Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

Active vibration control of machine tool structures - Part 2: An experimental active-vibration control system

F. Haase, S. Lockwood & D.G. Ford
The Precision Engineering Centre, University of Huddersfield, UK

Abstract

The presented work is part of a project aimed at improving machine tool performance due to forced and self-excited vibration. Adaptive algorithms used in digital signal processing (DSP) are implemented in order to model machine tool structures and control the vibration. Self-excited machine tool vibration occurs when the cutting load exceeds the dynamic stiffness of the machine. The phenomenon is called chatter and has a direct impact on the surface finish, tool life and productivity. To avoid this, an experienced machine tool operator would try to change the cutting parameters or the clamping of the tool and work-piece. The aim for this research is to model machine tool structures adaptively in the digital domain, in order to control self-exited, but also forced vibration of machine tool structures. This means that the stiffness and damping of a machine tool structure could be changed actively during operation. The system presented here is a test rig, which is designed to show the potential of this approach and also the difficulties to overcome in order to control machine tool structures. This has been done through simulation and experimental validation.

1 Introduction to adaptive vibration control

The goal of vibration control is to reduce the vibration of a mechanical system. It can be either active or passive. Traditional vibration control uses passive elements in order to control the system, by increasing its stiffness or damping.

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

The major limitation of this technique is that the vibration attenuation is only effective in a narrow bandwidth and it is not capable of adjusting itself automatically if the structural response or the system changes. The goal of active vibration control is to reduce the vibration of the mechanical system by modifying the system's structural response automatically.
The main components are:

- A sensor to detect the vibration
- An electronic or digital controller to manipulate the measured vibration in a certain way
- An actuator to influence the mechanical response of a system

1.1 Adaptive filters

Adaptive filters are digital filters [1] with self-adjusting characteristics. Where digital filters are working in an open loop manner, the transfer-function remains static. Adaptive filters on the other hand, operate in a closed loop or feedback arrangement, where a feedback algorithm controls the frequency or impulse response of the filter. One of the main applications for adaptive filters is direct system modelling or system identification, which is described in more detail in section 4.

1.2 Adaptive control

Adaptive control uses adaptive filters in order to control a plant or dynamic system. The most important difference between adaptive control and traditional system identification schemes, based on adaptive digital filters, is that the summing junction is not a digital number. In adaptive control the summing junction will be an acoustic summing point or for mechanical vibration control a mechanical summing point [2]. In mechanical structures forces can be superimposed as long as the structure is linear, which is the assumption made here, and for vibration testing (modal testing) in general.
Figure 1 shows a LMS adaptive feed-forward controller.

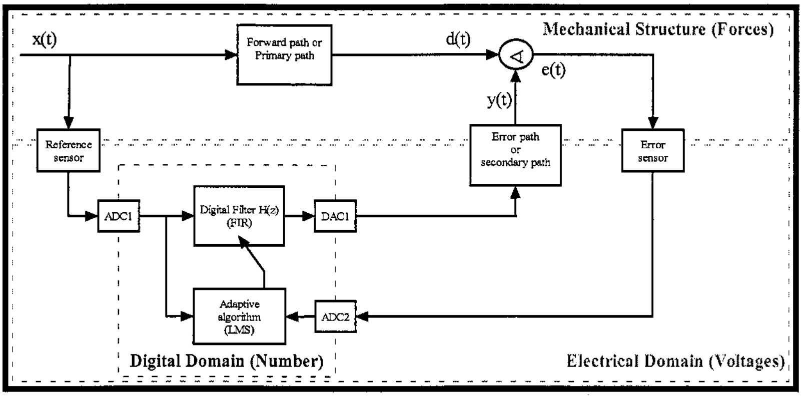

Figure 1: Parts of an adaptive control scheme

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

It is important to realise that the signals need to be converted between 3 different domains:

- Digital Domain
- Electrical Domain
- Domain whose units needed to be controlled (e.g. mechanical)

To convert from the electrical domain to the domain where the controller should perform actuation (electro-dynamic shakers or loudspeakers), sensors are used the other way round (force sensors, vibration sensors e.g. accelerometers, microphones etc.). The conversion from the digital domain to the electrical domain and vice versa is done by analog to digital converters (ADC) or digital to analog converts (DAC) respectively.

