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A System Performance Index Approach to the Design of Boring Bars

By

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Abstract

A new methodology is developed for the boring bar structural design based on the theory of optimal control. This methodology takes into account the effect of cutting data selection on the boring bar performance in the design stage. For establishing the design criterion, a system performance index is introduced, which is defined as the summation of norm of each harmonic component of the system transfer function at a specified frequency bandwidth. Consequently, the process of minimizing this index is equivalent to an optimal setting of the design variables of the boring bar structure through the transfer function of the boring machining system. A case study of designing a flatted boring bar structure is provided. The process of determining the flat orientation demonstrates the design criterion of keeping the stochastic part of tool vibration during machining at a possibly low level. A rotatable flatted boring bar is designed for this study. Experiments are carried out and the predicted optimal flat orientation is compared with corresponding measured roughness AA values at different orientation settings, showing good agreements.

1 Introduction

As a precision machining operation to size and finish an existing hole, vibration control of the boring bar during machining is a major concern regarding quality and productivity of the boring operation.

Extensive research has been made on the control of boring bar chatter during machining. The concept of designing a boring bar with high stiffness to resist vibration during machining has been well accepted. For example, the high rigidity of a solid cemented boring bar, although the cemented material is expensive and hard to process, keeps the boring bar in the small vicinity of its dynamic equilibrium position during machining [1]. To increase the dynamic stiffness for vibration control during machining, a damped vibration absorber is fitted to the boring bar [2-3]. This transfers vibration energy to an auxiliary system. For an on-line control of the boring bar motion during machining, a pivot mechanism to actively track the tool tip motion was designed to improve the boring bar performance [4-6]. These methods were found to be effective for the vibration control during machining. However, applicable cutting conditions of these methods have been narrow. For example, the effectiveness of a specific absorber is dependent on its tuned condition which is related to the dynamic characteristics of the cutting force generated during machining [3]. As a result, a boring bar with damped vibration absorber may function well in the vibration control while machining steel materials, but may not meet the need for the vibration control while machining aluminum materials because of the difference in the dynamic characteristics of the cutting force between the two machining processes. In addition to this shortcoming, the high cost associated with the complicated structural design discourages wide applications of these methods in practice.

On the other hand, it has been found that the selection of boring machining data is also an effective means to control the boring bar vibration during machining [7]. Evidently, a large depth of cut could induce a severe vibration of the boring bar, leading to an unstable machining process. Small depths of cut, although they are associated with a low level of vibration, are not desirable with regard to machining productivity. Recent research has shown that a proper selection of machining data such as depth of cut, feed, and cutting speed for a given boring bar under specific machining conditions may benefit the finish quality of a bored surface as well as the machining productivity [7]. Research indicates that the optimal values of the cutting data selected are related to the machining system parameters such as the tool geometry, part material, and structural design of the boring bar. This suggests the need to search for a new method which integrates the activities in both the boring bar structural design and the machining data selection for a better vibration control during machining.

The research work presented in this paper aims to develop a methodology for the design of boring bars from the manufacturing system engineering perspective. This methodology takes into account the effect of cutting data selection on the boring bar performance in the design stage. Instead of being given a boring bar to optimally select the cutting data, this study focuses on the interaction between the structural and performable characteristics of a boring bar to search a criterion for an optimal design of boring bars. The concept of system performance index in control system design is introduced in this study. The defined index is related to the control of the stochastic part of tool vibration during machining. To minimize this index with respect to design variables of the boring bar is equivalent to designing an optimal boring bar as far as the surface finish quality is concerned.

This paper is organized as follows: In Section 2, a mathematical formulation for designing an optimal boring bar is presented. Section 3 presents a case study to demonstrate the process of minimizing the defined system performance index where the orientation setting angle of a flatted boring bar is assumed to be the design variable. Section 4 provides an experimental verification to justify the proposed approach. Section 5 discusses the insight and usefulness of this new methodology. Finally, Section 6 presents conclusions of this research.

2 Mathematical Formulation

2.1 Physical Boring Machining System

In this research, a lathe boring bar clamped at one end with the tool end free is considered, as shown in Fig. 1a. The onset of chatter is assumed to be governed solely by the boring bar. The boring bar is represented by a discret lumped mass system with two degrees of freedom, each of which displays second-order dynamics as illustrated in Fig. 1b. The angle α in Fig. 1b represents the direction of the first principal mode with respect to the horizontal. Because of symmetry, it is very likely that the numerical angle could be 45^0 for boring bars with a circular cross-section. This angle may, however, vary due to uneven boundary conditions at the clamped end. In order to control the directional angle α, boring bars with flats on it, where two distinguished stiffnesses K_1 and K_2 are present, have been recommended [8-10]. Because the direction of the first principal mode is dependent on the flat orientation in space, this directional anlge is also called the flat orientation. It has been reported that adjusting K_1 and K_2 is a means of effectively controlling the tool vibration in the direction normal to the machined surface, which directly relates to the profile formation of a machined surface. Therefore, parameters K_1, K_2, and α are three design variables of the flatted boring bar in addition to those conventional design variables such as the diameter, length, and material of boring bar.

2.2 System Performance Index

As illustrated in Fig. 1a, tool vibration during machining results from the inherent flexibility of the flatted boring bar. While the cutting force generated excites the slendered boring bar, the tool vibration changes the instantaneous chip load, as indicated in Fig. 2a. This leads to a dynamic variation of the cutting force. From a system engineering standpoint, the boring machining operation is best characterized by its closed-loop transfer function $M(j\omega)$, as illustrated in Fig. 2b. It is evident that this transfer function $M(j\omega)$ is a function of the design variables of a boring bar as well as the cutting parameters, tool geometry, and workpiece material. A detailed discussion of evaluating $M(j\omega)$ for a given boring machining operation can be found in [12-13].

