Chapter

Utilization of Dynamic and Static Sensors for Monitoring Infrastructures

Chung C. Fu, Yifan Zhu and Kuang-Yuan Hou

Abstract

Infrastructures, including bridges, tunnels, sewers, and telecommunications, may be exposed to environmental-induced or traffic-induced deformation and vibrations. Some infrastructures, such as bridges and roadside upright structures, may be sensitive to vibration and displacement where several different types of dynamic and static sensors may be used for their measurement of sensitivity to environmental-induced loads, like wind and earthquake, and traffic-induced loads, such as passing trucks. Remote sensing involves either in situ, on-site, or airborne sensing where in situ sensors, such as strain gauges, displacement transducers, velometers, and accelerometers, are considered conventional but more durable and reliable. With data collected by accelerometers, time histories may be obtained, transformed, and then analyzed to determine their modal frequencies and shapes, while with displacement and strain transducers, structural deflections and internal stress distribution may be measured, respectively. Field tests can be used to characterize the dynamic and static properties of the infrastructures and may be further used to show their changes due to damage. Additionally, representative field applications on bridge dynamic testing, seismology, and earthborn/construction vibration are explained. Sensor data can be analyzed to establish the trend and ensure optimal structural health. At the end, five case studies on bridges and industry facilities are demonstrated in this chapter.

Keywords: health monitoring, accelerometers, velometers, displacement transducers, strain sensors, frequency response function, cross-power spectrum, power spectral density, bridge dynamic testing, seismology, earthborn/construction vibration, infrastructure

1. Introduction

In order to acquire infrastructural health data, proper sensor knowledge and technology are required. This article first introduces in situ remote sensing and then provides a review of some sensors that are useful and currently implemented in health monitoring projects, especially those associated with vibration.

A project on the development of a self-sustained wireless integrated structural health monitoring (ISHM) system for highway bridges was sponsored by the USDOT Research and Innovative Technology Administration (RITA) [1]. **Figure 1** shows the wireless ISHM system with remote sensing ability: (1) wireless sensor nodes including AE sensors, strain gages, accelerometers, thermocouples, etc.; (2) wireless smart sensor network with (3) energy harvester; (4) data acquisition system (DAQ), with wireless communication modem; and (5) web-based remote data processing and data storage for application.

In situ sensors may include the capability to collect static and dynamic data and then apply algorithm to extract and combine relevant condition information from sensor data. Typical vibrational sensors used include accelerometers and velometers (velocity transducers), while static sensors include displacement transducers, strain gauges (transducers), tilt meters, and weather-related sensors to measure and record temperature, humidity, barometric pressure, wind velocity, wind direction, etc. When using vibration data, especially in conjunction with modeling systems, the data is often measured in the form of acceleration, velocity, and displacement. Sometimes different analyses require measured signals in different forms. Even if we measure in the form of acceleration, velocity, or displacement (**Figure 2**), we may apply simple mathematics to convert between them through integration or differentiation. For instance, if the measured signal is from accelerometers, we may obtain the velocity through integration and displacement through double integration. On the other hand, if the measured signal is from velocity or displacement

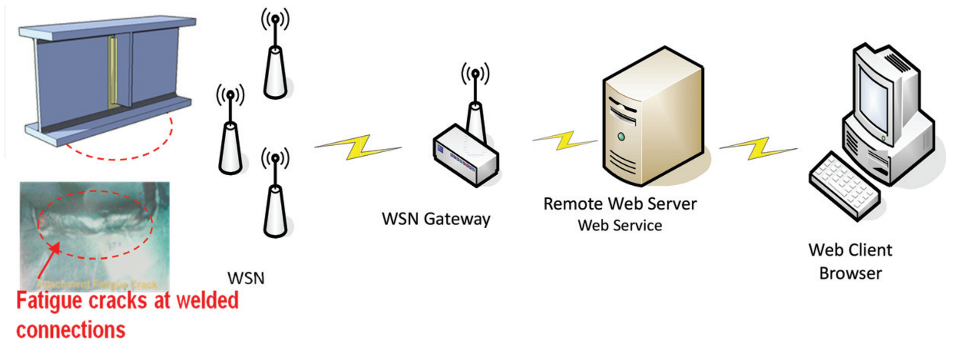

Figure 1.
Remote wireless bridge monitoring system.

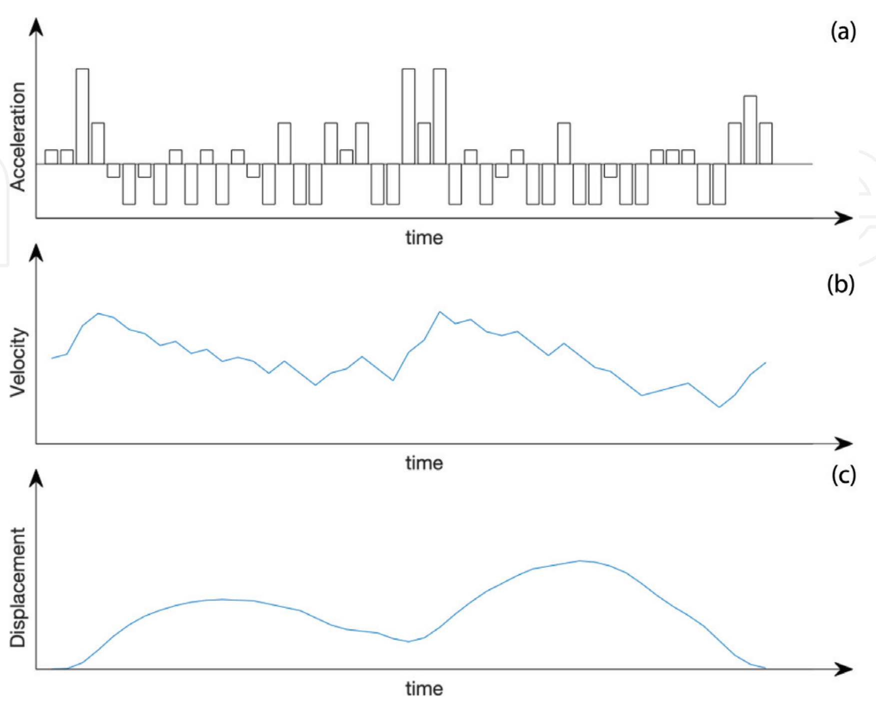

Figure 2.
Measured signals in different forms: (a) acceleration (raw data), (b) velocity (single integration from acceleration), and (c) displacement (double integration from acceleration).

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transducers, we may obtain acceleration through differentiation or double differentiation, respectively. Usually, unless there are special circumstances, the suggested method to measure vibration is with an accelerometer. However, care is required to remove accelerations of very low frequencies for possible noises if any integration to velocity or displacement is needed.

Accelerometers and strain sensors are widely used dynamic and static monitoring sensors. The modern-day systems are small, lightweight, and robust and are typically quite simple to calibrate and to convert output to acceleration or strain data. Accelerometers are useful for measuring with low to very high sampling rates. They have shown to be useful in a wide variety of applications. On the other hand, velocity sensors are generally used to measure dynamic response in the low- to medium-range frequencies. They are typically used for similar applications as accelerometers [2].