2 The mechanical structure of the test rig

A standard cantilever beam was chosen for the experiments. The shape of the structure is the same as a cutting tool in a tool post or spindle and therefore very common for this kind of research. The modal frequencies are also in the same range as the ones measured on the previous investigation on a vertical-milling machine. [3]

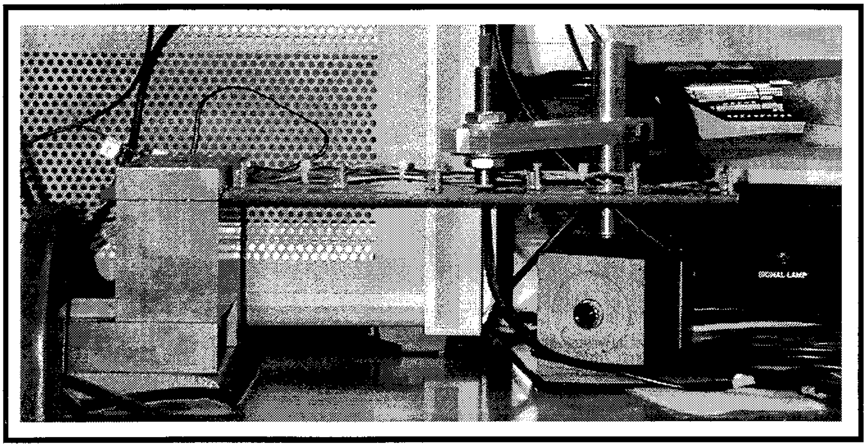

Figure 2: The investigated cantilever beam structure

The structure has been simulated analytically and numerically (finite element) in order to predict the frequency response and match the modal frequencies with those of the chattering milling machine. A modal test then confirmed and validated the models. Each mode has been excited separately, and the mode shape captured with micro-machined accelerometer [3]. Figure 3 shows the frequency response function (FRF) taken at the end point of the beam. Since the measured output is acceleration it is called accelerance transfer function.

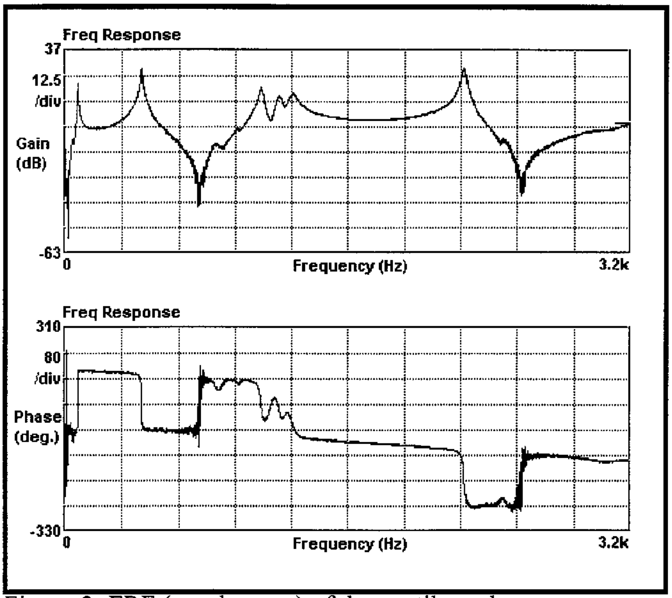

Figure 3: FRF (accelerance) of the cantilever beam

From this the first three modal frequencies can be seen directly:

1. Mode at 70 Hz
2. Mode at 428Hz
3. Mode at 1150Hz

In order to identify or model the Frequency response function of the structure digital filters can be used. This approach is different to traditional techniques, since these are numerical models based on a sample by sample bases instead of continuous.

3 System identification of the FRF's using digital filters

The main focus of this paper is to design digital filters, which have the same frequency response as the measured FRF's of the modal test from the beam. This then can lead onto a simulation program for the beam structure, in order to control the vibrations adaptively.
First the two relevant transfer-function must be measured:

- The primary or feed forward path
- The secondary path or error path

Both transfer-functions were measured in order to obtain the non-parametric model using the HP spectrum analyser 3566. The parameter estimation of the unknown plants has been done using an adaptive IIR LMS algorithm sometimes also called Feintuch IIR LMS [4,5].
The block diagram of this algorithm is shown in figure 4.

