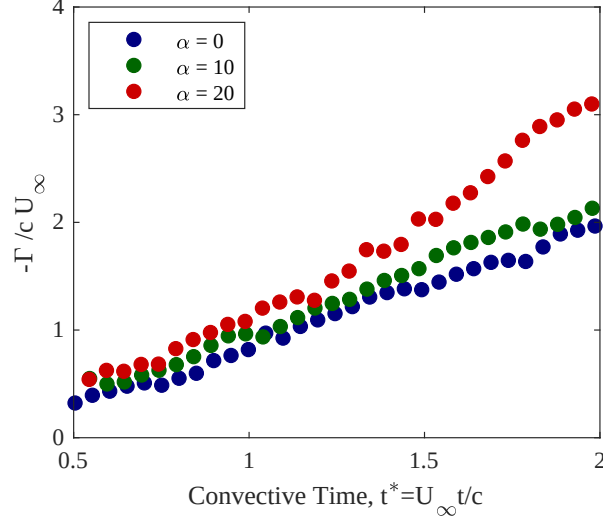


Figure 4.3: Nondimensional circulation for various angles of attack at a gust ratio of 0.5.

The leading-edge vortex strength was calculated using the segmentation method explained in section 2.6.2 for all cases. Figure 4.3 shows the nondimensional circulation shed during the gust encounter. In this plot, the x -axis shows the convective time. Note that the calculations were only done for the convective times between 0.5 and 2 since the leading-edge vortex is not sufficiently strong for $t^* \leq 0.5$, and cannot be distinguished from the gust shear layer for $t^* \geq 2$. The leading-edge vortex strength is invariant for all cases discussed here at $t^* \approx 0.5$. As can be seen from this figure, the circulation shed from the leading edge increases as the wing moves toward the center of the gust, which can also be seen qualitatively from Figure 4.2. The rate of the circulation shed is almost the same for all angles of attack until $t^* \approx 1.5$, after which point more considerable differences in circulation production occur. Furthermore, the strength of the leading-edge vortex increases

with increasing angle of attack in the same vein as the change in the forces.

To sum up, in this section, the angle of attack effects were evaluated using three different cases. The force transients were explained using PIV flowfields and circulation production calculations. Both lift and drag coefficients were found to experience a peak value when the wing was in the middle of the gust. Note that this peak is negative for drag coefficient of $\alpha = 0^\circ$ case, and positive for other cases. These force peaks were found to align with the existence of a leading-edge vortex on the upper surface of the wing for all cases. Furthermore, the force peaks increased with increasing angle of attack (within the tested angle of attack range) in the same vein as the circulation shed from the leading edge. The gust recovery portion of the response was found to differ for $\alpha = 0^\circ$ and $\alpha > 0^\circ$ cases. For the $\alpha = 0^\circ$ case, the forces recovered from the gust upon the exit, and thereafter no dominant flow structures were observed. However, for $\alpha > 0^\circ$, the trailing- and leading-edge vortices caused a local minimum and a secondary maximum in the forces as the wing exited and sometime after the exit, respectively.

4.1.2 A Detailed Investigation of Force Transients

The previous section discussed the trends of forces, flowfields, and circulation production for high-amplitude gust encounters. By doing so, it highlighted the fundamental flow physics for various angles of attack. In this section, the reader will find a more detailed analysis of the force transients for wing 1 (5 cm chord, 20 cm span) encountering relatively low-amplitude ($0.08 \leq GR \leq 0.32$) gusts. An

extensive data set will be used to investigate the behavior of the aforementioned force extrema.

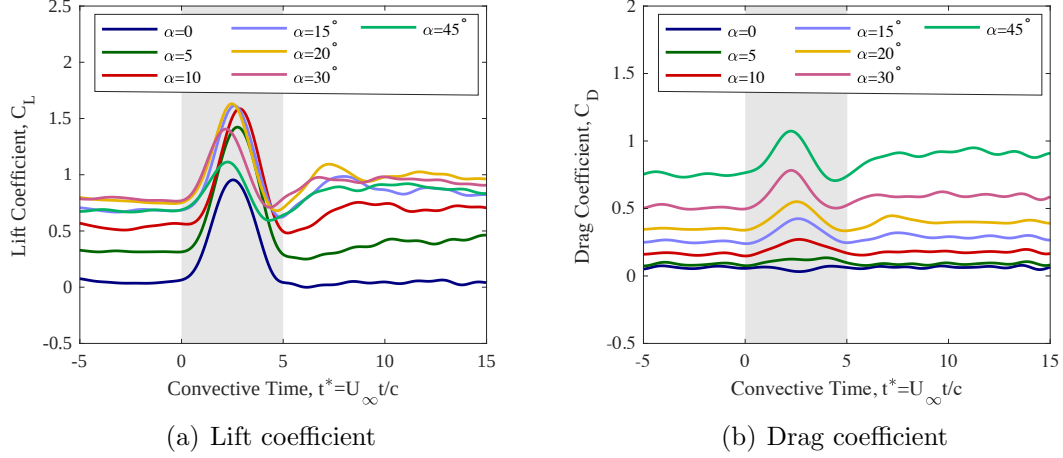


Figure 4.4: Lift and drag coefficients for various angles of attack at a gust ratio of 0.26.

Figure 4.4 shows the force histories for 7 different angles of attack at a gust ratio of 0.26. The x -axis shows the convection time. The trailing edge of the wing exits the gust at 5, 4.99, 4.98, 4.97, 4.93, 4.87, and 4.71 convective times for $\alpha = 0^\circ$, $\alpha = 5^\circ$, 10° , 15° , 20° , 30° , and 45° , respectively. The wing/gust interaction region is marked for the wing at 0° angle of attack with a grey box in Figures 4.4, 4.16. Figures 4.4(a) and 4.4(b) display the lift and drag coefficients, respectively. Before the wing encounters the gust ($t^* < 0^\circ$), the forces are at their steady-state values, which are given in Table 4.1. Similar to the cases discussed in the previous section, the force transients display three extrema which are the maximum (except the drag coefficient for $\alpha = 0^\circ$ case, which experiences a minimum) when the wing is centered in the gust, minimum as the trailing edge of the wing exits the gust, and secondary maximum after the wing exits the gust. In addition to these force trends, the large

data set on low-amplitude gust encounters used here allows for a couple of more details to reveal. The value of the maximum lift coefficient increases up to a certain limit around 15° , whereas the value of the maximum drag coefficient increases with increasing angle of attack for all cases tested. The secondary lift and drag peaks occur only when $\alpha \geq 10^\circ$ and $\alpha \geq 15^\circ$, respectively. The $\alpha = 5^\circ$ case does not exhibit a dominant drag maximum. More detailed analysis on the behavior of drag coefficient at low angles of attack will be detailed in section 4.4. The following subsection will discuss the aforementioned force extrema.

Table 4.1: Steady-state lift and drag coefficients for various angles of attack.

Angle of attack, (deg)	$C_{L_{SS}}$	$C_{D_{SS}}$
0°	0.03	0.07
5°	0.32	0.09
10°	0.56	0.16
15°	0.69	0.25
20°	0.77	0.35
30°	0.75	0.51
45°	0.69	0.75

4.1.2.1 Behavior of Force Maximum

The maximum force values were extracted for each angle of attack and gust ratio tested and plotted in Figure 4.5. The x -axis represents the angle of attack. Figure 4.5(a) shows the peak lift coefficient for various gust ratios. As can be seen from this figure, the behavior of the peak lift coefficient with angle of attack is analogous to a stall of an airfoil. This “stall angle” around 15° angles of attack for the cases shown here. As can be seen from this figure, the linearity breaks down around 10° . The slope of the increase in maximum lift coefficient is approximately

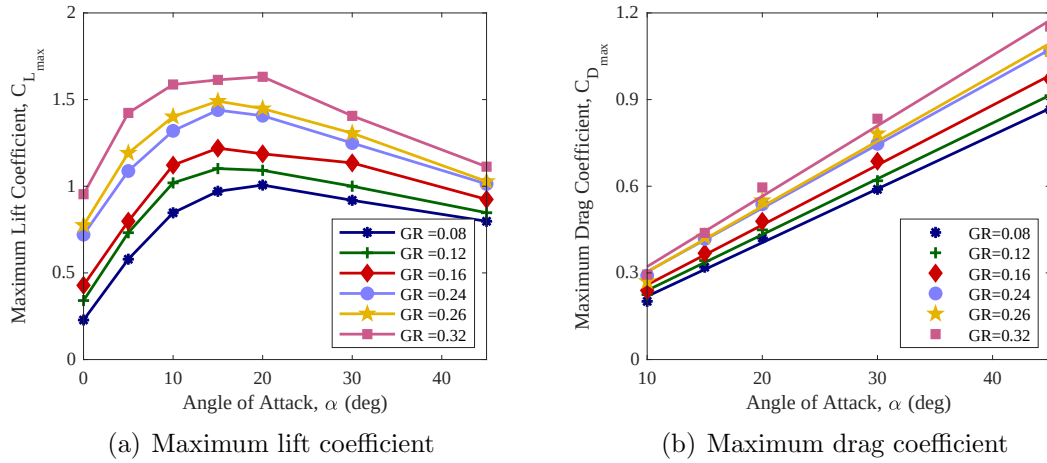


Figure 4.5: Maximum lift and drag coefficients versus angle of attack for various gust ratios.

the same for different gust ratios tested here when $\alpha \leq 10^\circ$. The cases where $10^\circ \leq \alpha \leq 20^\circ$, the maximum lift coefficient experiences a nonlinear “transition” region. On the other hand, for $\alpha \geq 20^\circ$, the maximum lift coefficient display a linear decrease. Increasing the gust ratio increases the peak lift coefficient measured for a given angle of attack value.

Figure 4.5(b) shows the maximum drag coefficient for various angles of attack and gust ratios. Linear fits characterize these measured extracted maximum drag coefficients. Note that only angles of attack larger than 5° were plotted here since the drag force does not exhibit a dominant drag maximum when the angle of attack is lower than 10° . As can be seen from this figure, the peak drag coefficient shows a linear dependence on the angle of attack. The slope of the linear fit increases with the increasing gust ratio. More detailed analysis on the force peak dependency on the gust ratio will be provided in section 4.2.2.1.

4.1.2.2 Behavior of Force Minimum

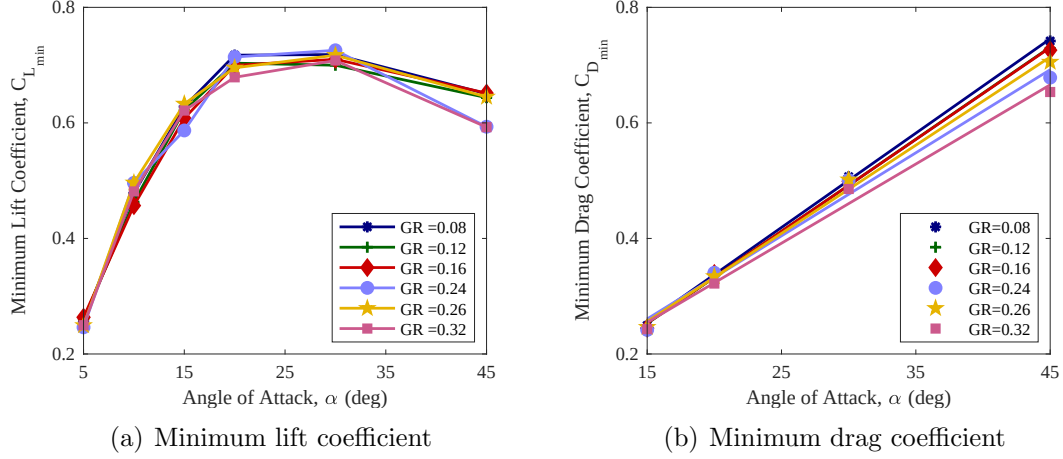


Figure 4.6: Minimum lift and drag coefficients versus angle of attack for various gust ratios.

The measured extracted lift minima are shown in Figure 4.6(a) for various gust ratios. As discussed earlier, the lift minima are experienced only when the angle of attack is larger than 0° . Similar to the lift maxima, the lift minima also display a stall-like behavior with a “stall angle” is around $\alpha = 25^\circ$. One thing to note here is that changing the gust ratio does not significantly affect the minimum lift coefficient except for a very large angle of attack around 45° , where the lift force displays a sharper dip.

Figure 4.6(b) shows the measured minimum drag coefficients and their linear fit for various gust ratios versus angle of attack. Since the drag force exhibit a minimum only when $\alpha > 10^\circ$, the x -axis displays $15^\circ \leq \alpha \leq 45^\circ$. As can be seen from this plot, increasing the angle of attack causes a larger minimum, presumably because of the higher impact of the existence of a stronger trailing edge vortex on

a larger cross-section wing. As expected, higher gust ratios result in larger minima.

Please refer to section 4.2.2.2 for more details.

4.1.2.3 Behavior of Force Secondary Maximum

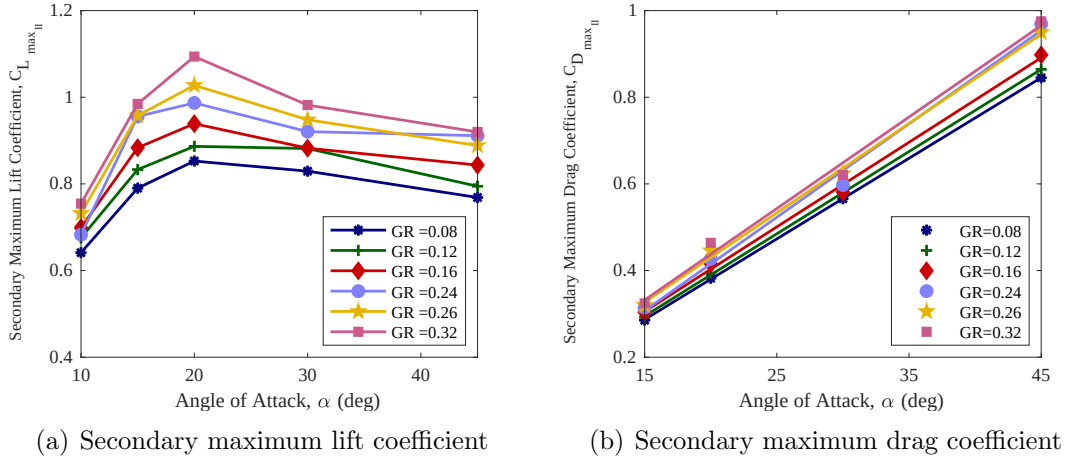


Figure 4.7: Secondary peak lift and drag coefficients versus angle of attack for various gust ratios.

The secondary maximum forces were also extracted for each case. Figure 4.7(a) illustrates the secondary peak lift coefficient for $\alpha \geq 10^\circ$ cases, where a secondary leading-edge vortex forms on the upper surface. Just like the above-mentioned lift coefficient extrema, the secondary maximum lift also displays a stall-like behavior, whose “stall angle” is around 20° similar to the maximum lift coefficient. The value of this secondary lift peak depends greatly on the gust ratio and increases with the increasing gust ratio.

Figure 4.7(b) shows the secondary peak drag coefficient versus angles of attack ($15^\circ \leq \alpha \leq 45^\circ$). As can be seen from this figure, the secondary peak drag coefficient is linearly dependent on the angle of attack similar to other drag coefficient extrema.

The secondary drag peaks increase with increasing gust ratio for a given value of angle of attack. The behavior of the secondary force peaks are remarkably similar to the behavior of above-mentioned force peaks since the transients in forces are caused by a chain vortex shedding mechanism such that the latter force transients are induced by the earlier shed vortices (detailed in section 4.1.1.2).

To sum up, the lift maximum was found to occur for every angle of attack tested ($0^\circ \leq \alpha \leq 45^\circ$), whereas a dominant maximum in drag was observed only when $\alpha \geq 10^\circ$. Please note that a negative peak was observed only for $\alpha = 0^\circ$ case whose value is small for the gust ratios investigated here. Both the lift and drag coefficients were found to experience a local minimum when $\alpha \geq 5^\circ$ and $\alpha \geq 15^\circ$, respectively, as the wing exits the gust. The secondary maximum in the lift was visible for cases where $\alpha \geq 10^\circ$, whilst the secondary maximum in drag was only present for $\alpha \geq 15^\circ$ cases. Overall, the lift coefficient extrema were found to exhibit a stall-like behavior. The linearity of the transients was found to break down around the angle of attack of 10° . On the other hand, the drag coefficient extrema displayed a linear dependence on the angle of attack. A novel normalization method, which uses the knowledge built thus far, will be introduced in the next chapter.

4.1.3 Exposed Projected Area Normalization

The gust-exposed projected area changes with angle of attack as shown in Figure 4.8. As the angle of attack increases, the gust-exposed projected area (in the transverse direction), $c \cos \alpha$, decreases while the freestream-exposed projected

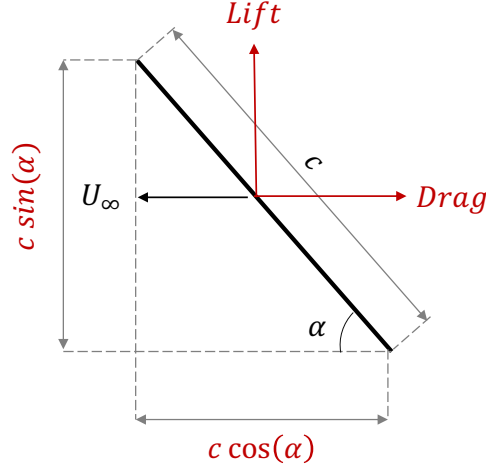


Figure 4.8: Sketch that shows gust-exposed and freestream-projected area of the wing.

area (in the longitudinal direction), $c \sin \alpha$, increases. The measured lift and drag coefficients will be non-dimensionalized based on the gust-exposed and freestream-projected areas, respectively to minimize the aforementioned effects of the angle of attack on the forces during the sine-squared gust encounters. The steady-state values of the force coefficients given in Table 4.1 are calculated for a region where the wing has not yet interacted with the gust ($-10 \leq t^* \leq 0$) and subtracted from each case to remove the effect of attached flow. Thus, this scaling method allows for a direct comparison of the gust encounter effects, and is given by

$$C'_L = \frac{2L}{\rho U_\infty^2 c \cos \alpha} b - C_{L_{ss}} \quad (4.1)$$

$$C'_D = \frac{2D}{\rho U_\infty^2 c \sin \alpha} b - C_{D_{ss}} \quad (4.2)$$

Figure 4.9 shows the lift and drag coefficients normalized by the gust-exposed and freestream-exposed projected areas, respectively, for the same cases shown in

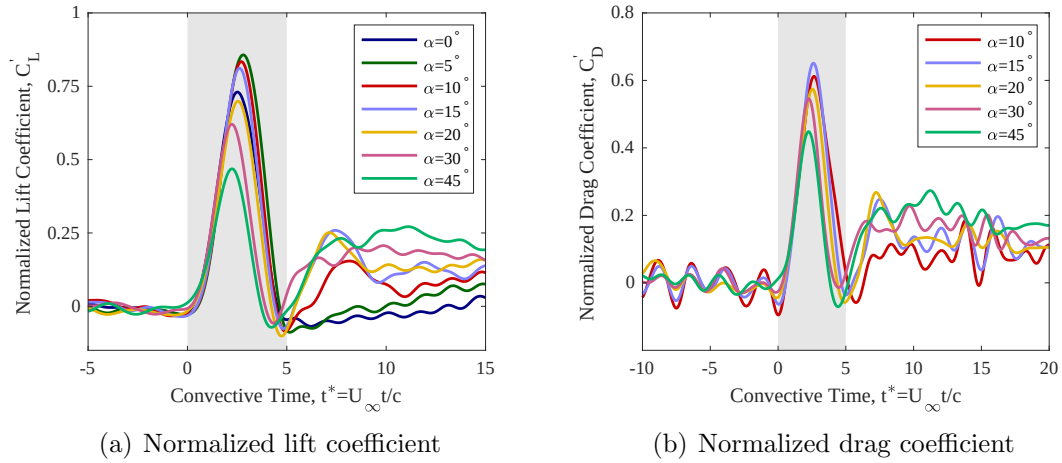


Figure 4.9: The gust-exposed and freestream-projected normalized lift and drag coefficients for various angles of attack at a gust ratio of 0.26.

Figure 4.4. The normalized lift coefficients exhibit similar peak values for $\alpha \leq 15^\circ$, as shown in Figure 4.9(a). However, this non-dimensionalization does not quite cure the nonlinear effects that occur at larger angles of attack. Be that as it may, it enhances the peak values of $\alpha > 15^\circ$ cases to match better with the peak values of $\alpha \leq 15^\circ$ cases. In addition, the normalized secondary lift peak values from various angles of attack yield similar results.

Figure 4.9(b) displays the normalized drag coefficients for 6 different angles of attack. The drag coefficients for the $\alpha = 0^\circ$ and $\alpha = 5^\circ$ cases are not discussed here since they do not exhibit a dominant drag maximum. Please keep in mind that this normalization cannot be used for $\alpha = 0^\circ$ even though the encounter yields a large maximum since $\sin(0) = 0$ and therefore $C'_D = \infty$. This clearly is not realistic but instead an artifact of non-dimensionalization. Overall, this normalization minimizes the differences between the drag extrema, and the drag coefficients obtained at different angles of attack somewhat exhibit similar peak values. Overall, it can

be concluded that the exposed projected area is not the only factor that affects the transients of various angles of attack. However, a comparison of Figures 4.9 with 4.4 demonstrates that exposed projected area plays a prominent role.

4.2 Variations in Gust Ratio

This section seeks to examine the effects of the gust ratio on the unsteady transients of the sine-squared gust encounters. The discussion will start with the trends of force and flow structure transients and continue with a more in-depth analysis of the force extrema. Lastly, a normalization method will be introduced, which can scale the forces that arise from gust encounters.

4.2.1 Trends of Forces, Flowfields, and Circulation Production

This section will initiate the discussion of the effects of gust ratio variations by analyzing the trends of forces, flowfields, and circulation production of high-amplitude sine-squared gust encounters. The results of which will provide a baseline for gusts of various strengths ranging from 0.5 to 1.5. Please note that wing 2 (3 in chord, 12 in span) was used as the test article to obtain the results discussed in the following subsections.

4.2.1.1 Lift and Drag

Figure 4.10 shows the lift response during the sine-squared transverse gust encounter of a 0° angle of attack flat plate for high-amplitude gust ratios of $GR =$

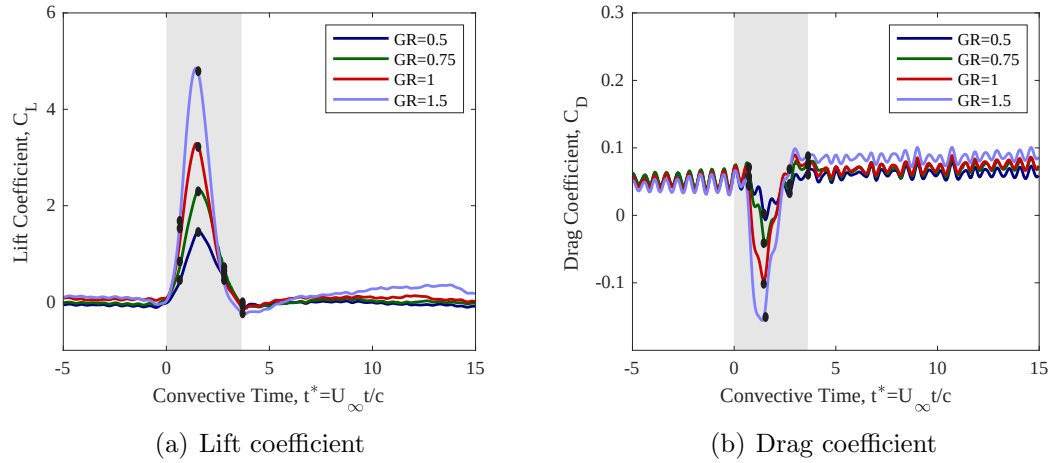


Figure 4.10: Lift and drag coefficients for various gust ratios at 0° angle of attack, circles on this plot corresponds to flowfields in Figures 4.11–4.14.

0.5, 0.75, 1, and 1.5. The wing-gust interaction region is marked with a grey box in this figure. The limits of this box are between $t^* = 0$ and $t^* = 3.6$ since the experiments shown here were performed using wing 2, please see section 2.2 for more details.

The lift histories of the above-mentioned cases are displayed in Figure 4.10(a). The lift coefficients are at their steady-state values before the encounter ($t^* \leq 0$), which are -0.06, -0.02, 0.05, and 0.07 for gust ratios 0.5, 0.75, 1, and 1.5, respectively. These steady-state values are approximately zero for all cases since the angle of attack of interest is 0° . The differences in these values are attributed to the measurement uncertainties quantified in section 2.5. When the wing is centered in the gust (at $t^* = 1.8$), the lift force experiences a maximum. The values of which increases with increasing gust ratio. After the wing passes through the strongest part of the gust ($t^* \geq 1.8$), the lift coefficient starts to decrease and reverts to steady state immediately after the exit (at $t^* = 3.6$) since all cases investigated here are for

a flat plate at 0° .

The transients in the drag coefficient are shown in Figure 4.10(b). Before the wing encounters the gust the drag coefficients are also at their steady-state values ($t^* \leq 0$), which are -0.05 for the $GR = 0.5$ case, -0.05 for the $GR = 0.75$ case, -0.05 for the $GR = 1$ case, and -0.04 for the $GR = 1.5$ case. The drag coefficient exhibits a dominant negative peak at $t^* = 1.8$. The value of the minimum drag increases as the gust ratio increases. Section 4.4 will provide a detailed discussion of the drag coefficient at low angles of attack. As the wing moves through the less substantial portion of the gust, the drag coefficients increase until they reach their steady-state values at $t^* = 3.6$. Even though the values of the steady-state drag coefficient before ($t^* \leq 0$) and after $t^* \geq 3.6$ the encounter seem different, please note that the limits of the drag coefficient (y -axis) are very tight and the differences in these values are within acceptable limits of the measurement uncertainties. In an attempt to provide further insight into the force transients explained here, the PIV flowfield measurements will be discussed in the next section.

4.2.1.2 Flowfields

Figures 4.11–4.14 display the ensemble-averaged flowfields at various convective times ($t^* = 1, 1.8, 2.5, 3.6$) for the same cases shown in Figure 4.10, where the corresponding convective times are marked with circles. Since the steady-state flowfields do not get affected by the variations in gust ratio, they are not shown in this section. The reader can find the flowfield for the $GR = 0.5$ & $\alpha = 0^\circ$

case in Figure 4.2(a). Since the gust ratio is adjusted by varying the pump speed, increasing the gust ratio results in a stronger gust shear layer, as can be seen in Figures 4.11–4.14.

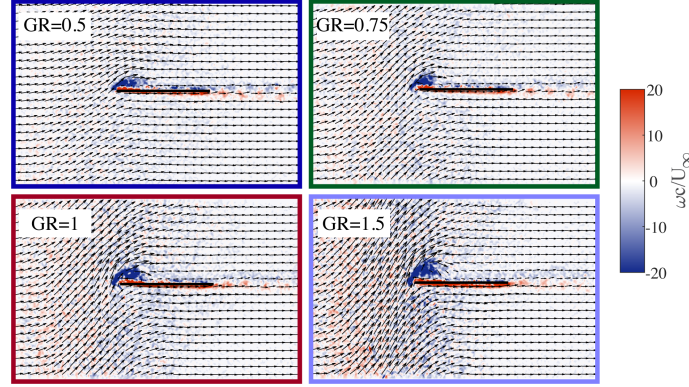


Figure 4.11: Flowfields at $t^* = 1$ for gust ratios of 0.5 to 1.5.

Figure 4.11 shows the experimental flowfields at $t^* = 1$, when the wing is fully immersed in the gust. Please note here that the strength of the vorticity at the edges of the velocity sine-squared profile is exceptionally small, causing the flowfields to seem not fully immersed. The flow separates from the leading edge of the wing and rolls into a leading-edge vortex for all cases investigated here. Qualitatively, the strength of this leading-edge vortex for the $GR = 0.5$ and $GR = 0.75$ cases looks quite similar. However, a further increase in gust ratio ($GR > 0.75$) results in a stronger leading-edge vortex. The circulation shed from the leading edge is calculated for every case shown here and will be discussed in section 4.2.1.3. Increasing the gust ratio causes the leading-edge vortex to advect away from the wing surface in the stream-normal direction, presumably due to the larger gust velocities present in the flow. The wake looks planar for all cases at this instant.