The output of the machining system is the tool vibration during machining. The tool vibration observed on the shop floor can be decomposed into two parts, i.e., the deterministic and stochastic parts [11], as indicated in Fig. 2a. The determinstic part is referred to as the part of tool vibration mainly due to the nominal chip load. The stochasitc part is associated with random excitation present during machining. Therefore, the input to the machining system consists of two components, namely, the nominal chip load and random excitation.

Study on the surface characterization has indicated that the surface irregularities formed during machining are mainly related to the stochastic part of tool vibration. As indicated in Fig. 2b, the system response due to random excitation, or the stochastic part of tool vibration can be evaluated by, in the frequency domain,

$$\sum_{i=0}^{\infty} Y(j\omega_i) = \sum_{i=0}^{\infty} [W(j\omega_i)] \; [M(j\omega_i)] \tag{1}$$

where

$\omega_i = i^{th}$ circular frequency,

$Y(j\omega_i) = i^{th}$ harmonic component of the system response,

$W(j\omega_i) = i^{th}$ harmonic component of the random excitation function, and

$M(j\omega_i) = i^{th}$ harmonic component of the system transfer function.

An assumption is made in the present study with regard to the random excitation function. This assumption is that this function represents white noise, which has an essentially flat power spectrum and can be considered a mixture of all frequencies with random amplitudes and phase angles, as illustrated in Fig. 2b. Based on this assumption and neglecting the influence of phase angles, the summation of norms of all frequency components of the stochastic part of tool vibration can be evaluated by a summation of the product of two corresponding norms, i.e., the norm of harmonic component of the white noise and the norm of harmonic component of the system transfer function. Instead of using Eq. (1), we may use Eq. (2) to estimate the stochastic part of tool vibration when subjected to a white-noise excitation.

$$\sum_{i=0}^{\infty} |Y(j\omega_i)| = \sum_{i=0}^{\infty} |W(j\omega_i)| \; |M(j\omega_i)| \tag{2}$$

where

$\omega_i = i^{th}$ circular frequency,

$|Y(j\omega_i)|$ = norm of the i^{th} harmonic component of the system response,

$|W(j\omega_i)|$ = norm of the i^{th} harmonic component of the random excitation function, and

$|M(j\omega_i)|$ = norm of the i^{th} harmonic component of the system transfer function.

Note that the term $|W(j\omega_i)|$ enclosed in the summation sign of Eq. (2) can be further separated from the summation sign because these norms, $|W(j\omega)|s$, have no difference from the statistical point of view. This transforms Eq. (2) to Eq. (3) for the evaluation of the stochastic part of tool vibration.

$$\sum_{i=0}^{\infty} |Y(j\omega_i)| = |W(j\omega)| \sum_{i=0}^{\infty} |M(j\omega_i)| \tag{3}$$

If the objective for designing a flatted boring bar is to keep the tool random vibration at a possibly low level for high quality of surface finish, Eq. (3) can be used to characterize the boring bar performance during machining. For example, a small value of the summation $\sum_{i=0}^{\infty} Y(j\omega_i)$ will signify al a low level of tool random vibration during machining. The system performance index defined in this research is a normalized form of the stochastic part of tool vibration in the frequency domain. This normalized form is the summation of norm of each harnomic components of the system transfer function.

$$J = \frac{\sum_{i=0}^{\infty} |Y(j\omega_i)|}{|W(j\omega)|} = \frac{|W(j\omega)| \sum_{i=0}^{\infty} |M(j\omega_i)|}{|W(j\omega)|} = \sum_{i=0}^{\infty} |M(j\omega_i)| \tag{4}$$

When intervals of $(\omega_{i+1} - \omega_i)$ used in Eq. (4) approach to zero, the summation in Eq. (4) is replaced by an integral. The defined system performance index is given by

$$J = \frac{1}{\omega_{max}} \int_0^{\omega_{max}} |M(j\omega)| \, d\omega \tag{5}$$

Note that the introduction of parameter ω_{max} in eq. (5) specifies a frequency bandwidth over which the defined system performance index is integrated.

2.3 Criterion for Analytically Designing a Flatted Boring Bar

As indicated in Eq. (4) and Eq. (5), a mathematical representation of the system transfer function is needed for the evaluation of the defined system performance index J. The state-space method in the modern control theory has been used in this regard [12-13]. Referring to Fig. 1b, four state variables in terms of the displacements and the velocities of the two significant modes of the boring bar are introduced to uniquely characterize the boring machining operation. The dynamic equation in vector-form in the state space to define the status of the boring machining system is given by

$$\begin{aligned} \dot{X}(t) &= [A]X(t) + [B]u(t) \\ y(t) &= [C]X(t) \end{aligned} \tag{6}$$

where matrices $[A], [B]$, and $[C]$ are system matrices, $y(t)$ is the tool vibratory motion in the direction normal to the machined surface, $[X(t)]^T = [X_1, X_2, X_3, X_4]$, and

$X_1(t) =$ displacement of mode 1 $= q_1(t)$

$X_2(t) =$ velocity of mode 1 $= \dot{q}_1(t)$

$X_3(t) =$ displacement of mode 2 $= q_2(t)$

$X_4(t) =$ velocity of mode 2 $= \dot{q}_2(t)$

The criterion of designing an optimal boring bar with respect to keeping the tool random vibration at a possibly low level can be stated in a general form as follows:

$$\begin{aligned} \text{Minimize:} \quad J &= \frac{1}{\omega_{max}} \int_0^{\omega_{max}} |M(j\omega)|\, d\omega \\ \text{subject to:} \quad \dot{X}(t) &= [A]X(t) + [B]u(t) \text{ and} \\ y(t) &= [C]X(t) \\ \text{where} \quad u(t) &= \textit{white noise} \end{aligned}$$

Consequently, the process of minimizing the defined system performance index is equivalent to optimally set the design variables, which define the elements of the system matrices $[A], [B]$, and $[C]$ [12-13].