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

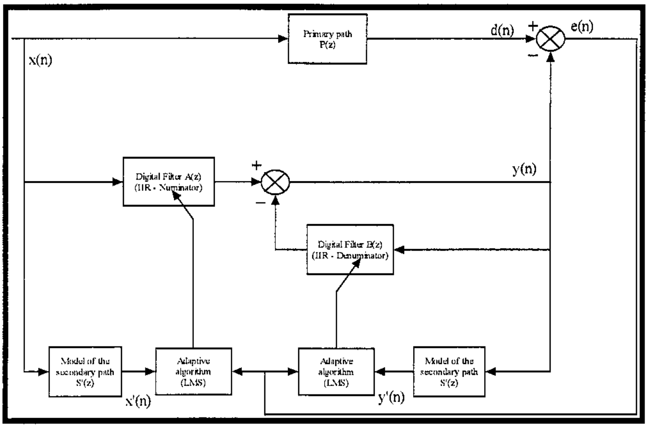

Figure 4: The identification of the primary path using an adaptive IIR filter (LMS)

MATLAB/SIMULINK was used as an off line identification and simulation platform, because of its graphical user interface. All the necessary SIMULINK blocks have been written in C using S-functions [6], since SIMULINK just offers standard digital and adaptive filters. These custom SIMULINK blocks then were compiled and added to SIMULINK's library.

Figure 5 shows the graphical user interface of SIMULINK file to do the parameter estimation of the secondary path.

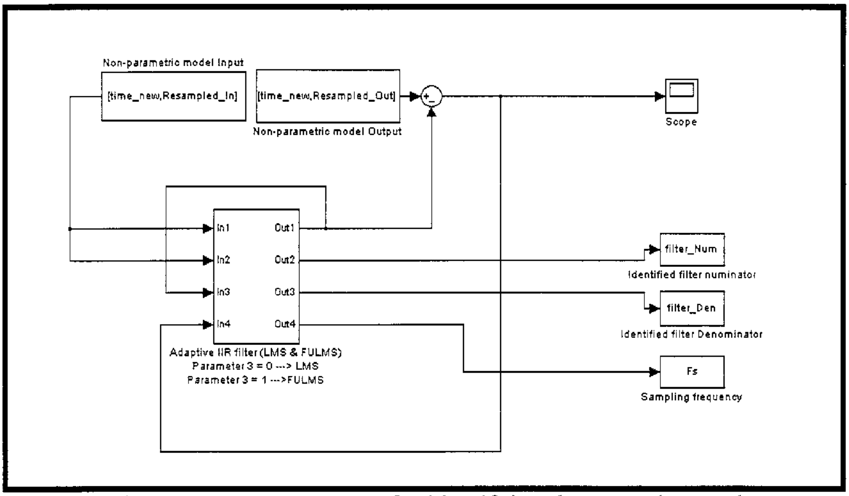

Figure 5: The SIMULINK program for identifying the secondary path

A MATLAB M-file then was written to compare the transfer function of the unknown system (secondary path) and estimated filter. Figure 6 shows the simulation result of an 25^{th} order adaptive IIR LMS filter with a adaptive step size μ of 0.0025.

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

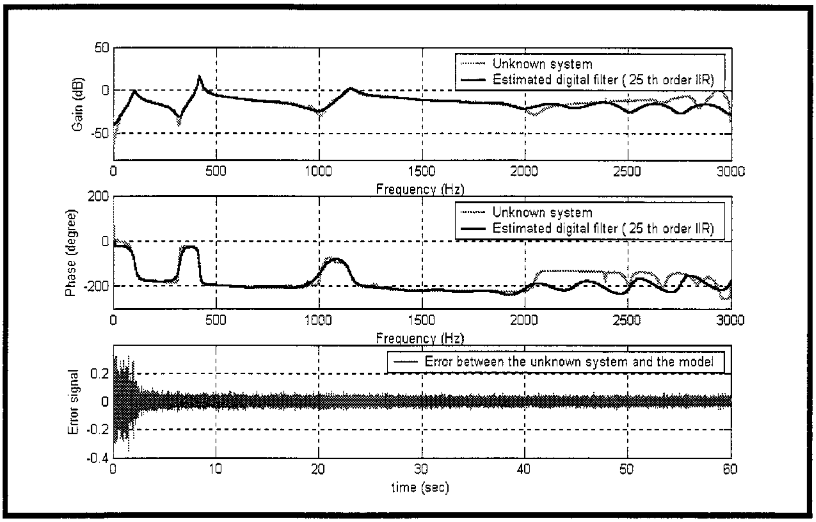

Figure 6: The comparison between the unknown seconday path and an 25th order IIR filter

