ACTUATOR PLACEMENTS AND VARIATIONS IN THE CONTROL PATH ESTIAMTES IN THE ACTIVE CONTROL OF BORING BAR VIBRATIONS

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Abstract

A classical example of chatter prone machining is the boring operation. Turning under conditions with high vibrations in the cutting tool deteriorates the surface finish and may cause tool breakage. Severe noise is also a consequence of the high vibration levels in the boring bar. Active control is one possible solution to the noise and vibration problem in boring operations. In boring operations the boring bar usually have vibration components in both the cutting speed and the cutting depth direction. The introduction of the control force in different angles in between the cutting speed and the cutting depth directions have been investigated. Furthermore, control path estimates produced when the active boring bar was not in contact with the workpiece and during continuous cutting operation are compared. Experimental results indicate that the control force should be introduced in the cutting speed direction. Although the vibrations are controlled in just the cutting speed direction the vibrations in the cutting depth direction are also reduced significantly.

INTRODUCTION

The lathe is a very useful and versatile machine in the workshop, and is able to perform a wide range of machining operations. A boring operation is a metal cutting operation that bores deep precise holes in the workpiece. A boring bar is characterized by a substantial length compared to its cross-sectional dimensions. The boring bar is clamped at one end to a tool post or a revolver and has a cutting tool attached at the free end. Since a boring bar usually is long and slender it is inclined to vibrate. Deep internal boring of a workpiece is a classic example of chatter prone machining. Performing metal cutting under vibrating conditions will yield an unsatisfactory result in terms of surface finish of the workpiece, tool breakage and undesirable noise. The boring bar vibration pattern has been investigated in [1, 2]. Active vibration control is one approach to enhance the performance of the boring operation.

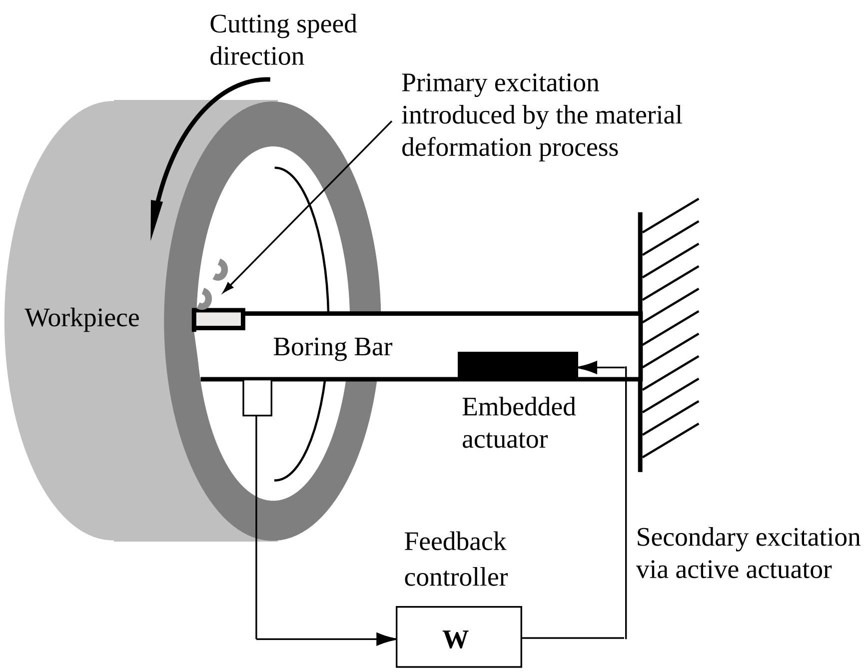


Figure 1: A schematic figure of active vibration control in a boring operation.