3 Case Study: Optimal Flat Orientation Setting

It has been reported that the directional angle of the first principal mode (α), or the flat orientation, plays an important role in controlling the vibration of a flatted boring bar during machining. In this paper, the determination of an optimal flat orientation setting under given cutting conditions is taken as an example to demonstrate the procedure of using the proposed methodology for the design of a flatted boring bar. Assume that other design variables are set to certain fixed values, part of which used in the evaluation of the defined system performance index J is listed below.

$$
\begin{aligned}
Feed &= 0.10 && mm/rev \\
DepthofCut &= 0.50 && mm \\
CuttingSpeed &= 82 && m/min \\
K_1 &= 4.07\text{x}10^6 && N/m \\
K_2 &= 3.06\text{x}10^6 && N/m \\
C_1 &= 104 && N-m/sec \\
C_2 &= 89.2 && N-m/sec
\end{aligned}
$$

Note that using different flat orientation angles during the evaluation of the defined system performance index simulates a situation where boring bars are designed with different flat orientation settings. The calculated values of the system performance index for twelve different orientation settings are listed below.

α	90^0	75^0	60^0	45^0	30^0	15^0	0^0
J	.365	.330	.317	.304	.303	.306	.312

α	-15^0	-30^0	-45^0	-60^0	-75^0
J	.322	.333	.349	.377	.380

Figure 3 is a polar plot of the above calculated data, which represents the system performance index as a function of the directional angle, α. Upon examining Fig. 3, it is evident that the minimum value of the system performance index, $J_{min} = 0.303$, occurs at $\alpha = 30^o$ or -150^o because of the symmetric nature of the orientation settings in space. Based on the design criterion, this orientation setting of the flatted boring bar is most preferred under the given cutting conditions in terms of keeping the tool random vibration at a possibly low level during machining.

Figure 4a presents three typical $|M(j\omega)|$ plots for $\alpha = 30^o$, 60^o, and -75^o to interpret the observation from Fig. 3. When comparing these three areas under the three $|M(j\omega)|$ curves, it is evident that the smallest area is associated with the orientation setting of $\alpha = 30^o$, or the minimum system performance index value, $J_{min} = 0.303$. Recalling Eq. (4) and Eq. (5) and examining the three rectangles in Fig. 4a, the geometrical interpretation of the defined system performance index is that it represents the height of a rectangle, the area of which is equal to the area under the $|M(j\omega)|$ curve (the two areas share the same base length equal to ω_{max}). Figure 4b presents three phase angle plots. Upon examining these three associated $\angle M(j\omega)$ phase plots, different orientation settings have offered different patterns of the phase angle as a function of frequency. For $\alpha = 30^o$, within the whole frequency region of interest from 0 to 640 Hz, only one mode was significantly excited at a small subregion (250 Hz to 285 Hz) as indicated in Fig. 4a. This results in the smallest area of the $|M(j\omega)|$ plot among the three. On the other hand, for $\alpha = -75^o$, both modes were significantly excited at a large subregion (200 Hz to 300 Hz). This results in the largest area of the $|M(j\omega)|$ plot among the three.

Table 1 is a list of the data used to construct the three $M(j\omega)$ magnitude and phase plots shown in Fig. 4. The purpose of presenting this data is to justify the assumption made in defining the system performance index, i.e., neglecting the influence of phase angles in the evaluation of the system performance index. Without this neglection, the cancellation among positive and negative terms in Eq. (1) could cause the defined system performance index to be less sensitive, or even fail to characterize the cohesive relations between the system transfer function and the design variables of a boring bar.

4 Experimental Verification

A testing boring bar is designed for this study. Figure 5 depicts its structural design. The bar diameter is 32 mm and the length-to-diameter ration is 5.3:1. Two parallel flats along the longitudinal axis of the boring bar are made to assure two distinguishable directional

Table 1 Numerical Values of the Calculated $|M(j\omega)|$ and $\angle M(j\omega)$ for $\alpha = 60^0, 30^0$, and -75^0

ω	$\alpha = 60^o$		$\alpha = 30^o$		$\alpha = -75^o$	
Hz	$\|M(j\omega)\|$	$\angle M(j\omega)$	$\|M(j\omega)\|$	$\angle M(j\omega)$	$\|M(j\omega)\|$	$\angle M(j\omega)$
0	0.320	-0.02	0.272	-0.02	0.442	-0.03
80	0.348	-2.20	0.292	-1.82	0.490	-2.77
160	0.466	-5.49	0.373	-4.21	0.659	-7.25
190	0.572	-7.72	0.439	-5.42	0.861	-10.52
223	0.746	-11.33	0.542	-6.13	1.034	-15.92
255	0.963	-19.06	0.982	12.66	0.959	-25.60
271	0.905	-29.42	0.968	-22.89	0.803	-32.24
286	0.960	-26.60	0.946	-27.00	0.697	-36.20
302	0.626	-41.30	0.827	-34.94	0.908	-19.86
318	0.332	-71.87	0.569	-50.12	0.418	62.34
334	0.238	68.36	0.345	77.35	0.178	-17.03
350	0.227	43.09	0.255	69.00	0.180	3.28
382	0.207	23.40	0.221	32.58	0.160	9.28
414	0.177	16.14	0.196	20.40	0.144	9.05
446	0.149	12.45	0.159	14.90	0.125	8.17
477	0.126	10.21	0.134	11.82	0.109	7.35
557	0.087	7.19	0.091	7.94	0.079	5.79
637	0.064	5.64	0.066	6.08	0.059	4.79

stiffnesses ($K_1 = 4.07\text{x}10^6 N/m$ and $K_2 = 3.06\text{x}10^6 N/m$). The directional angle of the first principal mode of the testing boring bar, α, can be set to six different orientations because the shank part of the boring bar is designed as a prismatic shape, as indicated in Fig. 5. With a rotatable tool holder, the flat orientation of the testing boring bar can be set at $\alpha = 90^o, 60^o, 30^o, 0^o, -30^o, \text{and} \; -60^o$, respectively.