The same identification procedure has been followed for the primary path of the beam in order to have an exact model of the test rig. It is then possible to simulate the required adaptive controller.

4 Simulation results

Before the implementation of the adaptive filter into the data acquisition system, a simulation model was constructed. The simulation will help to find the most suitable algorithm for our application and to get a feel for the right parameter settings of the adaptive controller. Again MATLAB SIMULINK was used and the simulation blocks have been written and compiled in C using S- functions. The simulation times of the new SIMULINK blocks are as fast as the blocks from the SIMULINK library.
Three different adaptive algorithms have been tested in order to cancel the forced vibration on the test rig:

- Adaptive FIR feed-forward controller using the LMS algorithm
- Adaptive FIR feed-forward controller using the filtered-x LMS algorithm (FXLMS) [7]
- Adaptive FIR feedback controller using the error signal as reference signal (FXLMS algorithm) [8,9]
- Adaptive FIR feedback controller using IMC (Internal Model Control) (FXLMS algorithm) [10]

The next 3 figures show the simulation results (the beam structure is vibrating at 400Hz).

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

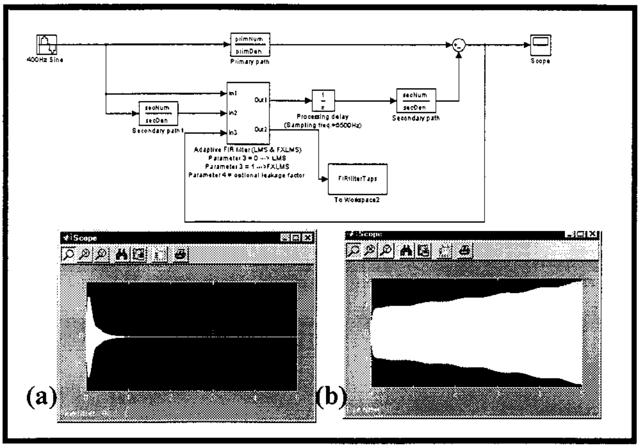

Figure 7:
The simulation results of the effectiveness of an adaptive FIR feed-forward controller on the beam structure

Left (a): FXLMS algorithm
Right (b): LMS algorithm

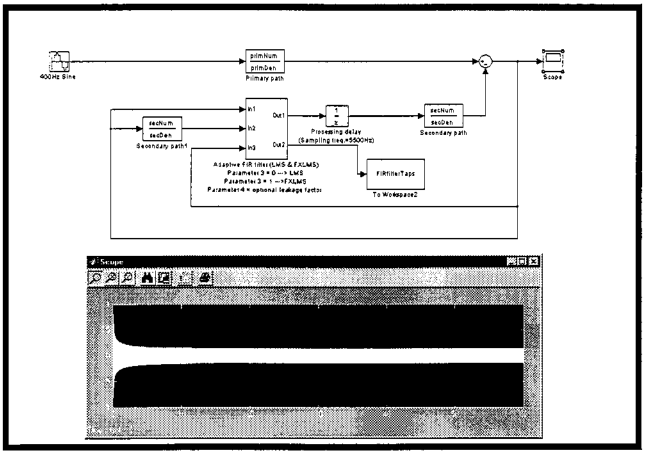

Figure 8:
The simulation results of the effectiveness of an adaptive FIR feedback controller using the error signal as reference signal (FXLMS algorithm)