For the static monitoring sensor, displacement transducers are used to measure relative displacement. These sensors are available in both contacting devices, like string pot and linear variable differential transformer (LVDT), and non-contacting devices, like laser displacement, global positioning systems (GPS), and photogrammetry. The major limitation for contacting displacement-measuring devices in the field is that the measured displacement is a relative displacement. GPS-type sensors are gradually more often used in civil engineering studies because of recent developments allowing measurements to be taken at high fidelity. Displacement measurements from laser sensors, ultrasonic distance sensors, and strain pot were used on different occasions to determine the vertical deflection of a bridge. These techniques are useful because they can result in relative and absolute displacement states. Strain sensors, including optical fiber strain, can be monitored at dynamic rates, while traditional foil strain gauges have been widely used on civil engineering structures, even in remote sensing.

2. Mathematical models for computing accelerometer sensor data

The data acquisition system may be set to measure acceleration time histories and calculate frequency response function (FRF), cross-power spectrum (CPS), and power spectral density (PSD) [3].

For a continuous time series, $x(t)$, defined on the interval from 0 to T, the Fourier spectrum (Fourier transform), $X(f)$, is defined in Eq. (1) as

$$X(f) = \int_0^T x(t)e^{-i2\pi ft}dt \tag{1}$$

where $i = \sqrt{-1}$ and $f = cyclic\ frequency(Hz)$.

This function is complex, and the magnitude is typically plotted in engineering units (EU), such as m/s^2 or g's, versus frequency.

This power spectrum is defined in Eq. (2) as

$$|X(f)|^2 = X(f)X(f) \tag{2}$$

where * denotes a complex conjugate. The power spectrum is a real-valued frequency domain function and has the units of $(EU)^2$.

The power spectral density (auto-spectral density, or abbreviated as PSD), $G_{XX}(f)$, is defined in Eq. (3) as

$$G_{XX}(f) = \frac{2}{T} E\left[(X(f))^2\right] \tag{3}$$

where $E[n]$ indicates an ensemble average for a specific t over n samples of $X(f)$. This PSD is a real-valued frequency domain function and has the units of EU^2/Hz.

The cross-power spectrum (cross-spectrum density, or abbreviated as CPS), $G_{XY}(f)$, relating two time histories, $x(t)$ and $y(t)$, is defined in Eq. (3) as

$$G_{XY}(f) = \frac{2}{T} E[X(f)Y(f)] \tag{4}$$

For a linear system, the frequency response function (transfer function, or abbreviated as FRF), $H(f)$, which relates an input $X(f)$ to a response $Y(f)$, is defined in Eq. (5) as

$$H(f) = \frac{Y(f)}{X(f)} = \frac{G_{XY}(f)}{G_{XX}(f)} \tag{5}$$

In actual dynamic testing, discrete time series are measured. Refer to Bendal and Piersol [4] for the discrete representations on the functions listed in Eqs. (1)–(5).

There are several factors that would affect system-level measurement accuracy, which are (1) sensitivity error and initial absolute offset, (2) nonlinearity of the data, (3) total offset variation from initial absolute offset, and (4) noise. To improve the accuracy, two- or three-point calibrations recommended by manufacturers may be needed.

The output spectrum (measured with accelerometers) can be assumed to be linearly related to the input spectrum through the FRF, which contains both resonant frequency and damping information of the vibrating system. Resonant frequencies can be determined from peaks in the output spectrum, and damping values can be determined by the half-power bandwidth (HPBW) method.

The damping ratio, or damping coefficient, ξ, is defined as $c/c_c = c/2\sqrt{km}$ to be used in the dynamic analysis. Normally, steel bridges have a low damping coefficient $\xi \leq 0.02$. The half-power (bandwidth) method is the most commonly used experimental method [5] to determine the damping in the structure by using two frequencies shown in **Figure 3** and Eq. (6):

$$\xi = \frac{f_2 - f_1}{f_2 + f_1} \tag{6}$$

Mathematically the most common and easy way is to use the Rayleigh damping method with a linear combination of the mass and the stiffness matrices as Eq. (7):

$$c = a_0 m - a_1 k \tag{7}$$

where c, m, and k are the damping, the mass, and the stiffness matrices, respectively, a_0 and a_1 are proportional constants, and c_c represents the critical damping coefficient. The relationship between the damping ratio and the frequency for Rayleigh damping is shown in **Figure 4**. By simplification, these lead to Eq. (8):

$$\begin{Bmatrix} a_0 \\ a_1 \end{Bmatrix} = \frac{2\xi}{\omega_n + \omega_m} \begin{Bmatrix} \omega_n \omega_m \\ 1 \end{Bmatrix} \tag{8}$$

The CPS plot between the signals from two accelerometers can then be used to determine the vibration mode shape information based on the relative phase of

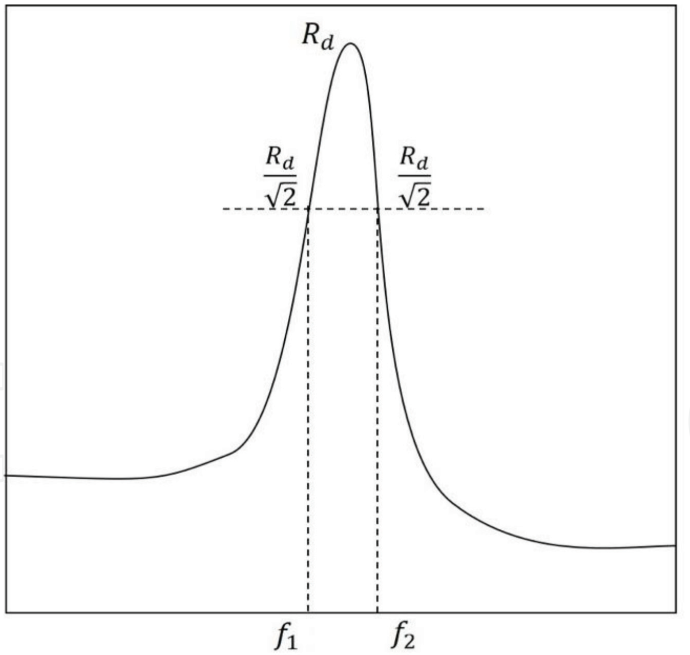

Figure 3.
Half-power method to estimate damping by experiment.

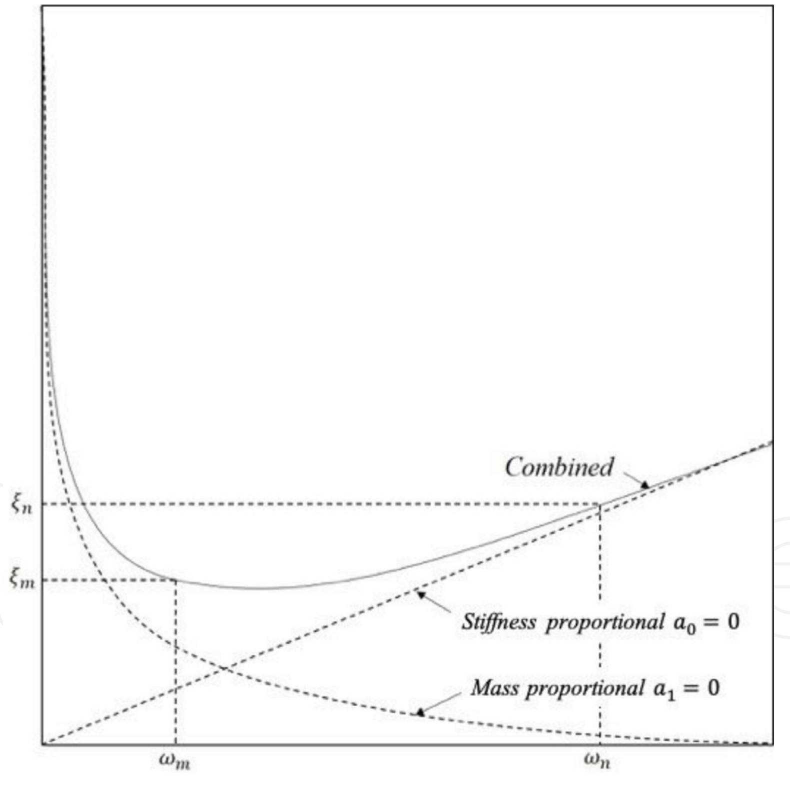

Figure 4.
Relationship between damping ratio and frequency for Rayleigh damping.

