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ACTIVE CONTROL OF MACHINE-TOOL VIBRATION IN A LATHE

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Abstract

In the turning operation the relative dynamic motion between cutting tool and workpiece, or vibration is a frequent problem, which affects the result of the machining, in particular the surface finish. The tool life is also influenced by the vibrations. When the working environment is considered, noise is frequently introduced by dynamic motion between the cutting tool and the workpiece.

By proper machine design, e.g. improved stiffness of the machine structure, the problem of relative dynamic motion between cutting tool and workpiece may be partially solved. However, by active control of machine-tool vibration, a further reduction of the dynamic motion between cutting tool and workpiece can be achieved.

It was found that adaptive feedback control based on the filtered-x LMS-algorithm enables a reduction of the vibration with up to 40 dB at 1.5 kHz and simultaneously with approximately 40 dB at 3 kHz. A significant improvement of the workpiece surface was observed and a substantial improvement of the acoustic noise level was obtained with adaptive control.

1 INTRODUCTION

In the turning operation the tool and tool holder shank are subjected to a dynamic excitation due to the deformation of work material during the cutting operation. The stochastic chip formation process usually induces vibrations in the machine-tool system. Energy from the chip formation process excites the mechanical modes of the machine-tool system. Modes of the workpiece may also influence the tool vibration. The relative dynamic motion between cutting tool and workpiece will affect the result of the machining, in particular the surface finish. Furthermore, the tool life is correlated with the

amount of vibrations and the acoustic noise introduced. The noise level is sometimes almost unbearable.
It is well known that vibration problem is closely related to the dynamic stiffness of the structure of the machinery and workpiece material. The vibration problem may be solved in part by proper machine design which stiffens the machine structure. In order to achieve further improvements the dynamic stiffness of the tool holder shank can be increased more selectively.
A solution to these problems is active control of the tool vibrations. The tool vibrations in a turning operation are mainly composed by vibrations in two directions, the cutting speed direction and in the feed direction [1, 2]. Consequently, the control problem involves the introduction of two secondary sources, driven such that the anti-vibrations generated by means of these sources interferes destructively with the tool vibration [3]. Generally, machine-tool systems are classified as narrow-band systems [2] and consequently tool shank vibrations can usually be described as a superposition of narrow-band random processes at each modal frequency, which added up together form a somewhat more wide-band random process [2]. The statistical properties of the tool vibration imply a controller which is based on control employing the statistical correlation of the vibrations [4]. A classical statistical criterion is the mean square error criterion [5]. However, a controller based on this criterion can not generally solve this control problem, since a such controller is only "optimum" in a stationary environment [6]. The statistical properties of the tool vibrations may vary during the machining process. Changes in cutting data and material properties influence the statistical properties of tool vibrations [1, 2]. Variation within the allowed cutting data interval may also influence the structural response of the tool holder [1]. A solution to the controller problem is an adaptive controller which is able to adjust its behaviour in a non-stationary environment [1, 6]. A complication in the turning operation is that the original excitation of the tool vibration, the chip formation process, cannot be observed directly and thus cannot be used as a feedforward control signal.

A single-channel feedback controller which is based on the well known filtered-x LMS-algorithm [6] has been used for the control of tool vibrations in the cutting speed direction. The single channel control system is illustrated in Fig. 1.

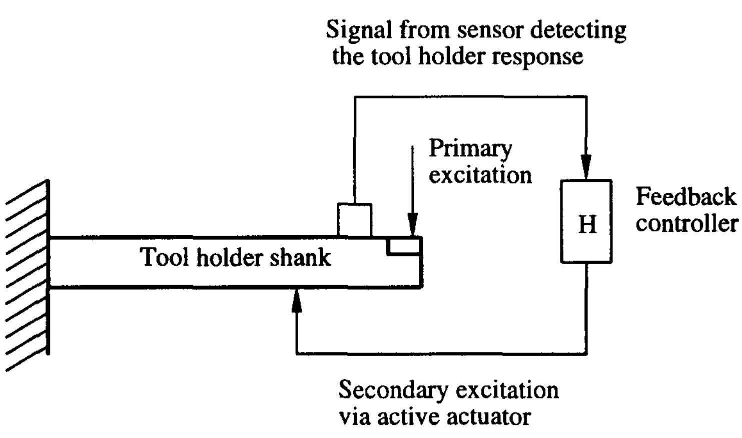

Figure 1: A machine-tool feedback control system[1].