When the mid-chord of the wing is approximately in the middle of the gust,

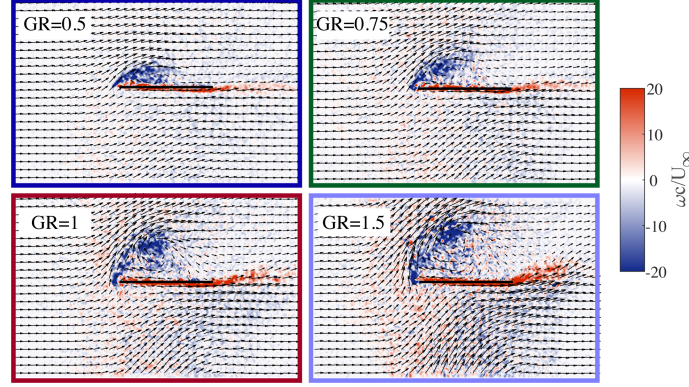


Figure 4.12: Flowfields at $t^* = 1.8$ for gust ratios of 0.5 to 1.5.

which corresponds to the time that the force coefficients peak (at $t^* = 1.8$), a strong leading-edge vortex exists on the upper surface of the wing as shown in Figure 4.12. As can be seen qualitatively from this figure, the strength of the vortex increases with increasing gust ratio in the same vein as the lift force. As the strength of the leading-edge vortex increases, the drag coefficient decreases to a larger minimum. The core of the leading-edge vortex moves further away from the wing surface as the gust ratio increases. The secondary separation of positive vorticity is visible for the high-amplitude gusts investigated here. Increasing the gust ratio also causes the vortex to advect towards the trailing edge. The vortex core is located at $0.34c$, $0.37c$, $0.39c$, and $0.41c$ for the $GR = 0.5$, $GR = 0.75$, $GR = 1$, and $GR = 1.5$, respectively. There is no visible wake deflection for the $GR = 0.5$ case. However, for $GR > 0.5$ cases, the trailing wake deflects upwards. The larger gust ratios result in larger wake deflections due to the higher levels of vorticity contained in the background gust shear layer.

Figure 4.14 displays the experimental flowfields at $t^* = 2.5$, where the wing has passed the strongest portion of the gust. At this instant, the forces have decreased

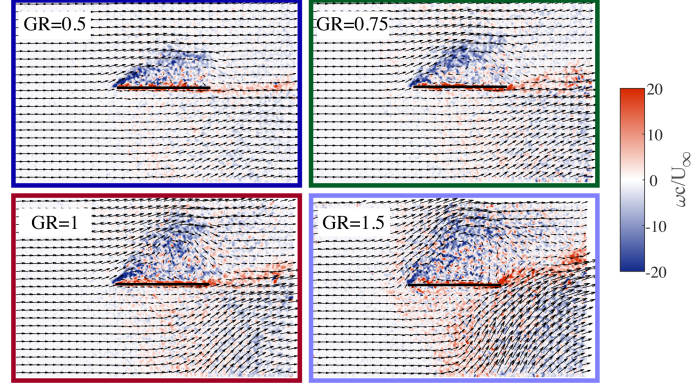


Figure 4.13: Flowfields at $t^* = 2.5$ for gust ratios of 0.5 to 1.5.

from their peaks. The aforementioned leading-edge vortices have burst for all cases, which is probably the reason why the forces start to recover to their steady-state values. The nonlinearity in the wake persists for cases where the gust ratio is larger than 0.5.

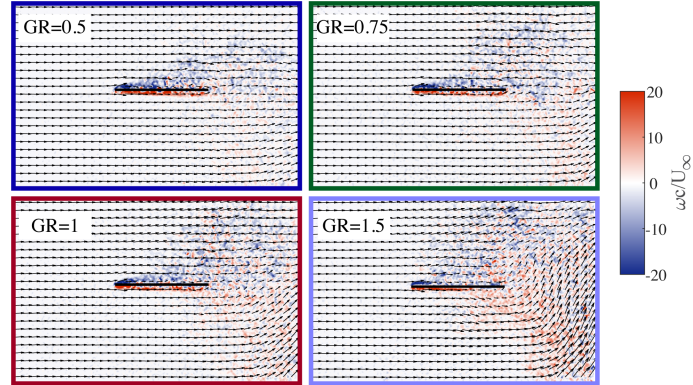


Figure 4.14: Flowfields at $t^* = 3.6$ for gust ratios of 0.5 to 1.5.

The flowfields at $t^* = 3.6$ are given in Figure 4.14. At this moment in time, the wing trailing edge exits the gust and forces recover to their steady-state values. There are no dominant structures visible at this instant, and the flowfields look very turbulent. The level of turbulence seems to increase with the increasing gust ratio, which indicates that the three-dimensional effects are stronger for larger gust ratios. Please refer to section 4.5 for more details. Shortly after this instant the flowfields

revert to steady state as shown for the $GR = 0.5$ & $\alpha = 0^\circ$ case in section 4.1.1.2.

4.2.1.3 Circulation Production

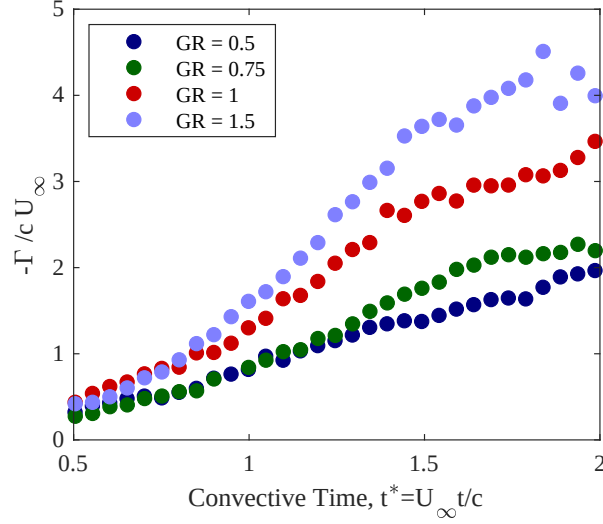


Figure 4.15: Nondimensional circulation for gust ratios at 0° angle of attack.

The leading-edge vortex strengths for a flat plate at 0° angle of attack encountering various strengths of transverse gusts are plotted in Figure 4.15. In this plot, the x -axis shows the convective time. As mentioned before, this analysis was performed for the convective times between 0.5 and 2. The leading-edge vortex strengths are observed to be similar until $t^* = 0.75$. Only after this point in time, where the wing moves toward a stronger part of the gust, does the circulation shed from the leading edge starts to differ. As can be seen from this plot, the increase in the gust ratio results in a larger circulation shed from the leading edge and correlates with larger force extrema.

Overall, trends of forces, flowfields, and circulation production were examined for a flat plate at 0° angle of attack encountering gusts of various strengths ($0.5 \leq$

$GR \leq 1.5$) in this section. The results showed that increasing the gust ratio increases the lift maxima and drag minima. However, the gust ratio was found to have minor effects on the gust recovery phase since the angle of attack discussed here is 0° . Please refer to section 4.1.1 for more information on the recovery of $\alpha > 0^\circ$ cases. Moreover, the circulation shed from the leading edge was found to increase with increasing gust ratio in the same vein as the values of the force peaks.

4.2.2 A Detailed Investigation of Force Transients

The previous section detailed the trends of forces, flowfields, and circulation production for a flat plate (wing 2) encountering high-amplitude gusts of strengths of 0.08 to 0.32. This section will extend the discussion of the relationship between the force transients and gust ratio. The analysis will be performed on the experimental force measurements obtained using wing 1 (5 cm chord, 20 cm span) on low-amplitude ($0.08 \leq GR \leq 0.32$) gust encounters.

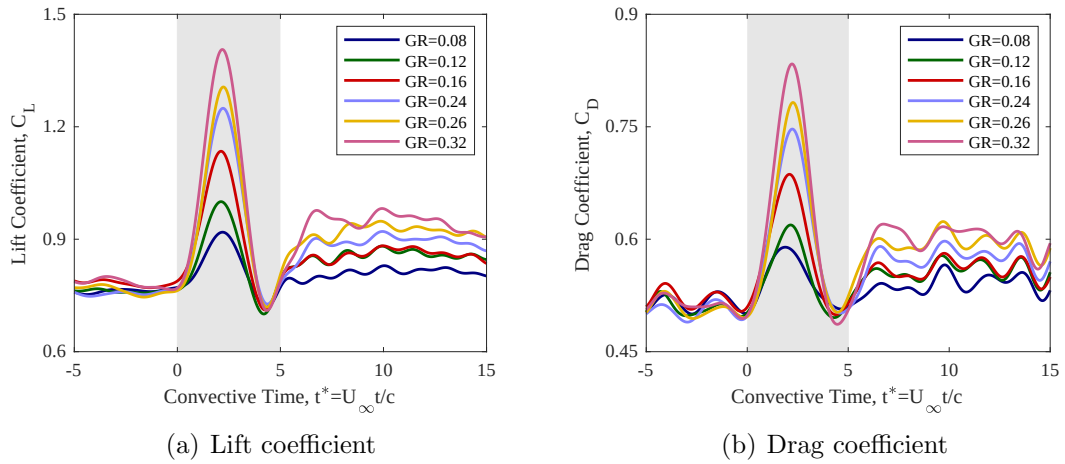


Figure 4.16: Lift and drag coefficients for low-amplitude (0.08 to 0.32) gust ratios at 30° angle of attack.

Figure 4.16 shows the lift and drag coefficients for 6 different low-amplitude gust ratios for a flat plate at 30° angle of attack. As the wing moves towards the center of the gust, the forces increase from their steady-state values to their maxima. These maximum values of both lift and drag coefficients increase with increasing gust ratio, similar to the high-amplitude gust encounters discussed in section 4.2.1.1.

Since the angle of attack discussed here is larger than 15° , both force coefficients experience a local minimum as the wing exits the gust and a secondary maximum sometime after the exit. As explained in section 4.1.1.2, these latter transients are caused by a chain vortex shedding mechanism (a leading-edge vortex forms and sheds during the encounter, which induces a trailing vortex, which then induces a secondary leading-edge vortex). Therefore, the amplitudes of these latter transients are directly related to the amplitude of the former lift maximum. Since higher gust ratios result in larger force maxima, the value of the local minimum and secondary maximum increase with increasing gust ratio. Moreover, the time required for the forces to revert to steady state also increases with the increasing gust ratio. All cases investigated here was found to revert to steady-state after 20 convective times. The effect of the gust ratio on the force extrema will be discussed in the following subsections.

4.2.2.1 Behavior of Force Maximum

The maximum force values of all cases tested for low-amplitude gusts were extracted for each gust ratio in Figure 4.17. The x -axis represents the gust ratio.

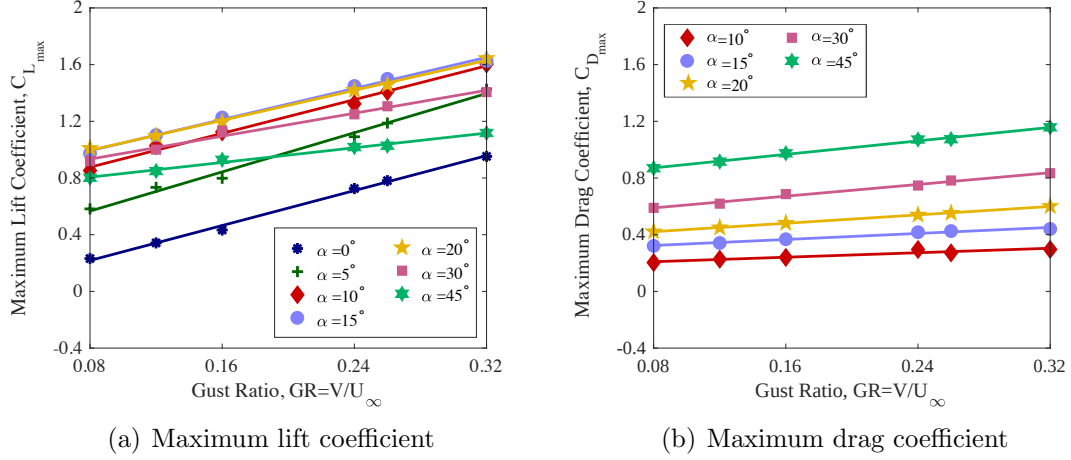


Figure 4.17: Maximum lift and drag coefficients versus gust ratio for angles of attack of 0° to 45° .

Figure 4.17(a) shows the maximum lift coefficients for various angles of attack, which are found to exhibit linear dependency on gust ratio and are characterized by linear fits of various slopes. As can be seen from this plot, increasing the gust ratio increases the maximum lift coefficient. One intriguing outcome of this analysis is the fact that the slopes of the lines used to characterize the measured maxima are approximately the same for $0^\circ \leq \alpha \leq 20^\circ$. However, for $\alpha \geq 20^\circ$ cases, the slopes of these lines decrease, meaning the gust ratio plays a less dominant role for larger angles of attack.

The maximum drag coefficients and linear fits to the extracted values for constant angles of attack ($10^\circ \leq \alpha \leq 45^\circ$) are displayed in Figure 4.17(b). As mentioned earlier, the low-amplitude gust encounters do not result in a predominant peak for $\alpha < 10^\circ$. Therefore, they are not shown here. The peak drag coefficients for $10^\circ \leq \alpha \leq 45^\circ$, however, increase as the gust ratio increases for a given angle of attack. Unlike the maximum lift coefficient, the maximum drag coefficient gets

more affected by the variation in gust ratio for the cases where $\alpha \geq 20^\circ$.

4.2.2.2 Behavior of Force Minimum

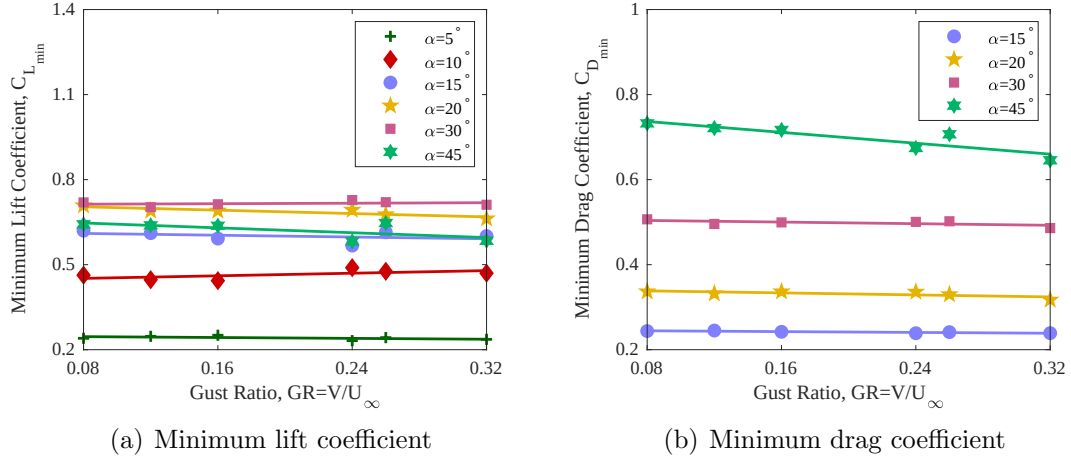


Figure 4.18: Minimum lift and drag coefficients versus gust ratio for angles of attack of 0° to 45° .

The minimum force coefficients were extracted from the data acquired using wing 1. Figure 4.18 displays these minimum lift and drag coefficients characterized by linear fits versus gust ratio. The cases shown here are selected based on the fact that the lift and drag coefficients do not experience a minimum when $\alpha \leq 5^\circ$ and $\alpha \leq 15^\circ$, respectively. As can be seen from this figure, the gust ratio does not play a major role on the amplitude of the force minimum within the tested gust ratio range except for the angle of attack of 45° case, where increasing gust ratio results in a more predominant force minimum.

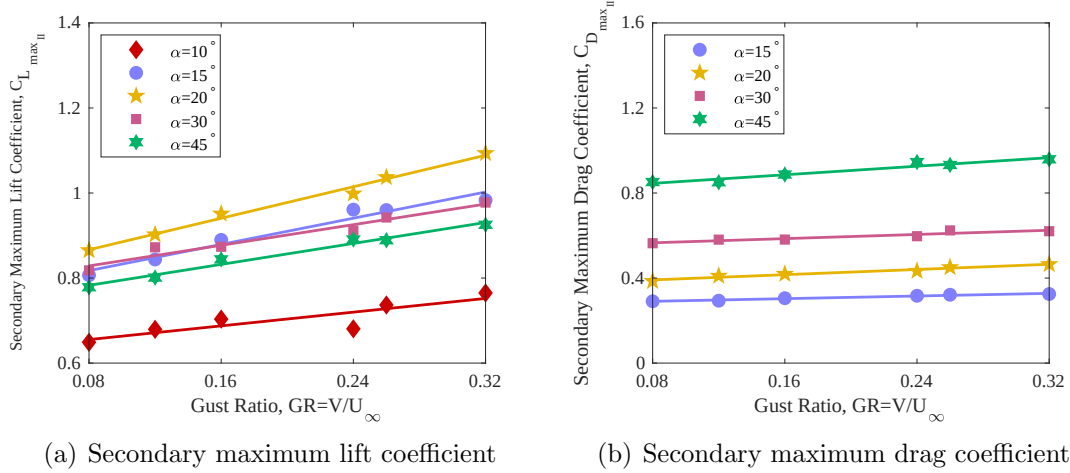


Figure 4.19: Secondary maximum lift and drag coefficients versus gust ratio for angles of attack of 0° to 45° .

4.2.2.3 Behavior of Force Secondary Maximum

The extracted secondary maximum values versus gust ratio are plotted for angles of attack of 0° to 45° in Figure 4.19. The secondary maximum lift values and linear fits to those are given in Figure 4.19(a) for $10^\circ \leq \alpha \leq 45^\circ$ since for the cases, which the angle of attack is smaller than 10° , do not produce a secondary lift peak. Even though all cases show a linear dependency on the gust ratio, 20° angle of attack was found to be the one case that is the most affected by the changes in gust ratio (the highest slope is observed for this angle of attack). One thing to note here is that for $\alpha \geq 30^\circ$ the secondary lift peak values depend more on the gust ratio than the maximum values discussed earlier in section 4.2.2.1.

Figure 4.19(b) shows the extracted secondary maximum drag coefficients and their linear fits for $10^\circ \leq \alpha \leq 45^\circ$. The remaining angles of attack were not included since they do not exhibit a secondary drag peak. As can be seen from this figure,

the secondary maximum drag coefficients are less affected by the gust ratio than the secondary maximum lift coefficients. The changes in gust ratio substantially alter the values only for the $\alpha = 45^\circ$ case.

To sum up, the effects of the gust ratio on force transients and extrema were discussed for low-amplitude gust encounters using an extensive data set. The analysis showed that the force maximum, minimum, and secondary maximum depends linearly on the gust ratio. Increasing the gust ratio was found to result in a more significant force maximum. The impact of the gust ratio variations on the maximum lift coefficient was found to lessen at very large angles of attack ($\alpha \geq 30^\circ$). At the same time, it had a more predominant effect on the maximum drag coefficient at larger angles of attack. On the other hand, within the tested range ($0.08 \leq GR \leq 0.32$), altering the gust ratio exerted a minor effect on the force minimum for the cases where, $\alpha < 45^\circ$. Similar to the force maxima, for very large angles of attack ($\alpha \geq 30^\circ$), the variations in the gust ratio played a minor role on the maximum secondary lift and a very crucial one on the secondary maximum drag.

4.2.3 Gust Ratio Normalization

The previous sections examined the effects of gust ratio on forces, flowfields, circulation production, and force extrema. This section attempts to normalize the forces using the gust ratio parameter. The normalization discussed in this section takes its starting point from Küssner's model, which expresses the lift coefficient as

$C_l = 2\pi GR \psi(t^*)$, where $\psi(t^*)$ is the Küssner function and GR is the gust ratio. As can be seen clearly from this expression, it suggests that the lift coefficient can be normalized using the gust ratio. Even though this normalization is expected to work only for lift coefficient that results from small disturbances, the current section deepens the discussion of this normalization and explores its applicability for both lift and drag coefficients that arise from a wide range of disturbances ($0.08 \leq GR \leq 1.5$ and $0^\circ \leq \alpha \leq 45^\circ$). For each case, the gust ratio normalization is performed after subtracting the steady-state values (the values of which are given in section 4.1) from the coefficients. This is done to isolate the effect of gust encounters from the effect of attached flow. This normalization is given by

$$\frac{\Delta C_L}{GR} = C_L - C_{L_{SS}} \quad (4.3)$$

$$\frac{\Delta C_D}{GR} = C_D - C_{D_{SS}} \quad (4.4)$$

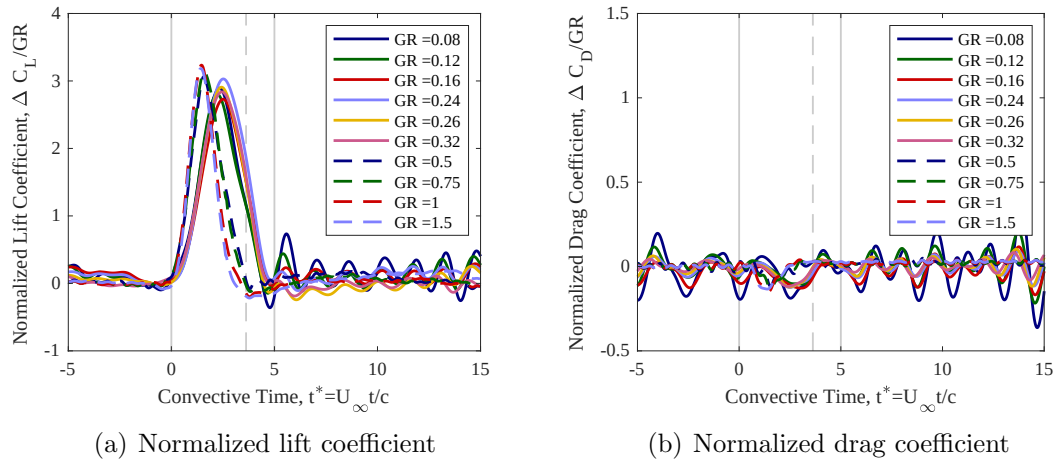


Figure 4.20: Gust ratio normalized lift and drag coefficients for various gust ratios at 0° angle of attack.

Figure 4.20 shows the lift and drag coefficients normalized by gust ratio for a flat plate at 0° angle of attack. Results from both the low-amplitude (experiments performed using wing 1) and high-amplitude (experiments performed using wing 2) gust encounters are displayed in this plot. The solid lines in this figure represent the low-amplitude gust encounter coefficients, while the dashed lines represent the high-amplitude gust encounter coefficients. Both wings 1 and 2 enter the gust at $t^* = 0$. However, they exit the gust at different times since the chord lengths of the wings are different. The exit times are $t^* = 5$ (marked with a solid grey line) and $t^* = 3.6$ (marked with a dashed grey line) for wings 1 and 2, respectively.

The history of normalized lift coefficients for gusts of various strengths are given in Figure 4.20(a). As can be seen from this figure, the normalization does an excellent job scaling the coefficients from a wide range of gust ratios, notwithstanding the fact that the results were obtained using different wings. The slight differences in the normalized lift coefficients are attributed to the differences in measurement uncertainties of two data sets, the details of which are provided in section 2.5. After the wing exits the gust, the normalized lift coefficients exhibit large fluctuations for very small gust ratios, such as 0.08, 0.12, 0.16. Since ΔC_L is approximately zero at this instant, it is clear that these fluctuations occur because of an artifact in the normalization for very small gust ratios.

Figure 4.20(b) shows the normalized drag coefficients for several gust ratios at 0° angle of attack. As pointed out in the earlier sections, the drag coefficient experiences a negative peak when $\alpha = 0^\circ$. The physical mechanisms that cause these differences will be discussed in section 4.4. As can be seen from this figure,

the normalization scales the low and high-amplitude gust encounter drag coefficients very well. Similar to the lift coefficient, the drag coefficient, where $\Delta C_D \approx 0$, also exhibits large fluctuations for small gust ratios ($GR \leq 0.16$).

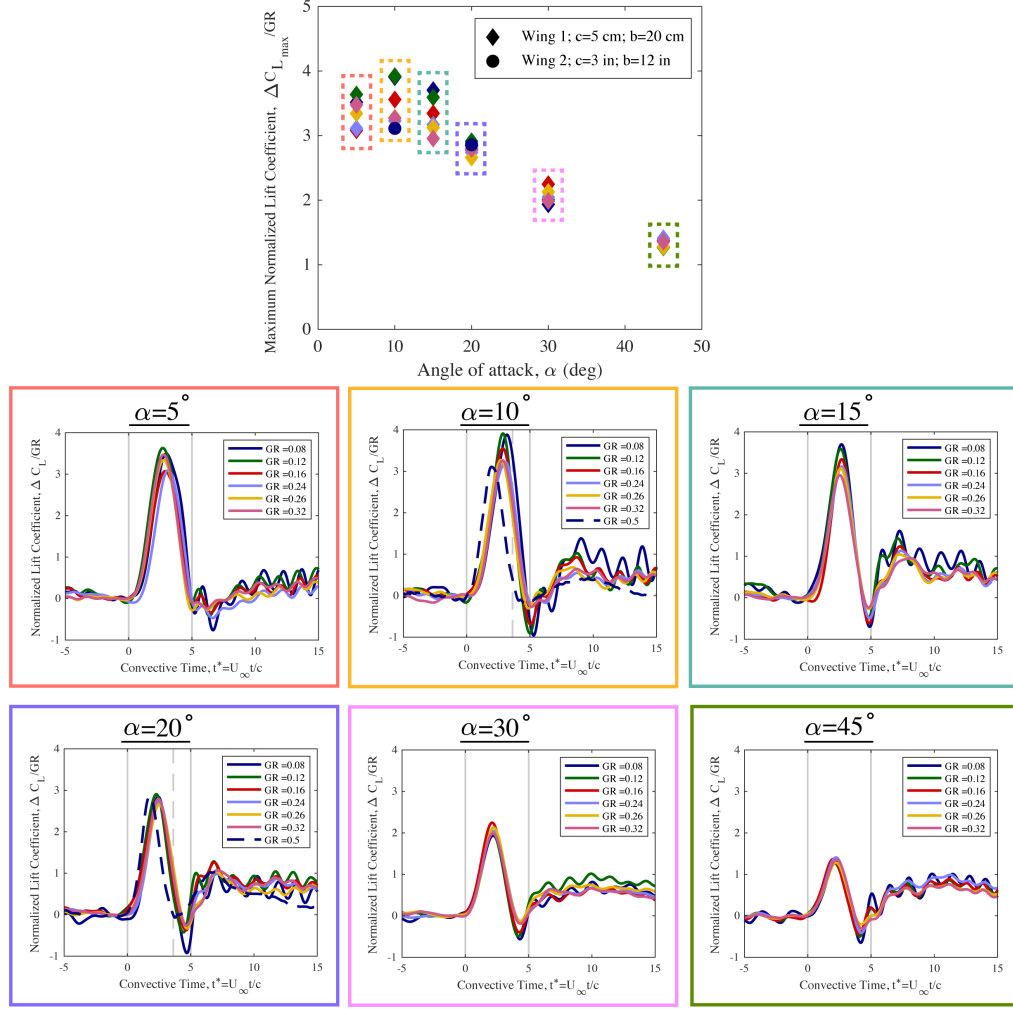


Figure 4.21: Maximum gust ratio normalized lift coefficient for various angles of attack (top plot) and corresponding gust ratio normalized lift histories.

The maximum normalized lift coefficients were extracted for all cases tested and plotted in Figure 4.21 (top plot). In this top plot, different symbols were used to differentiate the data obtained using wings 1 and wing 2. The normalized lift histories for various gust ratios at a constant angle of attack, which are pertinent to

the normalized maximum lift coefficients in the top plot, are displayed in small color-coded boxes in the bottom plots in Figure 4.21. The various gust ratios investigated are highlighted with different colors, as seen from the legends of these normalized lift histories. Similar to the above-mentioned $\alpha = 0^\circ$ case, the high-amplitude lift histories are shown with dashed lines, while solid lines were used to illustrate the lift response of low-amplitude gust encounters. The coefficient of variations of the maximum normalized lift coefficient are given for various angles of attack in Table 4.2. As can be seen from this table, the maximum coefficient of variation is 9.6% and observed for $\alpha = 10^\circ$. Furthermore, unexpectedly, the most significant variations in the maximum normalized lift coefficient are observed for relatively smaller angles of attack. As can be seen from Figure 4.21, the largest discrepancies in the maximum normalized lift coefficient occur for $GR = 0.08, 0.12$, and 0.16 cases at $\alpha \leq 15^\circ$, where the maximum lift is larger compared to other angles of attack. This is thought to be an artifact of the normalization since very small gust ratios ($GR \leq 0.16$) over-amplify the already larger lift peaks. Furthermore, the gust ratio normalization also nicely scales the lift minima and secondary maxima of different cases.