the two signals. One signal is termed the reference signal, and the process is repeated at various stations on the bridge to map out the mode shapes. Typically, in vibration testing FRFs are used to estimate the dynamic properties of a structure. Further interpreted from the CPS, it can be seen that two measured responses are correlated only at the resonant frequencies of the structure. Therefore, the CPS will show peaks corresponding to the resonant frequency which shows another method estimating the resonant frequencies from peaks in the response power spectra. Mode shapes are estimated from the relative magnitudes of these peaks, where relative phase information can be obtained from either the CPS or FRF and modal damping values can be obtained by applying the HPBW method to these peaks, which need very-high-frequency resolution to obtain the values. Mode shapes can be determined from cross-power spectra of the various accelerometer readings relative to the reference accelerometer [3]. Examples of field dynamic applications are shown in the next sections.

3. Representative applications

3.1 Bridge dynamic testing

Dynamic testing on bridges has been conducted for many years. Measured data were usually in the form of deflections and strains, but some measurements were in acceleration. For bridge dynamic testing, ambient and forced vibrations can be performed.

- Ambient vibration testing—Ambient vibrations in bridges can be induced by a wide variety of environmental factors, such as traffic, seismic, and wind loading.

- Forced vibration testing—Some techniques of forced vibration testing of bridges such as variable frequency rotating dynamic shaker, servo-hydraulic inertial actuators, impact hammer, and controlled truck loading can be applied. Accelerometers can be used to determine the resonant frequencies, damping ratios, and mode shapes.

By using accelerometers, acceleration time histories can be obtained, transformed into Fourier spectra and CPS, and then analyzed to determine damping, resonant frequencies, and corresponding modal shapes.

3.2 Seismology

Devices can be used to measure seismic data. Two types of sensors (transducers) were used by Caltrans to measure seismic record [6].

- Seismometer—A seismometer, also called a velocity transducer, measures velocity directly using a signal conditioner. It measures low frequencies of ground motions (usually 1–200 Hz) and produces a voltage proportional to velocity through magnetic induction. A seismometer can catch low rate vibrations during monitoring.

- Accelerometer—An accelerometer measures acceleration directly by using the piezoelectric crystal material. This type of sensor, which is widely used by Caltrans, is pressure sensitive and can also obtain velocity and displacement with an integrator. Accelerometer is usually a small sensor with a wide frequency range, and typically not as sensitive as the seismometer. The frequency range could be narrowed from 0.1 to 1.0 KHz when using as large sensor as around 1 pound in weight and more sensitive technical methods, typically from 1.0 to several KHz.

3.3 Earthborn/construction vibration

Humans have varying sensitivities to vibrations at different frequencies. In general, humans are more sensitive to low-frequency vibration. Construction activities could induce vibrations that caused building surface movements, shaking or rattling of windows, hanging items, and lightweight furniture [7]. This type of low-frequency vibrations, when acting on the structural component, can also produce an audible rumbling noise, which referred to earthborn noise. The noise could be a problem when the upper end of the range frequencies (60–200 Hz) dominates the originating vibration spectrum, or the construction activities are connected to the structure by foundations or utilities.

Earthborn vibrations can be detected and measured by accelerometers which could be mounted to heavy blocks of steel (about 5–10 kg) directly placed directly on the ground or other surfaces by magnets [6, 8]. Activities and motions of the vibration-sensitive land shall be monitored and measured during constructions occur within 15 m (50 ft) to establish the level of vibrations. Construction projects of foundations, like pile driving, jackhammering, and soil compacting, may also produce high-level vibrations by their equipment operations. Measured vibration data from construction are commonly classified as broadband or random vibrations with various ranges of frequencies. The general frequency ranges of most earthborn vibrations are from less than 1.0 to 200 Hz.

Vibration levels can be represented in terms of velocity (in/sec or mm/sec) or acceleration (in/sec^2 or mm/sec^2), which demonstrates vibration severity. Vibration levels for construction activities are recognized as the highest during demolition activities and soil compacting. Vibration levels are required to remain below 0.5 in/sec (15 mm/sec) at residences along the project corridor and minimized risk for structural damage. Vibration levels from other general construction activities will also be well below the 0.5 in/sec (15 mm/sec) criteria.

The US Department of Transportation (USDOT) has guidelines for vibration levels from construction related to their activities and recommends that the maximum peak-particle-velocity levels remain below 0.05 in/sec (1.5 mm/sec) at the nearest structures. Vibration levels above 0.5 in/sec (1.5 mm/sec) have the potential to cause architectural damage to normal dwellings. The USDOT also states that vibration levels above 0.015 in/sec (0.45 mm/sec) are sometimes perceptible to people and the level at which vibration becomes annoying to people is 0.64 in/sec (19.2 mm/sec).

3.4 Types of accelerometers and their advantages/disadvantages

Popular types of accelerometers used in the infrastructural areas are (1) bulk micromachined capacitive, (2) bulk micromachined piezoelectric resistive, (3) capacitive spring-mass system based, and (4) laser accelerometers [9].

The work principles of different types of accelerometers are based on piezoelectric effect due to accelerative forces and displacement sensing based on displacement of mass. The advantages of piezoelectric resistive are (1) rugged and inexpensive, (2) high impedance, (3) high sensitivity, and (4) high-frequency response. However, their disadvantages are (1) sensitive to temperature, (2) hysteresis error, (3) less longevity, and (4) decreased efficiency with time.

On the other hand, displacement sensing or seismic-type accelerometers are using spring-mass-damper system, and their advantages are (1) easy calculation, (2) simple and reliable, and (3) durable and efficient. Their disadvantages are (1) spring system not always accurate and (2) fluctuation in mass leading to wrong calculation.

4. Case study 1: Wireless accelerometer sensing of a self-sustained wireless integrated structural health monitoring (ISHM) system on Beaufort #25 bridge, NC

A scalable integral structural health monitoring (ISHM) system sponsored by the USDOT had been developed by the University of Maryland (UMD) and North Carolina State University (NCSU) with the URS (later named AECOM) Corporation [1]. This system, with remote sensing capability, is designed to be suited for fatigue condition assessment of highway steel bridges. Furthermore, the ISHM system would help in damage detection and deterioration diagnosis in early stages, predicting the remaining service life more accurately when compared with the traditional SHM system with reliable technology to improve current inspection methods, and reduce the operating and maintenance costs.

