M2VIP 2002

# Active Control of Internal Turning Operations Using a Boring Bar

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**Abstract:** Vibrations in internal turning or boring operations are usually a cumbersome part of the manufacturing process. The manufacturing industries are having problems with these kinds of cutting operations. When cutting in pre-drilled holes the cross sectional area of the boring bar is limited at the same time as it is long. Since a general boring bar is long and slender it is sensitive to external excitation and thereby inclined to vibrate. The vibration problem affects the surface finish in particular. The demand for smaller and smaller tolerances of the surface finish leads to that the manufacturing industry seeks for a solution to the boring bar vibration problem. The tool life is also likely to be influenced by the vibrations involved in a cutting operation. Another problem in boring operations is the high noise level in the cutting process. The noise level in the environment of the operators is today more and more regulated, especially in the western world. Active vibration control will reduce the amount of vibrations in the cutting operations. Since the noise is induced by the vibration of the boring bar, the noise level will also be reduced due to the cancellation of the noise source. Preliminary results show reduction of vibrations in the boring bar by up to 30dB.

**Keywords:** Active vibration control, Boring bar, Piezo actuator

## 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 to meet the desired tolerances. The majority of the problems in boring operations are vibration related. Common boring bars are long and slender and as a consequence they are sensitive to excitation forces, such as the forces in metal cutting. When the boring bar vibrates the surface finish is deteriorated. The tool life is also likely to be influenced by the amount of vibrations induced in the cutting operation. Severe noise in the operator area is also frequently a result of the boring bar vibrations. In boring operations the motion of the boring bar has components in both the cutting speed and the cutting depth directions [1]. The vibrations are usually dominated by the first two resonance frequencies of the boring bar, one resonance in each direction. The vibration level in the cutting speed direction is generally larger than the vibration level in the cutting depth direction [1]. Thus active vibration control in the cutting speed direction is a good first step towards a solution to the noise and vibration problem in boring operations.

The active control of boring bar vibration involves a secondary source, driven in such a way that it will interfere destructively with the original vibration induced by the cutting operation. A complication in cutting operations is that the original excitation cannot be observed directly, thus the control system must be based on a feedback approach. An actuator is used as a secondary source and an accelerometer is needed to provide the control algorithm with sufficient information regarding the boring bar vibration. The boring bar is modified to fit a piezo ceramic actuator and an accelerometer. The actuator and accelerometer are embedded and sealed to protect them from cutting fluid and the chips from the metal cutting operation.

During the machining of a workpiece, variations in the spectral properties of boring bar vibrations are likely to occur. Variations in the spectral properties are caused by changes in the excitation of the boring bar and/or changes in the structural response of the boring bar. A solution to the controller problem is to use an adaptive FIR filter controller that is able to handle the nonstationary environment introduced by the cutting process. Such a control algorithm is the feedback filtered X LMS algorithm. The reason for choosing this algorithm was due to a so-called forward path or secondary path. The forward path is the difference between the output of the controller and the input of the accelerometer. An estimate of the forward path is needed to reduce the effects of A/D converters, amplifier, transfer path in the boring bar and D/A converters. The forward path is estimated in an initial phase before the actual control of boring bar vibration by using an ordinary LMS algorithm.

One of the objectives in this research project was to find a control solution that fits in a standard lathe. Since both the actuator and the accelerometer are embedded into a standard boring bar, the only modification that is required on a standard lathe to enable the active control of tool vibration is the installation of signal cables to the actuator and accelerometer.

This paper discusses single channel feedback control of boring bar vibrations in boring operations. In Fig. 1 a boring operation is illustrated.

## Materials and Methods

### Experimental Setup

The cutting trials have been carried out in a Mazak SUPER QUICK TURN - 250M CNC turning center, see Fig. 2. With 18.5 kW spindle power, maximal machining diameter 300 mm, with 1007 mm between the centers. The boring bar is based on a standard WIDAX S40T PDUNR15 boring bar, see Fig. 3. It is modified to fit a piezo ceramic stack actuator and an accelerometer to enable active vibration control. The amplifier used was custom designed for piezo ceramic actuators.