A challenge is to incorporate electronic devices into the harsh environment of a lathe. An active vibration control application includes actuators and sensors in conjunction with a control system. Protecting the actuators and accelerometers from the metal chips and cutting fluids is necessary. Another goal was to make the active control system applicable to a general lathe. Embedding the actuators and accelerometers protects these from the surrounding environment. The design is applicable to a general lathe as long as the mounting arrangement is fairly similar. Due to the recent development of piezo ceramic actuators the technique is possible to embed into a boring bar. Milling a space in the boring bar reduces the stiffness but with the piezo ceramic actuator technology, the space can be kept small, hence the bending stiffness reduction is moderate. Two different placements of the actuator have been compared. The difference is the angle between the cutting speed direction and where the force is introduced to the active boring bar in the cutting speed - cutting depth plane. The actuator was, in both cases, mounted in the length direction below the centerline of the boring bar. When the actuator applies a load on the boring bar in its length direction due to the expansion of the actuator the boring bar will bend. Fig. 1 illustrates the active vibration control system in a boring operation.

The control system involves a secondary source driven in such a way that the summation of the original vibrations, deriving from the cutting process, and the secondary vibrations will cancel each other. Since the original excitation, the material deformation process itself cannot be observed directly, the control algorithm must be built on a feedback approach. A feedback version of the filtered x-LMS algorithm has been proven able to reduce the vibration problem in boring operations [3]. The filtered-x LMS requires a fairly accurate estimate of the forward path at frequencies to be controlled [4]. In this application the forward path is estimated off-line, i.e. the boring bar is not in contact with the workpiece. However, the boundary conditions of the tool differs between continuous cutting operations and when the boring bar is not in contact with the workpiece. Thus, the forward path during continuous cutting operation and the forward path when the boring bar is not in contact with the workpiece have been compared.

MATERIALS AND METHODS

Experimental Setup

All the experiments have been carried out on a MAZAK 250 Quickturn lathe, with 18.5 kW spindle power, maximal machining diameter 300 mm and 1007 mm between the centers. In order to save material the cutting operations were performed as external turning operations, although a boring bar was used as a tool holder.

In the cutting experiments the workpiece material was chromium molybdenum nickel steel. The diameter of the workpiece was chosen large (< 200mm) rendering the workpiece vibrations negligible.

Active Boring Bar

The boring bar used in the experiments were based on standard WIDAX S40T PDUNR15 boring bars. The diameter of the boring bar was 40 mm and length was 300 mm, where 100 mm is required for the clamping thus 200 mm constitutes the overhang part. To be able to perform active vibration control, an actuator and accelerometer must be applied to the vibrating object. In the case of a boring bar the extra equipment must be built in to the design without reduce the bending stiffness of the boring bar significantly. Two different mounting locations of the actuator have been tested in real cutting experiments. The difference is the angle between the cutting speed direction and where the force is introduced to the active boring bar in the cutting speed - cutting depth plane. The two active boring bars tested uses an angle of $0°$ (just in the cutting speed direction) and $30°$. In all three cases the actuator was mounted in the length direction below the centerline of the boring bar. When the actuator applies a load on the boring bar in its length direction due to the expansion of the actuator the boring bar will bend.

Control System

The application requires that the control system is based on a feedback approach since the original excitation, i.e. the cutting process, cannot be observed directly during control. Another important consideration is the forward path, which is the transfer path from the output of the adaptive algorithm to the accelerometer. This forward path must be included in the LMS algorithm to produce the filtered-x LMS algorithm in order to ensure convergence [5]. The cutting process has non-stationary properties [6] and an algorithm able to work under the circumstances mentioned above, is a feedback version of the filtered-x LMS algorithm, which is shown in Fig. 2. The algorithm

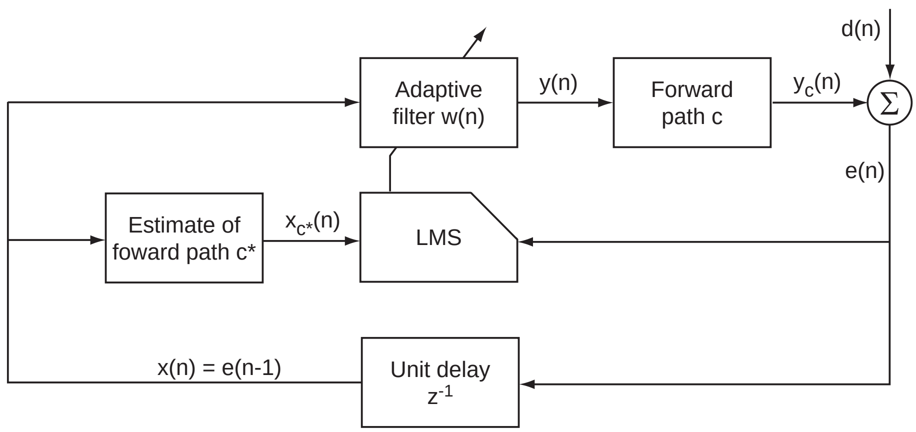


Figure 2: Block diagram of the feedback filtered-x LMS algorithm.