The tool holder in this application is a construction with integrated actuators, i.e. secondary sources, which has been developed at DPME[1] [7]. The construction of the tool holder is shown in Fig. 2.

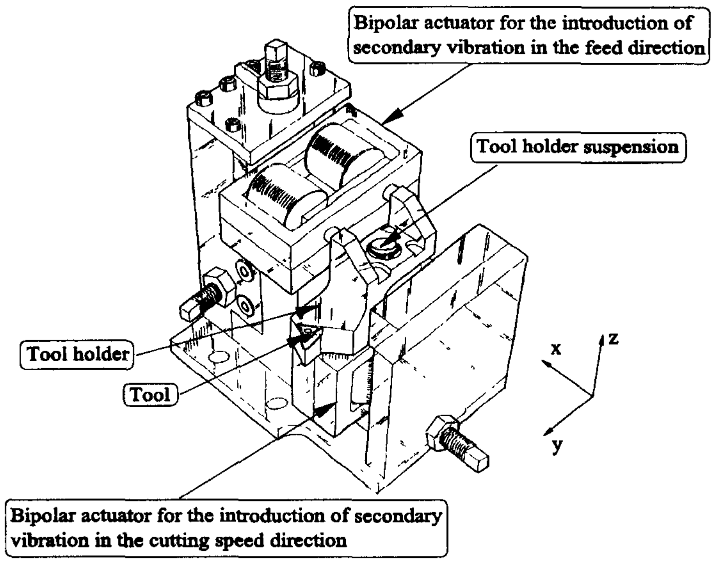

Figure 2: Tool holder with integrated actuators for the control of tool vibrations in the metal cutting process [7].

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SETUP

The cutting experiments have been carried out on a Köping lathe with 6 kW spindle power. The equipment that has been used in the experiments are:

1. Tool holder construction with integrated actuators [7].
2. Accelerometer *Brüel & Kjær model 4374*
3. Charge amplifier *Brüel & Kjær model 2635*
4. Current amplifier *Techron 7700 series*, 5kW power supply for the actuators.
5. Frequency Analyzer *HP 35665A Dynamic Signal Analyzer*, Bandwidth: 102 kHz one channel, or 51 kHz, two channels.
6. Signal processing unit *Burr - Brown, PCI-20202C*, digital signal processor carrier with TMS320C25 signal processor.
7. A/D-converter *Burr - Brown, PCI-20023M-1*,180 kHz, 8 inputs with 12 bits resolution.

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8. D/A-converter *Burr - Brown, PCI-20003M*, 120kHz, 2 outputs with 12 bits resolution.

9. Programmable two channel low-pass filter *Kemo VBF10M-Opt 25.*

The accelerometer was mounted on the cutting tool in order to measure the vibrations in the cutting speed direction.
The tool holder construction with integrated actuators [7], is based on two bipolar actuators [7]. The bipolar design is motivated by an urge for a linear behaviour and is composed of two actuators that works with 180° phase difference. The actuators are based on high magnetostrictive material.

2.1.1 WORK MATERIAL - CUTTING DATA - TOOL GEOMETRY

The workpiece material SS 2541-03, chromium molybdenum nickel steel [2], was used in the experiments. This work material excites the machine-tool-system with a narrow bandwidth in the cutting operation. After a preliminary set of trials a suitable combination of cutting data and tool geometry was selected, see table 1. The combination was

Geometry	Cutting speed, v (m/min)	Depth of cut a (mm)	Feed s (mm/rev)
DNMG 150604-PF 4015	80	0.9	0.25

Table 1: Cutting data and tool geometry.

selected to cause significant tool vibrations which resulted in an observable deterioration of the workpiece surface and severe acoustic noise. The diameter of the workpiece was chosen large, over 100 mm. The workpiece vibrations can therefore be neglected.

2.2 ADAPTIVE CONTROL OF TOOL VIBRATION

The original excitation of the tool vibrations, originating from the material deformation process, cannot be directly observed. Consequently, the controller for the control of machine-tool vibration is based on a feedback approach. The response of the tool holder can be measured with a sensor mounted on the machine-tool. By introduction of secondary anti-vibrations with a secondary source, actuator, the response of the tool holder can be modified [1]. The actuator is steered by a controller which is fed with the accelerometer signal sensing the vibrations of the tool holder, see Fig. 1 A block diagram of the feedback control system
Adaptive digital FIR filters based on the method of steepest descent are popular in various application areas, e.g. active control of sound [4, 6], active control of vibration [8, 1] and in other applications, such as electrical noise canceling, system identification, adaptive beamforming, etc. [9, 10]. This is due to the simplicity of the implementation and their unimodal error surface in the feedforward application. A feedforward active controller can easily be controlled to converge towards a feasible solution [9]. Usually adaptive FIR filters are used in feedforward control [4, 6] but can also be used in feedback control [3, 11], even though there is no guarantee that the error surface will be unimodal under these conditions [12]. Similar problems can also be observed in feedforward control systems, when the control problem is ill conditioned. A method to improve such systems