The workpiece material used is shown in Fig. 6. There were six sections on the workpiece. For each of the six flat orientation settings of the testing boring bar, a section on the workpiece was cut under the comparable cutting conditions used in the theorectical evaluation of the system performance index in the previous case study. After machining, a trace of the roughness profile on this machined section was taken on a Talysurf-10 surface profilometer. Six cutting tests were performed at $\alpha = 90^o, 60^o, 30^o, 0^o, -30^o, \text{and} \; -60^o$, respectively. The six recorded traces taken from the six sections of the workpiece are presented in Fig. 6, together with the measured AA (Arithmetic Average of the profile heights) values.

Examining these measured AA values, the smallest measured AA value is 0.50 μm, which occurred at the section of $\alpha = 30^o$. Comparing this result with the theoretical evaluation of the system performance index, this flat orientation setting for $\alpha = 30^o$ gave the minimum value of the system performance index in the case study. Another observation from the comparison between the theoretical predictions and experimental results is that the largest measured AA value among the six flat orientation settings is 0.65 μm which occurred at the section for $\alpha = -60^o$. This flat orientation setting is very close to the flat orientation setting of -75^o, which gave the maximum value of the system performance index in the case study. The discrepancy between the two setting angles is mainly due to the fact that the testing boring bar only allows the flat orientation set at $\alpha = -60^o$ or $\alpha = -90^o$, but does not allow the flat orientation set at $\alpha = -75^o$ during testing. Figure 7 is a polar plot of the measured AA values as a function of the directional angle α. The similarity in the basic pattern between the two polar plots can be easily seen. Not only do the maximum and minimum values match between the two polar plots, but also both the predicted J and measured AA values monotonically increase as the setting angle of the flat orientation decreases, showing good agreements.

5 Discussion of Results

The appropriateness of the proposed methodology using the system performance index approach for an analytical design of the flatted boring bar has been confirmed by experimental results. The main contributions of this research to the design of boring bars and control of the boring machining operation could be seen from the following perspectives.

5.1 Creation of an Integrated Design Environment

The defined system performance index J is a direct reflection of the system transfer function $M(j\omega)$. In terms of the harmonic components of the system transfer function, the defined system performance index is a quantitative indication of effects of the dynamics of the boring bar structure on its machining performance, namely, its vibratory behavior. In addition to the design variable of the flat orientation angle α, other design variables such as the directional stiffnesses K_1 and K_2 can be readily included in the multi-variable design process. One of the attractive advantages associated with this approach is that considerations of selecting cutting data to fully utilize the inherent vibration-resistance of the boring bar structure have been incorporated in the design stage. It should be recognized that the definition of the word "optimal" in the present case study is referred to how minimizing the effect of the tool vibration on the stochastic part of a bored roughness profile where a white-noise random excitation is assumed. If a new system performance index were introduced which concerns the system stability, the flat orientation set at $\alpha = 30^o$ would not be the best choice among those setting angles. This fact indicates that a specific qualifier to define the design goal is a necessary condition to initiate an optimal design process.

5.2 Selection of Optimal Cutting Data

This developed methodology can also be used for an optimal selection of the cutting data such as feed, depth of cut, and cutting speed when the dynamic characteristics of a boring bar are the given. Under these circumstances, the design variables of the boring bar structure are set to constants based on their given values, the system transfer function becomes a function of those parameters related to the cutting data only. The process of minimizing the defined system performance index is equivalent to an optimal selection of cutting data [7]. Usually, an additional mathematical model is needed to define the quantitative relation between the system transfer function and those parameters in order to incorporate these cutting parameters into the defined system performance index. Following the same logics, if quantitative relations between the system transfer function and the tool geometry can be identified, this model can also be used for the selection of cutting geometry, which best fits a planned goal such as vibration control.

5.3 Relation between On-line Control and the Proposed Approach

On-line control to actively correct the tool path error induced by tool vibration has been studied and developed [5-6]. Using sensing techniques, the feedback signal releases the detected information related to the tool position for on-line tracking. It represents a significant progress in the area of vibration control. The contribution of this research to the on-line control methodology developed so far is that the present research provides an effective tool to perform an off-line optimization first. A boring bar, whose structural design has been well thought, will greatly facilitate the effort required from the on-line control.

6 Conclusions

As a continuation of the efforts to develop a systematic and analytical approach for an optimal design of boring bars, this research has formulated a new system performance index for an establishment of the design criterion. The new index is defined as the summation of norm of each harmonic component of the system transfer function at a specified frequency bandwidth. Design variables of a boring bar are incorporated in the system transfer function. Minimizing this index represents a process of seeking an optimal setting of these design variables. A case study of setting the orientation of a flatted boring bar is presented to demonstrate the design procedure. The validity of applying this new approach has been confirmed through experimental verification. The optimal setting of the flat orientation determined through cutting tests well matches the optimal flat orientation setting predicted by this proposed system performance index approach.

