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ANALOG AND DIGITAL APPROACHES OF ATTENUATION BORING BAR VIBRATIONS DURING METAL CUTTING OPERATIONS

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Abstract

In metal cutting operations tool vibration is a frequent problem. Vibrations appear under the excitation applied by the material deformation process during the machining of a workpiece. In order to perform an internal turning or boring operation, e.g. in a pre-drilled hole in a workpiece, it is generally required that the boring bar should be long and slender; therefore it is easily subjected to vibrations. These vibrations will affect the result of machining, in particular the surface finish, and also the tool life may be reduced. As a result of tool vibration severe acoustic noise frequently occurs in the working environment. The vibration problem is to a large extent related to the boring bar low-order fundamental bending modes. In order to control boring bar vibrations in the primary cutting direction an analog and a digital feedback controllers have been used. In both approaches an active boring bar with a built-in actuator has been used. In order to measure the response of the active boring bar, accelerometers are mounted nearby the area, where the excitation force is applied due to material deformation process. This means that in either approach the boring bar vibrations are attenuated actively by the controlled secondary anti-vibrations induced by the actuator. The digital controller, based on the feedback filtered-x LMS-algorithm, manages to reduce the boring bar vibrations in the primary cutting direction by up to approximately $44\ dB$ at the first bending resonance frequency. The analog controller, based on a flexible orthogonal gain and phase lag compensation, results in an attenuation of the boring bar vibrations in the primary cutting direction by up to approximately $40\ dB$ at the first bending resonance frequency. Both controllers also suppress all the harmonics of the first bending resonance frequency. Vibration attenuation performances of the two controllers are compared and discussed.

INTRODUCTION

Vibration is a general problem in metal cutting operations like external and internal turning, boring, milling etc. The vibrations affect the surface finish of workpiece, the tool life and the noise level in the surrounding environment. In order to increase productivity, tool life and tolerances of workpieces, high levels of vibrations must be avoided. There are several possible sources of boring bar vibrations: random excitation from the material deformation process, periodic excitation related to the residual rotor mass unbalance in the spindle-chuck-workpiece system , etc. [1]. The material deformation process excites broadband vibrations of the boring bar, which can be considered as a stochastic process with time varying parameters and non-linear characteristics. These vibrations can reach extremely high amplitude levels at frequencies corresponding to the low-order fundamental bending modes.

To reduce the harmful vibrations a number of methods have been proposed, these can be divided into three categories:

- "trial and error" - the operator tries to adapt the parameters of cutting process in an iterative way;
- passive control - constructional enhancement of the dynamic stiffness; can be achieved by increasing the structural damping and/or stiffness of the boring bar;
- active control- selective increase the dynamic stiffness according to the low natural frequencies of a particular system.

The trial and error approach requires continuous supervision and control of the machining process by a skilled operator. Passive control is frequently tuned to increase the dynamic stiffness at a certain eigenfrequency of e.g. a particular boring bar. This may results in redesign of the system, which is costly and inflexible solutions [2, 3]. Active control based on e.g. a adaptive feedback controller [4] and a boring bar with integrated actuator and vibration sensor can easily be adapted to different conditions, i.e. more flexible and thus likely to provide a preferable solution [5]. Active control of the boring bar can be implemented using either digital or analog approach. A digital controller based on feedback filtered-x LMS algorithm [6] results in high level of attenuation of vibrations, and exhibit stable behavior. However, it is of great interest to achieve same results by using analog controller, because of low complexity, cost and higher speed i.e. no extra delay is introduced as compared to the digital case.

MATERIALS AND METHODS

Experiment Setup

All experiments were carried out on a MAZAK 250 Quickturn lathe. It has 18.5 *kW* spindle power, a maximum machining diameter of 300 *mm* and 1007 *mm* between the centers. In order to protect sensitive measurement equipment from sharp chips and to have full control of the cutting process, the boring operations were performed as external turning operations. In the boring bar vibration control experiments an active boring

bar was used, i.e. standard WIDAX S40T PDUNR15 boring bar with an accelerometer and an embedded actuator. An accelerometer was mounted 25 *mm* from the tool tip to measure the vibrations in the cutting speed direction, since the largest excitation force component is in this direction. This position is selected as close as possible to the tool tip, but at a sufficient distance to avoid that the chips damage the accelerometer. The actuator was embedded into a milled space in the longitudinal direction below the centre line of the boring bar.