is to add a leakage factor to the adaptation algorithm [13]. This will also have the effect of limiting the energy in the impulse response of the adaptive filter, which is likely be advantageous in the case of feedback control. Furthermore, the leakage factor will also prevent accumulative build-up of bias in the coefficients of the adaptive filter [14].
The filtered-x LMS-algorithm is an adaptive filter algorithm suitable for active control applications [6] and is developed from the LMS algorithm, where a model of the the dynamic system between the filter output and the estimate, i.e. the forward path is introduced between the input signal and the algorithm for the adaptation of the coefficient vector [6, 9]. The filtered-x LMS-algorithm is given by the following four equations [6, 9];

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

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

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu \mathbf{x}_{C^*}(n)e(n) \tag{3}$$

and

$$x_{C^*}(n) = \sum_{i=0}^{I-1} c_i^* x(n-i) \tag{4}$$

where c_i^*, $i \in \{0, \ldots, I-1\}$ is an estimate of the impulse response of the forward (secondary) path. The leaky version of the filtered-x LMS-algorithm is obtained through a modification of the algorithm for the coefficient vector adaption of the filtered-x LMS-algorithm with a leakage factor γ. Hence, the the algorithm for the coefficient vector adaption of the leaky version of the filtered-x LMS-algorithm is given by [9]:

$$\mathbf{w}(n+1) = \gamma \mathbf{w}(n) + \mu \mathbf{x}_{C^*}(n)e(n) \tag{5}$$

The leakage factor γ is a reel positive parameter which satisfies the condition:

$$0 < \gamma < 1 \tag{6}$$

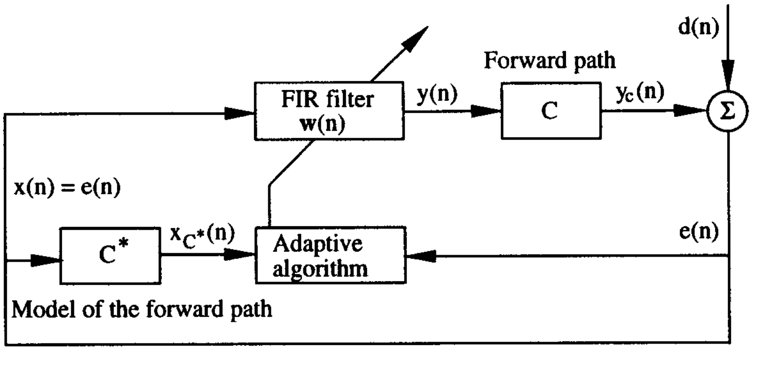

Figure 3: Equivalent block diagram of the feedback control situation with the filtered-x LMS algorithm[1].

The controller used in the experiments reported here is a feedback controller based on the well known filtered-x LMS-algorithm [1, 11]. The block diagram of the feedback control

system with the filtered-x LMS algorithm is shown in Fig. 3. In the figure, C represents the dynamic secondary system (forward path) under control, i.e. the electro-mechanic response. The estimate of this path is denoted C^*. The secondary path was estimated in an initial phase with another FIR filter, which subsequently is used to prefilter the input signal to the algorithm for the adaptation of the coefficient vector. In the experiments a 20 tap adaptive FIR filter was used together with a 16 taps FIR filter estimate of the secondary path [1].
The sampling rate of the digital filter was chosen to 15 kHz. In order to minimize the delay in the loop, no anti-aliasing or reconstruction filters were used, which demands extra care to be taken.

3 RESULTS

In order to illustrate the effect of feedback control, the spectral densities of the tool vibrations with and without feedback control are given. Fig. 4 shows a typical result obtained with adaptive feedback control of tool-vibration. It performs a broad-band attenuation of the tool-vibration and manage to reduce the vibration level with up to approximately 40 dB simultaneously at 1.5 kHz and 3 kHz.