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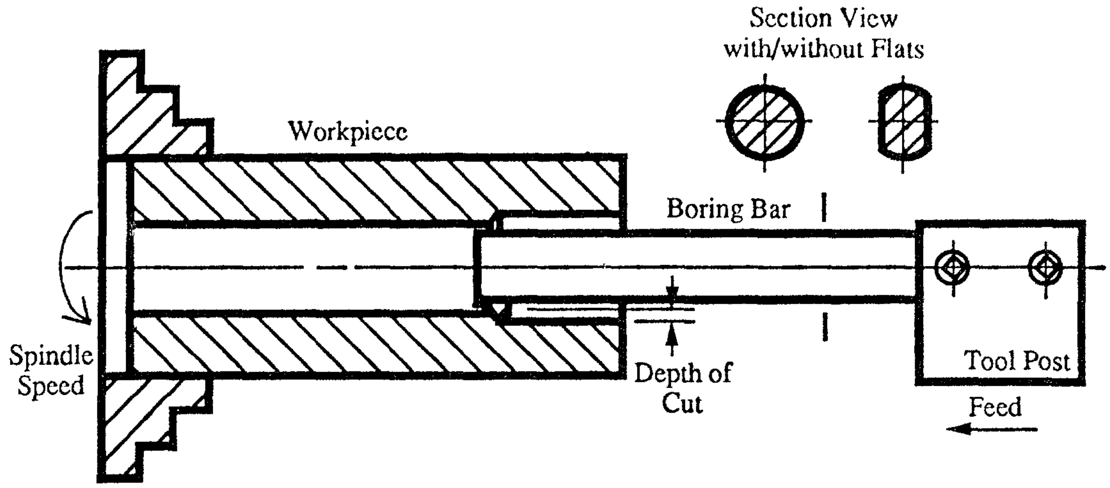
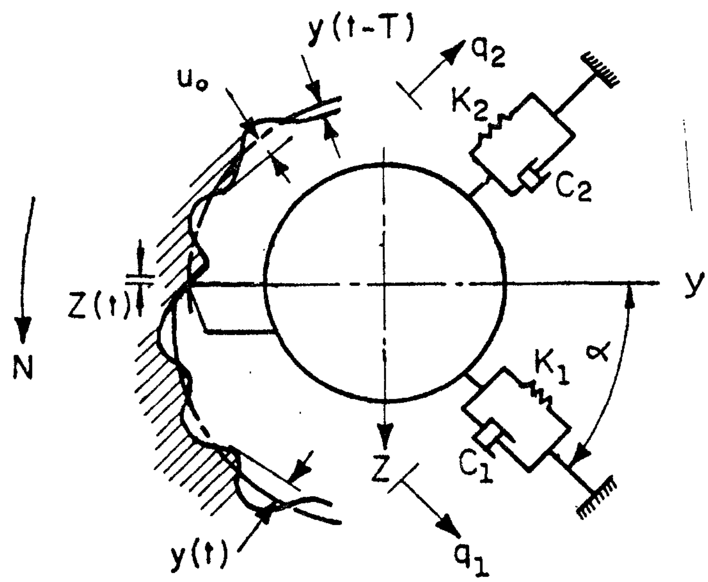
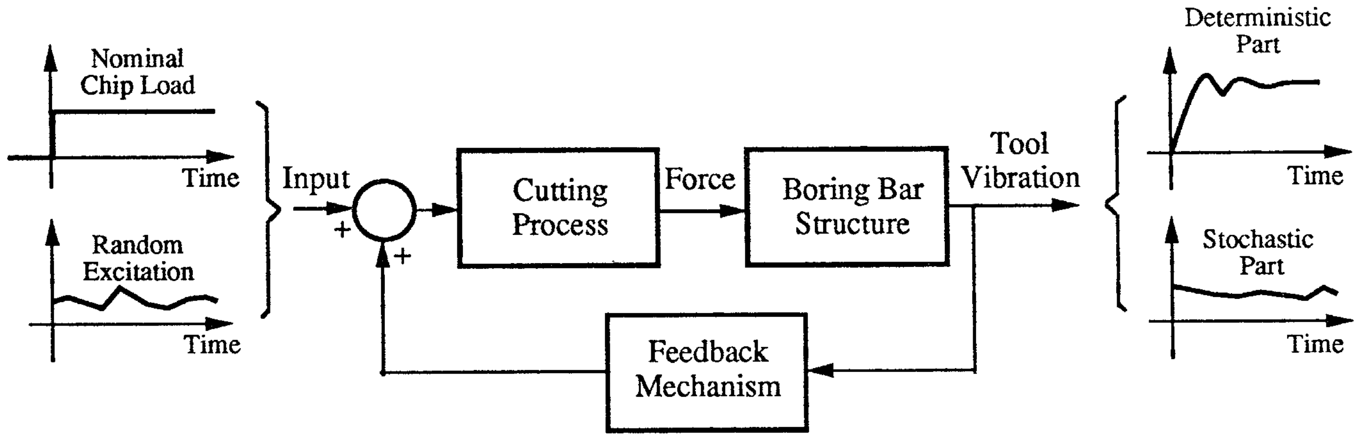