Measurement Equipment and Setup

Two different controllers were used in active control experiments: one adaptive digital controller steered by the feedback filtered-x LMS algorithm, and one analog controller, with an orthogonal gain and phase lag compensation. A block diagram of the experimental setup for both controllers can be seen in Fig. 1.
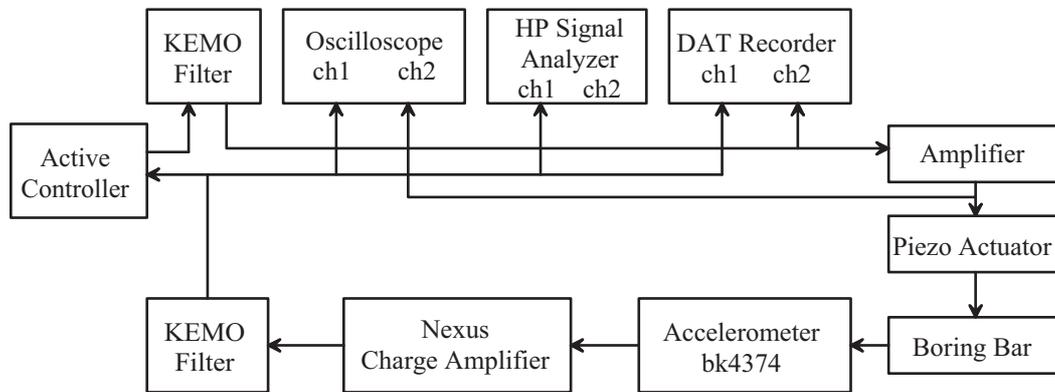
Figure 1: A block diagram describing the experimental setup for active vibration control system.

The following equipment was used in the experiment setup;

- 1 Brüel & Kjær 4374 accelerometer
- 1 Brüel & Kjær NEXUS 2 channel conditioning amplifier 2692.
- 2 KEMO Dual Variable Filter VBF 10M.
- TEAC RD-200T DAT recoder.
- A custom designed amplifier for capacitive loads.
- Active boring bar with embedded piezo ceramic actuator.
- Microphone PCB Piezotronics Inc.
- Texas Instrument DSP TMS320C32.
- Hewlett Packard 54601B Oscilloscope.
- Hewlett Packard 35670A Signal Analyzer.

Cutting Data and Machining Parameters

As a workpiece material chromium molybdenum nickel steel SS 2541-03 was used. The diameter of workpiece was in the order of 200 *mm* during the experiments. The above mentioned workpiece material excites narrow band boring bar vibrations in turning operations, which results in poor surface finish, tool fracture and severe acoustic noise levels.

As cutting tool a standard 55° diagonal inserts with geometry designed by ISO code 150618-SL, carbide grade TN7015 and chip breaker geometry for medium roughing was used. The cutting data was selected in order to obtain largest vibrations, which leads to significant workpiece surface deterioration. This choice of cutting data allows to test the performance of the controllers in a worst case scenario. After preliminary set of trials following cutting data was selected; feed rate $s = 0.2$ *mm/rev*, cutting depth $a = 1.5$ *mm* and cutting speed $v = 60$ *m/min*. This cutting data was used during experiments with both the digital and the analog controller.

Control Algorithms

The choice of the control algorithm can be explained by the phenomena of chip formation process (excitation source). This signal is impossible to measured separately to produced a feedforward reference signal, therefore a control algorithm should be based on feedback approach. The feedback signal was produced by an accelerometer mounted close to the tool tip where the excitation force is applied by the material deformation process.

