Active control of machine tool vibrations in external turning operations

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Abstract: Vibration and noise in metal cutting are ubiquitous problems in the workshop. The external turning operation is one kind of metal cutting that exhibits vibration-related problems. Severe noise is also a problem growing in proportion due to regulations in preventing hearing loss. Active vibration control is a potential solution to such problems. With the piezoceramic actuator technology of today, the size of the actuator can be kept small and still be able to produce a sufficient amount of force for the antivibrations. Results from several continuous cutting experiments show a 40 dB reduction of the cutting tool vibration level. The design of the active technique enables this technology to be applicable to a general lathe, provided the mounting arrangement is fairly similar.

Keywords: active vibration control, piezoceramic actuator, filtered-X LMS, turning operation

1 INTRODUCTION

The lathe is a very useful and versatile machine in the workshop. In metal cutting, vibration and noise are frequent problems. This paper deals with active vibration control in external turning operations. The vibration during a cutting operation affects the accuracy of the machining, which in turn affects the surface finish. Severe noise is also an important factor which is induced by tool holder vibration. Today the standard procedure to avoid vibration during machining is by careful planning of the cutting parameters. The methods are usually based on experience and trial and error to obtain suitable cutting data for each cutting operation involved in machining a product.

Research in vibration-related problems in metal cutting is important. A survey of past research in cutting dynamics is found in reference [1]. An attempt to determine the dynamics of the structure of a lathe and dynamics of the metal cutting can be found in references [2], [3] and [4]. Other approaches to control the vibrations in turning operations exist; in reference [5], the approach was to vary the cutting depth to alter the dynamic coupling between the cutting tool and workpiece. In references [6] and [7], the method to control the vibration in turning operations was to vary the speed of the spindle.

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 actuator and accelerometer from the metal chips and cutting fluid is necessary. Another goal was to make the active control system applicable to a general lathe. Embedding the active parts, i.e. the actuator and accelerometer, 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 piezoceramic actuators the technique is possible to embed into a tool holder. Milling a space in the tool holder reduces the stiffness, but with the piezoceramic actuator technology the space can be kept small; hence the stiffness reduction is moderate.

In active vibration control applications actuators excite the structure such that the vibration level is minimized at measurement points where accelerometers are placed. In external turning operations most vibrations are induced in the cutting speed direction [8]; thus active control in that direction is an adequate approach. A complication is that the accelerometer sensing the vibrations in the tool holder measures the vibrations both from the cutting process and the actuator. Since the original excitation, the cutting process itself cannot be observed directly and the control system must be built on a feedback approach. A cutting operation has non-stationary properties [9] and an algorithm that is able to work under these conditions is, for example, a feedback version of the filtered-X LMS algorithm [10].

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2 MATERIALS AND METHODS

2.1 Experimental set-up

The cutting trials have been carried out in a MAZAK 250 Quickturn lathe. The tool holder is described in section 2.2 in conjunction with the controller and the underlying algorithm is illustrated in section 2.3. The piezoceramic stack actuator is able to apply loads up to 1000N and was powered by a custom-designed amplifier for capacitive loads. The workpiece material was chromium molybdenum nickel steel (SS 2541-03) and the cutting tool had geometry DNMG 150508-SL. The cutting data used were cutting speed \( v = 80 \text{ m/min} \), cutting depth \( a = 0.9 \text{ mm} \) and feed rate \( x = 0.25 \text{ mm/rev} \). The workpiece diameter was chosen large (over 100 mm) in order to render the workpiece vibrations negligible.

2.2 Active tool holder

The active tool holder is based on a standard tool holder with base and height of 25 mm. The modifications involve milling a space into the bottom of the tool holder. This modification reduces the bending stiffness of the tool holder by 20 per cent, not including the preloaded actuator mounted in the milled space. A schematic model of the tool holder is shown in Fig. 1. A space for the accelerometer is also milled into the design, but since the accelerometer is small the reduction of stiffness is negligible. The accelerometer is mounted as close as possible to the cutting tool where the vibrations are to be minimized. Embedding and sealing the electronic devices protects the sensitive parts from the harsh environment in a lathe. It also enables the design to be fitted in different kinds of lathes with similar mounting arrangements.