(a) Physical Boring Machining System

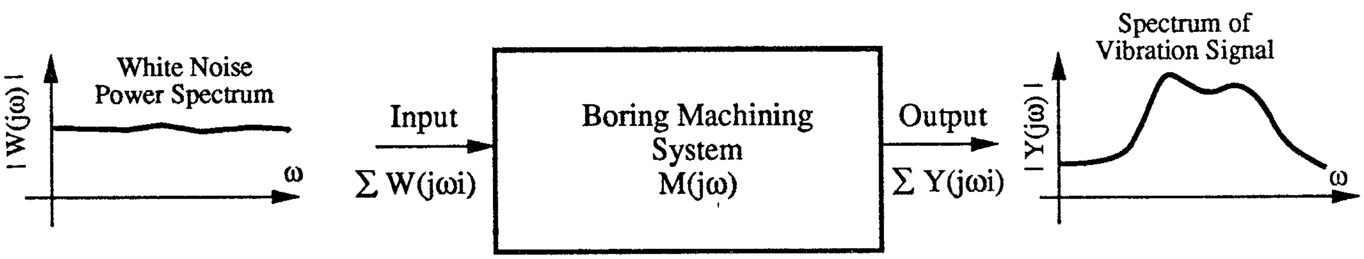


(b) Model of Two-Degree-of-Freedom

Figure 1 Physical Boring Machining System and Mathematical Model



(a). A Closed-Loop Boring Machining System



(b). System Analysis of the Stochastic Part in the Frequency Domain

Figure 2 Analysis of the Boring Machining System

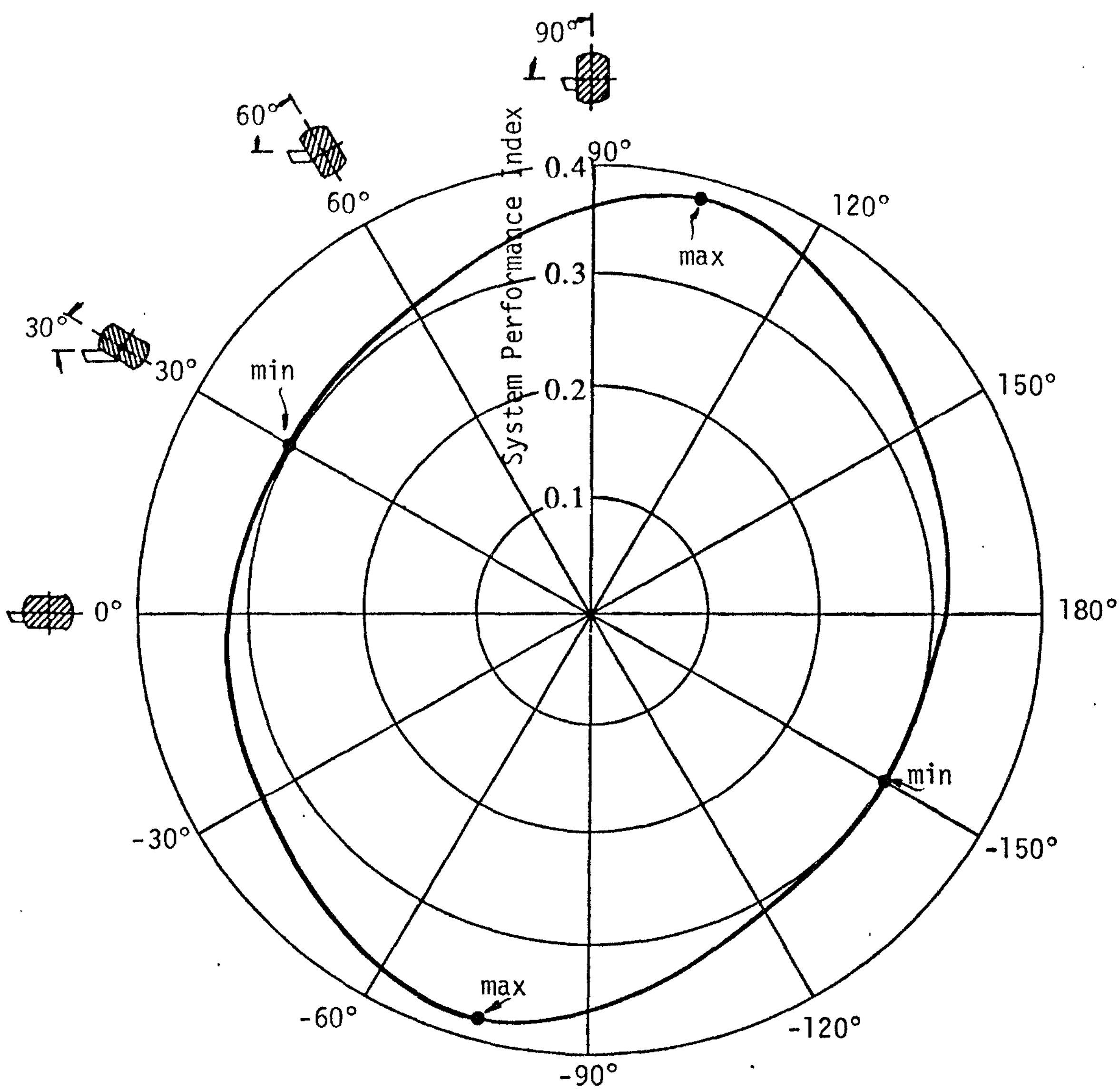


Figure 3 Polar Plot of the System Performance Index as a Function of the Flat Orientation Settings