Feedback Filtered-x LMS Algorithm

As a digital controller a feedback filtered-x LMS algorithm implemented in DSP was used. The algorithm is suitable in this application and gives a robust solution. The block diagram of feedback filtered-x LMS algorithm is shown in the Fig. 2 and can is described by equation (1-3).
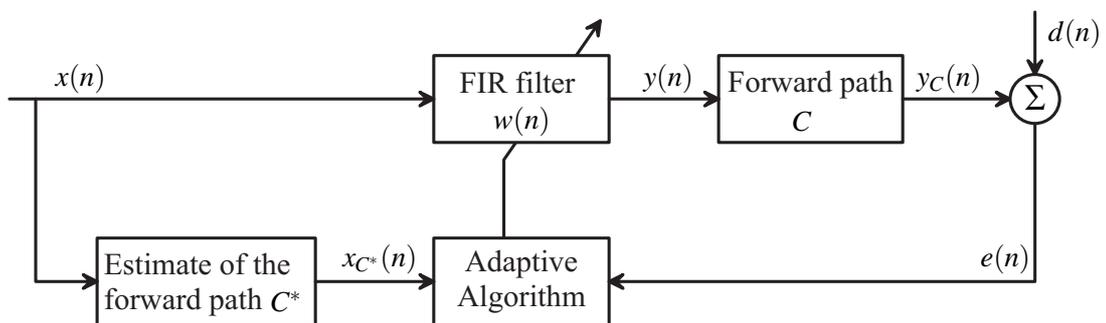

Figure 2: Block diagram of the feedback filtered-x LMS algorithm.

$$
\begin{aligned}
y(n) &= \mathbf{w^T}(n)\mathbf{x}(n) & (1) \\
e(n) &= d(n) + y_C(n) & (2) \\
\mathbf{w}(n+1) &= \mathbf{w}(n) - \mu\mathbf{x_{C^*}}(n)e(n) & (3)
\end{aligned}
$$

Where $w(n)$ is the FIR filter coefficient vector, $y(n)$ - the output from the FIR filter, $e(n)$ - the error signal, measured by the accelerometer, $y_C(n)$ - the secondary vibration, C^* - the estimate of the forward path, $d(n)$ - the disturbance signal (originates from the chip formation process), μ - the algorithm step size.

This algorithm uses an estimate of the forward path (D/A converter, amplifier, actuator and structural path in the boring bar) to produce an adequate direct gradient estimate that enables the minimization of the mean square error in the control application. The error is the sum of the disturbance signal and the signal induced by the actuator and transferred through the forward path. The estimate of the forward path was made with the use of the LMS algorithm prior to the active control.

Orthogonal Gain and Phase Lag Compensation Controller

This controller is implemented as an analog circuit, which consists of two parts: phase lead compensator in combination with an inverting operational amplifier. The phase lead compensator adjusts the phase, but also changes the amplitude. Thus the inverting operational amplifier attenuates with the same factor as the lead compensator amplifies and vice versa, in order to get an overall transfer function which only changes the phase or the amplitude. The block diagram of analog circuit is shown in the Fig. 3 a).

a)   b)
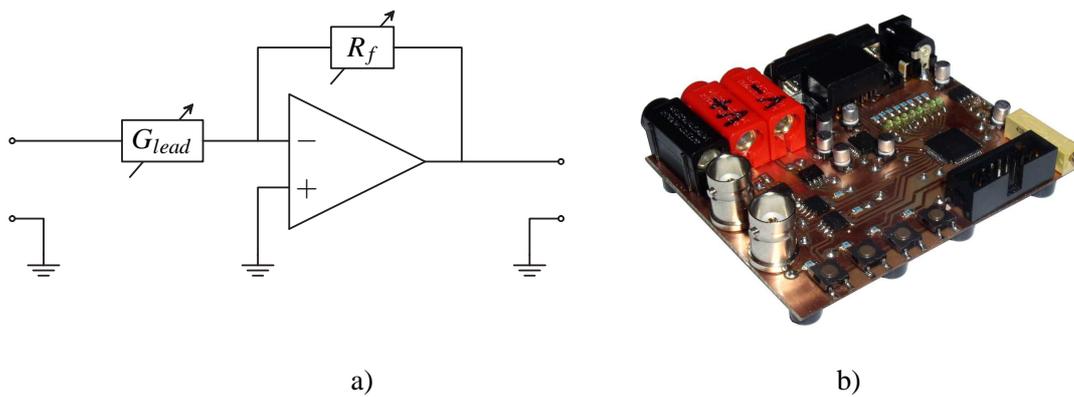
Figure 3: The orthogonal gain and phase lag compensation controller a) the block diagram and b) the analog controller implemented using standard circuits.

