Active Control of Boring Bar Vibration in Cutting Operations

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Abstract

Internal turning or boring operations have a history of being a cumbersome manufacturing process. The manufacturing industries are facing tougher tolerances of their product surfaces and a desire to process hard to cut materials and therefore the vibrations must be kept to a minimum. An increase in the productivity is also interesting from a production point of view. When cutting in pre-drilled holes the boring bar is usually long and slender and is thereby inclined to vibrate destructively concerning the machining result. The knowledge of the vibrations involved in boring operations and active control of external turning operations, have given a good basis for the active control solution in boring operations. The active control solution is based on a standard boring bar with an embedded piezo ceramic actuator placed at the peak modal strain of the boring bar. An accelerometer is also included in the design, mounted as close as possible to the cutting tool. The control algorithm is a filtered X LMS algorithm built on a feedback approach since the original excitation, the cutting process, cannot be observed directly. Preliminary results show reduction of the vibration in the boring bar by up to 30dB.

Introduction

Boring operations have a history of being a cumbersome metal cutting process in the workshop. Several boring operations are simply not possible to perform and in many boring operations it is impossible meet the desired tolerances. The problem with boring operations is vibration related. Frequently, boring bars are long and slender and as a consequence they are usually sensitive to excitation forces introduced by the material deformation process in the turning operation. When the boring bar vibrates the surface finish is deteriorated. The tool life is also likely to be dependent of the amount of vibrations induced in the cutting operation. Severe acoustic noise is also an undesired result of the boring bar vibrations.

In boring operations the boring bar motion usually have components in both the cutting speed direction and the cutting depth direction [1]. The boring bar vibrations are usually dominated by the two first resonance frequencies of the boring bar and the vibration levels are generally largest in the cutting speed direction [1]. Thus active control of boring bar vibrations in the cutting speed direction is likely to be a good first step to a solution to the noise and vibration problem in boring operations.

One important objective in the research on active control of boring bar vibration is a control solution that is possible to incorporate into standard lathes. By embedding both piezo ceramic actuators and an accelerometer in a boring bar it is possible to obtain an active solution to the boring bar vibration problem. If small piezo ceramic actuators are used, the space where the actuator is placed can be small and accordingly the bending stiffness of the boring bar is not reduced significantly. This boring bar construction is thus based on a standard boring bar and will thereby fit any lathe able to perform boring operations in the workshop. The only modification required is 2 wires that needs to be connected between the control system and the boring bar.

The original excitation, the cutting process, cannot be observed directly consequently the algorithm ought to be based on a feedback approach. The response of the boring bar is measured by an accelerometer mounted as close as possible to the cutting tool, where the vibrations should be kept to a minimum. The secondary vibrations are introduced via an actuator mounted in the feed direction to impose a bending moment in the boring bar. A suitable algorithm is a filtered X LMS algorithm [2].

This paper discusses single channel feedback control of boring bar vibration. In Fig. 1 the boring or internal turning operation is illustrated.

Materials and Methods

Experimental Setup

The cutting trials have been performed in a MAZAK quickturn 250M. A CNC turning center with 18.5 kW spindle power, maximum machining diameter 300 mm and 1007 mm between the centers. The boring bar construction is based on an embedded design with a piezo ceramic stack actuator and an accelerometer mounted on the boring bar to make it possible to measure the vibrations in the cutting speed direction. In order to operate the piezoelectric stack actuator a custom designed amplifier was used. A

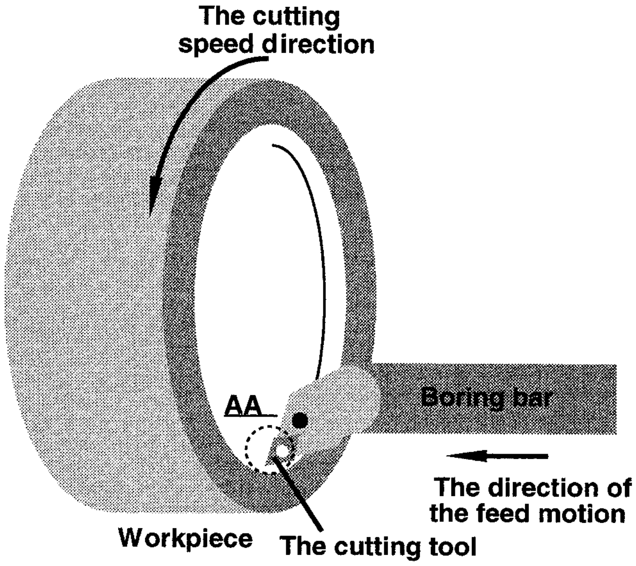

Figure 1: The internal turning operation.

digital signal processor controller was used and the measurements were recorded on a DAT-recorder. Furthermore, a two channel low-pass filter was used to adjust the input level to the A/D converter and the output level from the D/A converter.