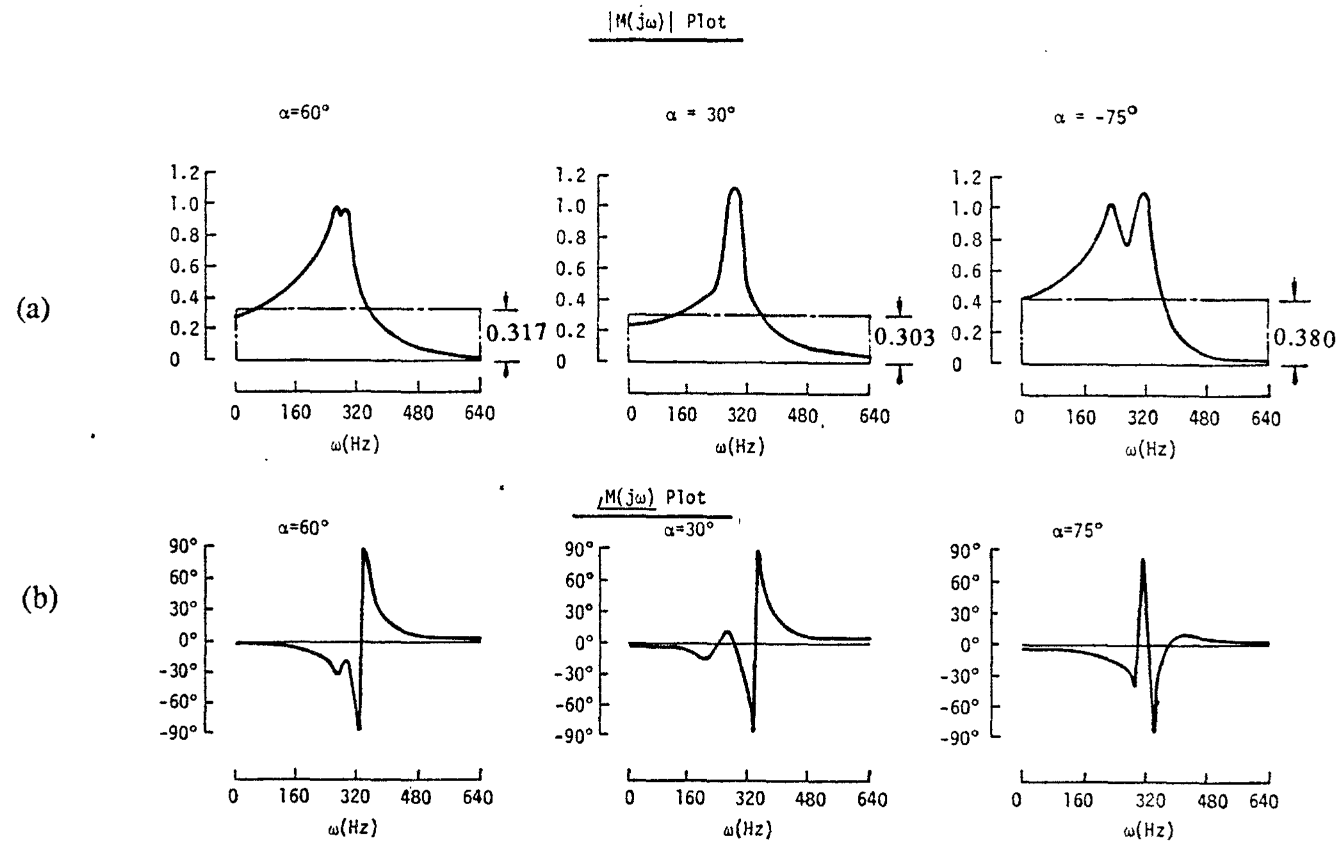


Figure 4 Plots of $|M(jw)|$ and $\angle M(jw)$ for $\alpha = 60^0, 30^0$, and -75^0