Where G_{lead} is the basic phase lead compensator.
The simplest case of the lead compensator consists of two resistors and one capacitor[7, 8]. The resistor R_f on the output of inverting amplifier controls the magnitude of the

signal and keeps it constant. Thus, the transfer function for the controller may be written as:

$$H(s) \; = \; -\frac{R_f}{G_{lead}(s)} \tag{4}$$

where s is the Laplace domain variable.

RESULTS

The results of active control of the boring bar vibrations are are presented with power spectral densities of boring bar vibration as well as power spectra of sound pressure levels with and without active vibration control.

Performance of Feedback Controller Based on Filtered-x LMS Algorithm

The feedback filtered-x LMS algorithm with following parameters was used in these experiments: number of coefficients M=20, step size =-0.5, sampling frequency of the DSP Fs=8 kHz.
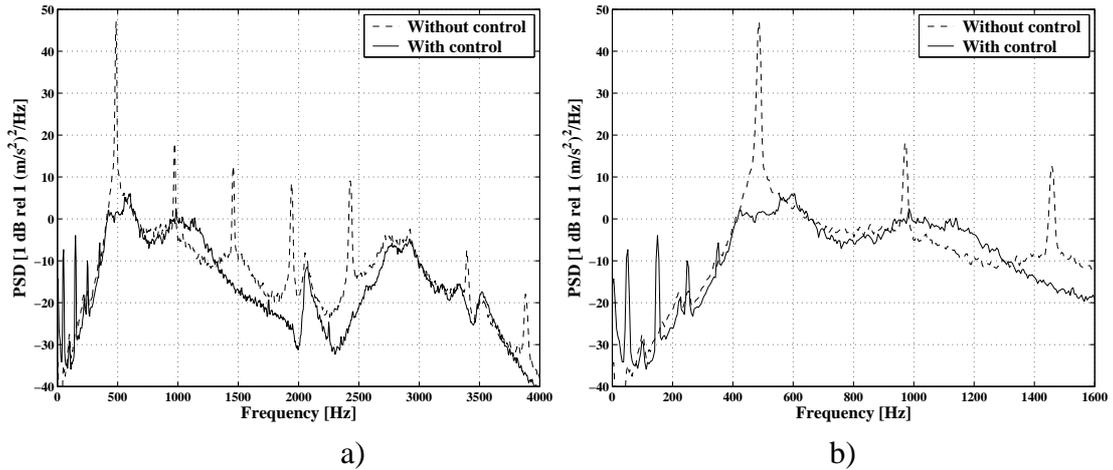

a)   b)

Figure 4: a) Power spectral densities of boring bar vibration in the cutting speed direction (solid line) with and (dashed line) without active control based on the filtered-x LMS algorithm and in b) the corresponding spectra zoomed in at the three first resonance peaks.

Performance of the Orthogonal Gain and Phase Lag Compensation Controller

The phase was tuned for the first bending mode frequency together with as large amplitude as possible while maintaining stable control. The phase and amplitude were then further adjusted in order to obtain robust control.

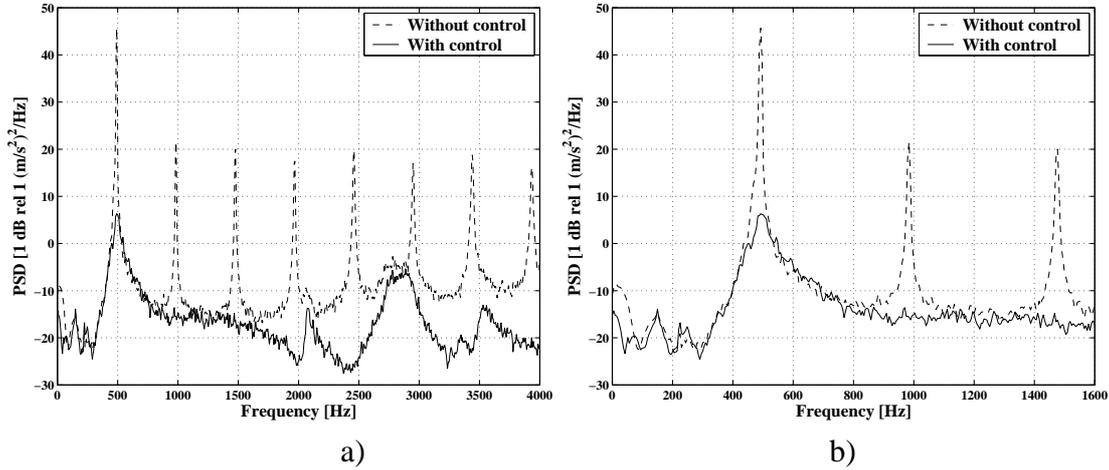a)   b)