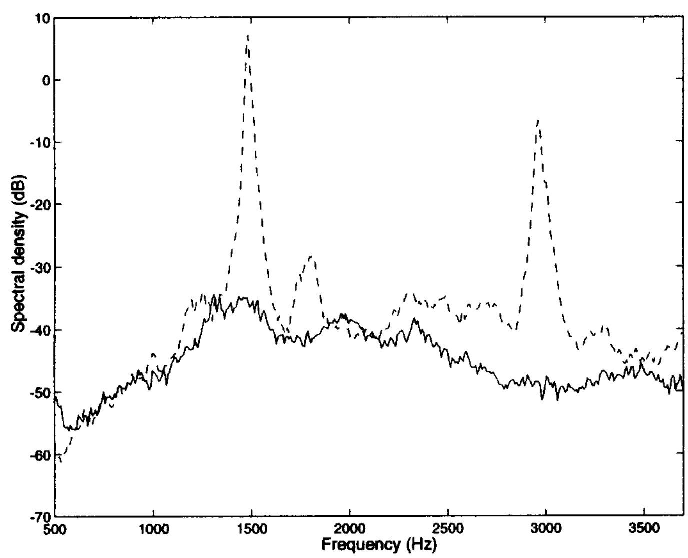

Figure 4: The spectral density of tool vibration with 20 tap FIR filter feedback control (solid) and without (dashed). Cutting speed $v = 80$ m/min, cut depth $a = 0.9$ mm, feed rate $s = 0.25$ mm/rev, tool DNMG 150604-PF, grade 4015.

Fig. 5 shows the vibration spectrum obtained with four different settings of the leakage factor in the adaptive algorithm that control the 20 tap FIR filter feedback controller. To illustrate the influence of the leakage factor on the spectral properties of the tool vibration the spectral densities are also given in a waterfall diagram, see Fig. 6.
In the experiments, it was observed that the adaptive feedback control lead to a significant improvement of the workpiece surface and a simultaneous reduction of the acoustic noise induced by the tool vibrations. In Fig. 7 a photo of the workpiece used in the experiments is shown.

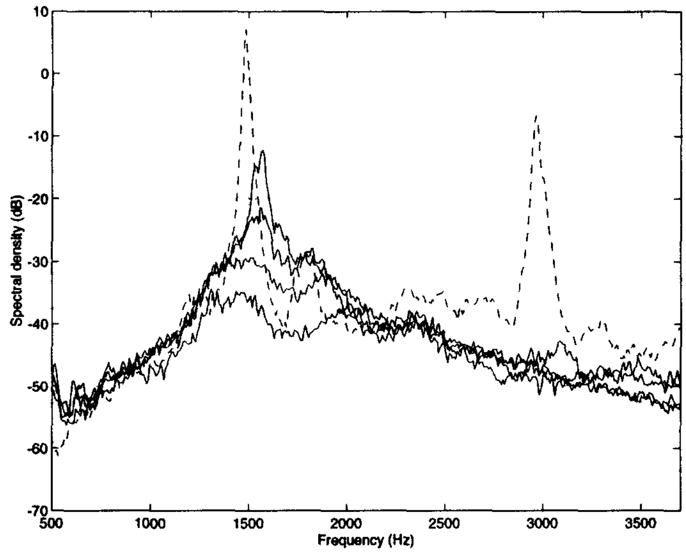

Figure 5: The spectral densities of tool vibrations with 20 tap FIR filter feedback control and four different leakage factors (solid) and the spectral density without feedback control (dashed). Leakage factors $\gamma = 1,\ 0.9999,\ 0.999,\ 0.99$, cutting speed $v = 80$ m/min, cut depth $a = 0.9$ mm, feed rate $s = 0.25$ mm/rev, tool DNMG 150604-PF, grade 4015.