Work Material, Cutting tool and Cutting Data

The material of the workpiece used in the cutting trials was chromium molybdenum nickel steel. After a preliminary set of cutting trials a combination of cutting data and tool geometry was selected, see table 1. The diameter of the workpiece was deliberately chosen large (> 150 mm), in order to render the workpiece vibrations negligible.

Geometry	Cutting speed, v (m/min)	Depth of cut, a (mm)	Feed rate s (mm/rev)
DNMG 150508-SL 7015	117	0.4	0.22

Table 1: Cutting data and tool geometry.

Active Boring Bar

In order to control the vibrations of a boring bar it is essential to select a location for the actuator so that the secondary vibrations are introduced into the vibrating modes of the boring bar. One way to introduce the secondary vibrations is to embed an actuator 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. A schematic figure of the active boring bar is shown in Fig. 2

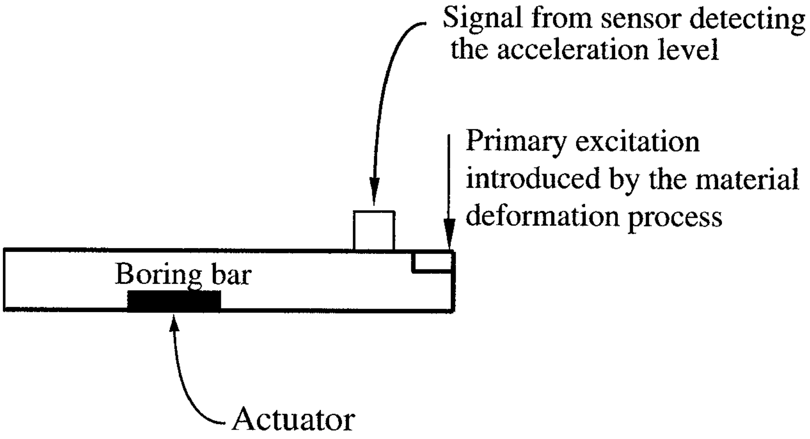

Figure 2: A schematic figure of the active boring bar with actuator and accelerometer.

The boring bar vibrations introduced by the stochastic chip formation process are in both the cutting speed and the cutting depth directions. By introducing secondary anti-vibrations, trough the actuator induced bending moment in the tool holder, the original vibrations from the cutting process may be reduced in both directions.

Adaptive Control System

The original excitation, the cutting process, cannot be observed directly consequently the algorithm ought to be based on a feedback approach. The response of the boring bar is measured by an accelerometer mounted as close as possible to the cutting tool, where the vibrations should be kept to a minimum. The secondary vibrations are introduced via an embedded actuator in the boring bar. A suitable control algorithm is a filtered X LMS algorithm. A block diagram of the feedback control system is shown in Fig. 3.

The reason for choosing filtered X LMS instead of an ordinary LMS algorithm is due to the so called forward path, which always is present in control applications [3]. Adaptive filters, e.g. the LMS algorithm, are normally defined for problems where the filter output is an estimate of a desired signal [4]. In control applications, however, the adaptive filter estimate, e.g. anti-vibrations, of a desired signal is the output signal from the forward path [3]. In our case the output signal from the adaptive filter has to pass a D/A converter, a amplifier, a actuator and a transfer path in the boring bar before the estimate is produced and sensed by the accelerometer. A block diagram showing the feedback filtered X LMS algorithm is shown in Fig. 3. In Fig. 3 the box with the unit delay operator z^{-1} at the input to the controller handles the fact that we are dealing with an adaptive digital filter in a feedback control system. C denotes the true forward path and C^* is the estimate of the forward path.