Figure 5: a) Power spectral densities of boring bar vibration in the cutting speed direction (solid line) with and (dashed line) without active control based on the filtered-x LMS algorithm and in b) the corresponding spectra zoomed in at the three first resonance peaks.

Performance of Sound Pressure Level Attenuation

One microphone was placed near the operator position on the lathe during the experiments. The following power spectra of the sound pressure levels were obtained.
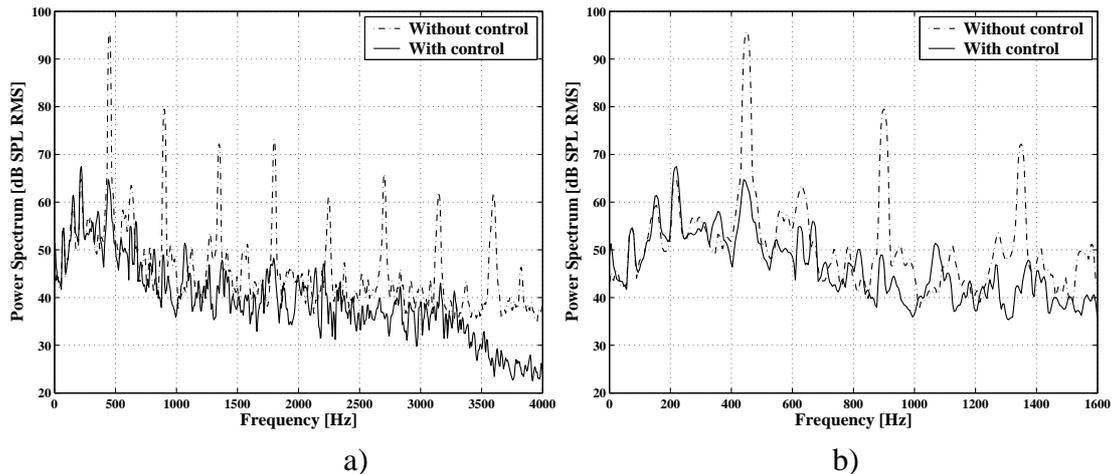

a)   b)

Figure 6: a) Power spectra of the sound pressure level (solid line) with and (dashed line) without active control based on the filtered-x LMS algorithm and in b) the corresponding spectra zoomed in at the three first resonance peaks.

CONCLUSION

Active vibration control is a powerful way of suppressing the boring bar vibrations during turning operations. The active boring bar in combination with the controller can be used in a general lathe and no essential redesign of the lathe is needed. The active control of the boring bar vibrations results in considerable attenuation of the first resonance peak as well as of its harmonics see Fig. 4 and 5. The results show that both approaches of controlling the boring bar vibrations yields high attenuation levels: above 40 dB for digital controller and up to 40 dB for analog. However, it can be noticed that these controllers work differently. The adaptive digital controller adjusts its output signal more selectively to de-correlate the residual boring bar vibrations with controller reference signal. This can be seen from better suppression of the first resonance peak. The analog controller is focused on attenuation of a wider band and does not succeed to fully de-correlate the first resonance peak. These levels of vibration attenuation lead to surface finish improvement, increased tool life and reduced sound pressure level of the acoustic noise induced by the boring bar vibrations. A significant suppression of the sound pressure level was obtained (up to 35 dB SPL RMS) with the usage of both controllers, see Fig. 6. Both controllers shows almost similar results. However, the digital controller based on the feedback filtered-x LMS algorithm is more expensive, since it contains DSP, A/D and D/A converters, but gives robust results. The analog controller, based on orthogonal gain and phase lag compensation, is rather inexpensive in implementation. However the analog circuit on the present step of development has one drawback - when using maximum attenuation it can result in stability problems. This is a common phenomenon within feedback control and is to be further developed.

ACKNOWLEDGEMENTS

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