requires an estimate of the forward path and the identification of the forward path is performed in an initial phase using an ordinary LMS algorithm. The actuator is feed with pseudo random noise generated by the DSP to minimize the hysteresis and nonlinear effects of the actuator. The result of the identification is a FIR filter used in the filtered-x LMS algorithm.

The search for a minimum can be performed by the feedback filtered-x LMS algorithm [7]. The input $x(n)$ at sample n to the adaptive algorithm is the previously sampled accelerometer signal $e(n-1)$

$$x(n) = e(n-1) \tag{1}$$

The accelerometer signal is directly used as an error signal in the algorithm. Using the error signal as input to the control algorithm will cause the algorithm to work as a feedback controller. This will complicate the relation between the mean square error and the filter coefficients, i.e. the mean square error will not be a quadratic function of the filter coefficients [7].

The output $y(n)$ of the adaptive algorithm is the input filtered with the adaptive FIR filter weights $\mathbf{w}(n) = [w_0(n), w_1(n), \ldots, w_{M-1}(n)]^T$ and is given by

$$y(n) = \mathbf{w}^T(n)\mathbf{x}(n) \tag{2}$$

where $\mathbf{x}(n) = [x(n), x(n-1), \ldots, x(n-M+1)]^T$ and M is the length of the adaptive filter. The output of the adaptive filter is feed to an amplifier which in turn is powering the actuator. The error is the summation in the tool holder of the vibration induced by the actuator $y_c(n)$ and the vibration from the cutting process $d(n)$, and is sensed by the accelerometer

$$e(n) = d(n) + y_c(n) \tag{3}$$

The objective of the adaptive algorithm is to minimize the instantaneous squared error. Since the output of the adaptive algorithm is altered by a forward path c, the input signal must be filtered by an estimate of the forward path $\mathbf{c}^*$ to ensure convergence. The filtered input signal is

$$x_{c^*}(n) = \mathbf{c}^{*T}\mathbf{x}(n) \tag{4}$$

where $\mathbf{c}^*$ is a vector containing FIR coefficients of the estimated forward path. The LMS algorithm is updating the filter weights in the negative direction of the gradient with a step size μ

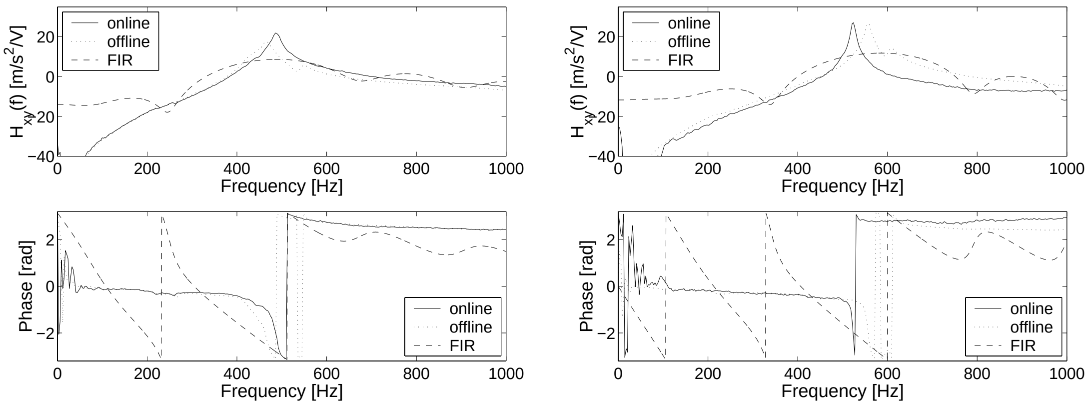
$$\mathbf{w}(n) = \mathbf{w}(n-1) - \mu\mathbf{x}_{c^*}(n)e(n) \tag{5}$$

where $\mathbf{x}_{c^*}(n) = [x_{c^*}(n), x_{c^*}(n-1), \ldots, x_{c^*}(n-M+1)]^T$. The algorithm loops equation 1 through 5 to continuously produce a control signal for the active tool holder.