Table 4.2: Coefficients of variation of the maximum gust ratio normalized lift coefficient for various angles of attack.

Angle of Attack, (deg)	Mean $\pm$ Stdev	Coefficient of Variation (%)
0°	2.98 ± 0.17	5.7
5°	3.36 ± 0.22	6.7
10°	3.47 ± 0.33	9.6
15°	3.32 ± 0.29	8.7
20°	2.80 ± 0.08	2.9
30°	2.06 ± 0.11	5.5
45°	1.34 ± 0.06	4.2

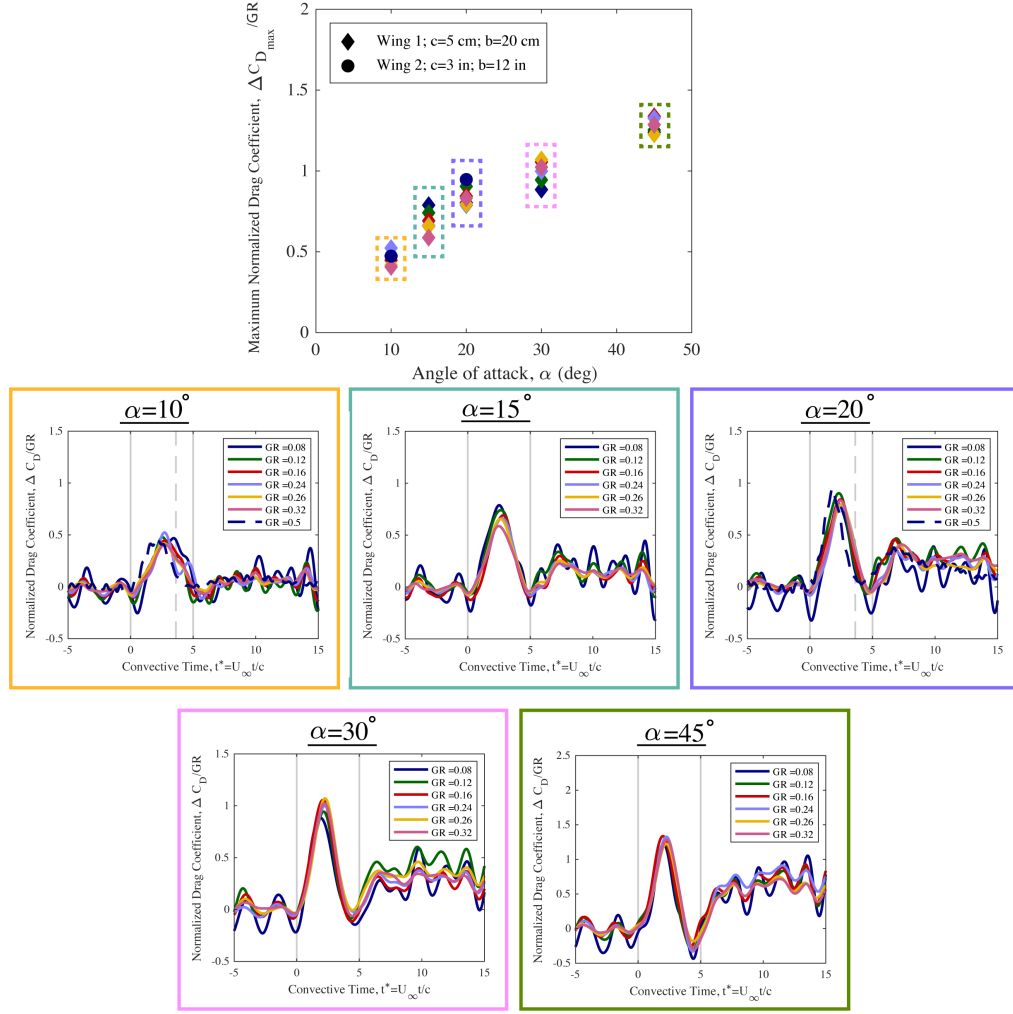


Figure 4.22: Maximum gust ratio normalized drag coefficient for various angles of attack (top plot) and corresponding normalized drag histories.

Figure 4.22 is structured similar to Figure 4.21. The only differences between the two figures are that the top plot in Figure 4.22 displays the maximum normalized drag coefficients, which were extracted for all cases tested, and the color-coded subplots show the normalized drag histories. Table 4.3 shows the coefficient of variations of the maximum normalized drag coefficient for several angles of attack. The maximum coefficient of variation is observed for $\alpha = 15^\circ$, which is 10.2%. Please note that the values of the maximum normalized drag are very low vis-à-vis

maximum normalized lift, which causes the coefficient of variations to be larger. Overall, the gust ratio normalization scales the drag histories well despite the fact that different data sets were used for this scaling. This normalization also does a good job scaling the drag minima and secondary maxima. Repeatedly, the very small gust ratios ($GR \leq 0.16$) cause considerable fluctuations in the normalized coefficients.

Table 4.3: Coefficients of variation of the maximum normalized drag coefficient for various angles of attack.

Angle of Attack, (deg)	Mean $\pm$ Stdev	Coefficient of Variation (%)
10°	0.46 $\pm$ 0.04	8.6
15°	0.69 $\pm$ 0.07	10.2
20°	0.84 $\pm$ 0.06	7.1
30°	1.00 $\pm$ 0.07	7.1
45°	1.28 $\pm$ 0.04	3.6

To sum up, the gust ratio parameter was found to be very effective in normalizing both lift and drag coefficients. The maxima, minima, and secondary maxima were found to scale well using this normalization. The only discrepancies were found to be caused by an artifact of the normalization at very small gust ratios ($GR \leq 0.16$). The broad investigation range showed that the linear effects dominate the sine-squared gust encounters even for very large gust ratios ($GR = 1.5$).

4.3 Maximum Effective Angle of Attack and Lift

Earlier, the effects of variations in the angle of attack and gust ratio on the force transients were discussed. In an attempt to narrow down the parameter space to only one parameter, this section discusses the effect of the effective angle of attack

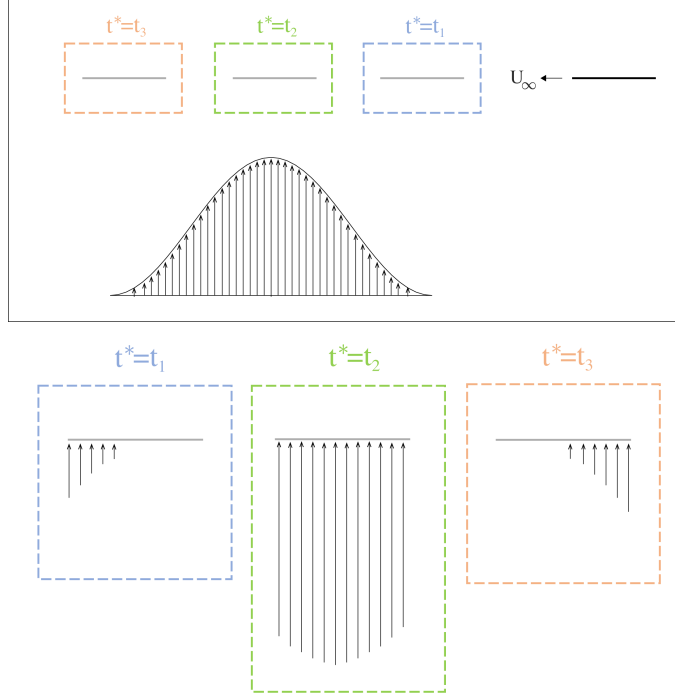


Figure 4.23: Sketch of a wing towing through a sine-squared gust, and three instances that show the gust velocity distribution along the wing.

on the lift force. When the wing encounters the sine-squared transverse gust, the vertical velocity introduced by the gust generates an induced angle of attack on the wing and causes the effective angle of attack to increase. The velocity distribution, therefore the effective angle of attack, is different for every location along the wing chord for every time step as the wing enters and passes through the transverse gust, as shown for three different instances in Figure 4.23. For a constant geometric angle of attack α , a forward velocity of U_∞ , and a transverse gust velocity of $V(t^*)$, the effective angle of attack at is defined as $\alpha_{\text{eff}}(t^*) = \alpha + \tan^{-1}(V(t^*)/U_\infty)$. In order to simplify the problem and avoid the complexity of manufacturing a model capable of dynamic camber, a point effective angle-of-attack assumption was taken here. Since the maximum lift force is experienced when the mid-chord of the wing is at the middle of the gust, as discussed in the earlier sections. This point was selected to be

mid-chord, where it sees the peak gust velocity of V_p , and experiences the maximum effective angle of attack ($\alpha_{\text{eff,max}} = \alpha + \tan^{-1}(V_p/U_\infty)$).

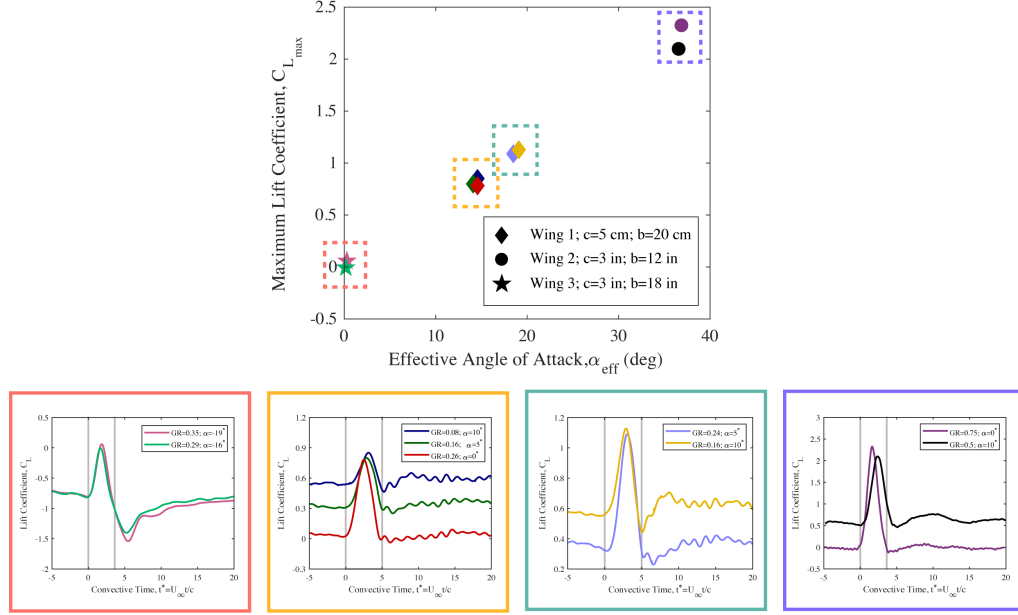


Figure 4.24: Maximum lift coefficients with similar maximum mid-chord effective angle of attack for different wings.

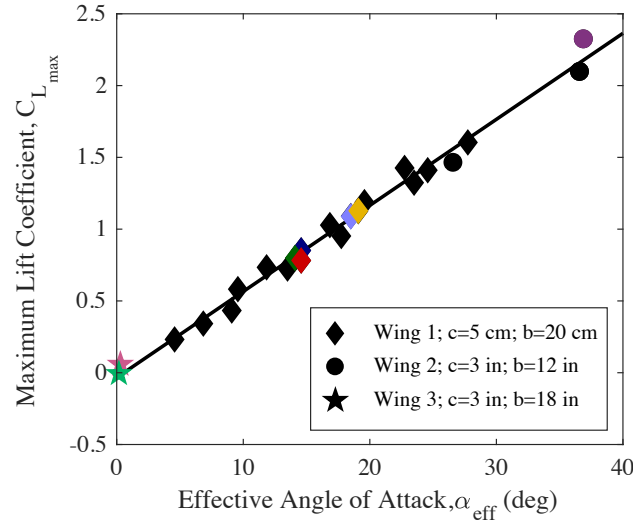


Figure 4.25: Maximum lift coefficients versus maximum mid-chord effective angle of attack for cases where $\alpha \leq 10^\circ$ and $\alpha_{\text{eff,max}} \leq 40^\circ$. The colors shown in this plot corresponds to the same cases displayed in Figure 4.24.

In order to investigate the relation between the maximum effective angle of

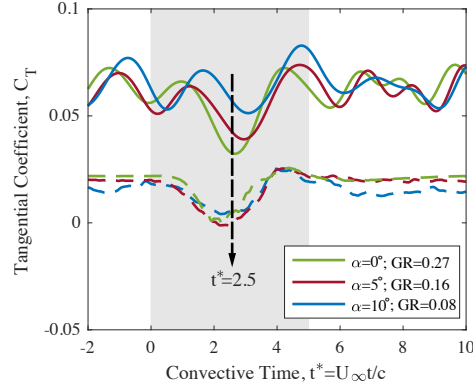
attack and the maximum lift coefficient, 4 data sets, all of which yield the same maximum effective angle of attack through different combinations of gust ratio and geometric angle of attack, from 3 different wings for various gust ratios and angles of attack are used and presented in Figure 4.24. In the top of this figure, the y -axis represents the maximum lift coefficient and the x -axis shows the maximum effective angle of attack achieved during the gust encounter. Different symbols are used to represent different sets from the 3 different wings. In the bottom of the same figure, the lift coefficient time histories of these cases are shown. As can be seen from this plot, the maximum lift coefficients are similar for similar maximum effective angles of attack if the geometric angle of attack of the wing is less than or equal to 10° , which is expected since the linearity of the transients was found to break down around the angle of attack 10° , see section 4.1.2.3. Interestingly, this relation works well for effective angles of attack as high as 40° . To further the investigation of this relation, all cases that satisfy $\alpha \leq 10^\circ$ and $\alpha_{\text{eff}_{\text{max}}} \leq 40^\circ$ are shown in Figure 4.25. As can be seen from this figure, the maximum lift coefficient is linearly dependent on the maximum effective angle of attack for the sine-squared gust encounters. The equation of this line is given by $C_{L_{\text{max}}} = 0.06\alpha_{\text{eff}_{\text{max}}} - 0.03$. Therefore, it can be concluded that by just having the prior information on the sine-square transverse gust (i.e., the geometric incidence of the wing and the maximum transverse velocity in the gust flow), it is possible to predict the maximum lift coefficient with a reasonable accuracy if $\alpha \leq 10^\circ$ and $\alpha_{\text{eff}_{\text{max}}} \leq 40^\circ$.

4.4 Drag Coefficients at Low Angles of Attack

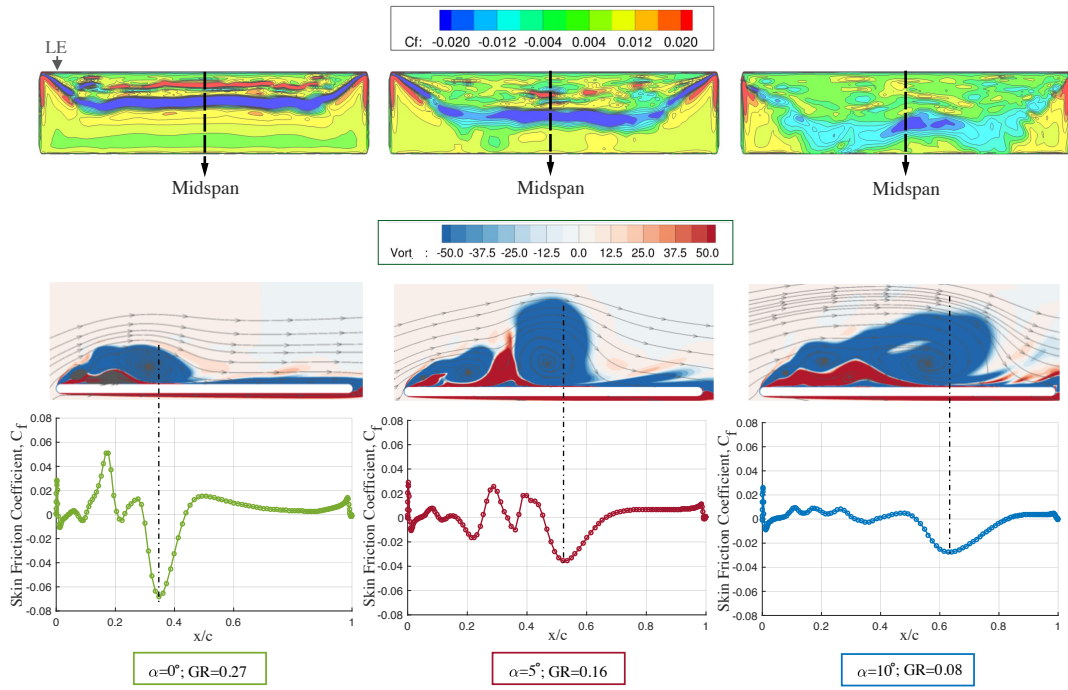
This section introduces and discusses the physical mechanism that causes the transients in the drag force using both experimental and computational data. The details of the computational methodology can be seen in section 3.1.1. Before focusing on the drag transients caused by the sine-squared gust encounters, let us recall the drag coefficient on a body in an incompressible flow, consists of two components: skin friction drag and form (pressure) drag. For a flat plate wing at a low angle of attack ($\alpha \approx 0^\circ$), the skin friction drag contributes to the total drag more than the form drag since the flow around this slender body is streamlined, and the pressure differences between the upstream and downstream of the body are extremely low. On the other hand, for larger angles of attack, the flow sees a larger cross-section in the streamwise direction, and the pressure differences across the body are higher; therefore, the form drag dominates the total drag coefficient.

In previous sections, the behavior of drag transients during sine-squared gust encounters was established. The drag coefficient was found to experience a negative peak, a small peak, and a positive peak when $\alpha = 0^\circ$, $\alpha = 5^\circ$, and $\alpha \geq 10^\circ$, respectively. In order to investigate the roots of these differences in the drag force responses of various angles of attack, the skin friction coefficient will be explored in this section, which is defined as

$$C_f = \frac{\tau_w}{0.5\rho U_\infty^2} \quad (4.5)$$



(a) Tangential coefficients



(b) Skin friction coefficient

Figure 4.26: Experimental (solid lines) and computational (dashed lines) tangential coefficients of a flat plate at angles of attack of 0° , 5° , and 10° , and gust ratios of 0.26, 0.16, 0.08, respectively. Computational skin friction contours on the upper surface at $t^* = 2.5$, computational vorticity contours at midspan, and the computational chordwise skin friction coefficients (at midspan).

where

$$\tau_w = \mu \frac{\partial u}{\partial n} \quad (4.6)$$

In the above equations, τ_w is the shear stress on the surface of the flat plate, μ is the dynamic viscosity, and $\frac{\partial u}{\partial n}$ is the change in the flow velocity in the outward normal direction. Since the shear stress is harder to measure experimentally, the skin friction coefficients were computationally obtained by collaborators at the UMD. Figure 4.26(a) shows the tangential coefficients from both experiments (solid lines) and computations (dashed lines) for $\alpha = 0^\circ; GR = 0.26$, $\alpha = 5^\circ; GR = 0.16$, and $\alpha = 10^\circ; GR = 0.08$ cases. Note here that the differences between the experimental and computational tangential coefficients are in the order of 0.04, which is well within the experimental measurement uncertainties detailed in section 2.5. Please refer to Refs. [80,86] for the validation of the simulations shown here. The tangential forces are at their steady state before the encounter (the wing/gust overlap is shown with a grey box in Figure 4.26(a)). After the wing enters the gust, the tangential force starts to decrease to a minimum. This minimum occurs approximately when the wing is centered in the gust ($t^* = 2.5$) for all cases. The tangential coefficient then returns to its steady value after the trailing edge of the wing exits the gust. Keeping in mind that the tangential force arises from skin friction, contours of skin friction on the upper surface of the wing at $t^* = 2.5$ are plotted along with the vorticity contours at this instant for each case in Figure 4.26(b). Both the skin friction and vorticity contours plotted in this figure are at the midspan. The blue color indicates negative skin friction, and the red color indicates positive skin friction, while the blue color represents the negative vorticity and the red color represents the positive vorticity. In the last row of Figure 4.26(b), the pertinent skin friction coefficients are given for each case, where the x -axis shows the nondimensional chordwise location (x/c)

along the wing such that $x/c = 0$ corresponds to the leading edge, and $x/c = 1$ corresponds to the trailing edge of the wing. As can be seen from this figure, the negative region of the skin friction coefficient is aligned with the leading-edge vortex since it produces a reverse flow along the wing surface. The location of the minimum skin friction is found to be near the center of the leading-edge vortex. The nondimensional location of this minimum skin friction coefficient is 0.35, 0.52, and 0.62 for $\alpha = 0^\circ, GR = 0.26$, $\alpha = 5^\circ, GR = 0.16$, and $\alpha = 10^\circ, GR = 0.08$ cases, respectively. Even though the drag responses of these three angles of attack were found to be very different, they exhibit very similar tangential coefficients. For every angle of attack investigated here, the leading-edge vortex induces a reverse flow region, which contributes to the skin friction drag. However, as the reader might recall from the earlier sections, the leading-edge vortex also creates a low-pressure region and, therefore, a suction force normal to the surface of the wing. This normal suction force contributes to the form (pressure) drag coefficient for $\alpha > 0^\circ$. Therefore, it can be concluded that the drag coefficient for a flat plate at 0° , where the skin friction drag dominates, experiences a negative peak due to the reverse flow induced by a leading-edge vortex. Moreover, the normal suction force induced by a leading-edge vortex contributes to the form drag, which dominates the total drag coefficient, therefore, causes a positive peak for $\alpha > 5^\circ$.

Figure 4.27 shows the experimental drag coefficients for low and high-amplitude gusts ($0.08 \leq \alpha \leq 1.5$) when the angle of attack of the test model is 0° . The low and high-amplitude gust encounter experiments were performed using wing 1 and wing 2, respectively. The drag coefficients for low-amplitude gust encounters

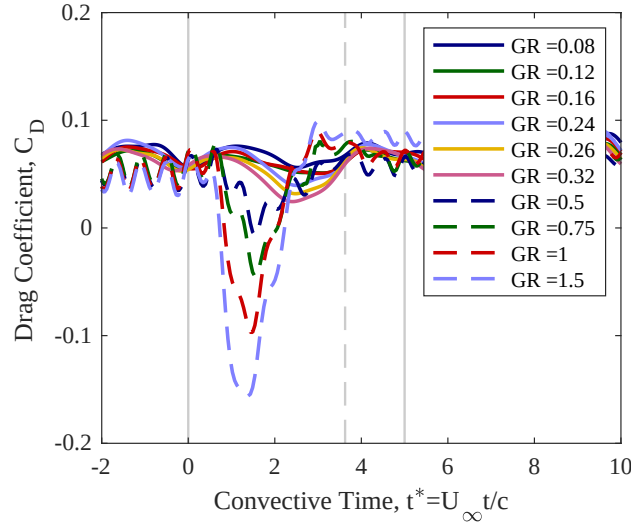


Figure 4.27: Experimental drag coefficients for a flat plate at 0° angle of attack encountering the sine-squared gust of various strengths. Experiments performed using wings 1 and 2 are represented with solid and dashed lines, respectively.

are shown with solid lines, whereas the drag coefficients for high-amplitude gust encounters are displayed with dashed lines in this figure. Since the angle of attack investigated here is 0° , the drag coefficients coincide with the tangential coefficient. As can be seen from this figure, the negative drag peak increases as the gust ratio increases, which is thought to be caused by the fact that the leading-edge vortex strength increases with increasing gust ratio (see sections 4.2.1.2, 4.2.1.3) as does the reverse flow region.

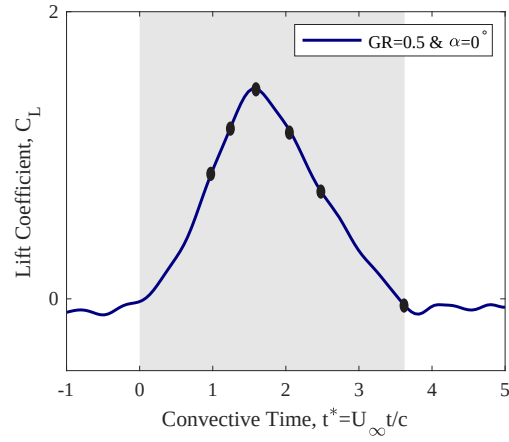
4.5 Three-dimensional Effects

The current section seeks to explore the three-dimensional effects during the sine-squared transverse gust encounters. Firstly, trends in experimental three-dimensional flowfields will be discussed. Then, the effects of aspect ratio on the force transients and three-dimensional flowfields will be examined.

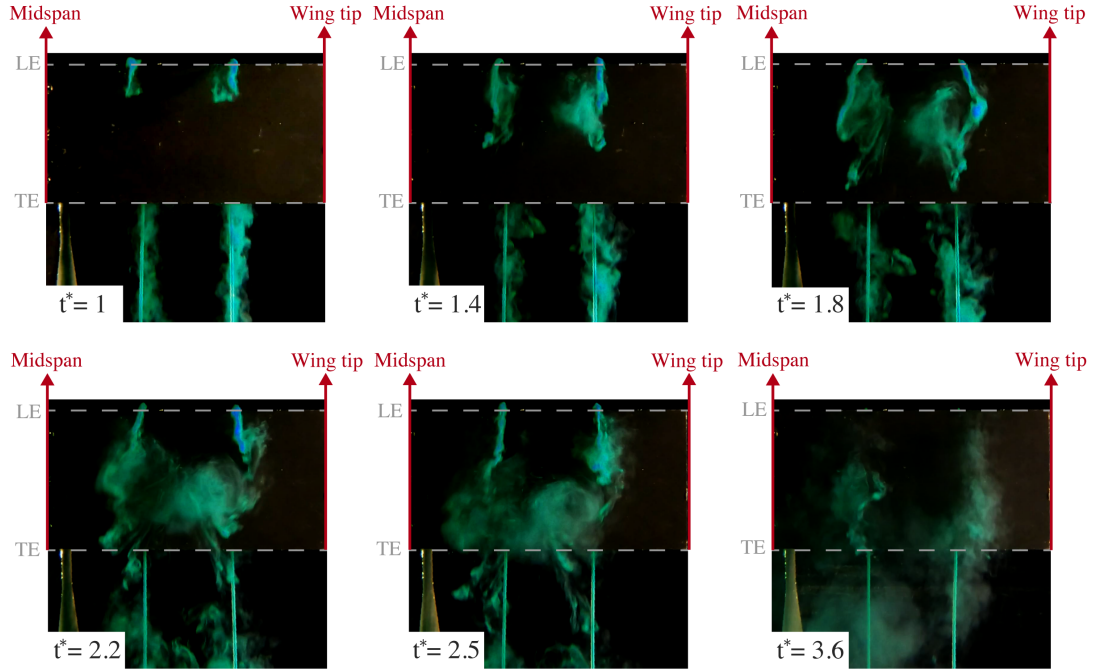
4.5.1 Trends in Three-dimensional Flowfields

In this section, the reader will find trends in experimental three-dimensional flowfields, which will establish a baseline for the sine-squared transverse gust encounter three-dimensionality. To this end, three cases, which are $GR = 0.5; \alpha = 0^\circ$, $GR = 1; \alpha = 0^\circ$, and $GR = 0.5; \alpha = 20^\circ$, were selected and experimental flowfields (top view) were obtained using wing 2 (3 in chord, 12 in span). The details of the dye-flow visualization setup can be found in section 2.6.3. Figures 4.28(a), 4.29(a), and 4.30(a) show the lift histories for the $GR = 0.5; \alpha = 0^\circ$, $GR = 1; \alpha = 0^\circ$, and $GR = 0.5; \alpha = 20^\circ$ cases, respectively. The circles in these lift plots correspond to the convective times of 1, 1.4, 1.8, 2.2, 2.5, and 3.6. The snapshots of the flow at these instances are shown in Figures 4.28(b), 4.29(b), and 4.30(b). Note that the flowfields given in this section are for a half wing (from the midspan to the wing tip, which are marked in the pertinent figures).