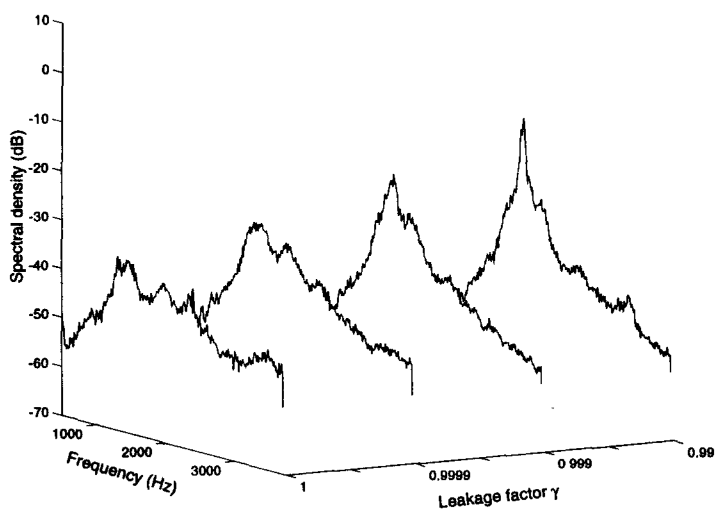

Figure 6: The spectral densities of tool vibrations with 20 tap FIR filter feedback control and four different leakage factors. Leakage factors $\gamma = 1,\ 0.9999,\ 0.999,\ 0.99$, cutting speed $v = 80$ m/min, cut depth $a = 0.9$ mm, feed rate $s = 0.25$ mm/rev, tool DNMG 150604-PF, grade 4015.

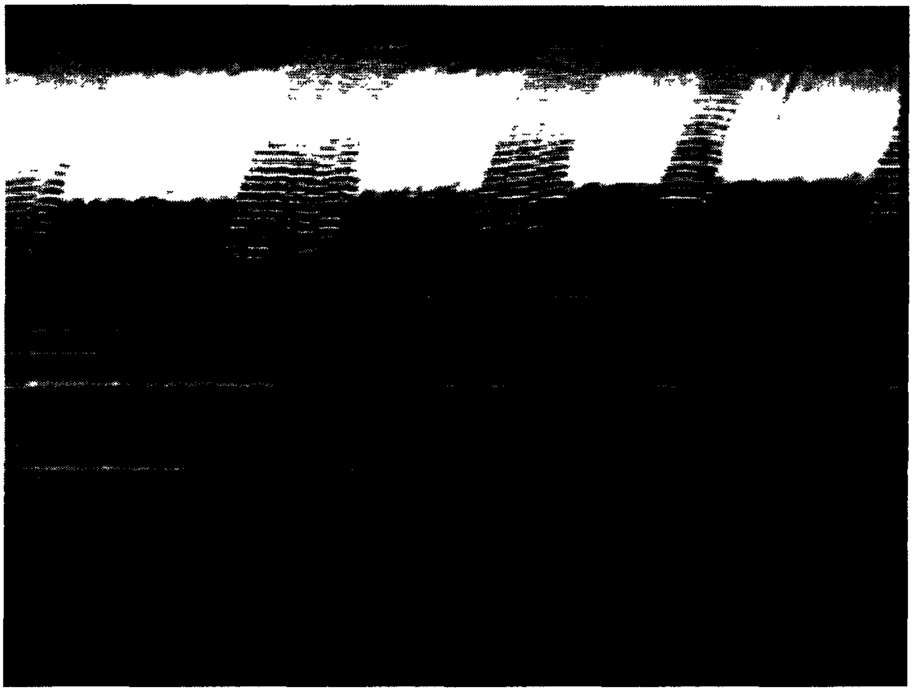

Figure 7: The workpiece surface with and without adaptive feedback control.

4 CONCLUSIONS AND FUTURE WORK

It is clear that tool vibrations in a lathe during metal cutting can be controlled with an active control system. The tool holder shank vibrations are fed into an actuator via a digital controller. Further, the well known filtered-x LMS-algorithm, traditionally used as feedforward controller, seems to be very promising for the feedback control of tool vibrations in the turning operation. The adaptive feedback control performs a broadband attenuation of the tool-vibration and manages to reduce the vibration level with up to approximately 40 dB simultaneously at 1.5 kHz and 3 kHz, see Fig. 4. As expected, the introduction of leakage will degrade the performance of the adaptive control, see Fig. 5 and Fig. 6.

The introduction of a leakage factor or a "forgetting factor" in the recursive coefficient adjustment algorithm will induce bias in the coefficient vector and thereby cause a somewhat reduced attenuation of the tool-vibration.

On the other hand, with the leaky version of the filtered-x LMS-algorithm it was observed a substantial improvement of the robustness of the control system to variations in cutting data.

From a manufacturing engineering point of view, the significant improvement of the workpiece surface, see Fig. 7, achieved with the adaptive feedback control of the tool vibration, is of great importance. The reduction of the noise introduced by the tool vibrations is also an important feature. It is also interesting to note that the adaptive technique does not affect the cutting data, it may even allow an increase of the material removal rate. Further, it is well known that there exists a correlation between tool vibrations and tool life. It is therefore likely that the adaptive feedback control of the tool vibration extends the tool life.

Future work includes for example the investigation of Internal Model Control based on the filtered-x LMS algorithm in the application. A theoretical foundation for the behaviour of the filtered-x LMS algorithm in this application is also urgent.

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