The ISHM system based on wireless sensor networks entails a few recent innovations which applied the current state of the practice in remote sensing and highway infrastructure management. Accelerometers, in this system, are used for monitoring the vibration response of bridges so that the modal frequency information could be obtained and used to calibrate the finite element model of the monitored bridge.

In this system, a new wireless piezoelectric sensor board had been designed and used. This board mainly consists of an 8-bit microcontroller, a FPGA, and a piezoelectric amplifier circuit. This device is enhanced with improved operating frequency and a four-wire, SPI-compatible interface while having lower power consumption. In the ISHM system, each single wireless sensor was tested on a shaker to verify that the developed sensor can recover the input information accurately. However, a single sensor could not catch enough data for structure monitoring and analysis. Thus, a number of wireless sensors along the bridge span are needed [1].

The example for the ISHM accelerometer monitoring case is the Structure No. 060025 Swing Bridge in Beaufort County, North Carolina (**Figure 5**, Beaufort #25 Bridge). The bridge consists of side spans and main spans. It should be noted that the structural support of the side span is a simply supported steel girder bridge, which has a relatively simple stress state compared with the main span because the

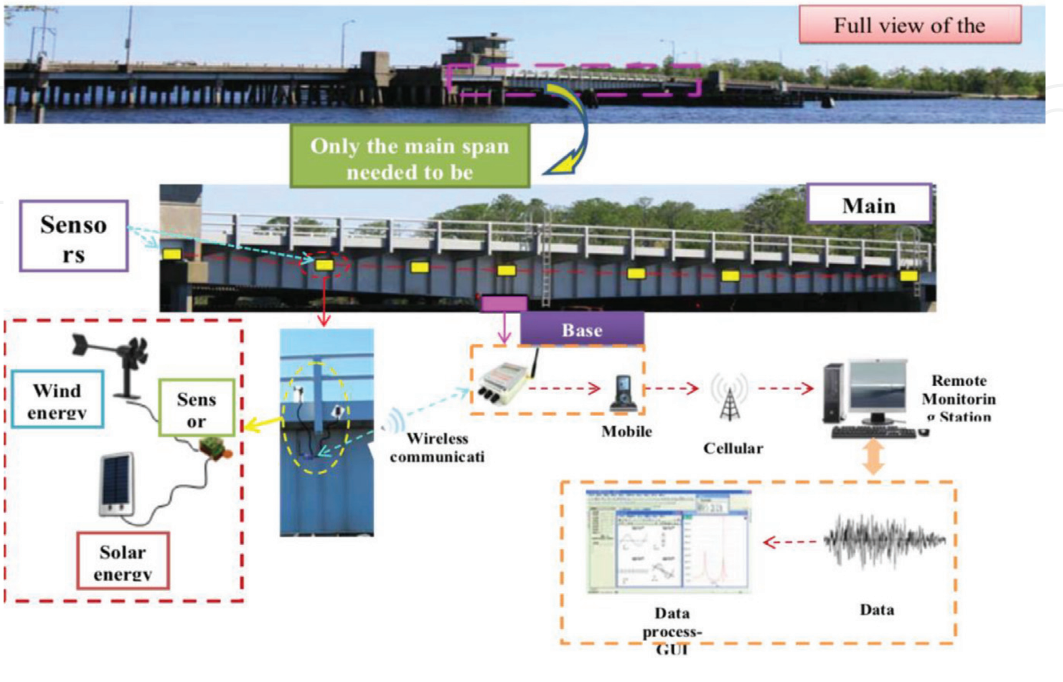

Figure 5.
Sketch plan for monitoring system.

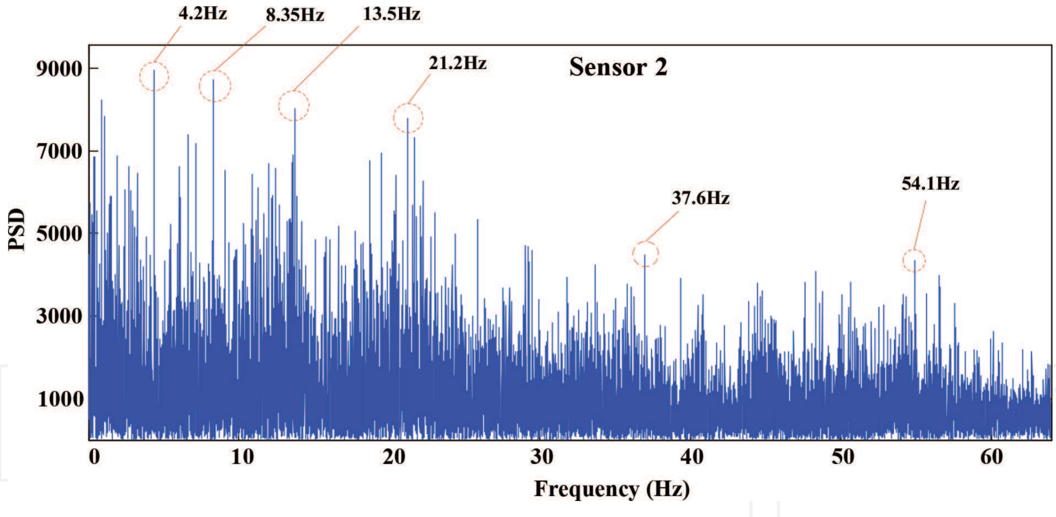

Figure 6.
The result of the field test of Beaufort #25 bridge.

boundary condition of the main span is changed between simply supported and cantilever due to the close or open of the main span. Thus, the researchers of NCSU chose the main span as the targeted monitoring case for the dynamic behavior considering the complex stress states.

In this case, a row of smart sensors was attached to the bridge girders in the main span. The dynamic behavior was analyzed by data from accelerometers. **Figure 6**