Figure 4.28 displays the lift force and three-dimensional flowfields for a 0.5 gust ratio and 0° angle of attack case. At $t^* = 1$, when the entire wing is immersed in the gust, and the lift force experiences an increase from its steady-state value, the leading-edge vortices are visible at both stations. No deflections in these vortices are visible, which indicates the flow is quasi two-dimensional at this instant. At $t^* = 1.4$, the leading-edge vortices become stronger, and are nearly uniform across the span. However, when the wing reaches the strongest portion of the gust and the lift force peaks (at $t^* = 1.8$), the leading-edge vortices tilt to the sides, which is presumably caused by a tip vortex. Therefore, it seems the most plausible to state



(a) Lift coefficient

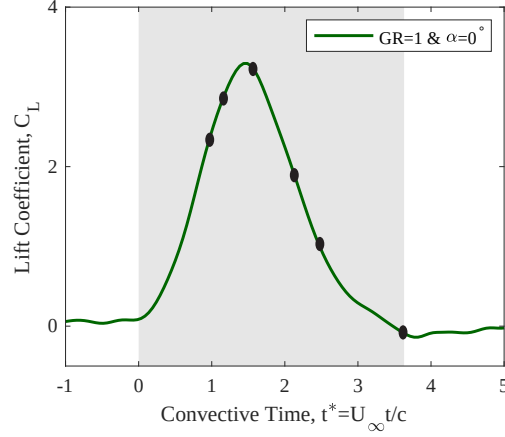


(b) Top view of the three-dimensional flowfields

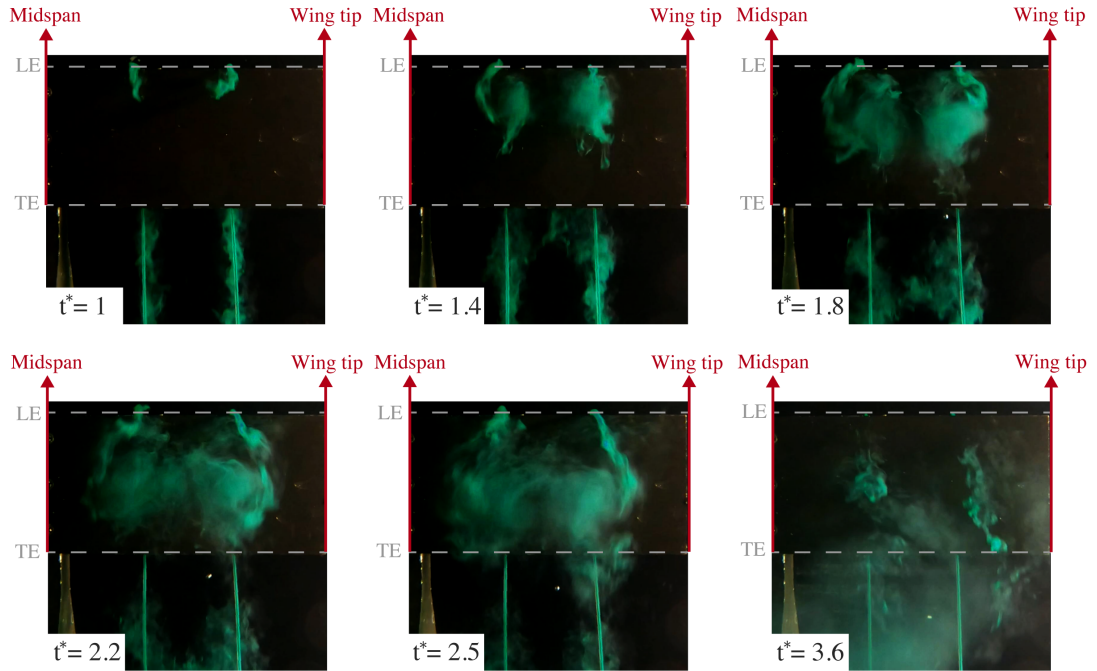
Figure 4.28: (a) Lift coefficient (circles on which corresponds to flowfields shown in (b)), and (b) the three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 0° angle of attack case of wing 2 (aspect ratio of 4).

that the two-dimensionality of the flow breaks down, and the three-dimensional effects start to dominate the flow at this instant. At $t^* = 2.2$, after the wing moves past the strongest portion of the gust and the lift force starts to decrease, the leading-edge vortices burst and are shed. At $t^* = 2.5$, these burst vortices advect

towards the trailing edge. Moreover, they are deflected in the spanwise direction, which is another indicator of a tip vortex. When the wing exits the gust, and the lift force reverts to steady state (at $t^* = 3.6$), no dominant flow structure is visible in the flow since the leading-edge vortices have already moved past the trailing edge.



(a) Lift coefficient

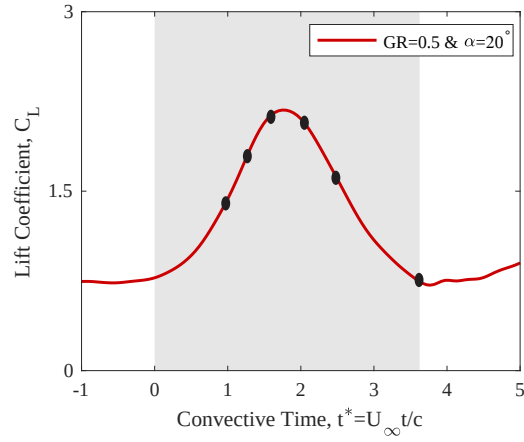


(b) Top view of the three-dimensional flowfields

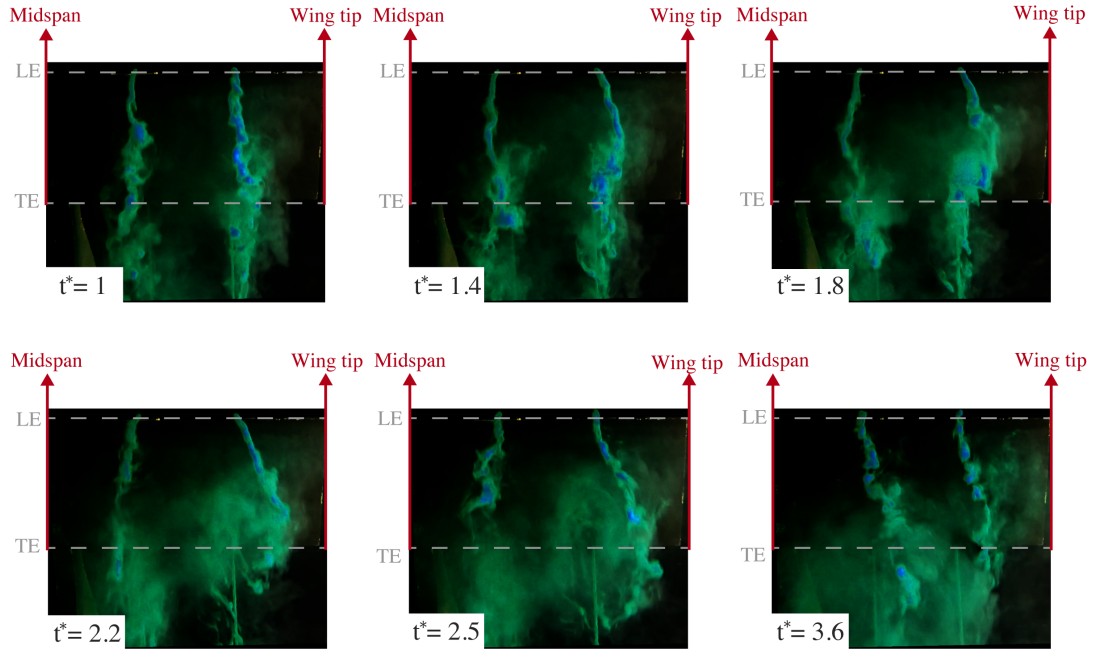
Figure 4.29: (a) Lift coefficient (circles on which corresponds to flowfields shown in (b)), and (b) the three-dimensional experimental flowfields (top view) for a 1 gust ratio and 0° angle of attack case of wing 2 (aspect ratio of 4).

The lift force and three dimensional flowfields for $GR = 1; \alpha = 0^\circ$ are shown in Figure 4.29. The effects of gust ratio on the flowfields will be investigated here by comparing the current set to the one shown in Figure 4.28. After the wing enters the gust, at $t^* = 1$, the approximately same size leading-edge vortices form on the wing upper surface, which do not deflect in the spanwise direction. Thus, the flow is quasi two-dimensional at this instant. However, at $t^* = 1.4$, a slight deflection in the leading-edge vortices in the spanwise direction is visible. At an instant where the lift force peaks (at $t^* = 1.8$), the leading-edge vortices tilt and deflect in the spanwise direction. Compared to the flowfields provided in Figure 4.28 for the $GR = 0.5; \alpha = 0^\circ$ case, the deflections in the leading-edge vortices for $GR = 1; \alpha = 0^\circ$ case are much clearer, which indicates a stronger tip vortex. The burst leading-edge vortices are visible at both $t^* = 2.2$ and $t^* = 2.5$. At $t^* = 3.6$, when the wing exists the gust, no dominant flow structure can be seen in the flowfields. Furthermore, the remaining dye mixture is drawn through the wing tip presumptively because of the strong suction that the tip vortex creates.

Figure 4.30 shows the lift coefficient and three-dimensional flowfields for a gust ratio of 0.5 and 20° angle of attack case. At $t^* = 1$, the leading-edge vortices form on the wing, which are at approximately uniform size. The flow at this instant is quasi two-dimensional. The spanwise deflections in these vortices become more dominant as the wing moves toward the strongest portion of the gust (see the flowfields at $t^* = 1.4$ and $t^* = 1.8$) indicating the formation of a tip vortex similar to the above-mentioned cases. The instabilities caused by this tip vortex persists as the wing moves past the strongest portion of the gust, see the flowfields at $t^* = 2.2$ and



(a) Lift coefficient



(b) Top view of the three-dimensional flowfields

Figure 4.30: (a) Lift coefficient (circles on which corresponds to flowfields shown in (b)), and (b) the three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 20° angle of attack case of wing 2 (aspect ratio of 4).

$t^* = 2.5$. At $t^* = 3.6$, the wake moves towards the wing tip, which is thought to be caused by the low-pressure region created by the tip vortex. Comparing the flowfields for the $GR = 0.5; \alpha = 0^\circ$ and $GR = 0.5; \alpha = 20^\circ$ cases shows that the deflections and instabilities are higher at larger angles of attack.

To sum up, the three-dimensionality of the sine-squared gust encounters was evaluated. The results showed that the flow stays nominally quasi two-dimensional until the wing reaches the strongest portion of the gust at $t^* = 1.8$. The deflections observed in the leading-edge vortices suggest the formation and shedding of a tip vortex. Furthermore, increasing both the angle of attack and gust ratio was found to cause larger three-dimensional effects.

4.5.2 Variations in Aspect Ratio

In this section, the reader will find the effects of aspect ratio on the sine-squared transverse gust encounters. Firstly, the force transients of three different wings with aspect ratios of 4 (3 in chord, 12 in span), 6 (3 in chord, 18 in span), and 8 (3 in chord, 24 in span) will be examined. Then, the three-dimensional flowfields of aspect ratio 8 wing will be discussed and compared to the ones of aspect ratio 4 wing detailed in the previous section.

4.5.2.1 Lift and Drag

In this section, the effect of aspect ratio on the forces for two angles of attack ($\alpha = 0^\circ$ and $\alpha = 20^\circ$) at a gust ratio of 0.5 will be evaluated. The wing gust/overlap is marked with a grey box in Figures [4.31](#) and [4.32](#). Since all of the wings used in this analysis has the same chord length, the wing/gust interaction times of different aspect ratio wings are also the same. Please note here that the aspect ratio 4 wing results shown in this section are already discussed in detail in sections [4.1.1.1](#)

and 4.2.1.1.

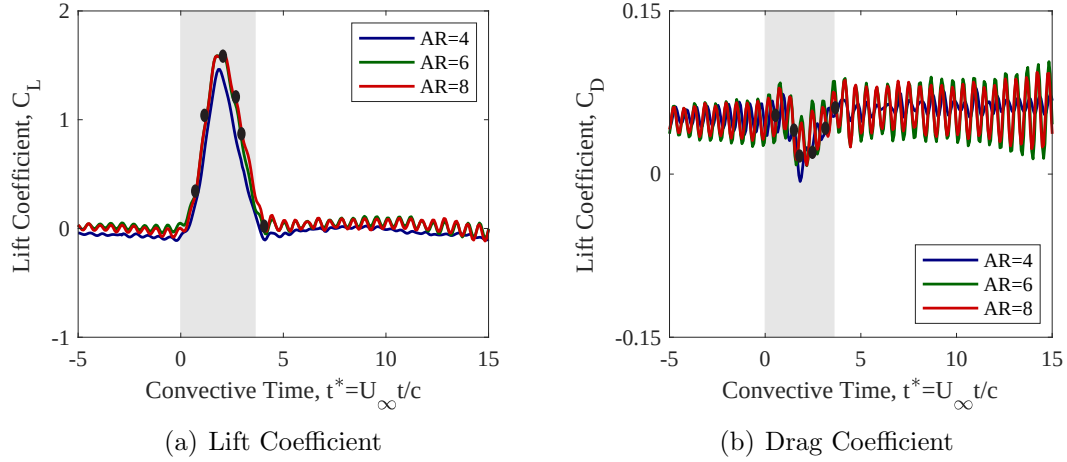


Figure 4.31: Lift and drag coefficients of aspect ratio 4, 6, and 8 wings for a 0.5 gust ratio and 0° angle of attack case, circles on this plot corresponds to flowfields shown in Figure 4.33.

Figure 4.31 displays the force histories obtained using 3 different aspect ratio wings ($\mathcal{R} = 4, 6$, and 8) for a 0.5 gust ratio and 0° angle of attack case. As expected, the variations in aspect ratio do not affect the trends of the force transients, which are already discussed in the earlier sections. As can be seen from this figure, the aspect ratio 6 and 8 wings result in a larger lift maximum and drag minimum than the aspect ratio 4 wing, though, these differences are minor. Please note that more significant fluctuations are visible for larger wings since they are more vulnerable to mechanical and electrical vibrations.

The force coefficients of 4, 6, and 8 aspect ratio wings for a 0.5 gust ratio and 20° angle of attack case are given in Figure 4.32. Both lift and drag forces experience a maximum during the gust encounter. After the wing exits the gust, a force minimum and a secondary maximum occur. Increasing the aspect ratio causes larger force extrema (e.g., larger maximum, smaller minimum, and a larger

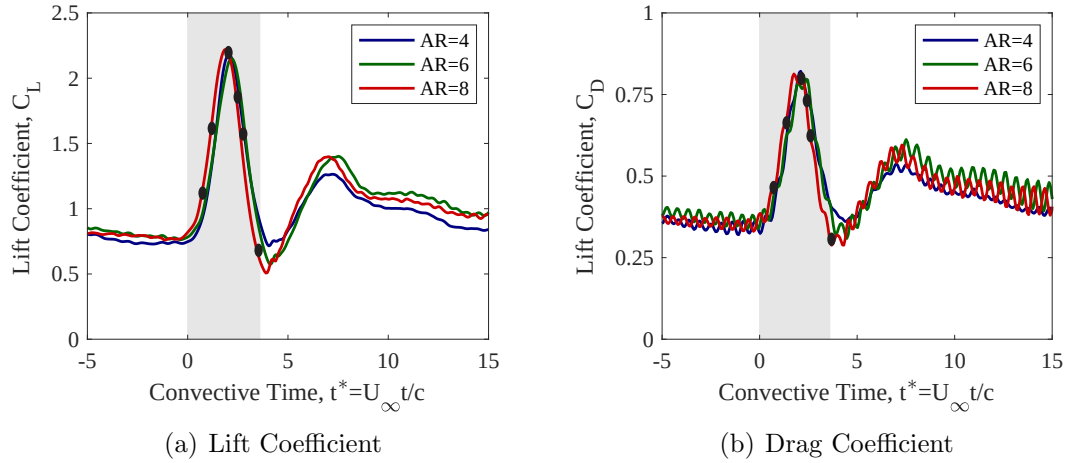


Figure 4.32: Lift and drag coefficients of aspect ratio 4, 6, and 8 wings for a 0.5 gust ratio and 20° angle of attack case, circles on this plot corresponds to flowfields shown in Figure 4.34.

secondary maximum). Please note that these differences are minor for the lift maximum and drag coefficient in general, whereas they are more predominant for the lift minima and secondary maxima. The three-dimensional flowfields provided in the following section will provide additional insight into the forces discussed here.

4.5.2.2 Three-dimensional Flowfields

The three-dimensionality of the flow for the aspect ratio 4 wing was discussed in section 4.5.1. In this section, the three-dimensional effects for aspect ratio 8 wing will be analyzed for two angles of attack, which are 0° and 20° . The circles on Figures 4.31 and 4.32 correspond to the convective times of 1, 1.4, 1.8, 2.2, 2.5, and 3.6, and the pertinent three-dimensional experimental flowfields are given in Figures 4.33, 4.34, respectively. Note that the flowfields are given for a half wing, where 4 dye ports were used, refer to section 2.6.3 for more details on the setup. Please note here that the flowfields were not obtained for aspect ratio 6 wing since

no significant differences occurred in the force responses of aspect ratio 6 and 8 wings.

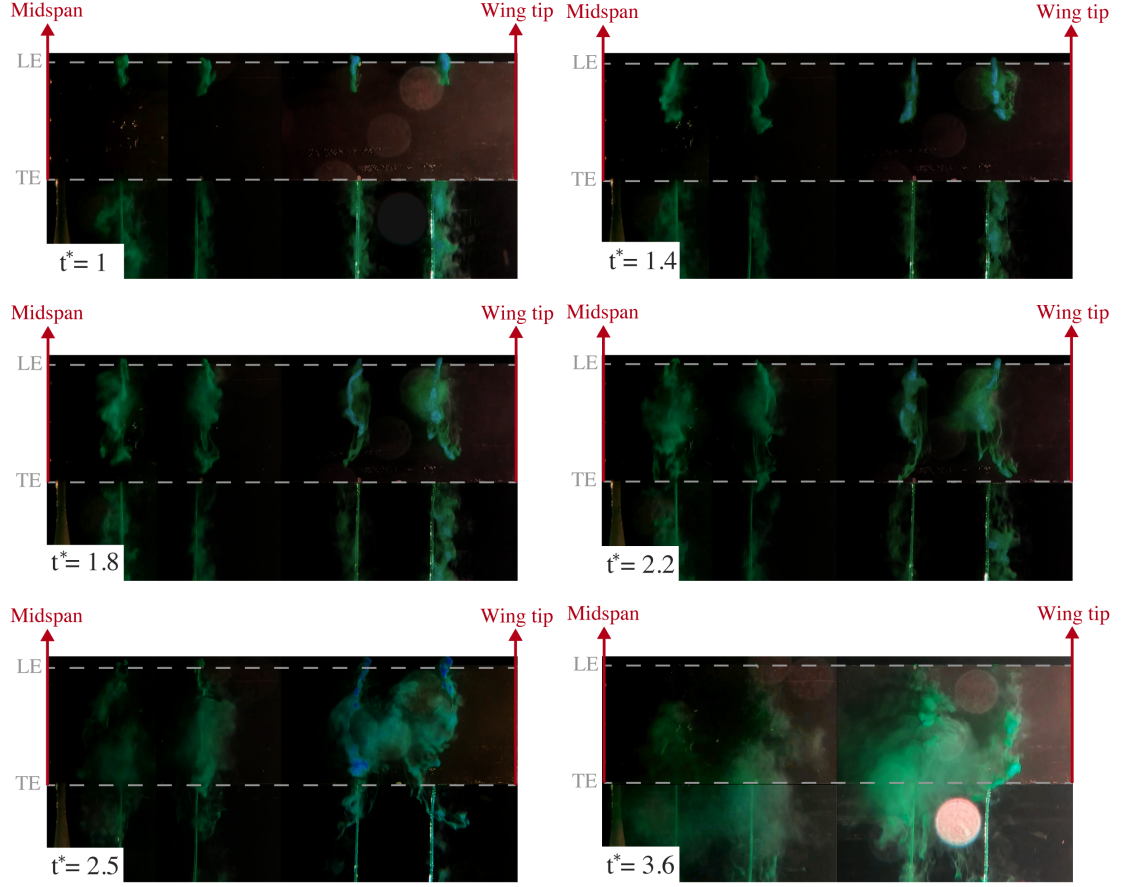


Figure 4.33: Three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 0° angle of attack case for wing 4 (aspect ratio of 8).

Figure 4.33 shows the experimental three-dimensional flowfields of aspect ratio 8 wing for a 0.5 gust ratio and 0° angle of attack case. During the period where the lift increment occurs ($t^* \leq 1.8$), the snapshots show the similar sized leading-edge vortices on the upper surface of the wing. No significant spanwise deflections in these leading-edge vortices are observed during this period. However, at $t^* = 1.8$, the leading-edge vortices at the outboard stations (2 stations from the wing tip) deflect, presumably because of a tip vortex whose effects do not reach the inboard

stations (2 stations that are closer to the midspan). As the wing moves past this strongest portion of the gust, the deflections of the outboard vortices persist. The leading-edge vortices are shed and advected towards the trailing edge of the wing, see $t^* = 2.2$ and $t^* = 2.5$ snapshots. At $t^* = 3.6$, when the wing exits the gust, the outboard burst vortices slightly move towards the midspan. Overall, the tip vortex affects the outboard stations more than the inboard stations. The flow at the inboard stations stays approximately quasi two-dimensional throughout the gust encounter. On the other hand, recall that the flow over the whole $\mathcal{R} = 4$ wing was three-dimensional.

Noting that the force coefficients discussed herein are integrated quantities (over the whole wing), it is the most plausible to conclude that a larger force maximum was observed for the $\mathcal{R} = 8$ wing since the three-dimensionality was contained only at the outboard stations.

Three-dimensional flowfields of the $\mathcal{R} = 8$ wing for a 0.5 gust ratio and 20° angle of attack case is displayed in Figure 4.34. At $t^* = 1$ and $t^* = 1.4$, the flow is quasi two dimensional along the whole wing, and the leading-edge vortices start to form at each station. As can be seen from the snapshot at $t^* = 1.8$, the vortices at the outboard stations deflect towards the midspan, whereas the vortices at the inboard stations do not similar to the $GR = 0.5; \alpha = 0^\circ$ case. After this point in time, the deflections at the outboard stations become more crucial (see snapshots at $t^* = 2.2$ and $t^* = 2.5$). As the wing exits the gust at $t^* = 3.6$, the vortices at the outboard locations are sucked towards the wing tip, likely because of the low-pressure region created by the tip vortex. Similar to the $\alpha = 0^\circ$ case, the flow

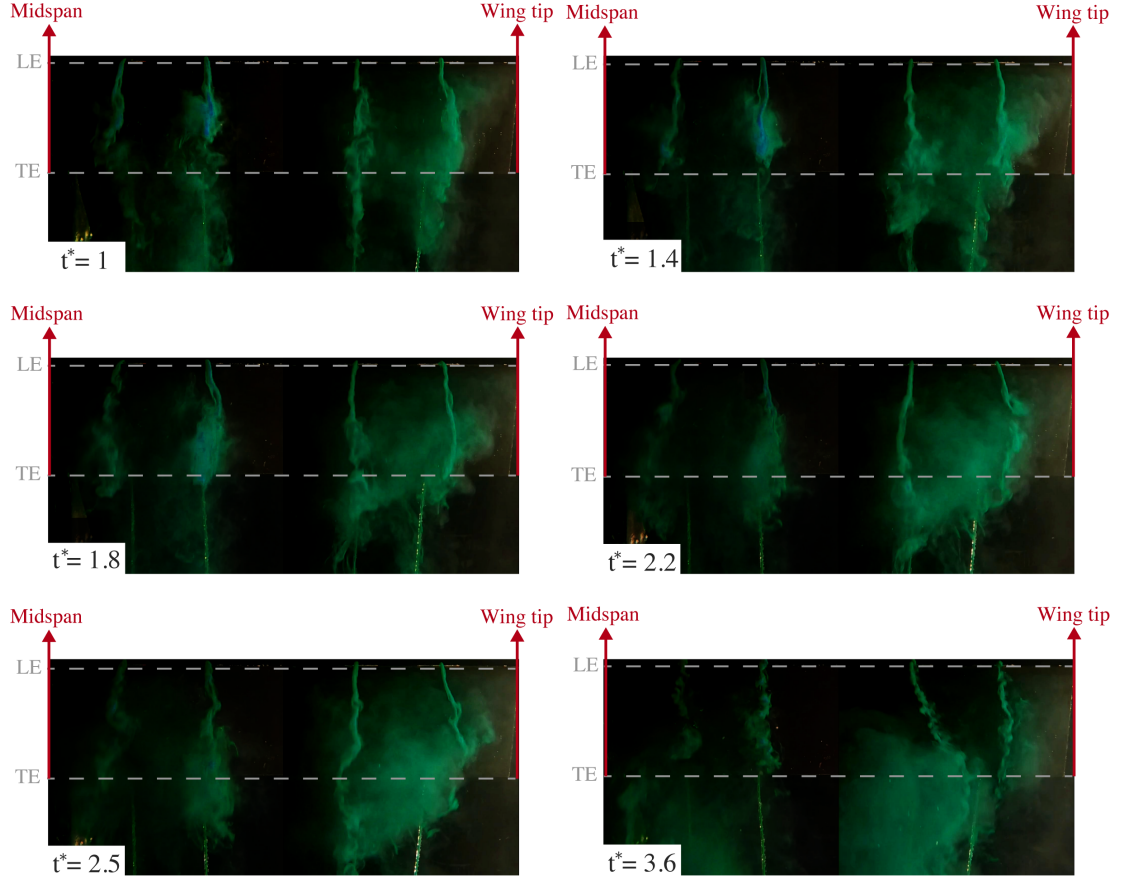


Figure 4.34: Three-dimensional experimental flowfields (top view) for a 0.5 gust ratio and 20° angle of attack case for wing 4 (aspect ratio of 8).

at the inboard stations remains nominally quasi two-dimensional, which is thought to be the reason why force extrema of aspect ratio 8 wing are larger than the ones of the aspect ratio 4 wing.

To sum up, the force transients and three-dimensional flowfields were analyzed for several aspect ratios. Increasing the aspect ratio was found to cause a slight increment in the force extrema. Unlike the aspect ratio 4 wing, where the three-dimensional effects dominated the whole wing, the three-dimensional effects were contained at the outboard stations for the aspect ratio 8 wing.

4.6 Chapter Summary

The purpose of this chapter was to explore the unsteady aerodynamics of sine-squared transverse gust encounters. To this end, the force transients and flowfields were investigated for a wide range of disturbances ($0.08 \leq GR \leq 1.5$ and $0^\circ \leq \alpha \leq 45^\circ$). The effects of variations in two parameters, namely the angle of attack and gust ratio, on the transients and force extrema were thoroughly investigated. Moreover, the relationship between the maximum effective angle of attack and lift were explored. The behavior of drag coefficient at low angles of attack was elucidated. Lastly, the three-dimensionality of the sine-squared gust encounters was discussed, and the effects of variations in aspect ratio on forces and three-dimensional flowfields were determined. The main findings of this chapter are summarized in the paragraphs below.

Lift and drag peaks were observed when the wing is approximately centered in the gust for all angles of attack. This peak was found to be positive for all cases except for the drag coefficient of $\alpha = 0^\circ$ case. The flowfields displayed the existence of a leading-edge vortex on the wing upper surface at this instant. Therefore, it can be concluded that the low-pressure region that the leading-edge vortex created caused the aforementioned force peaks. The value of these force peaks was found to increase with increasing angle of attack in the same vein as the circulation shed from the leading edge up to a limit around 15° . The gust recovery portion was found to differ for the $\alpha = 0^\circ$ and $\alpha > 0^\circ$ cases. For the $\alpha = 0^\circ$ case, the forces and flowfields were found to revert to the steady-state values almost immediately after

the exit, whereas the gust recovery took longer for the cases, where $\alpha > 0^\circ$. In this gust recovery portion of the $\alpha > 0^\circ$ cases, a consecutive shedding from the trailing and leading edges of the wing was generally observed, which caused the forces to experience a local minimum as the wing exited the gust and a secondary maximum thereafter, respectively. Overall, the lift coefficient extrema were found to exhibit a stall-like behavior versus the angle of attack. The linearity of this behavior was found to break down around 10° angle of attack. The drag coefficient extrema, on the other hand, showed a linear dependency on the angle of attack. The exposed projected area normalization was found to minimize the differences between the transients of various angle of attack cases.

Furthermore, increasing the gust ratio was found to increase the force extrema in the same vein as the circulation shed from the leading edge. All of the force extrema were found to be linearly dependent on the gust ratio. For very large angles of attack ($\alpha \geq 30^\circ$), the gust ratio was found to play a relatively minor role in the global (observed during the encounter) and local (observed during the recovery portion) lift maxima, whilst more considerable changes in global and local drag maxima were observed due to the inevitable increase in form drag. In addition, the gust ratio had almost no impact for the $\alpha < 45^\circ$ cases. The gust ratio was found to be very effective in scaling both the lift and drag forces even for very large gust ratios ($GR = 1.5$).

The cases in which gust ratio and geometric angle of attack were selected to produce a given value of effective angle of attack were found to produce similar lift peak coefficients if the $\alpha \leq 10^\circ$ and $\alpha_{\text{eff}_{\text{max}}} < 40^\circ$. Furthermore, the maximum lift

coefficient was found to have a linear dependency on the effective angle of attack for cases where $\alpha \leq 10^\circ$ and $\alpha_{\text{eff}_{\text{max}}} < 40^\circ$.