RESULTS

Forward path

The forward path is modeled as a FIR filter in the controller. Frequency function estimates of the forward path during continuous cutting operation and when the boring bar is not in contact with the workpiece have been produced based on the Welche's spectrum estimator [8]. Occasionally it is possible to perform a boring operation where the vibration levels are low. During such circumstances it is possible to estimate the forward path during boring in order to see whether the forward path characteristics have changed or not, due to the changed boundary conditions at the tool tip. Fig. 3 shows the frequency response function estimates of the forward path during continuous cutting operation and when the boring bar is not in contact with the workpiece as well as the Fourier transformed FIR filter estimate of the forward path. Note in particular that there is a slight change in the first resonance peak for both versions of the boring bars.



a) b)

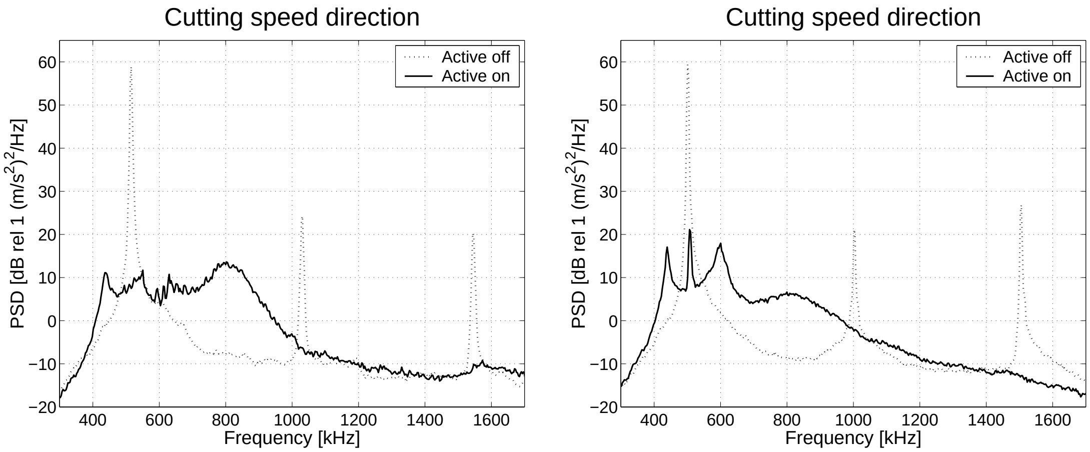
Figure 3: Frequency response function estimates of the forward path during continuous cutting operation,online, and when the boring bar is not in contact with the workpiece, offline. Fourier transformed offline FIR filter estimate of the forward path. In a) $0°$ and b) $30°$ active boring bar.

Active Vibration Control

The results of the active control of boring bar vibrations are illustrated as power spectral densities of boring bar vibrations with and without active vibration control. Two different boring bars where tested with an actuator mounted in different angles with reference to the cutting speed direction in the cutting speed-cutting depth direction plane. The performance of the two boring bars is evaluated using the filtered-x lms algorithm. Fig. 4a) shows the results of active vibration control using a boring bar where the actuator was mounted just in the cutting speed direction. Fig. 4b) shows the results of the active system using the other boring bar where the actuator is mounted in between the cutting speed and the cutting depth directions. Comparing these figures it is evident the boring bar with the actuator in the cutting speed direction is able to attenuate the vibrations better than with the other boring bar. Fig. 5a) and b) also shows that the vibration level was not only suppressed in the cutting speed direction but also that significant vibration reduction was found in the cutting depth direction.