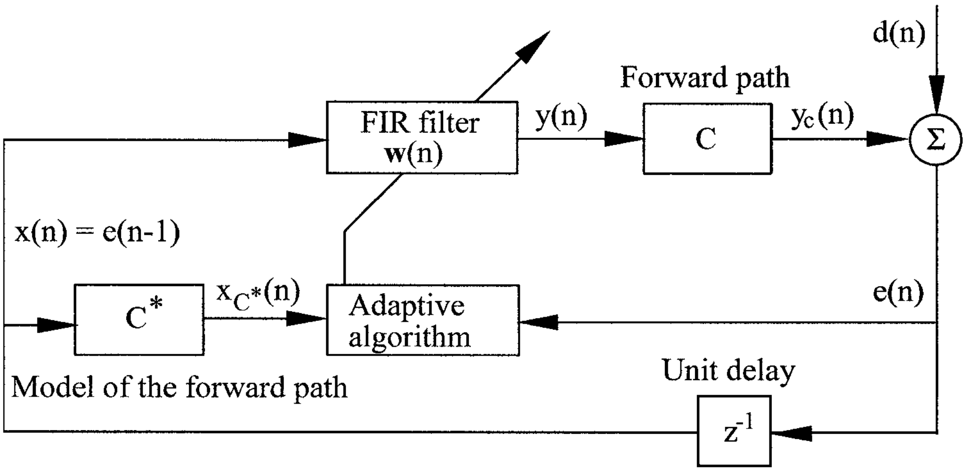

Figure 3: A block digram of the filtered X LMS algorithm used in the adaptive feedback control system.

The use of an error signal as input to the control algorithm will cause the algorithm to act 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. The search for a minimum in the mean square error sense can be performed by a filtered X LMS algorithm, which is defined by [2]

$$y(n) = \mathbf{w}^T(n)\mathbf{x}(n) \tag{1}$$

$$e(n) = d(n) - y_C(n) \tag{2}$$

$$\mathbf{x}_{C^*}(n) = \mathbf{c}^{*T}\mathbf{x}(n) \tag{3}$$

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\mathbf{x}_{C^*}(n)e(n) \tag{4}$$

where $\mathbf{x}_{C^*}(n)$ is the filtered reference signal vector.

It is in practice customary to use an estimate of the impulse response for the forward path. As a result, the reference signal $\mathbf{x}_{C^*}(n)$ will be an approximation, and differences between the estimate of the forward path and the true forward path influence both the stability properties and the convergence rate of the algorithm [3, 4, 5, 6].

The forward path was estimate in an initial phase by using the LMS algorithm and pseudo random noise. In the control of boring bar vibration a 20-tap adaptive FIR filter was used together with a 40-tap FIR filter estimate of the forward path. A 4 kHz sampling rate was chosen for the digital filter.

Results

To evaluate the active control of boring bar vibration during a continuous boring operation power spectral densities of boring bar vibrations have been measured with and without active vibration control, in both the cutting speed and the cutting depth directions. Fig. 4 shows power spectral densities of boring bar vibration in the cutting speed direction and Fig. 5 is from the cutting depth direction. The active technique shows an attenuation of the vibration of 25 dB in both the cutting speed and the cutting depth directions. The first three harmonics of the dominating resonance peak are attenuated approximately 30 dB in both the cutting speed and the cutting depth directions.