The reverse flow induced by the leading-edge vortex was found to cause the skin friction coefficient to experience a negative peak. Since the skin friction coefficient dominates the total drag coefficient at low angles of attack, a negative drag peak was observed during the gust encounter for the 0° angle of attack case. The value of this negative drag peak was found to increase with increasing gust ratio, which was caused by stronger leading-edge vortices creating more significant reverse flow regions.

The flow that developed during the sine-squared gust encounters was found to stay nominally quasi two dimensional until the wing reached the strongest portion of the gust, where the force peaks occurred. Only thereafter, the spanwise variations in the flow were observed, indicating that the flow is three-dimensional. The leading-edge vortices were found to be drawn through the wing tip, which is thought to be caused by the low-pressure region created by the tip vortex. Larger angles of attack and gust ratios were found to cause more complex flows. The aspect ratio variations were found to only subtly impact the force transients such that increasing aspect ratio increased the force extrema. This is thought to be caused by the fact that the three-dimensional effects were contained at the outboard stations for the $\mathcal{R} = 8$ wing while they dominated the whole $\mathcal{R} = 4$ wing.

Chapter 5: Comparison of Transverse Gust Velocity Profiles and Evaluation of Küssner’s Model

In the previous chapter, the reader found a detailed investigation of the sine-squared transverse gust encounters, where the effects of 4 crucial parameters, namely angle of attack, gust ratio, and effective angle of attack, and aspect ratio were explored. This chapter seeks to expand the discussion of the transverse gust encounters by examining a new parameter, gust velocity profile. To this end, section 5.1 compares and studies two transverse velocity profiles, the sine-squared and top-hat (data for the latter was provided by collaborators), in terms of lift response, flow structures, and circulation production. Using this comparison as a base, section 5.2 evaluates the accuracy and limitations of Küssner’s model for both gusts. Lastly, in an attempt to scale the lift responses of different transverse velocity profiles, a momentum flux-based normalization method is introduced. Overall, the results shown in this section will not only enhance knowledge of the transverse gust encounters but also provide valuable tools to predict and scale the lift responses of different transverse gust velocity profiles.

5.1 Comparison of Sine-squared and Top-hat Transverse Gusts

This section seeks to investigate the effect of transverse gust velocity profile by comparing the sine-squared and top-hat gusts in terms of lift force, flowfields, and circulation production. The comparison is only given for a flat plate at 0° angle of attack to establish a baseline for the investigation of Küssner's model's limitations. The reader is referred to Ref. [114] for the comparison of the responses of the two velocity profiles at larger angles of attack.

The experimental setups used to create the sine-squared and top-hat gusts are remarkably similar. Both setups use water towing tanks to facilitate the experiments. The working principles of the gust generator systems used are quite similar and based on recirculating the water that is in the tank. While the sine-squared gust was generated using a jet-like system, the top-hat gust was created using a gust-rig design that also includes a suction manifold. The details of the sine-squared and top-hat gust experimental setups can be found in chapters 2 and 3, respectively. Therefore, it seems plausible to state that the differences in the results shown in the following sections are not artifacts of the experimental setups; instead, they arise due to the difference in the transverse velocity profiles.

Figures 5.1(a) and 5.1(b) display the time-averaged vorticity contours for the sine-squared and top-hat gusts, respectively. As can be seen from these figures, the sine-squared gust has a continuous gust shear layer, whilst the top-hat gust shear layers are concentrated at the edges of the profile. The time-averaged gust profiles for both were extracted from a region where the wing flows and is given in

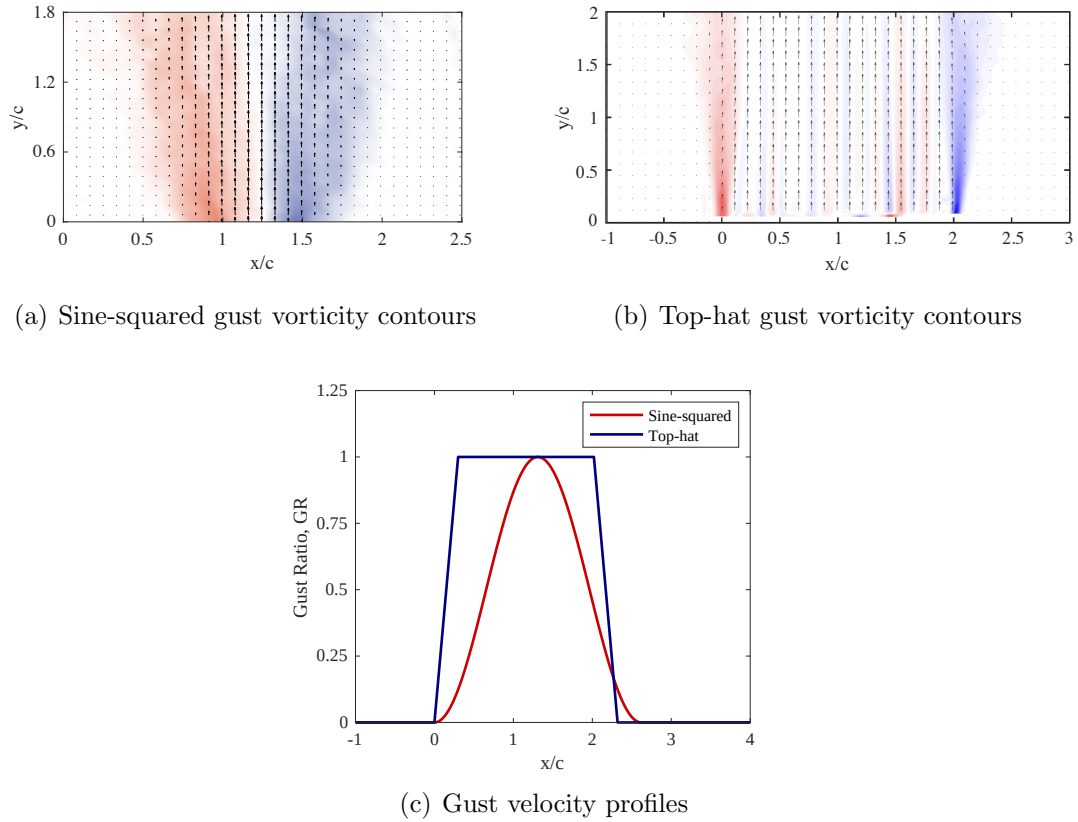


Figure 5.1: Gust characterization flowfields and gust velocity profiles for both the sine-squared and top-hat gusts.

Figure 5.1(c) for a gust ratio of 1. The sine-squared gust velocity profile displays smooth gradients due to the aforementioned continuous shear layers, whereas the top-hat gust contains sharp gradients on the edges of the profile because of the concentrated shear layers. The width-to-chord ratio is 2.6 and 2.32 for the sine-squared and top-hat gusts, respectively. Although the nondimensional gust width is larger for the sine-squared gust, the top-hat gust contains more momentum due to its velocity profile. An in-depth discussion of the momentum and momentum flux associated with each gust velocity profile is given in section 5.3.

5.1.1 Force Comparison

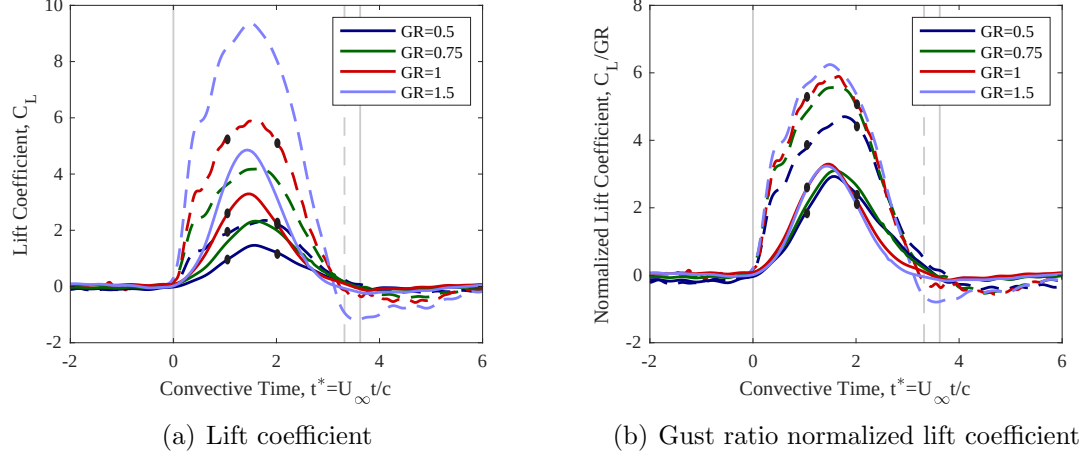


Figure 5.2: Lift and gust ratio normalized lift coefficients for gust ratios ranging from 0.5 to 1.5 at 0° angle of attack for both the sine-squared (solid lines) and top-hat (dashed lines) gusts, circles on this plot corresponds to flowfields in Figures 5.3 and 5.4.

Figure 5.2 shows the lift and gust ratio normalized lift responses of a flat plate at 0° angle of attack encountering gusts of various strengths ($0.5 \leq GR \leq 1.5$) for both gust velocity profiles. In this figure, the solid and dashed lines represent the results from the sine-squared and top-hat gusts, respectively. For both gusts, the wing's leading edge enters the gust at $t^* = 0$. However, the wing's trailing edge exits the sine-squared gust at $t^* = 3.6$ (marked with a solid grey line) and the top-hat gust at $t^* = 2.32$ (marked with a dashed grey line).

The lift transients caused by the sine-squared gust encounters were examined in detail in chapter 4. Similar to the sine-squared gust response, the lift force experiences a maximum during the top-hat gust encounters. The value of this maximum increases with increasing gust ratio, as can be seen in Figure 5.2(a). One

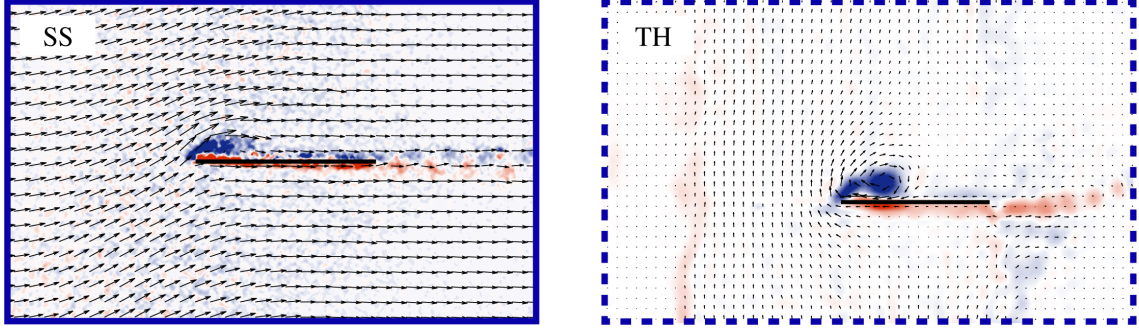
intriguing trend that is not visible in the sine-squared gust case is that the lift force experiences a “dip” as the wing exits the top-hat gust for the cases where $GR \geq 1$. The flowfields provided in the following section will highlight this phenomenon. Overall, the top-hat gust encounters result in a significantly larger maximum than the sine-squared gust encounters for the same gust ratio, proving that the transverse gust velocity profile is an important parameter to explore.

In section 4.2.3, the gust ratio normalization was discussed for the sine-squared gust encounters. The results showed that this normalization does a good job scaling the lift force of various gust ratio cases that range from 0.08 to 1.5. Thus, it was concluded that the forces that arise from the sine-squared gust encounters can be normalized using gust ratio, notwithstanding very large gust ratios. Figure 5.2(b) displays the gust ratio normalized lift coefficients for both gusts. Unlike the sine-squared gust case, the lift force experienced during the top-hat gust encounters does not scale well using this normalization. The following section will discuss the PIV flowfields and highlight the lift transients detailed here.

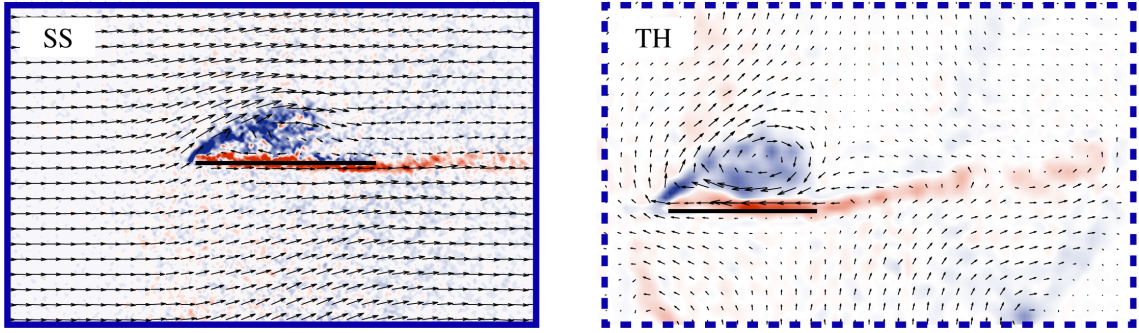
5.1.2 Flowfield Comparison

The flowfields for the $GR = 0.5$ and $GR = 1$ cases are selected to identify the flow structures that cause the aforementioned transients during both gust encounters and are displayed in Figures 5.3 and 5.4, respectively. Please note that the camera and laser were towed with the wing for the sine-squared gust experiments at UMD while they were stationary for the top-hat gust experiments at CU. Therefore, the

flowfields shown in this section are different in terms of their field of view.



(a) Flowfields at $t^* = 1$ for the sine-squared and top-hat gusts



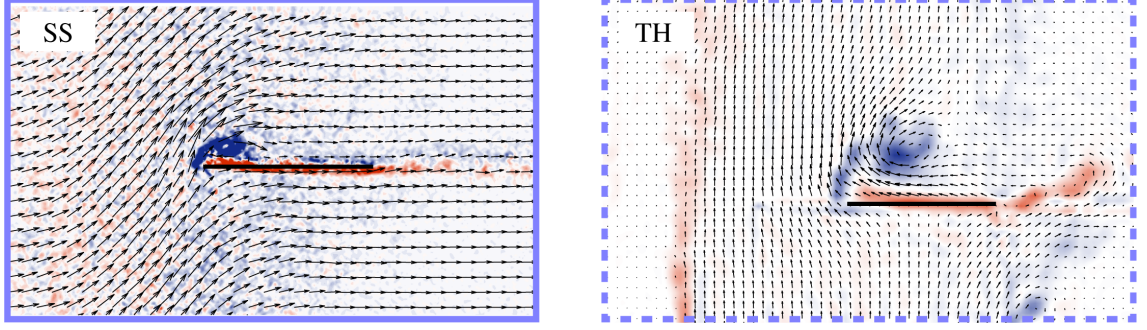
(b) Flowfields at $t^* = 2$ for the sine-squared and top-hat gusts

Figure 5.3: Flowfields for both the sine-squared (solid box) and top-hat (dashed box) gusts at a gust ratio of 0.5.

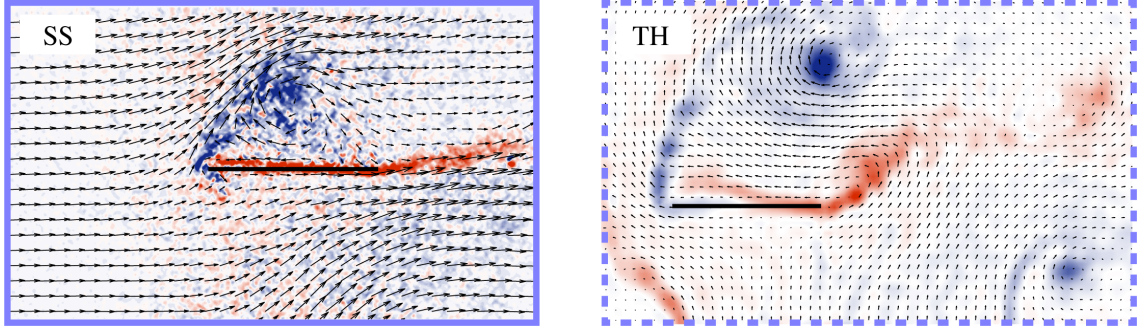
Figure 5.3(a) shows the flowfields for the $GR = 0.5$ case for both gusts at $t^* = 1$, when the wing is fully immersed in the gust. A leading-edge vortex is visible on the wing's upper surface for both gust velocity profiles. The low-pressure region that this vortex creates causes the aforementioned lift peaks. Qualitatively, the leading-edge vortex is stronger for the top-hat gust, presumably due to the larger momentum that the wing sees during the encounter. Please see section 5.1.3, which quantifies the circulation shed from the leading edge, for more details. At this instant, the vortex core is located at $0.17c$ for the sine-squared gust and $0.3c$ for the top-hat gust. The entry top-hat gust shear layer significantly deforms due

to the presence of the wing. The deflection in the sine-squared gust shear layer, on the other hand, is not as clear as the top-hat gust since the sine-squared gust shear layer is continuous. A slight trailing wake deflection is visible for the top-hat gust case, whereas a planar trailing wake is present for the sine-squared gust case at this instant.

Figure 5.3(b) displays the experimental flowfields for the $GR = 0.5$ case at $t^* = 2$. At this instant, the leading edge of the wing reaches the latter top-hat gust shear layer, and the wing is about to exit the top-hat gust. This instant also corresponds to 0.5 convective times after the lift force peaks for the top-hat case. For the sine-squared gust case, on the other hand, at this instant, the wing has already moved past the strongest portion of the profile. Furthermore, this moment in time also corresponds to 0.2 convective times after the lift force peaks. As can be seen from this figure, the leading-edge vortex builds up its strength vis-à-vis $t^* = 1$ for both gusts. Moreover, compared to $t^* = 1$, the leading-edge vortex advects downstream. The locations of the vortex cores are $0.5c$ and $0.67c$ for the sine-squared and top-hat gusts, respectively. A stronger leading-edge vortex is visible for the top-hat gust case. The leading-edge vortex is also further away from the wing surface for the top-hat gust case, which is thought to be caused by the larger velocities present in the flow. A secondary separation of positive vorticity from the boundary layer is visible for both cases. The shear layers in the top-hat gust significantly deform due to the wing's presence. The trailing wake is planar for the sine-squared gust case, while a 14° deflection is visible for the top-hat gust case presumably because of the larger momentum that the top-hat carries.



(a) Flowfields at $t^* = 1$ for the sine-squared and top-hat gusts



(b) Flowfields at $t^* = 2$ for the sine-squared and top-hat gusts

Figure 5.4: Flowfields for both the sine-squared (solid box) and top-hat (dashed box) gusts at a gust ratio of 1.

The experimental flowfields at $t^* = 1$ for the $GR = 1$ case are shown for both gusts in Figure 5.4(a). Similar to the $GR = 0.5$ case, the leading-edge vortex for the top-hat gust case is significantly stronger and further away from the wing's surface than the one for the sine-squared gust case. The vortex core is located at $0.17c$ and $0.3c$ for the sine-squared and top-hat gust cases, respectively. Even though the flowfields discussed here are early in the encounter, a secondary separation is visible for both gusts. A significant deformation in the entry top-hat gust shear layer is present. Moreover, the top-hat gust trailing wake is nonplanar, which shows a 13° deflection, contrary to the $GR = 0.5$ case. On the other hand, a planar wake is visible for the sine-squared gust case.

The flowfields at $t^* = 2$ for the $GR = 1$ case are displayed in Figure 5.4(b) for both gust velocity profiles. At this moment in time, the strength of the leading-edge vortex is increased compared to $t^* = 1$. The vortex core is located at $0.45c$ and $1c$ for the sine-squared and top-hat gusts, respectively. A 10° wake deflection is present for the sine-squared gust, whereas a larger deflection, 14° , is visible for the top-hat gust. Moreover, a trailing edge vortex forms for the top-hat gust case, which is thought to be the reason why the lift force experiences a dip at this instant. Qualitatively, larger levels of shed vorticity are present in the flow compared to the $GR = 0.5$ case for both gusts.

5.1.3 Circulation Comparison

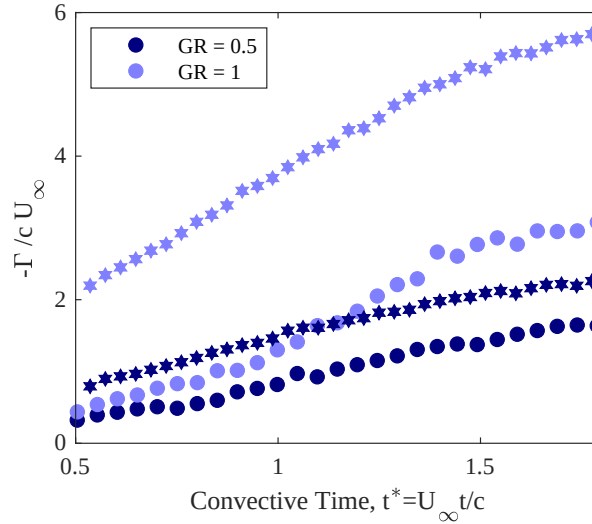


Figure 5.5: Nondimensional circulation for both the sine-squared (shown with a circle symbol) and top-hat (shown with a star symbol) gusts.

Figure 5.5 displays the circulation shed from the leading edge for the gust ratios 0.5 and 1 during both the sine-squared and top-hat gust encounters. The

circulation measurements were obtained for convective times between 0.5 and 2. When only half of a wing is immersed in the gust, at $t^* = 0.5$, a strong leading-edge vortex is visible for the top-hat gust case, presumably due to the sharp increase in the gust velocity profile, whereas a weak vortex is visible for the sine-squared gust case. For both gusts, a higher level of circulation is shed from the leading edge for the larger gust ratio of 1. On the other hand, for a given gust ratio, the top-hat gust encounters result in a stronger leading-edge vortex than the sine-squared gust encounters. This is thought to be the cause of the larger lift maxima observed in the top-hat gust case.

To sum up, the top-hat gust encounters were found to result in a larger lift maximum and a stronger leading-edge vortex than the sine-squared gust encounters. The gust ratio parameter was found to scale the lift response of the sine-squared gust, whilst it failed to do so for the top-hat gust despite the same gust ratios investigated. The lift force was found to experience a minimum presumably due to the formation of a trailing-edge vortex as the wing exits the top-hat gust for the cases where $GR \geq 1$. Flowfields showed that the leading-edge vortex remains closer to the wing's surface in the case of the sine-squared gust. In addition, the trailing wake was found to be significantly deflected during the top-hat gust encounters.

5.2 Accuracy and Limitations of Küssner's Model

This section seeks to evaluate the applicability, accuracy, and limitations of the Küssner's model [64] for high-amplitude transverse gust encounters. As described

in chapter [1.3.4.2](#), Küssner’s model is a linear analytical model to predict the lift force for a flat plate encountering a sharp-edged transverse gust with infinite gust width and it comes with quite strict assumptions, which are listed below.

1. The flow is two dimensional.
2. No viscous forces are present in the flow.
3. The flow is incompressible.
4. The disturbances are small.
5. The gust shear layer is rigid.
6. Vortex shedding is only allowed from the trailing edge of the wing.
7. The trailing wake is planar.

Although the Küssner’s Model is developed for an infinitely long gust, an analytical convolution can be found for an arbitrary transverse gust profile using the Duhamel superposition integral detailed in chapter [1.3.4.2](#). This section specifically focuses on the response of the sine-squared and top-hat velocity profiles. The sine-squared velocity profile is given as follows

$$V_{gss}(t^*) = V_P \sin^2 \left(\frac{\pi t^*}{w/c} \right), \quad (5.1)$$

where V_P is the peak gust velocity and w/c is the width-to-chord ratio, the value of which is 2.6 based on the characterized profile. The top-hat velocity distribution based on the characterized gust width is given as

$$V_{gTH} = \begin{cases} \frac{V_P}{0.3} t^*, & 0 \leq t^* < 0.3 \\ V_P, & 0.3 \leq t^* < 2.02 \\ -\frac{V_P}{0.3} t^* + \frac{2.32V_P}{0.3}, & 2.02 \leq t^* \leq 2.32 \end{cases} \quad (5.2)$$

A sharp-edged gust with a finite gust width will also be examined to provide a comparison to the top-hat gust since it was used in the earlier study to predict the lift response of the top-hat profile [114]. Therefore, the width-to-chord ratio of the sharp-edged gust is selected to match with the one of the top-hat gust, $w = 2.32c$. The sharp-edged gust velocity profile is given as

$$V_{gSE} = \begin{cases} V_P, & 0 \leq t^* < 2.32 \\ 0, & t^* \geq 2.32 \end{cases} \quad (5.3)$$

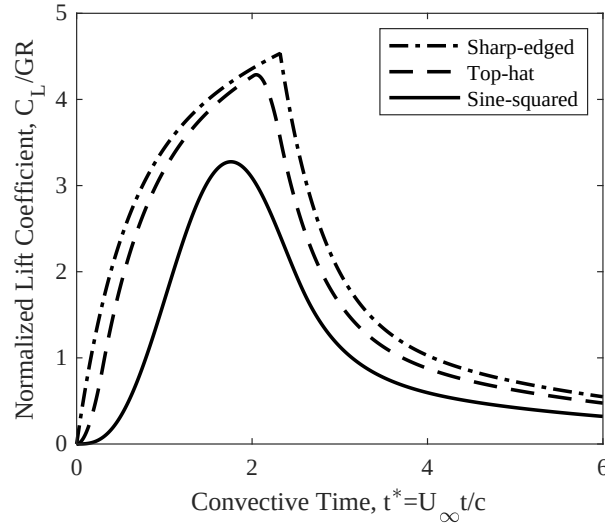


Figure 5.6: Gust ratio normalized lift coefficient from the Küssner's convolution for the sine-squared, top-hat, and sharp-edged gusts.

Figure 5.6 shows the gust ratio normalized lift coefficients from the Küssner's convolutions for the sine-squared, top-hat, and sharp-edged gusts. As can be

seen from this figure, all profiles experience similar lift trends. The lift coefficient increases to a maximum and then reverts to the steady state. The recovery from the gust takes a long time. The top-hat profile displays a lower maximum at an earlier time compared to the sharp-edged profile. On the other hand, the convolution of the sine-squared gust results in a significantly lower lift maximum than the other two profiles. Based on Küssner's predictions, the maximum lift coefficient strongly depends on the transverse gust velocity profile.

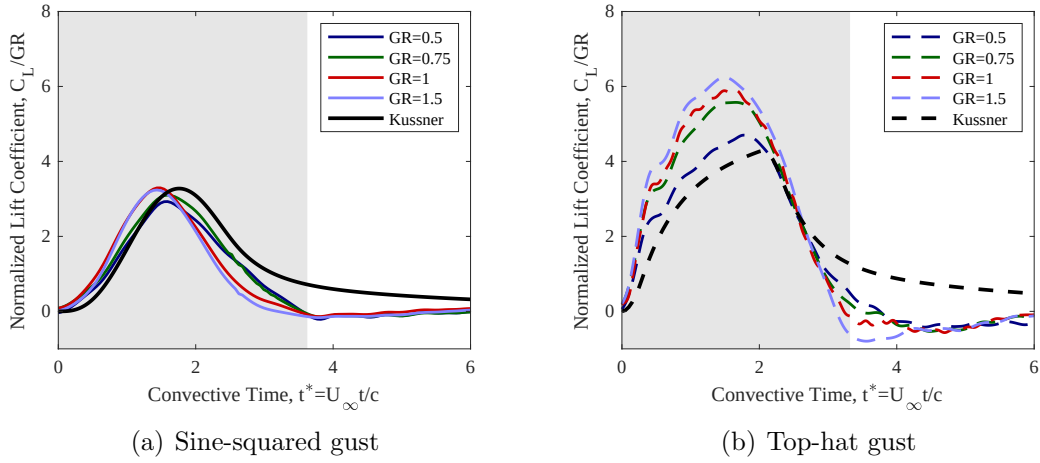


Figure 5.7: Gust ratio normalized measured lift coefficients and Küssner's convolution for the sine-squared and top-hat gusts.

To investigate the accuracy of the Küssner's predictions, it is essential to compare them to the measured quantities. Figure 5.7(a) displays the gust ratio normalized lift coefficients from the convolution and experimental measurements for the various strength sine-squared gust encounters. As can be seen from this figure, Küssner's model does a good job predicting the lift maximum and the transients up to that maximum despite the very large gust ratios investigated, where the small-amplitude disturbances assumption is violated. However, the model predicts

a slower recovery than the measurements. This is thought to be caused by the fact that the flow becomes three-dimensional after the time that the lift peaks, as discussed in section 4.5. Therefore, it is most plausible to state that the validity of the Küssner's model heavily depends on assumption 1, the flow is two dimensional. The flowfields discussed earlier showed that the flow separates from the leading edge, an obvious violation of the inviscid flow and the shedding is only allowed from the leading edge assumptions. Furthermore, as shown in section 4.2.1.2, for all gust ratios the trailing wake remains planar until the time where the maximum lift is observed (assumption 7) and the deflection in the continuous gust shear layer is minor (assumption 5). Therefore, assumptions 1, 3, 5, and 7 are valid at least for the region where the Küssner's model is able to predict the lift coefficients that arise from the sine-squared gust encounters. On the other hand, the results clearly violate assumptions 2, 4, and 6.