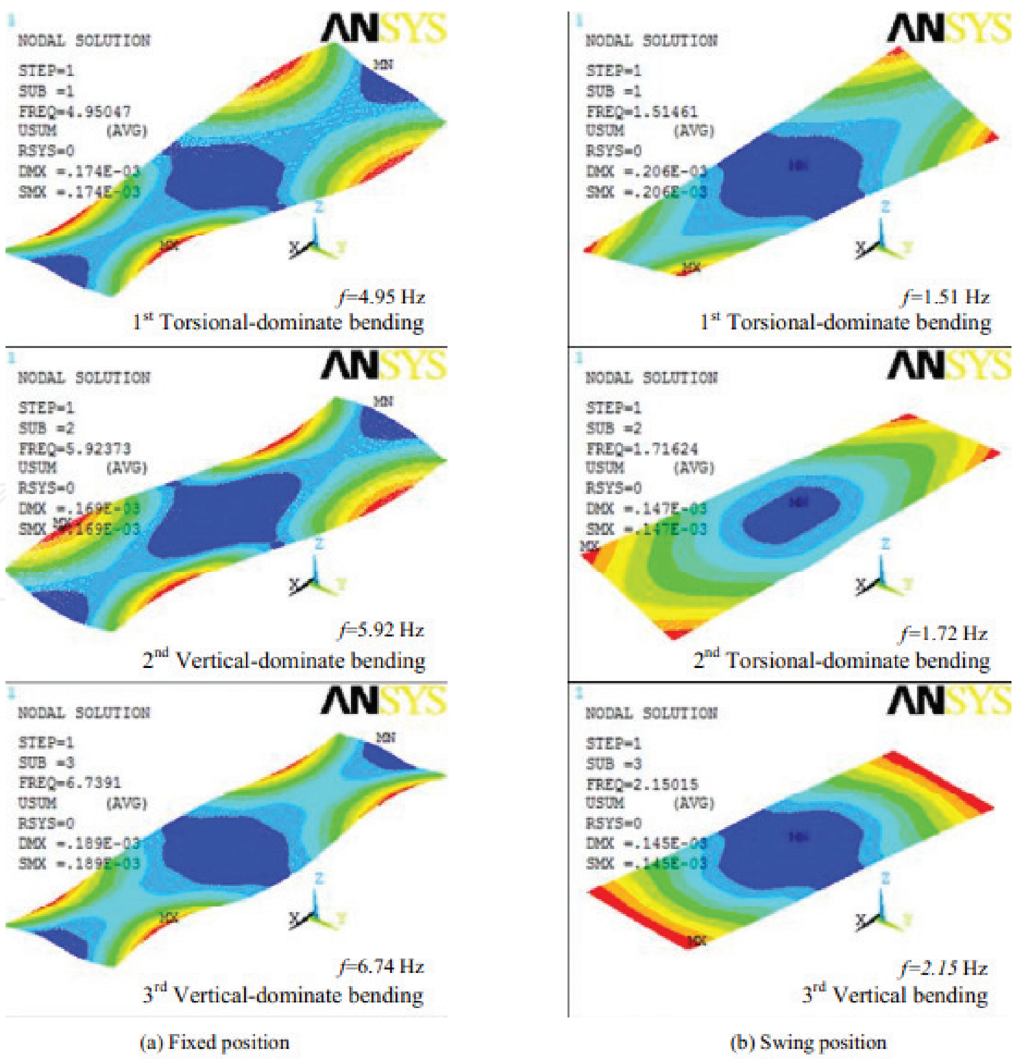

Figure 7.
The first three mode shapes from FE analysis.

Fixed position		**Swing position**	
First (torsional)	4.95 Hz	First (torsional)	1.51 Hz
Second (vertical)	5.92 Hz	Second (torsional)	1.72 Hz
Third (vertical)	6.74 Hz	Third (vertical)	2.15 Hz
Fourth (vertical)	7.48 Hz	Fourth (vertical)	2.51 Hz
Fifth (lateral)	8.18 Hz	Fifth (vertical)	2.58 Hz

Table 1.
Modal analysis results.

shows the test results of the bridge by using the set of wireless sensors. The data is processed using fast Fourier transform (FFT). The estimation of the natural frequency of the bridge about 4.0 Hz to 5.0 Hz was made by the NCSU researchers.

Meanwhile, the finite element model using the software ANSYS of Beaufort #25 Bridge was built and analyzed. The structural analysis was separated into two conditions due to the fact that the main span could swing. The first three mode shapes are illustrated in **Figure** 7, and the first five modes are summarized in **Table 1**. Depending on the relative amplitude of the mode shapes, these modes were noted as the vertical-dominated modes, the lateral-dominated modes, and the torsional-dominated modes (**Figure** 7).

The accelerometers are commonly used in highway bridges' monitoring for dynamic behavior. The monitoring results for the bridge are close to the finite element analysis result, and thus, the model was calibrated to be analyzed for other load conditions, and the test results were archived to be the baseline for future monitoring.

5. Case study 2: Remote monitoring of a self-sustained wireless integrated structural health monitoring (ISHM) system for highway bridges on I-270 bridge in MD

The second case study is under the same ISHM project [1] and was conducted by the University of Maryland at College Park. The types of sensors used in this project were (1) piezoelectric paint AE sensors; (2) wireless accelerometers; (3) laser sensor; (4) ultrasonic distance sensors; (5) BDI strain transducers; and (6) string pots.

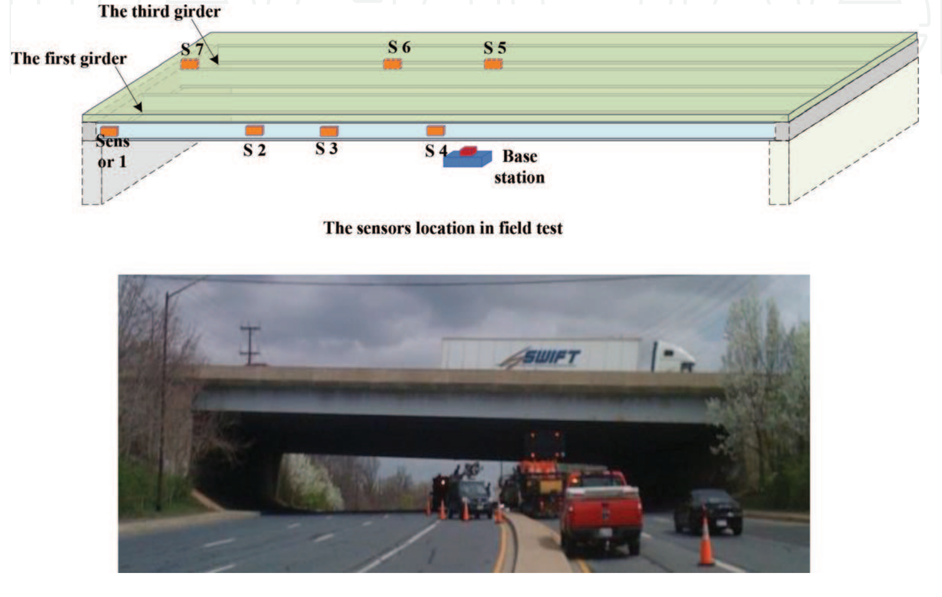

Figure 8.
Sensor locations.

In order to verify the reliability of the whole system, a field test for I-270 Bridge in Maryland by using this ISHM system was carried out with the accelerometer sensor locations shown in **Figure 8**. **Figures 9** and **10** show the test results collected by these wireless sensors.