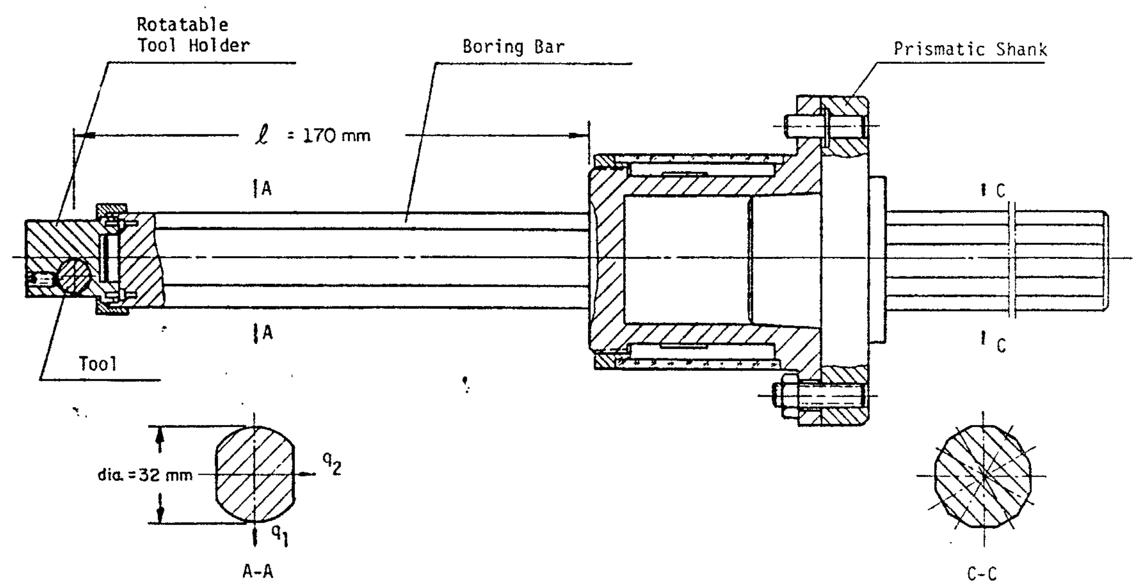


Figure 5 Structural Design of the Testing Boring Bar

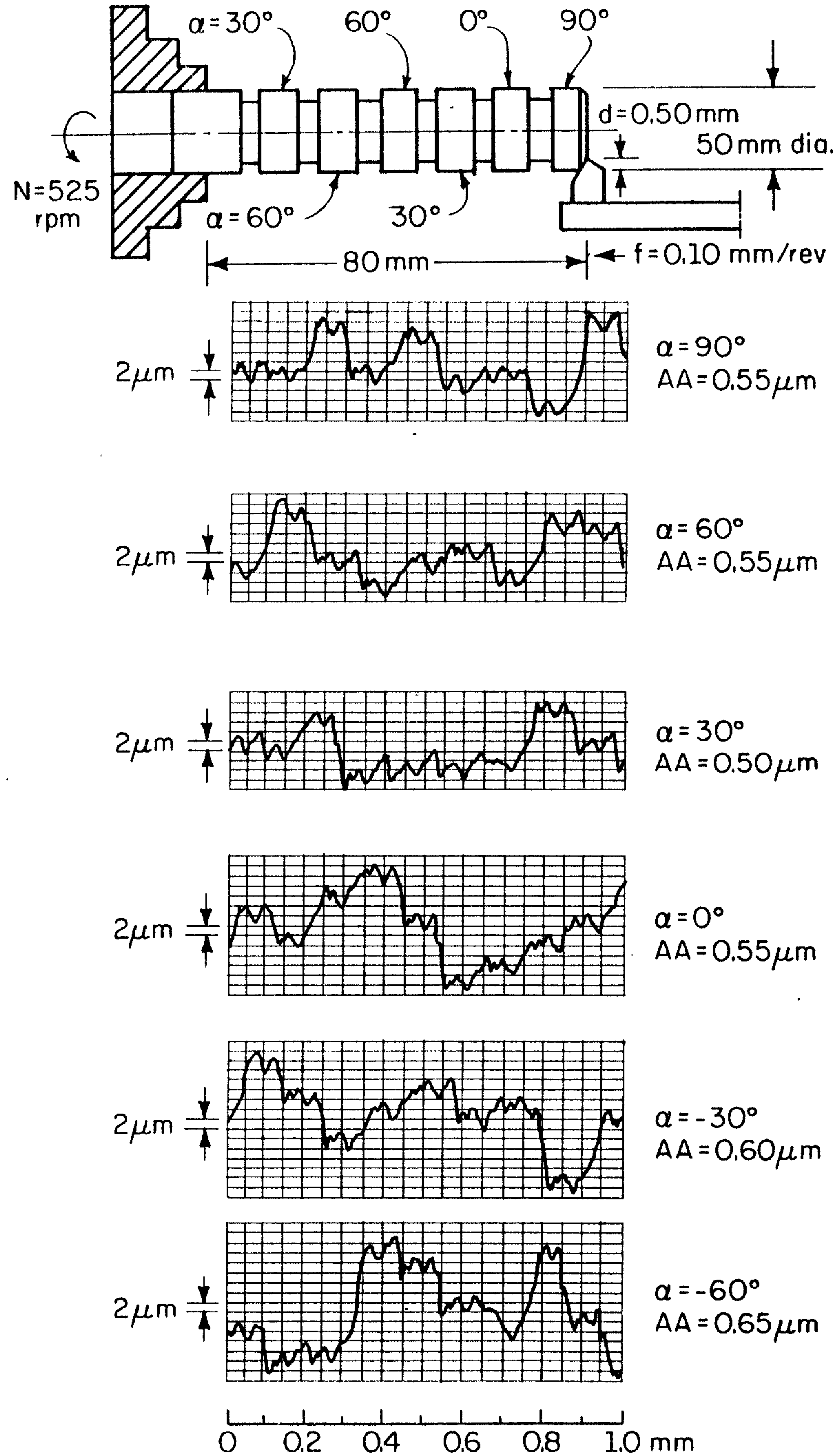
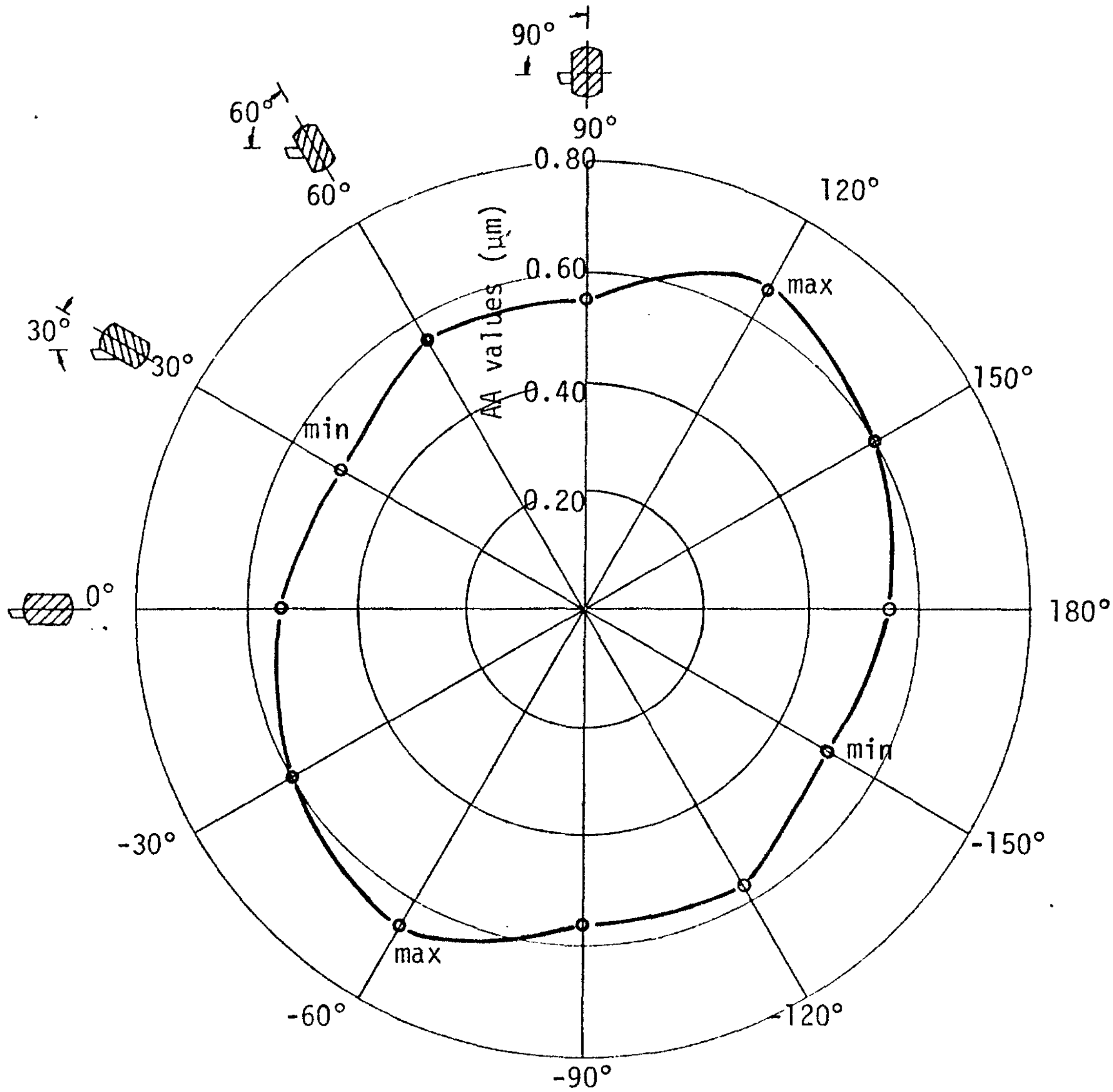


Figure 6 Experimental Setup and Typical Profile Traces Taken from the Machined Surfaces



Firgure 7 Polar Plot of the Measured AA Value as a Function of the Flat Orientation Settings