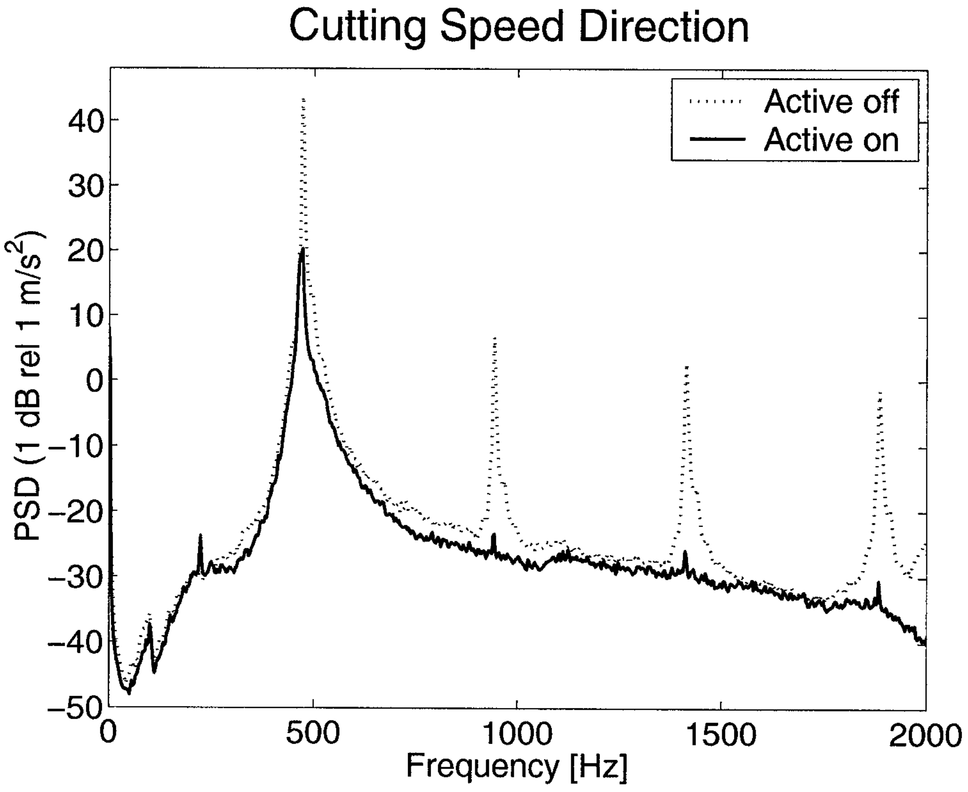

Figure 4: Power spectral density of boring bar vibrations with and without active vibration control in the cutting speed direction .

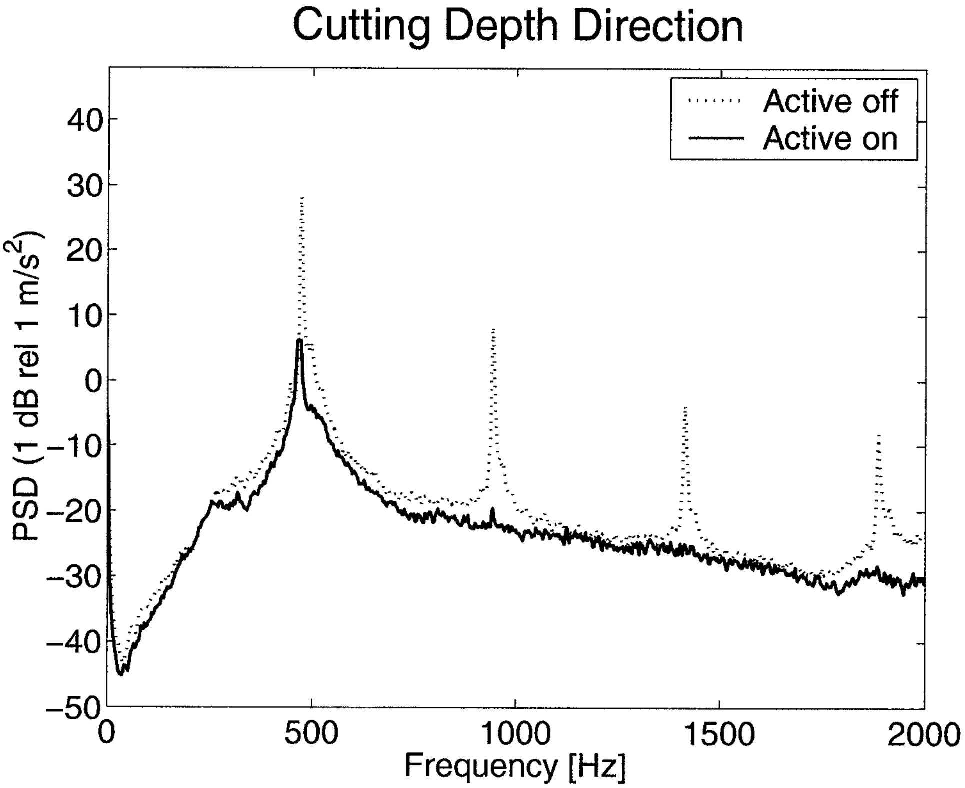

Figure 5: Power spectral density of boring bar vibrations with and without active vibration control in the cutting depth direction .

Summary

Active control in boring operation is a suitable solution to the noise and vibration problem. The embedded design of the actuator and accelerometer enables the technique to be applicable to a standard lathe used by the industry without any large modifications. The adaptive algorithm showed stable behavior during the cutting experiments. A leaky version of the algorithm is implemented but not tested yet. Incorporating a leakage factor is making the algorithm even more robust.

Future work in this project involves comparing different actuator placements. Investigating the possibility of controlling the vibrations in the cutting speed and the cutting depth direction separately by embedding two actuators, is also an important task. Although the control algorithm gave no sign of being unstable it is urgent to do further tests in that area. Looking at other control algorithms is also important.

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