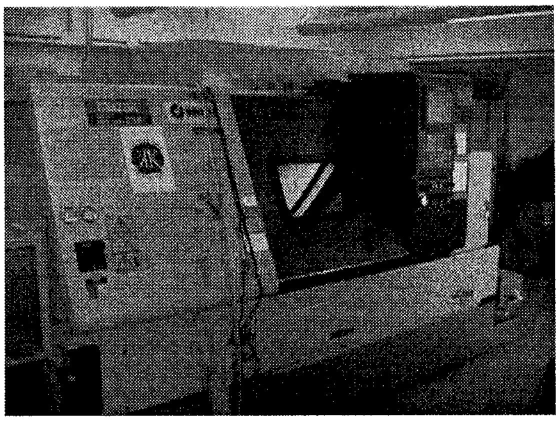

Figure 2: The lathe where the experiments were carried out.

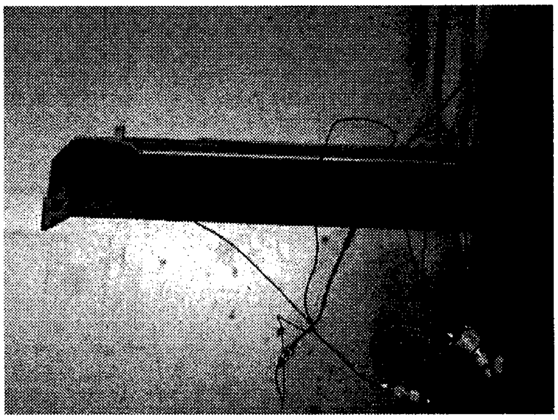

Figure 3: The modified active boring bar used in the experiments.

### 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.

### Active Boring bar

A considerable part in an active control application is to select a proper location for the

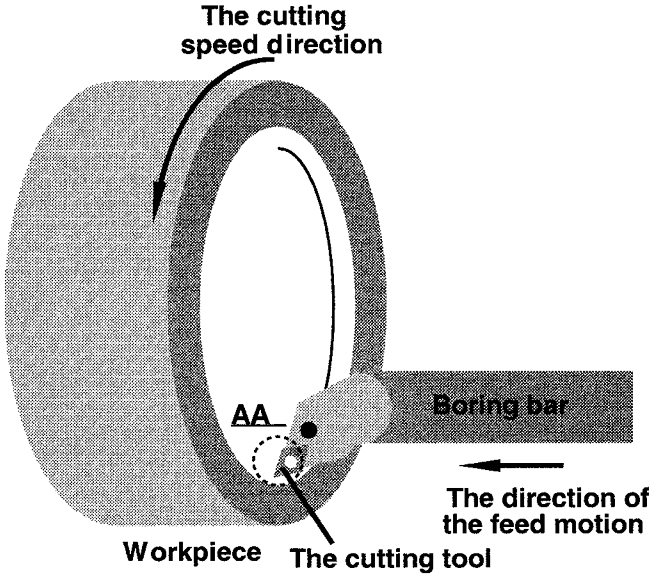

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Figure 1: A schematic picture of a boring operation.

| 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.

actuator. The actuator must introduce vibrations into the vibrating modes of the boring bar. The actuator is embedded in the length direction below the centerline of the boring bar. When the actuator applies load on the boring bar in its length direction, due to the expansion of actuator, the boring bar will bend. A schematic picture of the active boring bar is shown in Fig. 4. The active boring bar also incorporates an accelerometer, embedded as close as possible to the cutting tool.

## Control System

In boring operations it is impossible to measure the primary excitation, i.e. the excitation induced by the cutting process. A system based on a feedforward solution is consequently not possible, hence the control system must be based on a feedback approach. Another important matter in selecting a proper algorithm is that the error estimate is not the difference between the output signal from the adaptive filter and the desired signal. The only signal available is the signal from an accelerometer sensing the acceleration of the boring bar. The error estimate in our case is the vibrations induced by the actuator that are summed with the vibrations originated from the cutting process. The output signal from the adaptive filter will be filtered by a D/A converter, amplifier, actuator and the transfer path in the boring bar before it is picked up by the accelerometer. The transfer path the output signal from the adaptive filter has to pass before it is sensed by the accelerometer is called forward path or secondary path and is present in active control applications. A suitable control algorithm must be able to handle these kinds of conditions and such an algorithm is the filtered X LMS algorithm.