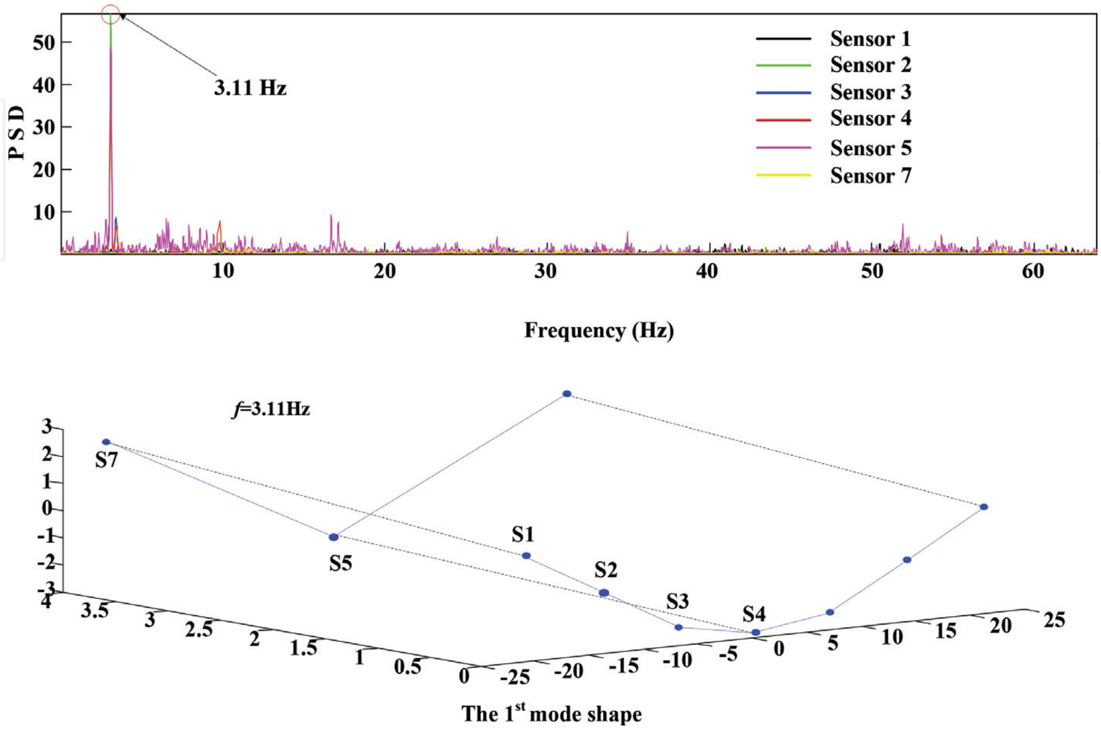

Figure 9.
PSD of these sensors and the first mode shape of the bridge.

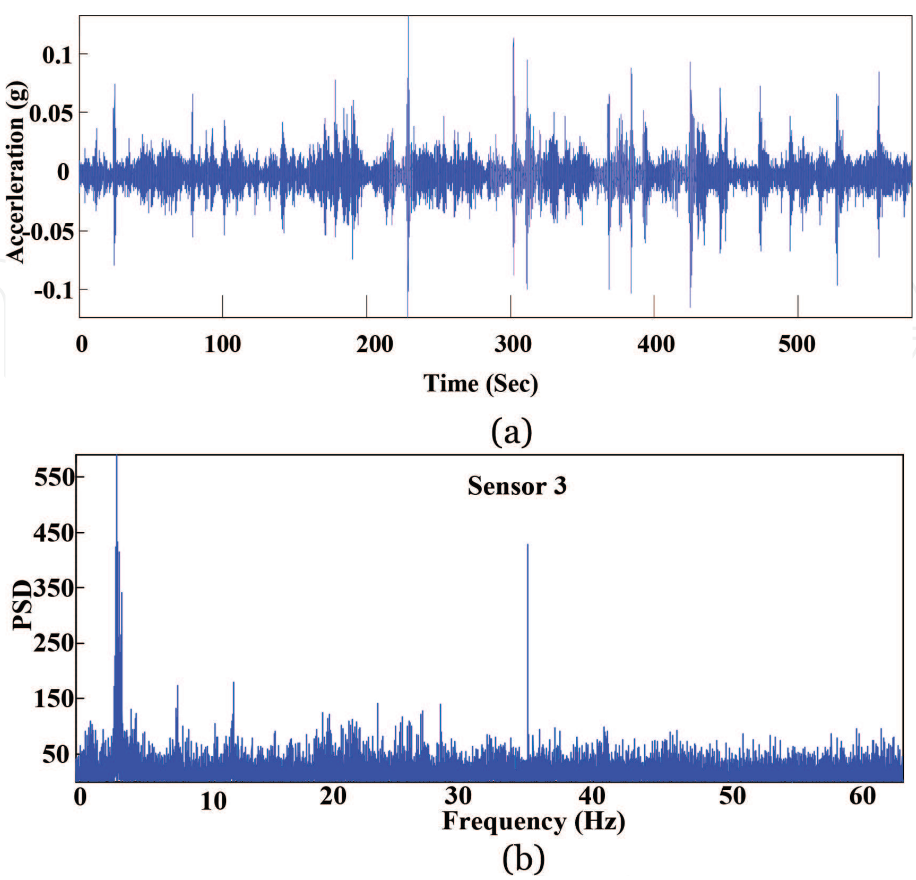

Figure 10.
The results of field test of I-270 bridge, MD: (a) the time-history data of sensor 3 and (b) the PSD of sensor 3.

6. Case study 3: Wireless structural monitoring of a newly replaced fiber-reinforced plastic (FRP) bridge deck

The use of FRP-composite bridge decks is viewed as a potential long-term solution for the concrete deck deterioration problem. A pilot project sponsored by the Federal Highway Administration (FHWA), USA, was undertaken by the Maryland State Department of Transportation, partnered with the University of Maryland to rehabilitate a steel truss bridge (MD24 over Deer Creek in Harford County, Maryland) using lightweight FRP deck [10, 11]. The existing steel truss bridge (**Figure 11**), built in 1934, carries two lanes of traffic, provides 9.14 m (30 ft.) of clear roadway, and is 37.50 m (123 ft.) long with severe roadway skew (**Figure 12**). The FRP deck panels are placed perpendicular to the stringers and act as a continuous plate between the stringer supports.

Load tests and structural monitoring were conducted to obtain information regarding the performance of the structure. For a relatively new material like FRP, the use of load tests can prove the structure's capacity. Wireless structural monitoring system developed through a previous FHWA small business innovation research (SBIR) contract to Invocon, Inc. in Conroe, Texas, was used. The system includes a data acquisition and communication nodes (**Figure 13**) connected to strain gages that can acquire data in digital form and relay the

Figure 11.
Steel truss bridge on MD 24 over deer creek.

Figure 12.
Replacement of a FRP deck panel.

data to a local base receiver attached to a personal computer. In this load test, five boxes were linked in a "smart" network to control the data acquisition process. By using this system, the effort of instrumenting a bridge was reduced by more than half compared to hardwired systems. All CEA-06-250-UN350 uniaxial gages installed on the bridge are produced by the Measurements Group, Inc. As shown in **Figure 13**, strain gauges were strategically placed at different locations to measure strains due to live load effect. Three stringers, as shown in **Figure 13(a)**, were load tested to check the distribution of live load over the stringers. Strain gages (data sets 2–1, 2–2, and 2–3 in **Figure 13(b)**) were located on the top of bottom flanges in the middle of the span. Comparison of finite element results and test results shows that the percentage difference ranged between 1.47 and 9.43%. The purpose of this test is to prove the integrated composite action between the steel stringers and the new FRP panels [10, 11].