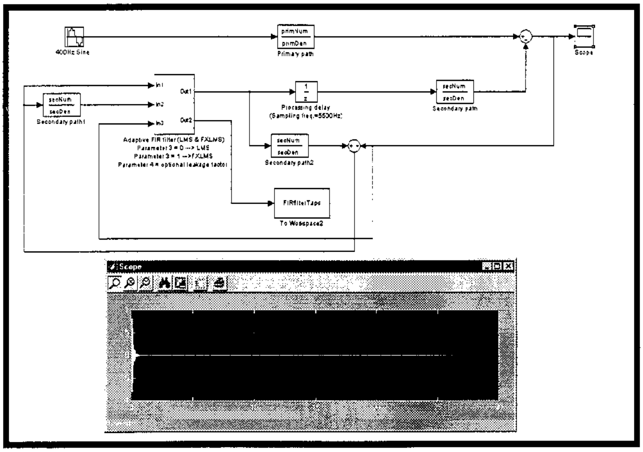

Figure 9:
The simulation results of the effectiveness of an adaptive FIR feedback controller using Internal model control to derive the reference signal. (FXLMS algorithm)

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

The simulation clearly shows that the LMS algorithm is not stable over the whole frequency band. This is because the dynamics of the secondary path are not included in the algorithms. To compensate for this the digital filter of the secondary path model is used in conjunction with the LMS algorithm. This is known as the filtered-x LMS algorithm, and showed stability over the whole frequency bandwidth. Since the reference signal is not available on a vibrating machine tool structure the adaptive feedback controller using internal model control offers the best performance and robustness.

5 Experimental validation

The promising simulation results needed to be validated against the real structure. The filtered X LMS algorithm assumes the knowledge of the secondary path. In order to do this on line, the Feintuch IIR LMS [3,4] has been added as an option to the program. When this "calibration procedure" is activated, a white noise generator excites the beam structure through the actuator and the error between the digital model and the unknown plant can be monitored on the oscilloscope. A 12-bit data acquisition board and DOS operating system has been used. The Programs are written in Borland C. Figure 10 shows the experimental set up and the performance of the adaptive controller by cancelling the forced vibration of the mode 2 (428Hz).

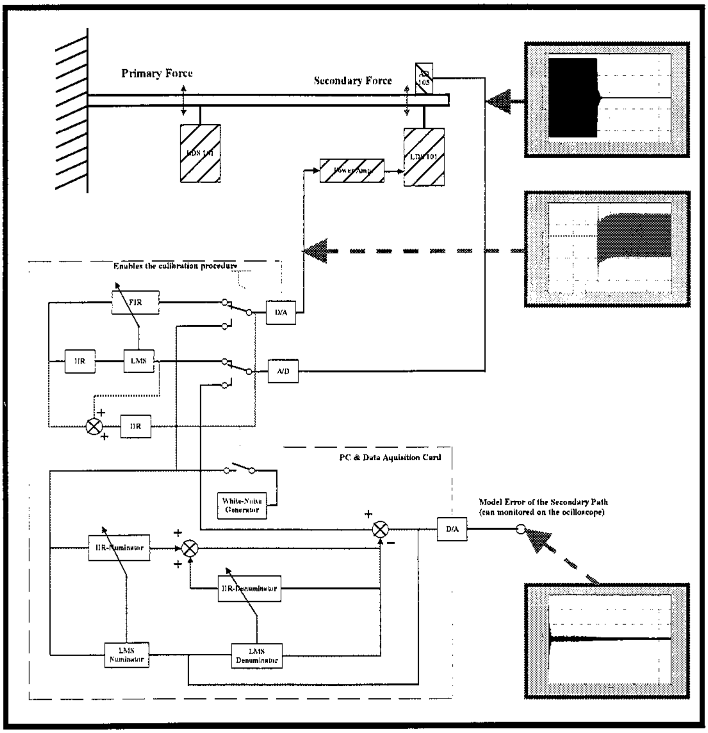

Figure 10: The adaptive controller on the beam structure

Instead of using harmonic vibration a more realistic signal to excite the test rig is chatter vibration recorded from a previous cutting test on a 3-axis vertical milling machine [2]. The data has been converted into a "wav" file in order to play the cutting process back over the sound card output of the PC. This was used to excite the test rig. The next 2 figures show the response of the adaptive controller due to this forced vibration.