The use of an error signal as input to the control algorithm causes the algorithm to act as

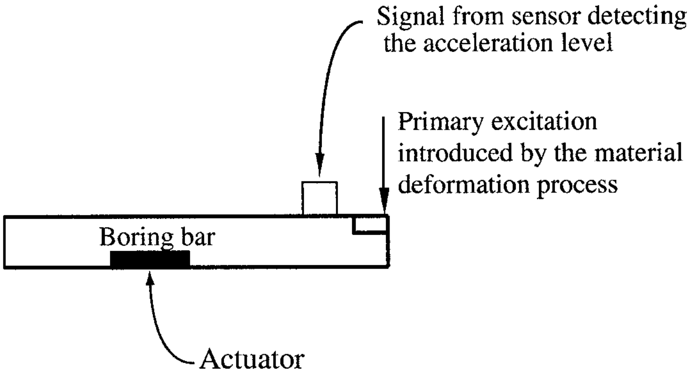

Figure 4: A schematic figure of the active boring bar with embedded actuator and accelerometer.

a feedback controller. A block diagram of the feedback filtered X LMS algorithm is shown in Fig. 5. The unit delay $z^{-1}$ handles the fact that we are dealing with adaptive digital filter in a real time environment, $C$ denotes the actual forward path and $C^*$ is the estimate of the forward path. $y(n)$ is the output signal from the adaptive FIR filter, $d(n)$ is the original excitation, $y_c(n)$ is the vibrations induced by the actuator and $e(n)$ is the signal from the accelerometer. The search for a minimum in the mean square sense is performed by the filtered X LMS algorithm which is given by [2]

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

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

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

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

where $\mathbf{x}_{C^*}(n)$ is the filtered reference signal vector. The difference between the estimate of the forward path and the true forward will affect both the stability and the convergence rate of the adaptive controller [3]. By using the error signal as input to the filtered X LMS algorithm, 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 forward path is estimated in an initial phase using an ordinary LMS algorithm. During the estimation the actuator is feed with pseudo random noise in order to minimize the hysteresis effects of the actuator. The hysteresis is highly variable based on different load and acceleration values. In the active control of boring bar vibrations the estimate of the forward path based on a FIR filter with 40 coefficients, the adaptive filter had 20 coefficients and the sample rate in the DSP was 8 kHz.

## Results

To evaluate the performance of the active control of boring bar vibrations power spectral densities have been estimated of the vibrations with and without active vibration control. The spectra are based on the acceleration signals from the accelerometers during a continuous boring operation in both the cutting speed and the cutting depth directions. In the cutting speed direction the accelerometer to provide an error signal for the control system was used. In the cutting depth direction an extra accelerometer was mounted in the boring bar for evaluation purposes.

The forward path is estimated in an initial phase. The 40 estimated FIR filter coefficients are shown in Fig. 6. An estimate of the amplitude and phase function of the forward path, based on 60 seconds time data during the identification process, is shown in Fig. 7.

The performance of the active control solution in boring operations is illustrated in Figs. 8 and 9. Fig. 8 shows the vibrations in the cutting speed direction with and without active control and Fig. 9 shows the vibrations in the cut-

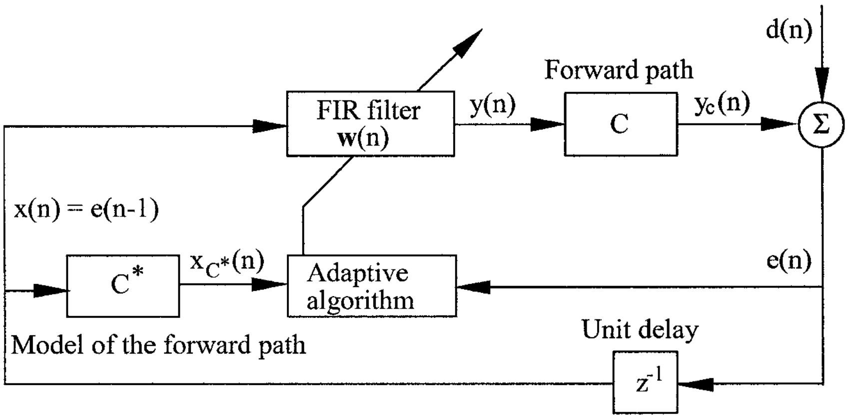

Figure 5: A block digram of the filtered X LMS algorithm used in the adaptive feedback control system.

