PERFORMANCE OF A CHATTER CONTROL SYSTEM FOR TURNING AND BORING APPLICATIONS

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Abstract. In the turning operation chatter or vibration is a frequent problem, which affects the result of the machining, and, in particular, the surface finish. Tool life is also influenced by vibration. Severe acoustic noise in the working environment frequently occurs as a result of dynamic motion between the cutting tool and the workpiece. In all cutting operations like turning, boring and milling vibrations are induced due to the deformation of the workpiece. This implies several disadvantages, economical as well as environmental. Many different solutions to minimize the problem have been developed but the fundamental problem is still there. The true nature of the vibrations, its causes, and implications were revealed in a doctor’s thesis in 1999, [1]. This has led to a breakthrough in this research area. Since then, through recent research results at Blekinge Institute of Technology, a new approach to controlling vibrations in cutting operations in a lathe has been implemented in a product called Acticut®, developed by Active Control Sweden AB. This new method controls vibrations in the cutting direction using embedded sensors and actuators and a filtered-x LMS algorithm. This paper will discuss the application but also the algorithm and its main numerical properties to accomplish a good result, still maintaining its stability properties.

NOMENCLATURE

\[ y(n) \] Output vector from adaptive FIR filter
\[ w(n) \] Coefficient vector of adaptive FIR filter
\[ x(n) \] Vector of input signal samples to the adaptive FIR filter
\[ e(n) \] Estimation error signal
\[ d(n) \] Desired signal
\[ y_c(n) \] Output signal from forward path
\[ e(n) \] Estimation error signal
\[ \gamma \] Leakage factor
\[ LMS \] Least Mean Square
\[ \mu \] Step size length
\[ \mu_0 \] Unscaled step size
\[ i \] Integer
\[ SPL \] Sound Pressure Level
\[ R_a \] Surface roughness

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. These problems can be reduced by active control of machine-tool vibration. In the active control system for the control of tool vibration a tool holder construction with integrated high magnetostriction actuators were used. However, these actuators generally have a non-linear behavior and it is a well-known fact that non-linear properties in the forward path in an active control system is likely to degrade the robustness of the control system.

A new generation embedded active tool holder shanks based on piezo ceramic actuators has been developed. Based on spectrum estimates, both coherence spectrum and frequency response function estimates has been calculated for both the old tool holder construction and the new generation active tool holder shank. From the results it follows that the phase delay is smaller and the linearity of the new generation active tool holder shank are superior compared to the old technology. The physical features and properties of the new generation active tool holders are superior to the old tool holder. Boring or internal turning is also of importance. This case, however, demands more from the system since the forces are different, due to the long arm that is needed in this cutting application, and the fact that the length direction of boring bar is orthogonal to the length direction of a tool holder shank used in external turning. A separate test will be discussed, focusing on boring or internal turning.

2. METHOD

One of the basic conclusions from this research was that the vibrations does not occur in the cutting depth direction, but in cutting speed direction as illustrated in figure 1. The other important result is that the vibration spectra were not correlated to the speed of the work piece, the rpm (rotations per minute), but to the frequency of the first bending mode of the tool holder. This gave the fundamental new and innovative idea to this approach: stiffen the tool holder for this mode.

The concept of active noise control was used. That means that the primary mode vibrations are inhibited by “anti-vibrations” using secondary vibrations applied through an actuator that can be controlled electronically. Figure 2 depicts the fundamental system solution.
3. CONTROL ALGORITHM

The feed-forward filtered-x LMS (Least-Mean-Square) algorithm, [2][3][4], is given by the following four equations:

\[ y(n) = \mathbf{w}^T(n) x(n) \]  \hspace{1cm} (1)

\[ e(n) = d(n) - y_c(n) \]  \hspace{1cm} (2)

\[ w(n+1) = w(n) + \mu \frac{e(n)}{C^*} c(n) e(n) \]  \hspace{1cm} (3)

and \( x_{C^*} \) is given by:

\[
x_{C^*} = \begin{bmatrix}
\sum_{i=0}^{I-1} c_{C^*} e(n-i-1) \\
\sum_{i=0}^{I-1} c_{C^*} e(n-i-2) \\
\vdots \\
\sum_{i=0}^{I-1} c_{C^*} e(n-i-M)
\end{bmatrix}
\]  \hspace{1cm} (4)

where \( c_{C^*} \), \( i \in \{0, ..., I-1\} \) 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, of the coefficient vector adaption of the filtered-x LMS algorithm with a leakage factor \( \gamma \). Hence, the algorithm for the coefficient vector adaption of the leaky version of filtered-x LMS algorithm is given by [2]:

\[ w(n+1) = \gamma w(n) + \mu x_{C^*} e(n) \]  \hspace{1cm} (5)

The leakage factor \( \gamma \) is a real and a positive parameter, which satisfies the condition:

\[ 0 < \gamma < 1 \]  \hspace{1cm} (6)

4. THE DEVELOPMENT OF THE NEW ACTICUT® SYSTEM

An piezo actuator and sensor was embedded into the tool holder and an adaptive control system was developed and applied using the above described control approach. The system is schematically depicted in figure 2 below, [5][6][7].
Several different control algorithms has been implemented and tested. The results in this paper are produced with the filtered-x LMS algorithm, a least mean square approach. This algorithm has been proven to be a good compromise thus being fast, stable, robust, accurate, yet being fairly easy to implement. The adaptive FIR filter approach using a steepest-descent method to minimize the error is frequently used in active noise control applications. In this project, however, a feedback approach in contrast to the more common feed-forward approach has been used. The robustness of the adaptive feedback controller is further improved by introducing a so called leakage factor in the filtered-x LMS algorithm, as described in equation (5).