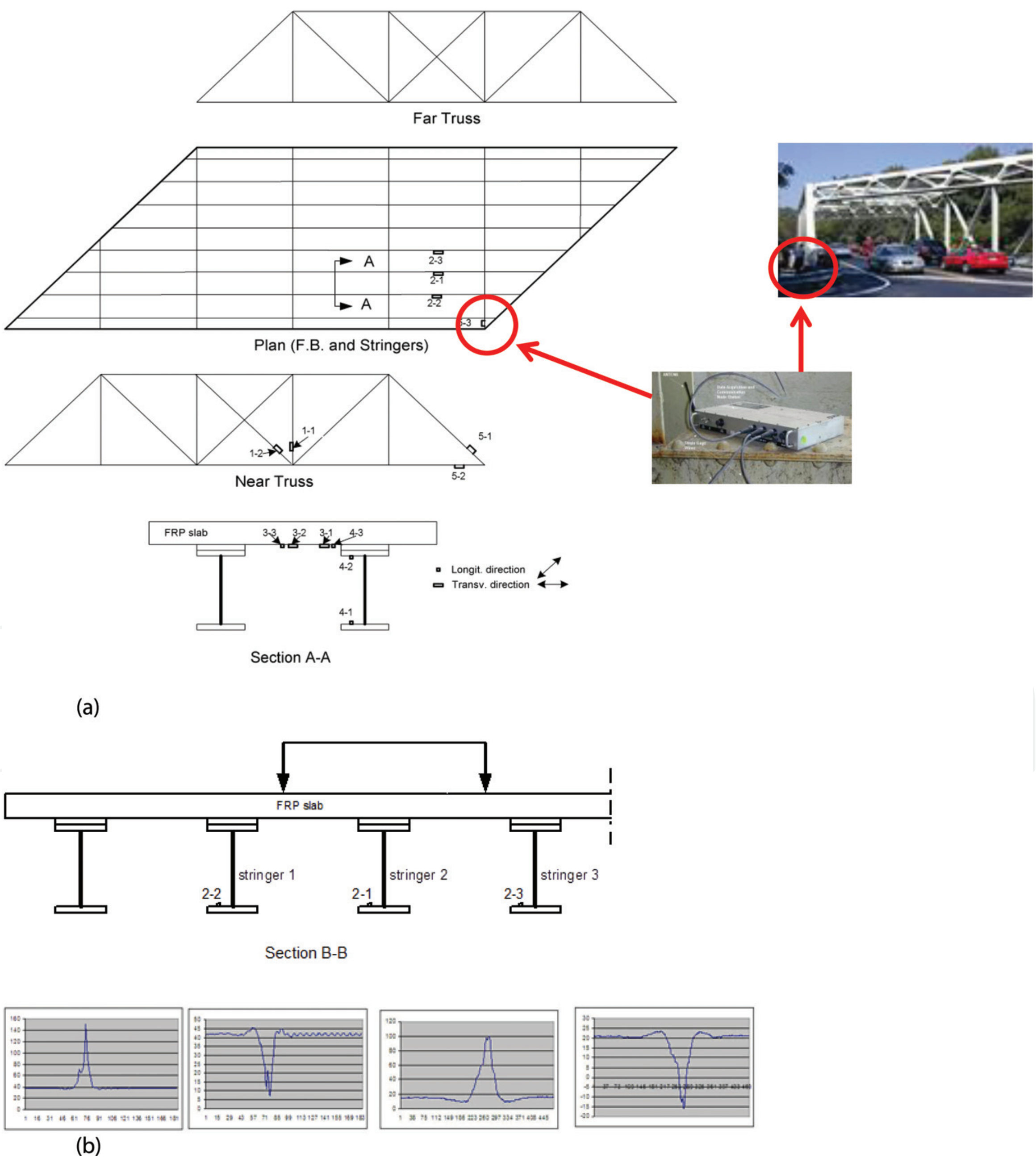

Figure 13.
Truss bridge deck, stringers, strain sensor locations, and data: (a) plan, elevation, and section A-A views and (b) section B-B and strain data measurement.

7. Case study 4: Digital accelerometer monitoring of hanger cables on arch bridges

Arch-girder bridges with hanger cables are a popular type of bridges because they have the advantages of both arch and girder forms. Therefore, it is critical to check the performance of the hanger cables in order to guarantee road safety. The hanger, which ties the arch and the girder, is a key determinant of bridge quality. If one hanger is damaged, the whole structure is at risk. By detecting bridge's hangers, we may make judgment whether the bridge is in good condition or not:

$$T_0 = ml^2\left(4.3865 f_1^2 - 0.2742 f_2^2\right) \tag{9}$$

where T_0 is the cable tension, m is the mass of the cable, l is the length of the cable, and f_1, f_2 are the first and second natural frequencies, respectively.

In Eq. (9), the stiffness of hanger cable is not needed to be tested, only frequencies. Therefore, it has an advantage of easy operation and usage. The demonstrated bridge here is a tied-arch bridge, and the above equation was used to calculate the cable forces, which are shown in Refs. [5, 12].

In the project, digital accelerometer JMM-268 dynamic testing instrument (**Figure 14**) was used to measure the first and second frequencies of hanger cables. When the frequencies were obtained, the hanger cable force can be calculated according to Eq. (9).

Comparing calculated hanger cable forces with cable force capacity, inspector of the bridge can locate critical sites and focus on those sites to do more detailed inspection. With the fast assessment method presented, only the first and second frequencies of the hanger cable need to be detected. This method was used to evaluate several arch bridges with hanger cables [5, 12].

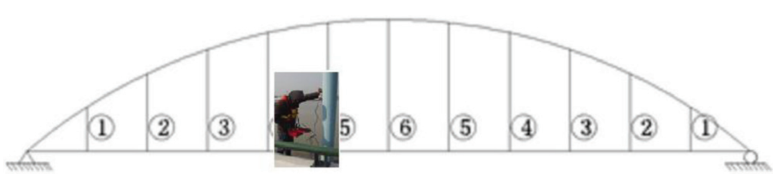

Figure 14.
Digital accelerometer JMM-268 dynamic testing instrument.

8. Case study 5: Accelerometer application on large steel frame structure

The steel frame structure is commonly used in the infrastructure of the petroleum industry to support numerous pipes and storage tanks. Vibration in steel frames is an industrial safety issue due to the movement of massive amounts of liquid, solid, and gas through the pipes. According to statistics published by David G. Maboney [13] regarding the causes of serious disasters in petrochemical industries, tube systems took up to 33% of the equipment. To identify the structural behavior of steel frames, accelerometers could be applied to detect vibrations. Shown here is an industry case that a new half-mile-long, 76-in (190 mm) diameter pipeline system is installed above a large 80-ft (24 m)-high steel frame structure in an oil refinery in Taiwan (**Figure 15**). The main function of the 76-in pipeline is to deliver massive amount of waste to the flare stack. However, an unexpected disturbance of the 76-in pipeline occurs which becomes the source of dramatic and

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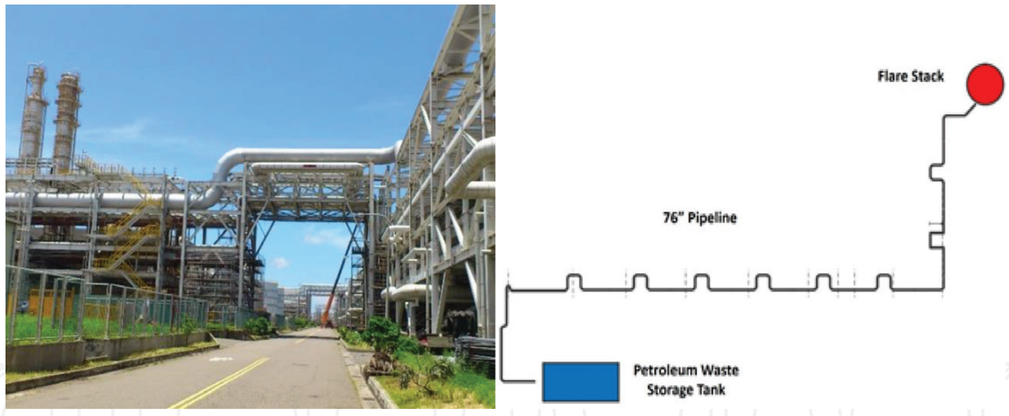

Figure 15.
76-in pipeline with steel frame and plan view [14].

continuous vibrations above the steel frames during the discharge process. The vibration in the steel frames caused by the 76-in pipeline disturbance might lead to cracks in the original pipes below, steel fatigue, and joint failure. Once the above incidents occur, it has potential to result in the escape of poisonous gas, interruption of the production process, and even conflagration. In this case, accelerometer monitoring records are used to detect dynamic structural weaknesses of the steel frames, and then, the structural systems could be retrofitted to reduce the probable essential structure faults leading to industry disasters. Disturbances occur randomly along the 76-in pipeline due to vaporization of solid or liquid waste whose volume expands dramatically and raises the pressure in the pipeline. Waste flow also causes impact force on curved parts of the 76-in pipeline when the flow direction changes.