Figure 5.7(b) shows the gust ratio normalized measured and predicted lift coefficients for the top-hat gust. As already established in the previous section, unlike the sine-squared gust, the measured lift coefficients do not scale well using the gust ratio. Küssner's model does a fair job predicting the shape of the lift response. However, the measured maximum lift is only predicted reliably for the lowest gust ratio tested, 0.5. Even at this gust ratio, the model slightly underpredicts the lift peak. Although the violation of small amplitude disturbances does not cause any issues for the sine-squared gust case, it is evident that this assumption is particularly crucial for the top-hat gust case, a profile that contains sharper velocity gradients. Similar to the sine-squared gust case, Küssner's model fails to

capture the recovery portion of the response, possibly due to the violation of two dimensional flow assumption. Furthermore, assumptions 2, 5, and 6 are violated, as discussed in the previous section, since a strong leading-edge vortex forms and advects away from the wing’s surface, and the gust shear layers significantly deform. Please note that the trailing wake only remains nominally planar until the lift peaks for the $GR = 0.5$ case, the only top-hat gust case that the Küssner’s model is able to predict the response of.

Overall, it can be concluded based on the above-mentioned findings that Küssner’s model can predict the maximum lift response if the following assumptions are valid.

1. The flow is two dimensional (at least until the time that the lift peaks).
2. The flow is incompressible.
3. The velocity gradients are small.
4. The leading-edge vortex is nominally close to the wing’s surface (at least until the time that the lift peaks).
5. The trailing wake is planar (at least until the time that the lift peaks).

5.3 Momentum Flux-based Normalization

Gust ratio normalization was found to scale the sine-squared velocity profile lift responses. However, it did not alleviate the discrepancies between different velocity profiles as seen in Figures 5.2(b) and 5.6. This section seeks a parameter

that can scale the lift responses of different velocity profiles. To this end, it uses both Küssner's model and the experimental results. As briefly mentioned in section 5.1, the different velocity profiles contain different momentum. The momentum flux (velocity times mass flow rate) can be defined as $\rho V(t)^2 w$, where ρ is the density, $V(t)$ is the gust velocity, and w is the gust width. In nondimensional form, the momentum flux of the gust flow is $GR(t^*)^2 w/c$. Based on this nondimensional quantity, the scaling factor can be defined as the gust ratio of a sharp-edged profile, which contains the same momentum flux of an arbitrary profile and is given as

$$K = \sqrt{\frac{1}{w/c} \int_0^{w/c} GR(t^*)^2 dt^*}, \quad (5.4)$$

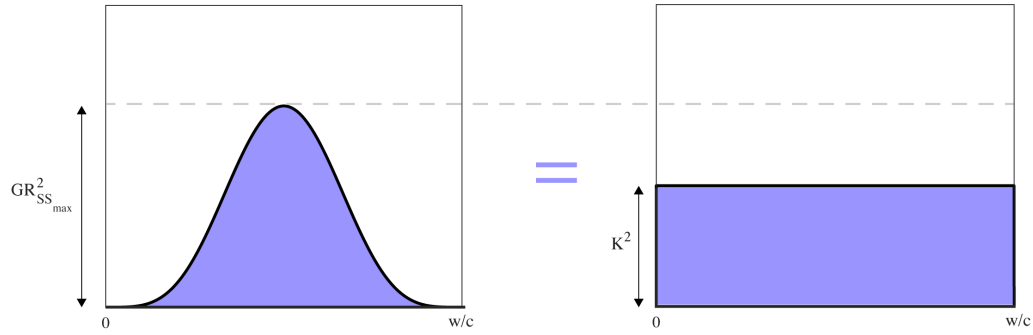


Figure 5.8: Momentum associated with the sine-squared gust (the purple area) and the corresponding sharp-edged gust.

Figure 5.8 shows the momentum flux of the sine-squared profile (the purple area under the curve) and the corresponding momentum flux of a sharp-edged profile with the same gust width. Since the sine-squared gust contains less momentum than the sharp-edged gust with the same maximum gust ratio, the scaling factor, K , is smaller than 1. The scaling factor is calculated using equation 5.4 and found to be 0.61 and 0.93 for the sine-squared and top-hat gusts, respectively.

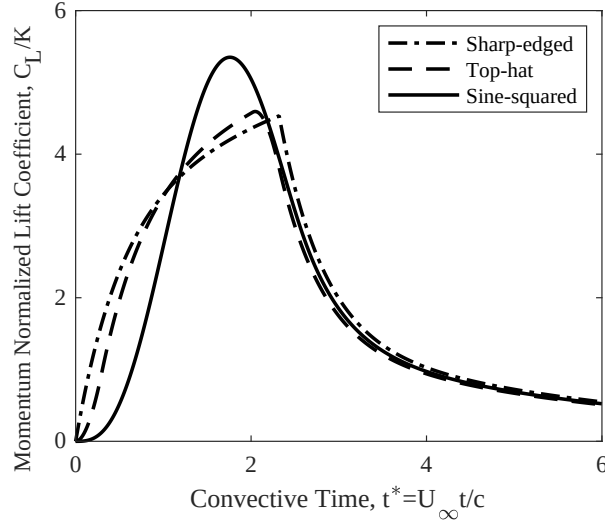


Figure 5.9: Gust momentum normalized Küssner’s convolutions for the sine-squared ($K = 0.61$), top-hat ($K = 0.91$), and sharp-edged ($K = 1$) gusts.

Figure 5.9 displays the momentum flux normalized Küssner’s convolutions for the sine-squared, top-hat, and sharp-edged gusts. Compared to Figure 5.6, where the lift coefficients are normalized with the gust ratio, the momentum flux-based normalization does a better job at scaling the responses of the top-hat and sharp-edged gusts whose maxima were not that different from each other, to begin with. Moreover, this normalization significantly increases the maximum of the sine-squared gust such that it exceeds the top-hat and sharp-edged gust’s maxima. This is thought to be caused by the fact that the gust widths of the sine-squared and top-hat gusts are not the same. As detailed earlier, the sine-squared gust has a width-to-chord ratio of 2.6, whereas the top-hat and sharp-edged gusts have a width-to-chord ratio of 2.32. As shown in an earlier study by Badrya et al. [86] for the sine-squared gust, increasing gust width causes the lift maximum to increase. Furthermore, it was also concluded in the same study that Küssner’s model is able

to accurately predict the lift maximum of the sine-squared gust up to gust widths of 4 chords. Therefore, the Küssner's model can be used to obtain the gust width's effect on the lift maximum, thereby allowing for a direct comparison of velocity profiles. Figure 5.10 shows the maximum lift coefficient extracted from Küssner's convolution for the sine-squared gust for various gust widths. As can be seen from this figure, the lift maximum has an exponential dependency on the gust width. Using this information, a new scaling factor can be introduced to the analysis for the sine-squared gust to alleviate the effect of gust width. Figure 5.11(a) displays the convolutions for all three velocity profiles with a correction on the sine-squared gust width. With this additional correction, all of the velocity profiles result in the same lift maximum. Therefore, it can be concluded that the differences in the gust momentum flux is the reason why different gust velocity profiles yield different lift maxima.

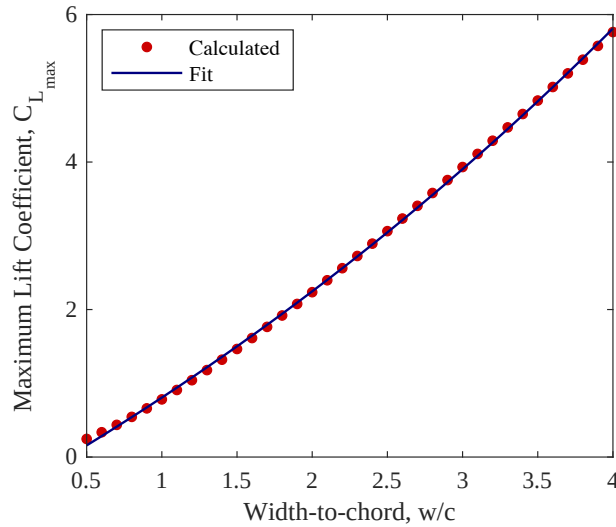
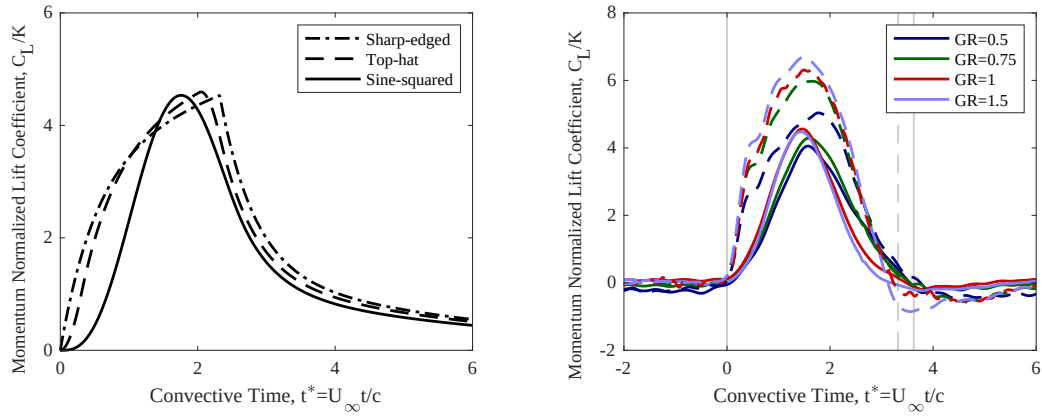


Figure 5.10: The maximum lift coefficient versus the width-to-chord ratio based on the Küssner's model.

Based on this gust width scaling factor and the momentum flux, the



(a) Gust momentum normalized convolutions (b) Gust momentum normalized lift coefficient

Figure 5.11: Gust momentum normalized Küssner's convolution (for the sine-squared, top-hat, and sharp-edged gusts) and measured lift coefficients (for the sine-squared and top-hat gusts) with a gust width correction.

experimental measurements for both the top-hat and sine-squared gusts are normalized and given in Figure 5.11(b). Compared to the gust ratio normalization shown in Figure 5.2(b), the momentum flux-based normalization considerably improves the results. The remaining discrepancies between the responses of sine-squared and top-hat gusts are attributed to the fact that the Küssner's model does not do a good job predicting the response of high-amplitude top-hat gust encounters.

5.4 Chapter Summary

This chapter explored the effect of the transverse gust velocity profile on the lift transients. To this end, the sine-squared and top-hat (data was provided by collaborators at CU) gusts were compared. Küssner's model was used to predict the lift responses for both profiles. Moreover, a momentum flux-based normalization method was discussed. The main findings of this chapter are summarized in the

following paragraphs.

The comparison of the sine-squared and top-hat gusts showed that the top-hat gust encounters result in a larger lift maximum than the sine-squared gust encounters, which is thought to be caused by the fact that a higher level of circulation is shed from the leading edge for the top-hat gust encounters. The flowfields showed that the leading-edge vortex that forms during the top-hat gust encounters moves further away from the wing's surface and advects more towards the downstream than the sine-squared gust case. A trailing edge vortex was found to form as the wing exits the gust when $GR \geq 1$ for the top-hat gusts, causing a minimum in the lift response. Moreover, for the top-hat gust, the trailing wake was found to show significant deflections, especially for gust ratios larger than 0.5, whereas the wake was found to remain nominally planar for the sine-squared gust case.

Küssner's model was found to accurately predict the maximum lift coefficient during the sine-squared gust encounters despite the large gust ratios investigated around 1.5. On the other hand, it failed to predict the maximum lift for the top-hat gust at relatively lower gust ratios around 0.75. In addition, it displayed minor discrepancies for the $GR = 0.5$ case. The limitations of Küssner's model were found to be different for different transverse velocity profiles despite the same gust ratios being investigated. Therefore, it is evident that the gust ratio is not the only parameter that should be considered while evaluating the model's accuracy. The transverse gust velocity profile and the velocity gradients attached to it were found to be an important parameter to consider. The smooth velocity gradients in the sine-squared gust allow for an accurate prediction even at high-amplitude disturbances,

while the sharp velocity gradients in the top-hat gust do not. On another note, the Küssner's model failed to predict the gust recovery portion of the lift response for both gusts since three-dimensional effects dominate the flow at those instants.

Lastly, a novel momentum flux-based normalization method was introduced. The results of this normalization were applied both to the Küssner's model and the measurements. The normalization method was found to do an excellent job scaling the responses of different transverse velocity profiles if the gust widths of the profiles are the same (or corrected using Küssner's model), and Küssner's model provide accurate predictions at the given amplitude and gust shape.

Chapter 6: Comparison of Gust Types and Flowfield-based Force Prediction Method

Thus far, transverse gust encounters and their effects on the force transients have been explored. Intending to deepen the understanding of gust encounters beyond the transverse gust, this chapter seeks to investigate the influence of different gust types, namely sine-squared transverse gust and vortex gust (data provided by collaborators), on the response of a flat plate wing. Section [6.1](#) discusses and establishes the lift transients experienced during vortex gust encounters and highlights the fundamental flow physics that cause these transients using flowfield and circulation measurements. Using the knowledge built in chapter [4](#) on the sine-squared transverse gust and section [6.1](#) on the vortex gust as a base, section [6.2](#) compares the trends of lift force, flowfields, and circulation production that arise from encountering both gust types. Lastly, section [6.3](#) introduces a flowfield-based force prediction method and furthers the discussion of the relationship between the gust-induced angle of attack and lift for both gusts. Overall, the results shown in this chapter will substantially contribute to the body of knowledge in gust encounters. Therefore, these results will pave the way for gust rejection systems for various gust types, which is especially important since air vehicles do not typically have any prior

knowledge on the gust type to be encountered during a real flight.

6.1 Vortex Gust

Chapter 4 explored the effect of sine-squared transverse gust encounters on forces and flowfields in detail. Before comparing the two gust types, namely the sine-squared transverse and vortex gusts, it seems most fit to introduce the force transients experienced during vortex gust encounters. As previously described in section 3.2, the vortex gust experiments were conducted at the Istanbul Technical University’s free surface water channel by collaborators. The vortex gust was generated by clockwise half-rotation of the upstream gust generator flat plate and shed from its leading edge. Even though various gust ratios were easily investigated for the sine-squared transverse gust by altering the towing speed and/or the pump speed, it is much harder to vary the gust ratio for the vortex gust experiments. Instead, the vertical offset, $\Delta y/c$, of the gust generator plate from the test model were altered, see Figure 3.4(b). The effects of varying the vertical offsets were explored in Ref. [90] and will not be discussed in this dissertation. Only the $\Delta y/c = 0.39$ case will be discussed here for the vortex gust encounters. This specific vertical offset was selected since the vortex gust initial shedding location is in line with the leading edge of the test model for this offset. Be that as it may, if other vertical offsets were used, the analysis and the comparison shown here would not change. The reader is referred to Ref. [90] for more details on the vortex gust encounters and the effect of vertical offset. Since the vortex gust is not continuous

in the stream-normal direction, unlike the sine-squared transverse gust, the path that the vortex gust follows becomes a parameter to be acknowledged. Figure 6.1 shows the vortex core positions for convective times between 1.5 and 3.625 for the $\Delta y/c = 0.39, \alpha = 0^\circ$ case. The x and y axes represent the horizontal and vertical positions in chords, respectively. The vortex core is aligned with the leading edge of the test model after being shed from the gust generator plate at $t^* = 1.5$, and it remains approximately at this vertical position for 1.25 convective times. Only thereafter, it starts to convect downwards in the vertical direction.

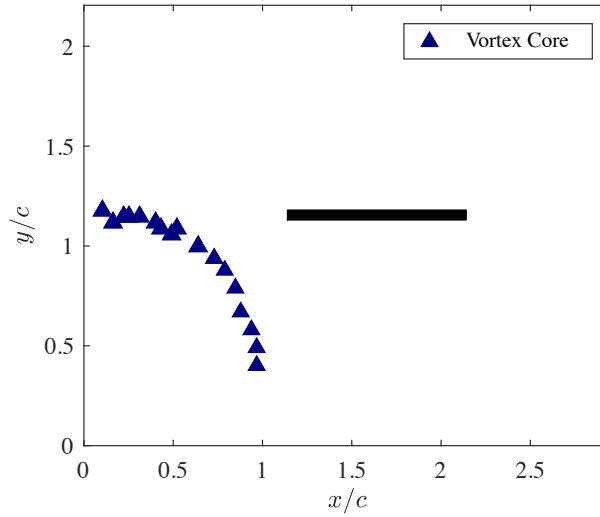
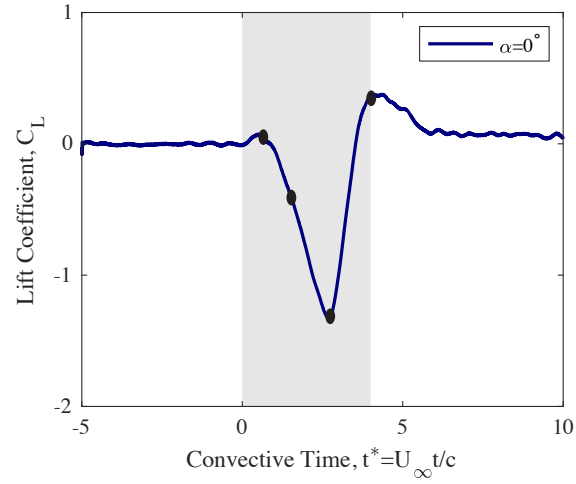
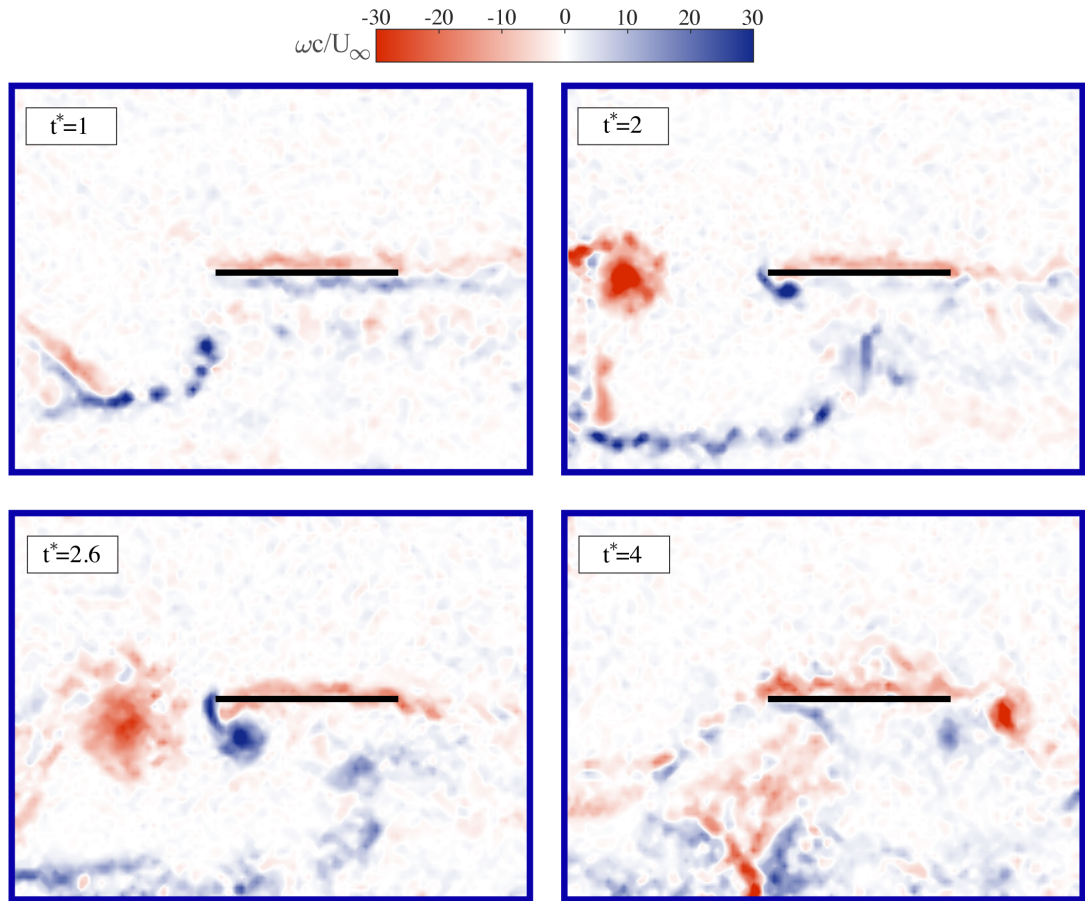


Figure 6.1: Path that vortex gust follows when the test model is at 0° angle of attack.

Figure 6.2 displays the lift coefficient and experimental flowfields for a flat plate at 0° angle of attack encountering a vortex gust. The x -axis of Figure 6.2(a) represents the convective time. Since the vortex gust is coupled with the wing and moves along the aforementioned path, the encounter does not occur in a fashion where the entry and exit times, and therefore the interaction time, can be determined. Therefore, instead of this interaction time, the convective times at



(a) Lift coefficient



(b) Experimental flowfields

Figure 6.2: Lift coefficient and experimental flowfields during vortex gust encounters for a flat plate at 0° angle of attack, circles on Figure 6.2(a) corresponds to flowfields in Figure 6.2(b).

which the gust generator plate moves ($0 \leq t^* \leq 4$) are marked with a grey box. Moreover, in this figure, the y -axis represents the lift coefficient. The lift transients observed during the vortex gust encounter will be highlighted using the experimental flowfields given in Figure 6.2(b) for convective times 1, 2, 2.6, and 4. Please note that the color bar has been flipped for an easier visual comparison with the transverse gust. Before the gust generator plate starts its motion ($t^* \leq 0$), the lift coefficient is at its steady-state value, zero, which proves that the vertical offset is sufficiently large to avoid interaction between the wake of the upstream gust generator and the test model that is at 0° angle of attack. Well after the motion of the gust generator starts, at $t^* = 1$, a local maximum is observed in the lift coefficient. As described earlier in section 3.2, the gust generator plate sheds a positive vortex from its trailing edge right after its motion starts. The flowfield shown at $t^* = 1$ in Figure 6.2(b) displays this positive vortex, which is thought to be the cause of the local maximum in the lift response at this instant. After the vortex gust is shed from the leading edge of the gust generator plate, the lift force starts to decrease from its local maximum. The flowfield given at $t^* = 2$ shows this negative vortex gust on the edge of the snapshot and the positive leading-edge vortex that forms on the pressure side of the test model. At $t^* = 2.6$, the lift force reaches a global minimum. At this instant, the vortex gust is closer to the test model and induces a strong positive leading-edge vortex, which creates a low-pressure region on the pressure side of the test model, causing the lift force to experience negative values. As the motion of the gust generator ends, at $t^* = 4$, the lift force experiences a secondary local maximum. The snapshot given at this instant shows a very chaotic flow. The vortex gust has

deflected downwards in the vertical direction, burst, and left the frame; the positive leading-edge vortex has shed and induced a strong negative trailing-edge vortex on the suction side. This trailing-edge vortex is presumably the reason why the lift force reaches a secondary maximum. After this instant, the lift force recovers from the encounter, and it reverts to its steady-state value around $t^* = 6$.

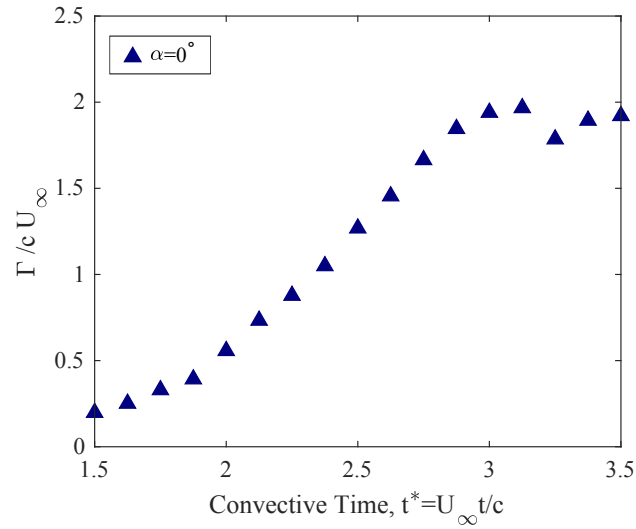


Figure 6.3: Nondimensional circulation shed from the leading edge for a flat plate at 0° angle of attack.

To provide further insight into the vortex gust encounter, the circulation shed from the leading edge of the test model was quantified using the segmentation method described in section 3.2.4. Figure 6.3 displays this nondimensional circulation for convective times between 1.5 and 3.5. This range was selected since the leading-edge vortex does not form until $t^* = 1.5$ and fully deforms and convects downwards in the vertical direction after $t^* = 3.5$. As can be seen from this figure, the strength of the leading-edge vortex increases as more time passes in the encounter. The value of the circulation shed reaches a maximum around $t^* = 2.6$,

which corresponds to the time the negative peak is observed in the lift coefficient. Only thereafter, the leading-edge vortex starts to lose its strength and eventually is shed from the test model.

To sum up, a wing at 0° encountering vortex gust was found to experience large transients in the lift force. A local maximum, a global minimum, and a secondary maximum were observed during the encounter. The flowfields provided highlighted the physical phenomena that cause these transients. The positive vortex initially shed from the gust generator was found to create the local lift maximum. On the other hand, the positive leading-edge vortex that forms on the pressure side of the test model was found to cause the global lift minimum. Lastly, the negative trailing edge vortex that forms on the suction side of the test model was found to give rise to the secondary lift maximum.

6.2 Comparison of Sine-squared Transverse and Vortex Gust Encounters

This section seeks to compare the two gust types, the transverse gust with a sine-squared profile and the vortex gust. The comparison will be made in terms of force, flowfield, and circulation production. Before initiating the discussion of the responses of these gusts, it is crucial to establish the differences between the gusts, some of which are artifacts of the experimental setup such that if one were to simulate the same gust type, these differences would diminish (e.g., an upstream gust generator plate). In contrast, others are inherent to the flow itself. Therefore,

these differences are categorized into two groups: effects of the experimental setup and effects of the gust type, which are tabulated in Table 6.1. As discussed earlier in Chapter 1, the transverse gust only contains transverse perturbations, whilst the vortex gust contains both longitudinal and transverse perturbations. The characterized horizontal and vertical velocity profiles are displayed in Figures 6.4(a) and 6.4(b), respectively for both the sine-squared transverse and vortex gusts. For more details on these velocity profiles and their characterization procedures, please refer to sections 3.2.2 and 2.3. In these figures, the x -axes represent the streamwise and stream-normal positions for the transverse and longitudinal profiles, respectively. Note here that the gust width definitions are different for the sine-squared transverse and vortex gusts. The width of the sine-squared transverse gust is defined based on the points where the fluid velocity reaches zero, whereas the width of the vortex gust is defined based on the core diameter of the vortex since the gradient of the decay of the vortex is exceptionally gentle. Therefore, the gust widths of the sine-squared transverse and vortex gusts are 2.6 and 0.4 chords, respectively. As mentioned in the previous section, the gust ratio can be altered quite easily for the transverse gust. However, it is much harder to achieve gust ratio variations for the vortex gust. Moreover, since the vortex gust is created by the motion of an upstream plate and a single vortex cannot be produced in isolation, an “unintentional vortex” sheds from the trailing edge of the gust generator plate immediately after the motion starts. This “unintentional vortex” was not characterized as a part of the vortex gust since its strength is relatively weak and remains sufficiently far away from the test model. On the other hand, the sine-squared transverse gust consists of continuous

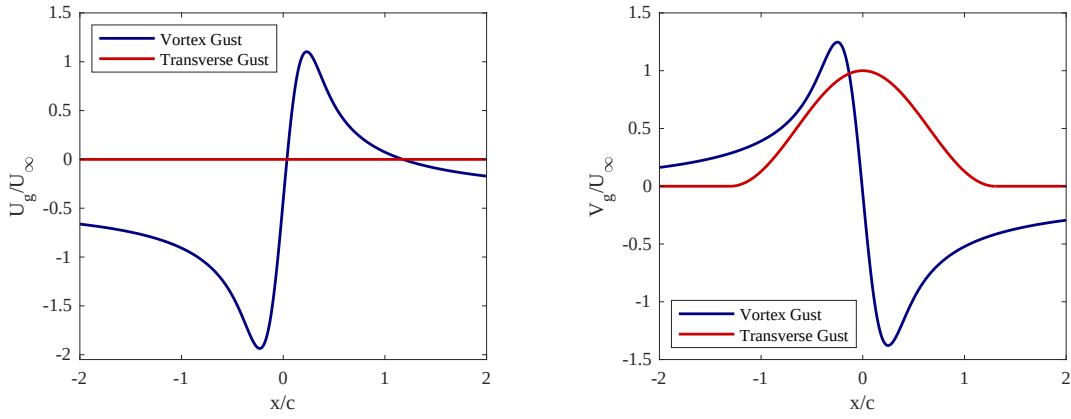
shear layers along the width of the gust, all of which were characterized as part of the gust flow. There is, of course, an upstream model, the gust generator plate, present in the flow for the vortex gust. Conversely, the only body in the flow for the transverse gust was the test model. Since the transverse gust is a jet-like flow, the gust is continuous in the stream-normal direction. However, this is not the case for the vortex gust; instead, the vortex gust follows the aforementioned path. Thus, an encounter time or a well-defined “entry” and “exit” cannot be determined for the vortex gust. Further differences arise due to model motion. The test model moves towards the transverse gust, whilst the vortex gust moves towards the test model, thereby causing the gust to deform as it convects. The transverse gust shear layers deflect as the wing moves through the gust. However, the deflection does not have any significant influence on force production Ref. [80].