SUMMARY

Active vibration control in boring operations clearly is a possible solution to reduce the vibrations present in this kind of machining. Embedding the actuator and accelerometer into the boring bar enables the design to be applicable to a general lathe as long as the mounting arrangement is fairly similar. Embedding the electronic devices also protects them from the harsh environment in a lathe. The metal chips from the cutting process and the cutting fluids would otherwise constitute big problems to the actuator and accelerometer.



a) b)

Figure 4: Power spectral densities of boring bar vibration in the cutting speed direction with and without active vibration control using in a) a 0° and in b) a 30° active boring bar. The cutting speed was 80 m/min, the cutting depth was 1.0 mm and in a) the feed rate was 0.2 mm/rev and in b) 0.3 mm/rev.

During continuous cutting operations the workpiece apply boundary conditions on the tool tip that are different compared to the free conditions obtained when the boring bar is not in contact with the workpiece [1, 2]. This will affect the fundamental bending modes of the boring bar, see Fig. 3. Consequently, the control path usually differs between continuous cutting operations and when the boring bar is not in contact with the workpiece. A phase difference of approximately 90 degree generally occurs at the resonance frequency to be controlled, see Fig. 3. To obtain a practical estimation of the control path, usually requires that the control path is estimated off-line, i.e. the boring bar is not in contact with the workpiece. With a phase error of approximately 90 degree in the forward path estimate the feedback filtered-x LMS will not converge and adaptive control of boring bar vibration is not possible. This problem may be reduced by using a forward path estimate with a 180 degree phase shift of the resonance frequency to be controlled distributed over a wider frequency band as compared to the actual forward path. A short FIR-filter off-line estimate of the control path thus enables sufficient phase accuracy for the adaptive control of bar vibration, see Fig. 3.

Two boring bars were developed for the experiments. They were both based an a standard boring bar WIDAX S40T PDUNR15 with a diameter of 40 mm and an overall length of 300 mm where 200 mm constitutes the protruding part. The difference between the active boring bars is the angle between the cutting speed direction and where the force through the actuator was applied in the cutting speed-cutting depth direction plane. Applying the actuator in the cutting speed direction showed best results in terms of vibration attenuation, compare Figs 4a) and b). Although the control systems aims at attenuating the vibration level in the cutting speed direction significant

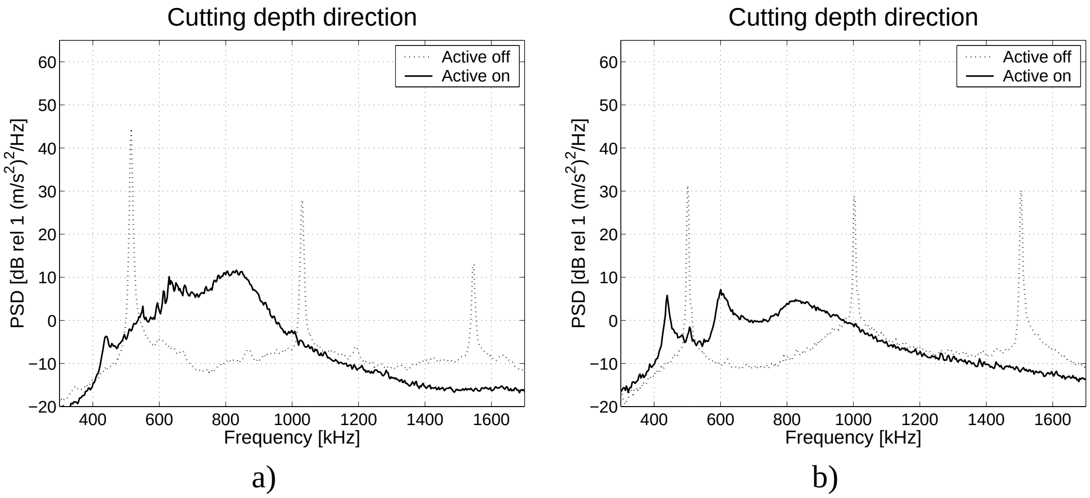


Figure 5: Power spectral densities of boring bar vibration in the cutting depth direction with and without active vibration control using in a) a $0°$ and in b) a $30°$ active boring bar. The cutting speed was 80 m/min, the cutting depth was 1.0 mm and in a) the feed rate was 0.2 mm/rev and in b) 0.3 mm/rev.

reduction was also achieved in the cutting depth direction, see Figs 5a) and b).

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