The IMI 603C01 piezoelectric accelerometer is used in this case. It is a shear-mode-type accelerometer with a ceramic sensing element. It is suggested that ceramic sensing elements provide great resolution and durability in noisy environments and it also covers both low-frequency and high-frequency measurements [15]. Fifty-six accelerometers in either vertical or horizontal direction are installed on the 76-in pipeline and the steel frame below. Accelerometers are aligned vertically along the 76-in pipeline and the steel frame since the response of the steel frame caused by disturbances could be monitored simultaneously by all sensors (**Figure 16**).

With acceleration data from long-term monitoring, locations of vibrations and vibration levels could be identified. To provide methods to reduce vibration, the first step is to build the finite element model verified with monitoring data. In this case, SAP2000 is used to build the finite element model of the steel frame and the 76-in pipeline (**Figure 17**). By assigning time history recorded by the accelerometer, the fundamental frequency of the steel frame could be obtained by the FFT. The fundamental frequency of the steel frame could be also calculated by finite element

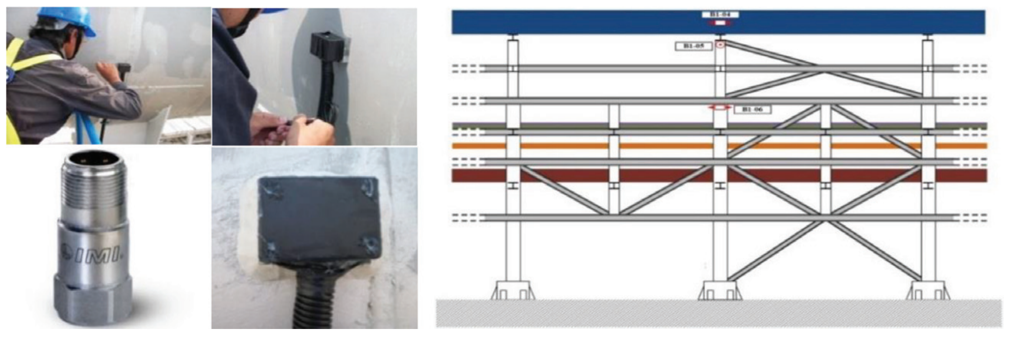

Figure 16.
Accelerometer installation and side view of design [14].

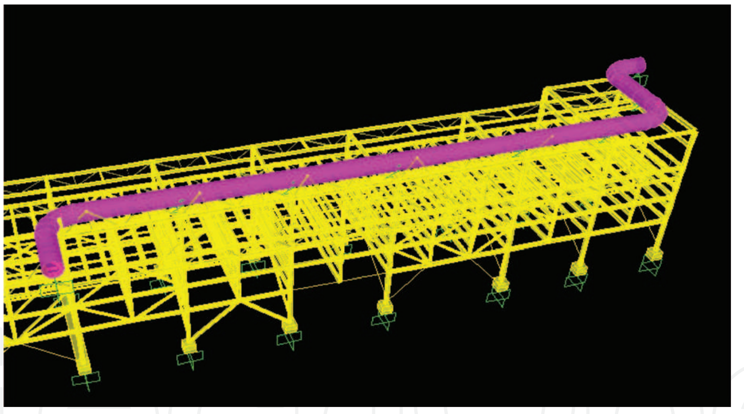

Figure 17.
Finite element model [16].

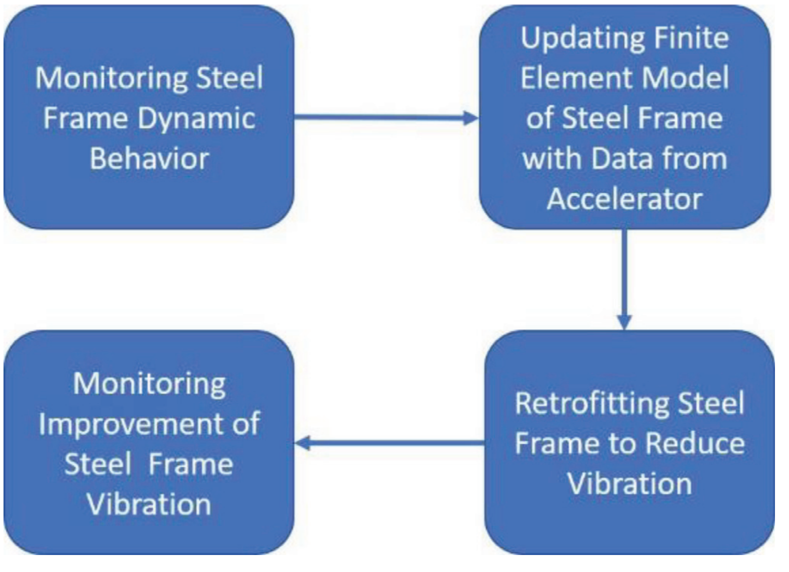

Figure 18.
Research flowchart [16].

software. Therefore, the finite element model could be modified to increase accuracy of the model by comparing frequencies with data recorded by accelerometers. The higher-vibrated steel frame structure is suggested to increase stiffness by installing steel bracing or enlarging column size. Based on the modified finite element model, the effect of retrofitted design could be evaluated in software. After retrofitting, the improvement of the steel frame could be demonstrated by further accelerometers monitoring (**Figure 18**).

The accelerometer plays an important role in this industry case because it provides critical information for steel frame dynamic behavior due to unexpected turbulence. Based on the monitoring data, the accuracy of the finite element model could be enhanced. More accurate models can help structural engineers figure out effective methods to reduce vibration which potentially leads to serious industrial disasters. The improvement could also be validated by further monitoring using accelerometers. On the other hand, steel frame vibration caused by the 76-in pipeline turbulence is also related to the volume of waste delivered to the flare stack. Therefore, the safe range of waste consumption could be determined to avoid insecure vibrations of the steel frame.

9. Conclusion

The purpose of the infrastructural monitoring is to have efficient use of the materials, energy, and labor to increase the performance of infrastructures. Advances of modern remote monitoring increase the efficiency, which is demonstrated in case studies. The emerging sensor technologies, no matter in situ, on-site, or airborne sensors, are increasingly used in the infrastructure sensing. An integrated structural health monitoring system (ISHM) includes the ability to extract information from sensor data to establish trends, such as the sensor signatures and structural damage, and make recommendation of actions to ensure the health of the infrastructures.

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