Table 6.1: Comparison between the sine-squared transverse gust and the vortex gust.

		Transverse Gust	Vortex Gust
Effects of the gust type	Transverse perturbations	✓	✓
	Longitudinal perturbations	✗	✓
	Continuous in stream-normal direction	✓	✗
	Gust is free to move with the flow	✗	✓
	Well-defined gust “entry” and “exit”	✓	✗
Effects of the experimental setups	Gust ratio variation is achievable	✓	✗
	Unintentional vorticity in the flow	✗	✓
	Upstream body present	✗	✓
	Fixed test model	✗	✓

6.2.1 Force and Flowfield Comparison

This section focuses on the comparison of the two gust types in terms of lift force and flowfields. Figure 6.5 displays the lift response for both the sine-squared transverse and vortex gust encounters. The same parameters were used for the



(a) Longitudinal velocity profile normalized by the freestream (b) Transverse velocity profile normalized by the freestream

Figure 6.4: Longitudinal and transverse velocity profiles for both the sine-squared transverse and vortex gusts.

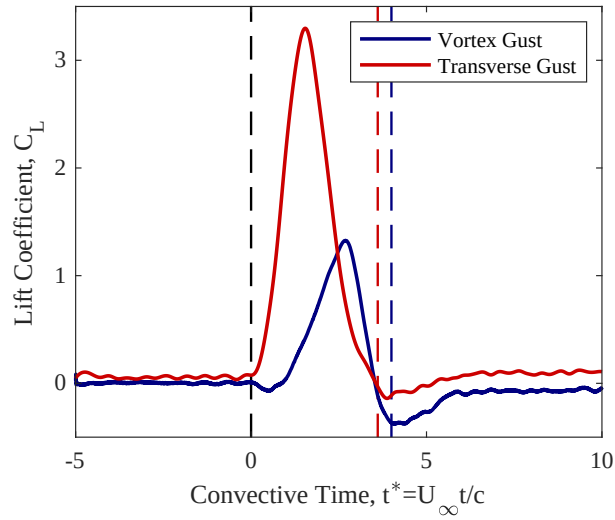


Figure 6.5: Lift histories during sine-squared transverse and vortex gust encounters for the $GR = 1, \alpha = 0^\circ$ case.

analysis, where the gust ratio is 1, and the angle of attack is $\alpha = 0^\circ$. In this plot, the x -axis represents the convective time. The wing enters the transverse gust at $t^* = 0$, whilst it fully exits the gust at $t^* = 3.6$, marked with a red dashed line in this figure. On the other hand, the vortex gust's entry and exit times are ambiguous due to the gust's deflection. Instead, the convective times at which the gust generator

plate moves were used as a reference. The gust generator's motion starts at $t^* = 0$ and ends at $t^* = 4$, which is marked with a blue dashed line in this figure. As established in the previous section, the vortex gust encounter results in a negative lift peak. In order to make the visual comparison easier, the measured lift coefficient for the vortex gust was flipped about the x -axis. Even though one might expect the lift responses of these two gust types to be distinctly different given the many above-mentioned differences, the transverse and vortex gust encounters result in similar trends in the lift force. Both encounters cause large transients in the lift. As can be seen from this figure, the response time, the time that passes between the steady state and the lift extreme value, of the two gust encounters are different. These differences are attributed to the fact that the wing begins immersing in the transverse gust at $t^* = 0$, while at this instant, vortex gust has not yet been shed from the gust generator. Moreover, the vortex gust contains an extremely gentle gust decay gradient as seen in Figure 6.4. Thus, the response time of the transverse gust is much shorter than the vortex gust. On another note, the reverse response time, which can be defined as the time that passes between the value of the lift extrema and the later steady state, is much larger for the sine-squared transverse gust. This is thought to be caused by the fact that the vortex gust contains relatively sharp gradients from one velocity extreme to another. Conversely, the sine-squared transverse gust velocity profile is symmetric (see Figure 6.4). The transverse gust encounter causes a significantly larger lift peak than the vortex gust despite the same gust ratio of 1. This is thought to be caused by two reasons. First of all, the vortex gust deflects downwards in the vertical direction due to the presence of the wing, whereas the

wing sees a stream-normal continuous gust in the sine-squared transverse gust case. Secondly, the gust width of the transverse gust is remarkably larger than the vortex gust's. Increasing gust width and vortex core diameter was previously found to cause a significant increase in the lift peaks for both gust types [86, 99]. In terms of the flow structures, the sine-squared transverse gust results in a leading-edge vortex, which causes a maximum in the lift. In contrast, the vortex gust encounters induce a positive leading-edge vortex on the pressure side of the test model and cause a minimum in the lift. Moreover, for the vortex gust, a trailing edge vortex forms on the suction side of the test model, causing a local lift peak right after the gust generator stops. On the other hand, the transverse gust encounter for a wing at 0° angle of attack does not yield any flow structures other than the aforementioned leading-edge vortex, presumably because of the large updraft a that transverse gust has.

6.2.2 Circulation Comparison

To provide further insight into the differences in the lift transients of both gust types, the circulation shed from the leading edge during the sine-squared transverse and vortex gust encounters was calculated and is displayed in Figure 6.6. Please recall that the convective time zero is defined differently for transverse and vortex gusts (see section 6.2). Since the wing gets fully immersed in the gust quicker, a leading-edge vortex forms at an earlier time in the case of the transverse gust. Moreover, it shows a steeper increase in the shed circulation than the vortex gust

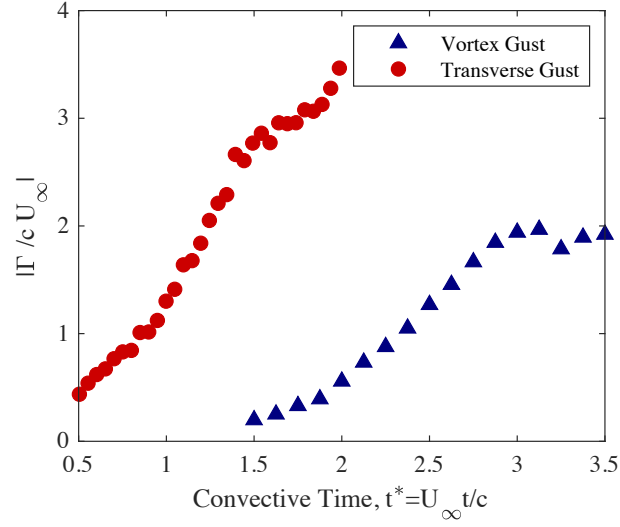


Figure 6.6: Nondimensional circulation shed from the leading edge during transverse and vortex gust encounters for the $GR = 1, \alpha = 0^\circ$ case.

case presumably because of the fact that the whole wing experiences the updraft caused by the transverse gust and the vortex gust has a more gentle rise in velocity gradients. Overall, the circulation shed from the leading edge reaches significantly larger values at a steeper rate, as does the lift force, in the case of the transverse gust encounter despite the same gust ratio investigated.

To sum up, both the sine-squared transverse and vortex gust encounters were found to result in similar trends in the lift force, notwithstanding the differences inherent to them. Despite the same gust ratio of 1, the lift force was found to reach significantly higher values, presumably due to the higher levels of circulation shed into the leading-edge vortex for the sine-squared transverse gust case. Furthermore, the increase in the lift force and the circulation shed into the leading-edge vortex was steeper for the transverse gust case.

6.3 Flowfield-based Force Prediction

Motivated by a desire to sense and predict the lift transients experienced during gust encounters, this section seeks to introduce a flowfield-based force prediction method and further the investigation of the gust-induced angle of attack. This method is used for both the sine-squared transverse gust and the vortex gust in an attempt to discover its applicability to different gust types. Figures 6.7(a) and 6.7(b) display sample vorticity contours from the sine-squared transverse and vortex gust encounters, respectively. In these figures, the x and y axes show the normalized streamwise and stream-normal positions. A line is displayed upstream of the wing in these figures. The distance between the leading edge and the line is defined as d . The length of this line is defined as l . This line is used to depict the region over which the vertical and horizontal velocities are averaged. This averaging is performed on the time-resolved PIV vector fields, thereby allowing the calculations of the average velocities in time. The time-varying gust-induced angle of attack is computed from these average velocities using the following equation

$$\alpha_{\text{ind}}(t^*) = \tan^{-1} \left(\frac{V(t^*)}{U(t^*)} \right), \quad (6.1)$$

where t^* is the convective time, $V(t^*)$ and $U(t^*)$ are the computed time-varying vertical and horizontal velocities, and α_{ind} is the time-varying gust-induced angle of attack. Then, this computed gust-induced angle of attack is shifted in time considering the convection with the freestream ($t_{\text{shift}} = -d/c$) to the leading edge.

These calculations were performed for various cases, including different vertical offsets for the vortex gust and gust ratios for the transverse gust for both gust types. Primarily based on the boundaries of the flowfields, different ranges of d were selected for different gust types investigated here. The parameter space was constrained to $0.1 \leq d/c \leq 1.2$ and $0.1 \leq d/c \leq 0.5$ for the transverse and vortex gusts, respectively. Please note here that the maximum value of d/c was set to 0.5 for the vortex gust due to the presence of the gust generator plate upstream. In an attempt to find the optimum position and length of the averaging line, a correlation between the trends in the change of the lift coefficient ($\Delta C_L(t^*) = C_L(t^*) - C_{L_{ss}}$) and the trends in the calculated gust-induced angle of attack were searched for a total of 10 different d and 10 different l parameter combinations for each gust type. As established in chapters 2 and 3, the flowfield and force measurements were sampled at different rates for both gust types. To allow the correlation between the force and the flowfield measurements, data were reduced to the greatest common factor, which corresponds to 100 Hz and 8 Hz for the transverse and vortex gusts, respectively. The obtained correlation values were explored for both gust types. Although the computed gust-induced angle of attack results yielded high correlations for various combinations of parameters d and l , a selection was made amongst them to ensure a high correlation for different gust ratios, vertical offsets, and different gust types. The latter is specifically important since in a real flight there is no prior knowledge on the gust (type, amplitude, and location) that the vehicle would encounter. The $d/c \approx 0.5; l/c \approx 1$ line was found to exhibit approximately 95% correlation for various transverse and vortex gust cases, and was therefore selected.

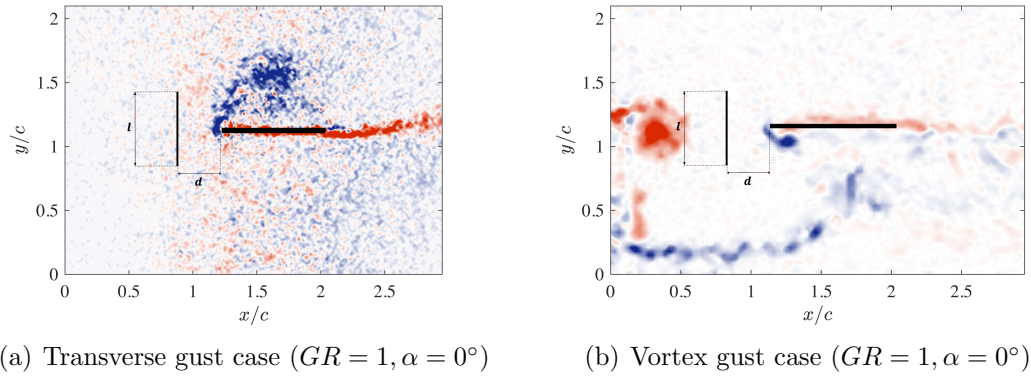


Figure 6.7: The lines upstream of the leading-edge that are used to compute the average velocities, which are displayed on the vorticity contours for both the sine-squared transverse and vortex gusts.

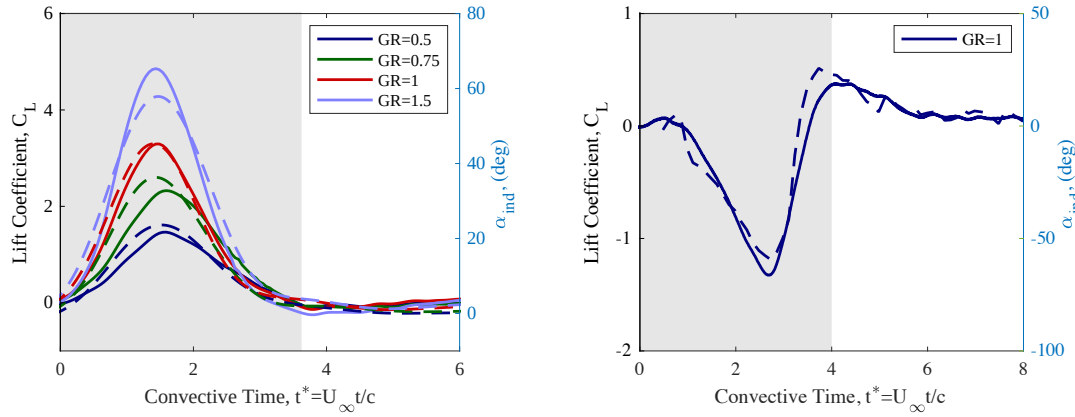
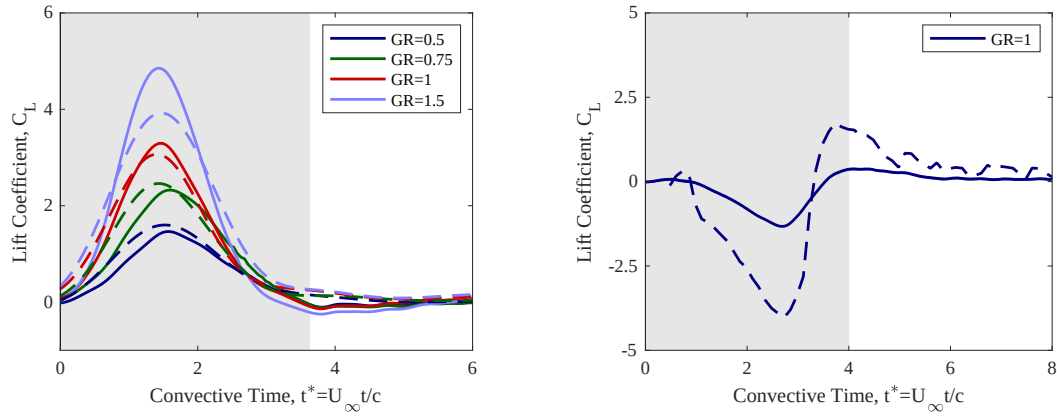


Figure 6.8: Lift coefficient from force measurements (solid lines) and gust-induced angle of attack (dashed lines) for both gust types.

The calculated gust-induced angles of attack with dashed lines (y -axis on the right) and measured lift coefficients with solid lines (y -axis on the left) for transverse and vortex gust encounters are displayed in Figures 6.8(a) and 6.8(b), respectively. Figure 6.8(a) shows the results of a flat plate at 0° angle of incidence encountering transverse gusts of various strengths. As can be seen, the trend in the measured

lift coefficient is accurately predicted by the calculated gust-induced angle of attack variations. The maximum calculated gust-induced angles of attack were 26° , 42° , 51° , and 63° for gust ratios of 0.5, 0.75, 1, and 1.5, respectively. Therefore, it is evident that the calculations are able to capture the trend the lift coefficient showed with increasing gust ratio. Moreover, there is almost no phase shift between the measured and calculated quantities, and the magnitude of C_L is not universally proportional to α_{ind} . Figure 6.8(b) displays the results of a flat plate at 0° angle of incidence encountering a vortex gust of gust ratio of 1. As established in section 6.1, the vortex gust displays three distinct regions in the lift response, which are the local maximum at $t^* = 1$, global minimum at $t^* = 2.6$, and secondary maximum at $t^* = 4$. The calculated gust-induced angle of attack is able to capture the trends in all of these regions. The minimum gust-induced angle of attack was calculated to be -60° . Just like the transverse gust case, there is no phase shift between the calculated and measured quantities.

To further the investigation of the effects of the gust-induced angle of attack, the lift force can be calculated. To achieve this, the Helmbold equation [120, 121],
$$C_L = \frac{2\pi\alpha_{ind}}{\sqrt{1+(2/AR)^2+2/AR}},$$
 was used to predict the lift responses based on the calculated gust-induced angles of attack for both gust types. The measured and predicted lift coefficients of a flat plate at 0° angle of attack encountering transverse gust with various strengths are shown in Figure 6.9(a). As can be seen from this figure, the flowfield-based method does a good job predicting the maximum lift for the cases where $GR \leq 1$, which corresponds to the cases, where the calculated gust-induced angle of attack is less than 51° . The method fails when the gust ratio and the



(a) Measured (solid lines) and predicted (dashed lines) lift coefficients for a flat plate at 0° angle of attack encountering sine-squared transverse gusts of various strengths

(b) Measured (solid lines) and predicted (dashed lines) lift coefficients for a flat plate at 0° angle of attack encountering vortex gust of strength GR=1

Figure 6.9: Lift coefficients from force measurements (solid lines) and predictions (dashed lines) for both gust types.

gust-induced angle of attack are larger than 1.5 and 51° , respectively. Please note here that one advantage this method offers over the Küssner's model discussed in the previous chapter is that it is able to predict the gust recovery portion of the lift response accurately. The lift coefficients obtained from both force measurements and predictions of a flat plate at 0° angle of attack encountering vortex gust are displayed in Figure 6.9(b). The flowfield-based method overpredicts the minimum and maximum lift coefficients, presumably due to the very high gust-induced angles of attack calculated ($\alpha_{ind} = -60^\circ$).

To sum up, the flowfield-based force prediction method, which provided some valuable information regarding the lift response, was introduced. The gust-induced angle of attack was found to follow the same trends as the lift response for both gust types. The Helmbold equation was used to predict the gust-induced angle of attack based lift coefficients. The predictions were found to agree well with the

measurements when the gust-induced angle of attack is sufficiently low. This method paved the way for MAV controller design since there is no prior information of the gust that the vehicle might encounter during an actual flight. If one is willing to place a sensor upstream of the wing and calculate the variations in the gust-induced angle of attack, the trends in the lift force can be predicted for different types of gusts despite the very high-amplitude disturbances. However, the accurate prediction of the amplitude of the lift response is limited to relatively lower gust-induced angles of attack.

6.4 Chapter Summary

This chapter explored the effects of gust type on lift transients. To this end, firstly, the transients in the lift force, flow structures, and circulation were established for the vortex gust encounters. Then, a comparison between the sine-squared transverse gust and the vortex gust (ITU) was provided. Lastly, a flowfield-based force prediction method was introduced. The main findings of this chapter are summarized in the following paragraphs.

The vortex gust was created by clockwise half-rotation of the upstream gust generator plate. Unlike the transverse gust, the vortex gust is not continuous in the stream-normal direction. Therefore, the wing-gust coupling effects are more profound in the case of the vortex gust encounters. Furthermore, the vortex gust was found to deflect downwards in the vertical direction due to the presence of the test model. Three distinct lift transients were observed during the vortex

gust encounters, which are a local maximum, a global minimum, and a secondary maximum. One convective time after the gust generator started its motion, the flowfields showed the presence of a positive vortex that is shed from the gust generator's trailing edge, causing the local maximum in lift. As the vortex gust advected towards the test model, a positive leading-edge vortex was found to form on the test model's pressure side, causing the minimum in lift. Moreover, the circulation shed from the leading edge was found to be maximum at this instant. After the gust generator stopped, the secondary maximum was observed in the lift force due to the formation of a trailing edge vortex on the suction side of the test model. The lift force was found to fully recover to its steady-state value 6 convective times after the start of the gust generator's motion.

The sine-squared transverse and vortex gusts were found to be distinctly different from each other. Some of these differences were demonstrated to be artifacts of the experimental campaigns, such as the presence of the upstream gust generator plate for the vortex gust case, whilst the others were found to be inherited to the gust type, such as the existence of longitudinal disturbances for the vortex gust case. Notwithstanding these differences, both gust encounters were found to cause large transients in the lift force. While the vortex gust encounters resulted in a lift minimum due to the low-pressure region created by the positive leading-edge vortex on the pressure side of the test model, the transverse gust encounters resulted in a lift maximum because of the suction force that the negative leading-edge vortex created. The increase in the lift force and circulation shed from the leading edge for the sine-squared transverse gust case was found to be steeper than the ones of the

vortex gust case. Moreover, a larger lift peak and higher levels of circulation shed were observed for the sine-squared transverse gust case.

The calculated average vertical and horizontal velocities along an upstream line were used to find the gust-induced angles of attack. A 95% correlation between the measured lift coefficients and calculated gust-induced angles of attack was observed for both gust types. The predicted gust-induced angles of attack were found to follow the same trends as the measured lift coefficients, even including the recovery portion of the response, which Küssner's model failed to do. The Helmbold equation was used to compute the gust-induced angle of attack based lift coefficient for both gust types. The predicted coefficients were found to agree well with the measurements only when the gust-induced angle of attack is lower than 51° .

Chapter 7: Conclusions

This dissertation focuses on a joint experimental and theoretical study performed on sine-squared transverse gust encounters in order to deepen the understanding of fundamental flow physics behind the unsteady force production during transverse gust encounters. Moreover, in an attempt to provide a comprehensive picture, the current work compares the results obtained for the sine-squared transverse gust encounters with experimental and numerical data provided by collaborators at the University of Cambridge (CU), Istanbul Technical University (ITU), and the University of Maryland (UMD) on the top-hat transverse (experimental), vortex (experimental), and sine-squared transverse (numerical) gust encounters, respectively. Hence, it significantly contributes to the body of knowledge required to achieve the ultimate goal of this research, which is to expand the operational envelopes of MAVs. The following sections include summary of research, the original contributions, and the suggestions for future work.

7.1 Summary and Conclusions

The first portion of the dissertation, where the bulk of the results are presented, focuses on understanding the fundamental flow physics behind the sine-squared

gust encounters by a series of experiments exclusively carried out at the free surface water towing tank located at the University of Maryland. Firstly, a gust generation system, which allows for variations in the gust velocity, was designed and constructed. The resulting gust flow was characterized using PIV and found to have a streamwise vertical sine-squared transverse and spanwise linear velocity profile. The characterization results showed that the peak gust velocity is repeatable and can be varied between 0.06 m/s and 0.4 m/s using this setup. The gust width was obtained to be 198 mm with a 11% coefficient of variation. Flat plates of several aspect ratios were used. Force, PIV, and dye-flow visualization experiments were performed for a flat plate at a constant angle of attack towing with a constant speed ($Re = 20,000$ or $Re = 40,000$) encountering a gust of determined strength. The time-resolved leading-edge vortex strengths were calculated from the PIV flowfields and contributed to understanding of gust encounters by providing a quantitative analysis on the force transients. The effects of various parameters, including angle of attack, gust ratio, effective angle of attack, and aspect ratio, were explored. These experiments allowed for a thorough investigation of the force transients using the insight that the two and three-dimensional flowfields provided. Moreover, the simulations performed by collaborators at the UMD highlighted the skin friction experienced at low angles of attack.

The effects of angle of attack on the transients were investigated for a wide range of angles ($0^\circ \leq \alpha \leq 45^\circ$). The results showed that both the lift and drag forces experience significant transients accompanied by vortex shedding from the wing's leading and trailing edges. For all angles of attack investigated, the encounter

resulted in a peak in both the lift and the drag when the wing is centered in the gust. The force peaks were found to correspond to maxima except for the $\alpha = 0^\circ$ case, where a minimum in the drag coefficient was observed. The flowfields revealed that the physics behind these force peaks. The flow was separated from the leading edge and rolled into a leading-edge vortex, which created a low-pressure region on the upper surface. The behavior of lift and drag was found to differ in terms of their dependency on the angle of attack. A detailed analysis of the forces showed that the extrema in the lift coefficient exhibit a stall-like behavior (“stall angle” around 15°) with an increasing angle of attack, whilst the drag coefficient displays a linear behavior. The leading-edge vortex strength calculations confirmed the trends observed in the forces. The trends in the forces after the aforementioned extrema (i.e., the gust recovery portion) was found to differ for $\alpha = 0^\circ$ and $\alpha > 0^\circ$ cases. While the forces and flowfields were found to revert to the steady state as the wing at a 0° of incidence exits the gust, the recovery response lasted longer for $\alpha > 0^\circ$ cases, where the forces experienced a consecutive minimum and maximum due to the shedding of trailing and leading-edge vortices. The exposed project area based normalization, which incorporates the gust-exposed and freestream-projected areas of the wing into the calculations, was found to minimize the differences in the responses of various angles of attack.

The effects of the gust ratio and effective angle of attack were more straightforward to analyze. An extensive range of gust ratios was investigated ($0.08 \leq GR \leq 1.5$). Both the lift and drag extrema increased with increasing angle of attack in the same vein as the circulation shed from the leading edge. The

effect of the gust ratio was found to be very subtle for the cases where $\alpha \geq 30^\circ$. The gust ratio normalization was found to scale both the lift and drag responses of various gust ratios even when nonlinear effects dominate the flow. The maximum lift force was found to be linearly dependent on the maximum effective angle of attack for the cases where $\alpha \leq 10^\circ$ and $\alpha_{\text{eff}_{\text{max}}} < 40^\circ$. Thus, the cases in which gust ratio and geometric angle of attack were selected to produce a given value of effective angle of attack produced similar lift maxima if the cases investigated are within the above-mentioned limitations.

Drag force was found to exhibit a negative peak for $\alpha = 0^\circ$ cases during the encounter. The skin friction coefficients provided by the collaborator (C.Badrya) provided significant insight into this behavior. The numerical results showed that the skin friction contains a negative region aligned with the leading-edge vortex that produces reverse flow along the wing surface. Since the skin friction coefficient dominates the total drag coefficient for low angles of attack, a negative drag peak is observed. The larger gust ratios were found to lead to stronger leading-edge vortices and cause larger reverse flow regions, therefore a more dramatic negative drag peak.

The effects of three-dimensionality and aspect ratio on the response of a flat plate encountering a sine-squared transverse gust was then examined. The three-dimensional flowfields obtained experimentally using dye-flow visualization showed that the flow stays nominally two-dimensional until the wing is centered in the gust. However, after that, significant spanwise variations occur in the flow. The suction of the leading-edge vortices towards the wing tips highlighted the existence of a tip vortex. Qualitatively, the flow was found to become more chaotic as the

gust ratio and/or angle of attack increased. The lift transients of three different aspect ratio flat plates ($\mathcal{R} = 4, 6, 8$) were investigated. The variations in the aspect ratio were found to alter the lift response slightly, where larger aspect ratios caused subtly larger lift extrema. This is found to be caused by the fact that the spanwise variations occur only towards the wing tips for the larger aspect ratio wing ($\mathcal{R} = 8$), whereas the whole wing is dominated by the three-dimensional effects for a smaller aspect ratio wing ($\mathcal{R} = 4$).

The second portion of the dissertation focuses on the accuracy and limitations of Küssner's model and the effect of the transverse gust velocity profile not only to explore a possible force prediction method but also to expand the knowledge on transverse gust encounters in general. The responses of a flat plate at 0° angle of attack encountering a sine-squared transverse gust and a top-hat gust (latter data provided by collaborators, I. Andreu and H. Babinsky) were compared in terms of lift transients and flow structures.

The results showed that the top-hat gust yields a larger lift maximum for a given gust ratio than the sine-squared gust, presumably because of a higher level of circulation shed from the leading edge. In addition, unlike the sine-squared gust encounters, a significant trailing wake deflection was observed for the top-hat gust case. Therefore, it can be concluded that more substantial nonlinearities arise in the case of the top-hat gust.