5. FIELD TEST RESULTS

The field tests has been accomplished using a regular CNC turning center, a Mazak Quickturn 250. As expected, the vibration spectrum, and also the sound spectrum, is tonal and dominant for specific frequencies without the active control system applied, as depicted in figure 4 and 5. The fundamental frequency is located at 1.5 kHz, and the first associated harmonic is located at 3 kHz. The noticeable result is that the vibrations are completely suppressed by the active system. The attenuation of the fundamental frequency is more than 40 dB, which means that only 1% of the vibration still exist, and 99% is attenuated. Another interesting consequence is that only the first mode, located at 1.5 kHz, is controlled. Despite that, all the associated harmonics are attenuated or in principal canceled. For LTI (Linear and Time Invariant) systems, this is impossible, but since this system is highly non-linear, the result is not unpredictable. The phenomenon becomes even more obvious when the broadband sound field is analyzed, as illustrated in figure 4.
The normal squeaking sound from the cutting process disappears totally, and the only sound that really is left, is the sound from the bearings and the electrical motor. The surface of the work piece is significantly improved as illustrated by figure 3. The roughness measured by $R_s$ went down from 9 $\mu$m to 1 $\mu$m and $R_{\text{max}}$ changed from 38 $\mu$m to 8 $\mu$m. This implies that the surface roughness can be improved a factor of 5-10 using this active approach to chatter control.

When performing boring, which normally is denoted boring bar in internal turning, the forces on the tool holder will be different, and the previous design might not be able to handle the control. Hence, a modified system has been developed, making it possible to test the method on a more difficult cutting operation. Despite the fact that this system is supposed to be an inside cutting process, an outside cutting process was performed. The forces on the tool holder is the most important factor, not if inside or outside cutting is chosen. The length of the tool holder is one critical parameter, and thus a setup with difficult parameters was chosen. The length of the tool holder was about five times the diameter of the work piece. Embedded actuators were used, and the material in the work piece was toughened steel, 2541. The same lathe, a Mazak Quickturn 250 CNC turning center, was used and in figure 5 the results from these test are depicted. The results are very promising and this test verifies that the selected approach is feasible and the used algorithm performs well. A very large attenuation of all key modes on the tool holder are heavily damped, with typical reduction values of about 25 dB. Again, it is of importance to notice that only one mode is controlled, but most modes are attenuated heavily.

Figure 4. Illustration of a typical SP L spectrum with (solid) and without (dashed) control, and the main forces active on the tool holder, of key importance for the control.

Figure 5. Illustration of a typical setup and the main forces active on the tool holder, of key importance for the control. Power spectrum of boring bar vibration in the cutting speed direction with control (red) and without (blue).
7. IMPLICATIONS

One implication of these results is that this technology applied to a normal lathe, would improve the productivity, decrease the consumption of tools, decrease the wear of the machine, enable higher speeds, and allow for thinner geometries of the work piece. All these features have been proved by testing in the laboratory. Not all lathes look the same, the dimensions vary significantly, and they also operate differently. This means that some adaption has to be performed before this type of technology implementation can become a standard part of every lathe. Nothing has been said about the limitations of this technology. There are of course limitations in their application. Some machines do not have vibration problems. The quality requirements do not call for a need to improve the result. There could be other limitations than vibrations, like machine power or the machine might already be running at maximum speed. It might be a vibration problem in some other part that exceeds the problems in the cutting tools. The producer might not desire to increase productivity. In all those cases there is no need for an Acticut®system. These installation types seem however, to be a small part of the existing machines in the industry today.

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CONCLUSIONS

It is clear that tool vibrations in a CNC turning center during metal cutting can be controlled using an active control system. In the proposed 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 a feed-forward controller, have a great potential with respect to feedback control of tool vibrations in turning operations. The adaptive feedback control performs a broad-band attenuation of the tool-vibrations, and is able to reduce the vibration level by up to approximately 40 dB simultaneously at 1.5 kHz and 3 kHz. Furthermore, in the operator area for the lathe, the vibration control results in a broad-band attenuation of the sound pressure in the frequency band 1.5 kHz to 25 kHz, with up to approximately 35 dB SPL at 3 kHz. 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, but increase the robustness significantly. The technology is now ready for further testing in more real life applications. One reference installation is planned for the first quarter of 2002. There is need for a few more reference installations before the system can be shipped to any more general place. The same type of control system has been used for boring. The results from these tests are very promising. A very large attenuation of all key modes has been accomplished.

REFERENCES