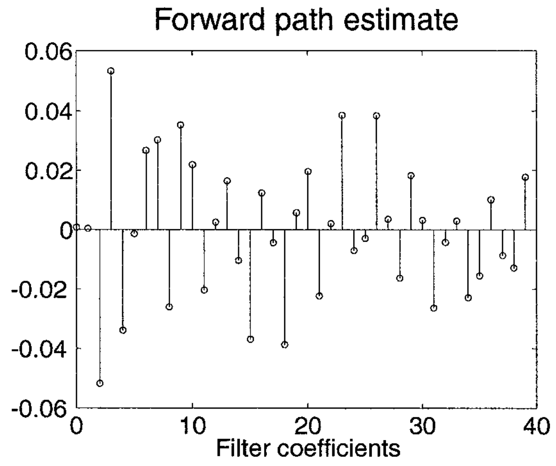

Figure 6: The FIR filter coefficients of the forward path used to filter the reference signal in the filter X LMS algorithm.

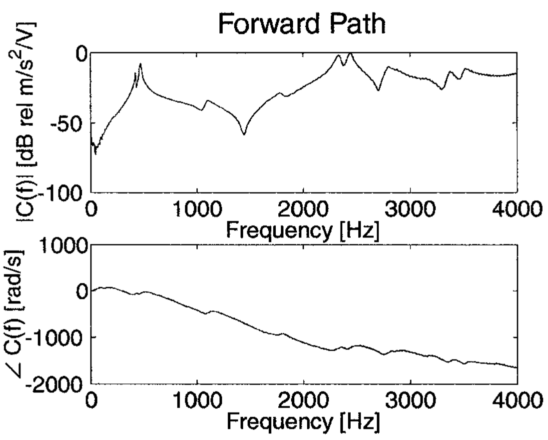

Figure 7: Estimate of the amplitude and phase function of the forward path based on 60 seconds time data from the identification process.

ting depth direction with and without active control.

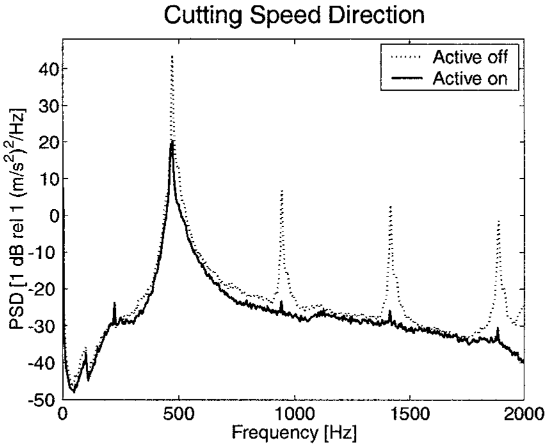

Figure 8: Power spectral density of boring bar vibrations with and without active vibration control in the cutting speed direction.

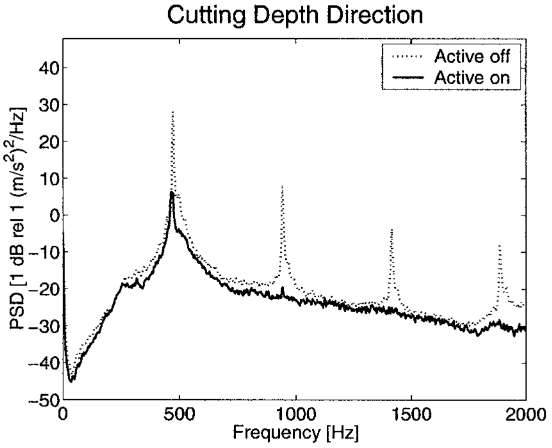

Figure 9: Power spectral density of boring bar vibrations with and without active vibration control in the cutting depth direction.

The active control application is able to attenuate the vibrations in the boring by approximately 25 dB at the first two resonance frequencies. Several harmonics are also attenuated significantly. At the first harmonic in both the cutting speed and the cutting depth directions the attenuation was approximately 30 dB.

## Summary

Active vibration control appears to be a suitable solution for the noise and vibration problem in boring operations. By using small piezo ceramic stack actuators large forces can be applied to the boring bar at the same time as the space where the actuator is located can be kept small. The filtered X LMS algorithm showed stable behavior during the cutting experiments. A leaky version of the algorithm has been implemented but not tested yet. A leakage factor will make the algorithm even more robust.

This solution is based on a single piezo ceramic stack actuator but future work will include a solution with two actuators to be able to control the vibrations in the cutting speed and the cutting depth directions separately. Investigating different algorithms is also an important task in this project.

## Acknowledgement

We thank our industrial partner, Staffansboda Compagnie AB, Fänestadsvägen 8, 330 12 Forsheda, Sweden, for their participation.

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