2.3 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. 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 in order to ensure convergence [10]. The cutting process has non-stationary properties [9] 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 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 fed with pseudo-random noise generated by the DSP to minimize the hysteresis and non-linear effects of the actuator. The result of the identification is an FIR (finite-duration impulse response) filter used in the filtered-X LMS algorithm.

The search for a minimum can be performed by the feedback filtered-X LMS algorithm [8]. The input \( x(n) \) at sample \( n \) to the adaptive algorithm is the previously sampled accelerometer signal \( e(n-1) \):

\[
x(n) = e(n-1)
\]

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 [8].

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

\[
y(n) = w^T(n)x(n)
\]

where \( x(n) = [x(n), x(n-1), \ldots, x(n-M+1)]^T \) and \( M \) is the length of the adaptive filter. The output of the adaptive filter is fed 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 \( y_e(n) \) and the vibration from the cutting process \( d(n) \), and is sensed by the accelerometer

\[
e(n) = d(n) + y_e(n)
\]

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 \( c^* \) to ensure convergence. The filtered input signal is

\[
x_c(n) = c^*T x(n)
\]

where \( c^* \) is a vector containing FIR coefficients of the estimated forward path. The LMS algorithm updates the filter weights in the negative direction of the gradient with a step size \( \mu \):

\[
w(n) = w(n-1) - \mu x_c(n)e(n)
\]

where \( x_c(n) = [x_c(n), x_c(n-1), \ldots, x_c(n-M+1)]^T \). The algorithm loops equations (1) to (5) to continuously produce a control signal for the active tool holder.

Limiting the energy in the control signal yields more robust behaviour and incorporating a leakage factor \( \gamma \) when updating the filter coefficients will have that effect [11]. Including a leakage factor will change the equation of filter coefficients adaptation in equation (5) to

\[
w(n+1) = \gamma w(n) - \mu x_c(n)e(n)
\]

where \( \gamma \) is a real positive number satisfying the condition \( 0 < \gamma < 1 \); typically \( \gamma = 0.99 \).

3 RESULTS

The aim of the active vibration control system was to reduce the vibrations in the tool holder in the cutting speed direction. To demonstrate the performance of the control system power spectral densities of tool vibration have been estimated with and without active vibration control. Figure 3 shows that the vibration in
the tool holder is attenuated by approximately 40 dB using this active control system. The effect on the surface finish is shown in Fig. 4. The finish of the surface is improved significantly using the active vibration control technique.

More results of this active control technique can be found in references [12] and [13]. The properties and estimation of the forward path is described in reference [12] and the performance of the more robust leaky filtered-X LMS algorithm is illustrated in reference [13].

4 SUMMARY AND DISCUSSION

Piezoceramic actuators and the feedback filtered-X LMS algorithm constitute a solid platform for an active vibration control application in external turning operations. Using the active technique enables a substantial reduction of the vibration level at the cutting tool. Power spectral density estimates show an attenuation of vibration of 40 dB at approximately 3.3 kHz. Furthermore, there was a remarkable improvement in the surface finish of the machined workpiece.

Embedding the actuator and accelerometer makes the design applicable to a general lathe as long as the mounting arrangement is similar. The only extra modification needed to the lathe is to install a cable between the active tool holder and the control system. Embedding the electronic parts into the design simplifies the sealing, which protects the actuator and accelerometer from the harsh environment in a lathe.

The controller seems to be robust; however, the feedback version of the filtered-X LMS algorithm is complicated to analyse mathematically. The robustness of the controller can be increased by incorporating a leakage factor into the algorithm, but at the expense of degraded performance.

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