Küssner's model was found to accurately predict the lift maximum of the sine-squared gust case even for very large gust ratios around 1.5, where almost all assumptions of the model are invalid. On the other hand, the model failed to predict

the lift maximum of the top-hat gust case for $GR > 0.5$. Therefore, it was found that the gust velocity gradients significantly affect the accuracy of Küssner’s model. While smoother gradients allow the model to predict the response even at very large disturbances, sharper gradients cause the model to fail. Overall, it is the most plausible to state that the Küssner’s model provides a first-order estimates for large-amplitude transverse gusts, which contains smooth gradients. For both velocity profiles, Küssner’s model failed to accurately predict the gust recovery portion of the response, where three-dimensional effects dominate the flow. A normalization method based on the momentum flux was introduced and found to scale the lift responses of different transverse velocity profiles as long as the responses can be predicted using Küssner’s model.

The last portion of the dissertation explores the similarities and differences between the responses of the sine-squared transverse and vortex gust encounters to pave the way for possible gust mitigation methods by enhancing the understanding behind gust encounters. The forces and flowfields for the vortex were obtained experimentally by collaborators at ITU (M. Saritas and O. Cetiner). The comparison was provided for an angle of attack of 0° and a gust ratio of 1. A flowfield-based force prediction method was discussed.

The results showed that both gust encounters result in large transients in the lift despite many differences in the nature of the gusts. The increase in the lift force and the circulation shed from the leading edge for the transverse gust case was found to be steeper than the vortex gust case, presumably because of the stream-normal continuous nature of the transverse gust. A line upstream of the leading edge was

used to compute the average horizontal and vertical velocity variations in time from experimental flowfields. The trends in the measured lift force for both gusts were confirmed to follow the same trends as the trends in the computed effective angle of attack, meaning that possible effective angle of attack-based gust mitigation models would work on both gusts. The effective angle of attack based lift coefficients were predicted using Helmbold's equation for both gusts. This force prediction method was found to do a good job only for low-to-moderate values of effective angles of attack around 51° .

7.2 Original Contributions

The current study provides significant contributions to the research performed on gust encounters, especially the sine-squared transverse gust encounters. These original contributions are summarized as follows:

1. Fundamental understanding of the flow physics of sine-squared transverse gust encounters was significantly improved by exploring not only the force transients and two-dimensional flowfields but also the circulation production mechanism, three-dimensional flowfields, and skin friction coefficients.
2. An extensive investigation of sine-squared transverse gust encounters was conducted using force, flowfield, and circulation measurements for various parameters, including the angle of attack, gust ratio, effective angle of attack, and aspect ratio.
3. The acquired forces, flowfields, and circulation for the sine-squared transverse

gust encounters established a unique and comprehensive database for the validation of computational studies.

4. Various normalization methods that can be used to scale the responses of different gust ratios, angles of attack, and transverse velocity profiles were proposed. Their applicability was ascertained using the experimental results.
5. The accuracy and limitations of Küssner’s model were evaluated for the sine-squared and top-hat (CU) transverse gusts using the experimental data. It was found that the effects of the amplitude of the gust are intertwined with the effects of the gradients in the velocity profile such that smoother gradients allow the model to accurately predict the response of very high-amplitude encounters. Based on the findings of this analysis, the assumptions of the Küssner’s model were reevaluated.
6. Fundamental understanding of gust encounters was enhanced by comparing different gust types, namely the sine-squared transverse and vortex gusts (ITU) and establishing the response relationship with the effective angle of attack. In addition, a flowfield-based force prediction method was proposed and found to be effective for the low-to-moderate effective angles of attack.

7.3 Suggestions for Future Work

This dissertation provided valuable information on the fundamental flow physics of gust encounters by exploring the effects of various parameters, evaluating

the accuracy of Küssner’s model, comparing different transverse gust velocity profiles and gust types, and proposing novel normalization methods. This section seeks to offer several suggestions for future work, which would help the research to reach the ultimate goal, expanding the operational envelopes of MAVs.

1. The experimental results discussed in chapter 4 was limited to only one wing geometry, which is the flat plate. Since changing the geometry would alter the response, exploring the effects of airfoil shape would allow finding an optimum geometry that minimizes the transients experienced during gust encounters. The results would provide valuable information for MAV, wind turbine, and rotorcraft design.
2. The effect of transverse gust velocity profile was explored in chapter 5 by comparing the sine-squared transverse and top-hat (CU) transverse gusts. The results showed that the gradients in the transverse velocity profile significantly affect the response. However, in this analysis, the effects of velocity profile and velocity gradients were coupled. Isolating the effect of the velocity gradients would enhance the knowledge of gust encounters.
3. The Küssner’s model discussed in chapter 5 was found to provide accurate maximum lift predictions even when the flow is highly nonlinear. Be that as it may, the model was also found to fail to predict the recovery region of the response, where three-dimensional effects dominate the flow. Modifying the model to account for the spanwise variations that occur at the recovery region would significantly enhance the model’s applicability.

4. The results have shown herein improved the understanding of flow physics behind transverse gust encounters. Incorporating this fundamental knowledge into a low-order model would allow for quick predictions of unsteady loads in a wide range of gust encounters.
5. The effect of gust type on the response of a wing was discussed in chapter 6. The analysis showed that the time-varying effective angle of attack significantly influences the response of both the transverse and vortex (ITU) gust encounters. Inclusion of this knowledge to an open-loop controller would help mitigate the detrimental effects of the gust encounters.

Bibliography

- [1] Yongsheng Lian and Wei Shyy. Aerodynamics of low reynolds number plunging airfoil under gusty environment. In *45th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, 2007. AIAA Paper 2007-71.
- [2] Avi Zaide and Daniella Raveh. Numerical simulation and reduced-order modeling of airfoil gust response. *AIAA Journal*, 44(8):1826–1834, 2006.
- [3] Guowei Yang and Shigeru Obayashi. Numerical analyses of discrete gust response for an aircraft. *Journal of Aircraft*, 41(6):1353–1359, 2004.
- [4] Vladimir Golubev, Reda Mankbadi, Miguel Visbal, James Scott, and Ray Hixon. A parametric study of nonlinear gust-airfoil interaction. In *27th AIAA Aeroacoustics Conference*, Cambridge, MA, 2006. AIAA Paper 2006-2426.
- [5] Adrian Bejan. The constructal law of organization in nature: tree-shaped flows and body size. *Journal of Experimental Biology*, 208(9):1677–1686, 2005.
- [6] Joel Grasmeyer and Matthew Keennon. Development of the black widow micro air vehicle. In *39th Aerospace Sciences Meeting and Exhibit*, Reno,NV, 2001. AIAA Paper 2001-0127.
- [7] Lin Chi Mak, Makoto Kumon, Mark Whitty, Jayantha Katupitiya, and Tomonari Furukawa. Design and development of the micro aerial vehicles for search, tracking and reconnaissance (mavstar) for mav08. *International Journal of Micro Air Vehicles*, 1(2):139–153, 2009.
- [8] Matthew Keennon, Karl Klingebiel, and Henry Won. Development of the nano hummingbird: A tailless flapping wing micro air vehicle. In *50th AIAA Aerospace Sciences Meeting*, Nashville,TN, 2012. AIAA Paper 2012-01588.
- [9] William R Davis, Bernard B Kosicki, Don M Boroson, and DE Kostishack. Micro air vehicles for optical surveillance. *Lincoln Laboratory Journal*, 9(2):197–214, 1996.

- [10] Wei Shyy, Hikaru Aono, Satish Kumar Chimakurthi, Pat Trizila, C-K Kang, Carlos ES Cesnik, and Hao Liu. Recent progress in flapping wing aerodynamics and aeroelasticity. *Progress in Aerospace Sciences*, 46(7):284–327, 2010.
- [11] Max F Platzer, Kevin D Jones, John Young, and Joseph CS Lai. Flapping wing aerodynamics: progress and challenges. *AIAA journal*, 46(9):2136–2149, 2008.
- [12] Nikolajs Glizde. Plotting the flight envelope of an unmanned aircraft system air vehicle. *Transport and Aerospace Engineering*, 4(1):80–87, 2017.
- [13] Abdulghani Mohamed, Kevin Massey, Simon Watkins, and Reece Clothier. The attitude control of fixed-wing mavs in turbulent environments. *Progress in Aerospace Sciences*, 66:37–48, 2014.
- [14] Wei Shyy, Yongsheng Lian, Jian Tang, Dragos Viieru, and Hao Liu. *Aerodynamics of low Reynolds number flyers*. Cambridge University Press, 2007.
- [15] Wei Shyy, Mats Berg, and Daniel Ljungqvist. Flapping and flexible wings for biological and micro air vehicles. *Progress in Aerospace Sciences*, 35(5):455–505, 1999.
- [16] Thomas J Mueller. *Fixed and flapping wing aerodynamics for micro air vehicle applications*. American Institute of Aeronautics and Astronautics, Inc., 2001.
- [17] Simon Watkins, Juliette Milbank, Benjamin J Loxton, and William H Melbourne. Atmospheric winds and their implications for microair vehicles. *AIAA journal*, 44(11):2591–2600, 2006.
- [18] Hendrik Tennekes. *The simple science of flight: from insects to jumbo jets*. MIT Press, 2009.
- [19] Kamal Viswanath and Danesh K Tafti. Effect of frontal gusts on forward flapping flight. *AIAA Journal*, 48(9):2049–2062, 2010.
- [20] Simon Watkins, Michael Thompson, Benjamin Loxton, and Mujahid Abdulrahim. On low altitude flight through the atmospheric boundary layer. *International Journal of Micro Air Vehicles*, 2(2):55–68, 2010.
- [21] Caleb White, Ee Wei Lim, Simon Watkins, Abdulghani Mohamed, and Mark Thompson. A feasibility study of micro air vehicles soaring tall buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 103:41–49, 2012.
- [22] Federico Fonte, Sergio Ricci, and Paolo Mantegazza. Gust Load Alleviation for a Regional Aircraft through a Static Output Feedback. *Journal of Aircraft*, 52(5):1559–1574, 2015.

- [23] Michael Ol, Greg Parker, Gregg Abate, and Johnny Evers. Flight controls and performance challenges for mavs in complex environments. In *AIAA Guidance, Navigation and Control Conference and Exhibit*, Honolulu, HI, 2008. AIAA Paper 2008-6508.
- [24] Abdulghani Mohamed, Mujahid Abdulrahim, Simon Watkins, and Reece Clothier. Development and flight testing of a turbulence mitigation system for micro air vehicles. *Journal of Field Robotics*, 33(5):639–660, 2016.
- [25] John Roy Garratt. The atmospheric boundary layer. *Earth-Science Reviews*, 37(1-2):89–134, 1994.
- [26] Christopher Scruton and Anthony Ray Flint. Wind-excited oscillations of structures. *Proceedings of the Institution of Civil Engineers*, 27(4):673–702, 1964.
- [27] Cezary Galiński. Gust resistant fixed wing micro air vehicle. *Journal of aircraft*, 43(5):1586–1588, 2006.
- [28] Matthias Roth. Review of atmospheric turbulence over cities. *Quarterly Journal of the Royal Meteorological Society*, 126(564):941–990, 2000.
- [29] Susanna Mohr, Michael Kunz, Alexandra Richter, and Bodo Ruck. Statistical characteristics of convective wind gusts in germany. *Natural Hazards and Earth System Sciences*, 17(6):957–969, 2017.
- [30] David S Nolan, Nathan A Dahl, George H Bryan, and Richard Rotunno. Tornado vortex structure, intensity, and surface wind gusts in large-eddy simulations with fully developed turbulence. *Journal of the Atmospheric Sciences*, 74(5):1573–1597, 2017.
- [31] Jonathan Nathaniel Lefebvre. *Cylinder-Airfoil Interactions and the Effect on Airfoil Performance*. PhD thesis, University of Maryland, College Park, 2021.
- [32] Mostafa Rahimpour and Peter Oshkai. Experimental investigation of airflow over the helicopter platform of a polar icebreaker. *Ocean Engineering*, 121:98–111, 2016.
- [33] James S Forrest and Ieuan Owen. An investigation of ship airwakes using detached-eddy simulation. *Computers & Fluids*, 39(4):656–673, 2010.
- [34] Luke Robert Smith. *Measurement and Prediction of the Separated Flow on a Rotor at High Advance Ratio*. PhD thesis, University of Maryland, College Park, 2020.
- [35] Chee Tung, Yung Yu, and Scott Low. Aerodynamic aspects of blade-vortex interaction (bvi). In *Fluid Dynamics Conference*, New Orleans, CA, 1996.

- [36] JS Marshall and JR Grant. Penetration of a blade into a vortex core: vorticity response and unsteady blade forces. *Journal of Fluid Mechanics*, 306:83–109, 1996.
- [37] Esteban Ferrer and Richard HJ Willden. Blade–wake interactions in cross-flow turbines. *International Journal of Marine Energy*, 11:71–83, 2015.
- [38] Antonio Crespo, J Hernandez, and Sten Frandsen. Survey of modelling methods for wind turbine wakes and wind farms. *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*, 2(1):1–24, 1999.
- [39] Hubert I Flomenhoft. Brief History of Gust Models for Aircraft Design. *Journal of Aircraft*, 31(5):1225–1227, 1994.
- [40] Gino Perrotta and Anya R Jones. Unsteady Forcing on a Flat-Plate Wing in Large Transverse Gusts. *Experiments in Fluids*, 58(8), 2017.
- [41] Robbie J Stevens, Holger Babinsky, Field Manar, Peter Mancini, Anya R Jones, Kenneth O Granlund, Michael V Ol, Toshiyuki Nakata, Nathan Phillips, Richard Bomphrey, et al. Low reynolds number acceleration of flat plate wings at high incidence. In *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016. AIAA Paper 2016-0286.
- [42] AVT-202. Extensions of fundamental flow physics to practical mav aerodynamics. Technical Report TR-AVT-202, National Advisory Committee for Aeronautics, 2014.
- [43] Holger Babinsky, Robbie J Stevens, Anya R Jones, Luis P Bernal, and Michael V Ol. Low order modelling of lift forces for unsteady pitching and surging wings. In *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016. AIAA 2016-0290.
- [44] JC Hunsaker and Edward Bidwell Wilson. Report on behavior of aeroplanes in gusts. Technical Report TR-1, National Advisory Committee for Aeronautics, 1917.
- [45] Z Wu, Y Cao, and M Ismail. Gust loads on aircraft. *The Aeronautical Journal*, 123(1266):1216–1274, 2019.
- [46] Bernard Etkin. Turbulent Wind and Its Effect on Flight. *Journal of Aircraft*, 18(5):327–345, 1981.
- [47] JG Jones. Modelling of Gusts and Wind Shear for Aircraft Assessment and Certification. *Proceedings of the Indian Academy of Sciences (Engineering Sciences)*, 3(1):1–30, 1980.
- [48] Dynamic gust loads. Technical Report AC 25.341-1, Federal Aviation Administration, 2014.

- [49] J Fuller and J Fuller. Evolution and future development of airplane gust loads design requirements. In *1997 World Aviation Congress*, volume 32, page 5577, 1997.
- [50] Joseph A Drischler and Franklin W Diederich. Lift and moment responses to penetration of sharp-edged traveling gusts, with application to penetration of weak blast waves. Technical Report TN-396, National Advisory Committee for Aeronautics, 1957.
- [51] Zhenlong Wu, Qiang Wang, and Hao Huang. A methodological exploration for efficient prediction of airfoil response to gusts in wind engineering. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 233(6):738–750, 2019.
- [52] Joseph A Drischler and Franklin W Diederich. Preliminary study of applied load factors in bumpy air. Technical Report 374, National Advisory Committee for Aeronautics, 1931.
- [53] Kermit G Pratt. A revised formula for tm calculation of gust loads. Technical Report TN-2964, National Advisory Committee for Aeronautics, 1953.
- [54] JG Jones. Statistical Discrete Gust Theory for Aircraft Loads and Dynamic Response. *Journal of Aircraft*, 26(4), 1989.
- [55] Anya R Jones and Oksan Cetiner. Introduction to the virtual collection: Unsteady aerodynamic response of rigid wings in large-amplitude gust encounters. *AIAA journal*, 59(3), 2021.
- [56] Anya R Jones, Oksan Cetiner, and Marilyn J Smith. Physics and modeling of large flow disturbances: Discrete gust encounters for modern air vehicles. *Annual Review of Fluid Mechanics*, 54, 2021.
- [57] John David Anderson Jr. *Fundamentals of aerodynamics*. McGraw-Hill Education, 2010.
- [58] Gordon J Leishman. *Principles of Helicopter Aerodynamics*. Cambridge University Press, 2006.
- [59] Theodore Theodorsen and WH Mutchler. General theory of aerodynamic instability and the mechanism of flutter. NACA Technical Report 496, 1935.
- [60] Th H von Karman and William R Sears. Airfoil theory for non-uniform motion. *Journal of the Aeronautical Sciences*, 5(10):379–390, 1938.
- [61] HM Atassi. The sears problem for a lifting airfoil revisited-new results. *Journal of Fluid Mechanics*, 141:109–122, 1984.
- [62] J Mayo Greenberg. Airfoil in sinusoidal motion in a pulsating stream. NACA Technical Report 136, 1947.

- [63] Herbert Wagner. Über die entstehung des dynamischen auftriebes von tragflügeln. 5(1):17–35, 1924.
- [64] Herbert G Küssner. Zusammenfassender Bericht über den Instationären Auftrieb von Flügeln. *Luftfahrtforschung*, 13(12):410–424, 1936.
- [65] John W Miles. The aerodynamic force on an airfoil in a moving gust. *Journal of the Aeronautical Sciences*, 23(11):1044–1050, 1956.
- [66] W. T. Kelvin. On vortex motion. 1869.
- [67] Robert T Jones. The unsteady lift of a wing of finite aspect ratio. NACA Technical Report 681, 1940.
- [68] SJ Corkery, Holger Babinsky, and WR Graham. Quantification of added-mass effects using particle image velocimetry data for a translating and rotating flat plate. *Journal of Fluid Mechanics*, 870:492–518, 2019.
- [69] Ashley Holt Halfman Robert L. Bisplinghoff, Raymond L. *Aeroelasticity*. Addison–Wesley, 1955.
- [70] David R Williams and L Grimaud. Scaling Vehicle Dynamics and Fluid Dynamics in Gusting Flows. In *52nd Aerospace Sciences Meeting*, National Harbor, MD, 2014. AIAA Paper 2014-1456.
- [71] David Greenblatt. Unsteady Low-Speed Wind Tunnels. *AIAA Journal*, 54(6):1817–1830, 2016.
- [72] Kenneth Granlund, B Monnier, M Ol, and David R Williams. Airfoil Longitudinal Gust Response in Separated vs. Attached Flows. *Physics of Fluids*, 26(2), 2014.
- [73] Luke R Smith and Anya R Jones. Vortex formation on a pitching aerofoil at high surging amplitudes. *Journal of Fluid Mechanics*, 905, 2020.
- [74] Juhi Chowdhury, Cameron Smith, and Matthew J Ringuelette. The lift force produced by an unsteady translating plate with a rotating tip. *AIAA Journal*, Under Review.
- [75] Karen Mulleners, Peter Mancini, and Anya R Jones. Flow development on a flat-plate wing subjected to a streamwise acceleration. *AIAA Journal*, 55(6):2118–2122, 2017.
- [76] Xiaowei He and David R Williams. Unsteady aerodynamic loads on an airfoil at high angle of attack in a randomly surging flow. *AIAA Journal*, Under Review.
- [77] Philip B Kirk and Anya R Jones. Vortex formation on surging aerofoils with application to reverse flow modelling. *Journal of Fluid Mechanics*, 859:59–88, 2019.

- [78] Arnold Kuethe. Circulation measurements about the tip of an airfoil during flight through a gust. NACA Technical Report TN-685, 1939.
- [79] DW Holmes. Lift and measurements in an aerofoil in unsteady flow. In *ASME International Gas Turbine Conference and Products Show*, volume 79801. American Society of Mechanical Engineers, 1973.
- [80] Hülya Biler, Camli Badrya, and Anya R Jones. Experimental and computational investigation of transverse gust encounters. *AIAA Journal*, 57(1):4608–4622, 2019.
- [81] SJ Corkery, Holger Babinsky, and JK Harvey. On the development and early observations from a towing tank-based transverse wing-gust encounter test rig. *Experiments in Fluids*, 59(9):135, 2018.
- [82] Nelson H Kemp. The unsteady forces due to viscous wakes in turbomachines. *Journal of the Aeronautical Sciences*, 22(7):478–483, 1955.
- [83] T Von Karman and Sears W R. Airfoil Theory for Non-Uniform Motion. *Journal of the Aeronautical Sciences*, 5(10):379–390, 1938.
- [84] Simon James Corkery. *Unsteady aerodynamics of wing-gust encounters*. PhD thesis, University of Cambridge, 2019.
- [85] Camli Badrya, Hülya Biler, Anya R Jones, and James D Baeder. Effect of gust width on flat-plate response in large transverse gust. *AIAA Journal*, 59(1):49–64, 2021.
- [86] Camli Badrya, Hülya Biler, Anya R. Jones, and James D Baeder. The effect of gust width on flat-plate response in large transverse gust at low reynolds number. *AIAA Journal*, 59(1):49–64, 2021.
- [87] Alex Moushegian and Marilyn J Smith. Analysis of a wing moving through a nonlinear gust. In *AIAA SciTech 2019 Forum*, San Diego, CA, 2019. AIAA Paper 2019-0637.
- [88] Amanda L Grubb, Alex Moushegian, Daniel J Heathcote, and Marilyn J Smith. Physics and computational modeling of nonlinear transverse gust encounters. In *AIAA SciTech 2020 Forum*, Orlando, FL, 2020. AIAA Paper 2020-0080.
- [89] Kader Engin, Egemen Aydın, Berk Zaloglu, Idil Fenercioglu, and Oksan Cetiner. Large scale spanwise periodic vortex gusts or single spanwise vortex impinging on a rectangular wing. In *AIAA Aviation Forum*, Atlanta, GA, 2018. AIAA Paper 2018-3086.
- [90] Hülya Biler, Girguis Sedky, Anya R Jones, Murat Saritas, and Oksan Cetiner. Experimental investigation of transverse and vortex gust encounters at low reynolds numbers. *AIAA Journal*, 59(3):786–799, 2021.

- [91] Esteban AL Hufstedler and Beverley J McKeon. Vortical gusts: experimental generation and interaction with wing. *AIAA Journal*, 57(3):921–931, 2019.
- [92] Di Peng and James W Gregory. Vortex dynamics during blade-vortex interactions. *Physics of Fluids*, 27(5):053104, 2015.
- [93] Albert Medina, Arun V Babu, Matthew Rockwood, Ashok Gopalarathnam, and Anwar Ahmed. Theoretical and experimental study of wake encounters on unsteady airfoils. In *AIAA SciTech 2019 Forum*, San Diego, CA, 2019. AIAA Paper 2019-0898.
- [94] David Fabre, Denis Sipp, and Laurent Jacquin. Kelvin waves and the singular modes of the lamb-oseen vortex. *Journal of Fluid Mechanics*, 551:235–274, 2006.
- [95] Matthew Rockwood and Albert Medina. Controlled generation of periodic vortical gusts by the rotational oscillation of a circular cylinder and attached plate. *Experiments in fluids*, 61(2):1–13, 2020.
- [96] Vladimir Golubev, Timothy Hollenshade, Lap Nguyen, and Miguel Visbal. High-accuracy low-re simulations of airfoil-gust and airfoil-vortex interactions. In *40th Fluid Dynamics Conference and Exhibit*, Chicago, IL, 2010. AIAA Paper 2010-4868.
- [97] Vladimir Golubev, Timothy Hollenshade, Lap Nguyen, and Miguel Visbal. Parametric viscous analysis of gust interaction with sd7003 airfoil. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, Orlando, FL, 2010. AIAA Paper 2010-928.
- [98] Vladimir V Golubev and Miguel R Visbal. Modeling mav response in gusty urban environment. *International Journal of Micro Air Vehicles*, 4(1):79–92, 2012.
- [99] Lap Nguyen, Vladimir V Golubev, and Miguel R Visbal. Numerical study of transitional sd7003 airfoil interacting with canonical upstream flow disturbances. *AIAA Journal*, 56(1):158–181, 2018.
- [100] Caleb J Barnes and Miguel R Visbal. Effects of vertical position and orientation on a vortical-gust/airfoil interaction at a transitional reynolds number. In *47th AIAA Fluid Dynamics Conference*, Denver, CO, 2017. AIAA Paper 2017-3320.
- [101] Gino M Perrotta and Anya R Jones. Transient aerodynamics of large transverse gusts and geometrically similar maneuvers. In *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016. AIAA Paper 2016-2074.
- [102] Gino Perrotta and Anya R Jones. Quasi-steady approximation of forces on flat plate due to large-amplitude plunging maneuvers. *AIAA Journal*, 56(11):4232–4242, 2018.

- [103] Jordan M Leung, Jaime G Wong, Gabriel D Weymouth, and David E Rival. Modeling transverse gusts using pitching, plunging, and surging airfoil motions. *AIAA Journal*, 56(8):3271–3278, 2018.
- [104] Ignacio Andreu Angulo and Holger Babinsky. Negating gust effects by actively pitching a wing. *AIAA Journal*, Under Review.
- [105] Hülya Biler, Anya R Jones, Murat Saritas, Idil Fenercioglu, Nuriye L Cetiner Yildirim, and Murat Bronz. Investigation of force transients during transverse and vortex gust encounters. In *AIAA Scitech 2019 Forum*, San Diego, CA, 2019. AIAA Paper 2019-0636.
- [106] Girguis Sedky, Francis D. Lagor, and Anya Jones. Unsteady aerodynamics of lift regulation during a transverse gust encounter. *sedky2020unsteady*, 5, 2020.
- [107] Girguis Sedky, Anya R Jones, and Francis D Lagor. Lift regulation during transverse gust encounters using a modified goman–khrabrov model. *AIAA Journal*, 58(9):1–11, 2020.
- [108] Markus Raffel, Christian E Willert, Fulvio Scarano, Christian J Kähler, Steve T Wereley, and Jürgen Kompenhans. *Particle image velocimetry: a practical guide*. Springer, third edition, 2018.
- [109] Alexander J Smits. *Flow visualization: techniques and examples*. World Scientific, second edition, 2012.
- [110] FO Thomas and KMK Prakash. An experimental investigation of the natural transition of an untuned planar jet. *Physics of Fluids A: Fluid Dynamics*, 3(1):90–105, 1991.
- [111] FO Thomas and VW Goldschmidt. Structural characteristics of a developing turbulent planar jet. *Journal of Fluid Mechanics*, 163:227–256, 1986.
- [112] Field Hogan Manar. *Measurements and modeling of the unsteady flow around a thin wing*. PhD thesis, University of Maryland, College Park, 2018.
- [113] Gino M Perrotta. *Unsteady force production on a flat plate wing by large transverse gusts and plunging maneuvers*. PhD thesis, University of Maryland, College Park, 2017.
- [114] Ignacio Andreu-Angulo, Holger Babinsky, Hülya Biler, Girguis Sedky, and Anya R Jones. Effect of transverse gust velocity profiles. *AIAA Journal*, 58(12):5123–5133, 2020.
- [115] V. K. Lakshminarayan and J. D. Baeder. Computational Investigation of Micro Hovering Rotor Aerodynamics. *Journal of the American Helicopter Society*, 55(1):14–29, 2010.

- [116] Camli Badrya, Ananth Sridharan, James D Baeder, and Christopher M Kroninger. Multi-Fidelity Coupled Trim Analysis of a Flapping-Wing Micro Air Vehicle Flight. *Journal of Aircraft*, 54(5):1614–1630, sep 2017.
- [117] Rajneesh Singh and James D Baeder. Direct Calculation of Three-Dimensional Indicial Lift Response Using Computational Fluid Dynamics. *Journal of Aircraft*, 34(4):465–471, 1997.
- [118] Jayanarayanan Sitaraman and James D Baeder. Field Velocity Approach and Geometric Conservation Law for Unsteady Flow Simulations. *AIAA Journal*, 44(9):2084–2094, 2006.
- [119] C Wales, D Jones, and A Gaitonde. Prescribed Velocity Method for Simulation of Aerofoil Gust Responses. *Journal of Aircraft*, 52(1):64–76, 2014.
- [120] Kunihiro Taira and TIM Colonius. Three-dimensional flows around low-aspect-ratio flat-plate wings at low reynolds numbers. *Journal of Fluid Mechanics*, 623:187–207, 2009.
- [121] HB Helmbold. Der unverwundene ellipsenflügel als tragende fläche. *Jahrbuch 1942 der Deutch Luftfanrtforsch*, pages 111–113, 1942.