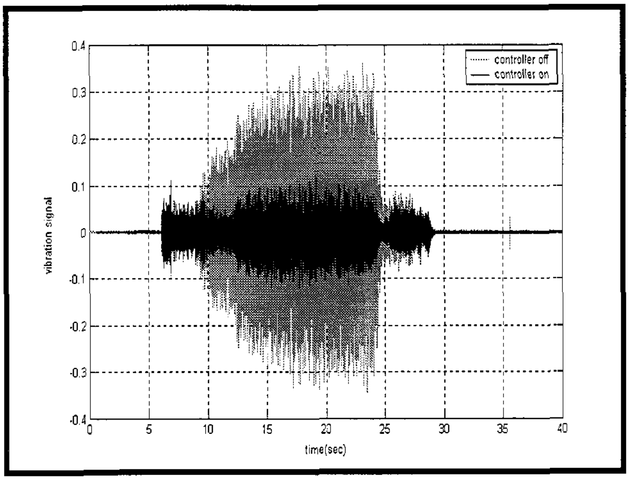

Figure 11: The effectiveness of the adaptive controller on the test rig due to chatter vibration (Time response)

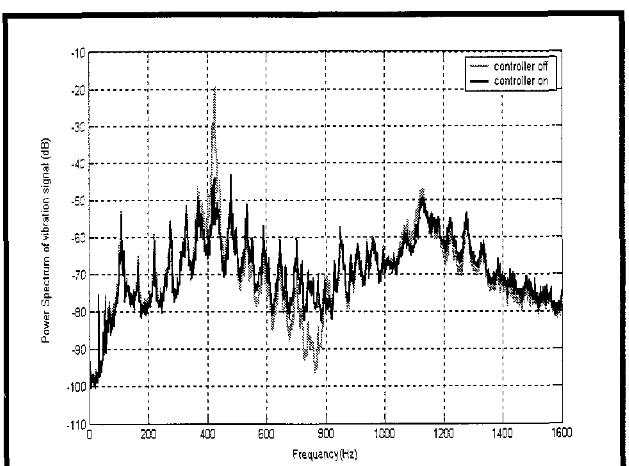

Figure 12: The effectiveness of the adaptive controller on the test rig due to chatter vibrations (Frequency response)

The vibration amplitude has been reduced to about 70% and furthermore the power spectrum shows a reduction of the main chatter vibration about 95%. It has been reduced down to the level of the tooth pass vibration by this particular cut [2].

6 Conclusions

An active vibration control system has been investigated. It needs to be shown that such a system is able to control machine tool vibration, such as chatter. Therefore the chosen mechanical system is a cantilever beam which represents the clamped tool in the spindle or tool post. The modal frequencies are similar to those of a previous investigated milling machine. Off-line simulation programs to identify the transfer functions of the structure have been written and based on these a simulation program for the mechanical structure has been written. This program allows the simulation of various adaptive algorithms to find the most appropriate. This has been implemented onto the data acquisition platform in order to validate the simulation results. It also has been shown that the adaptive controller was able to significantly reduce the forced vibration of a more complex signal. This signal was the previously recorded chatter vibration on a milling machine replayed over the sound card of a PC.

The purpose of this work was to learn about the adaptive algorithms and prove that they can be used to control the vibration of a milling machine. This system now has been used, including the simulation programs, to design and build a "universal active base" to be mounted under the work piece. The first static tests have been made on this base.

References

1. B. Widrow, S.D. Stearns, "Adaptive Signal processing", Prentice Hall 1985.
2. C.R. Fuller, S.J. Elliott, P.A. Nelson, " Active control of Vibration", Academic Press, 1996.
3. F. Haase, S. Lockwood, D.G. Ford, "Vibration modelling of machine tool structures", LAMDAMAP 2001.
4. M. H. Hayes, "Statistical Digital Signal Processing and modelling", John Wiley & Sons, 1996.
5. P.A. Nelson, S.J. Elliott, "Active Control of Sound", Academic Press, 1992.
6. The MathWorks, "SIMULINK – Writing S-Functions", Version 4.
7. S. M. Kuo, D. R. Morgan, "Active Noise Control Systems", John Wiley & Sons, 1996.
8. I.M. Stothers, T.J. Saunders, A.M. McDonald, S.J. Elliott, "Adaptive feedback control of sun roof flow oscillations", Proceedings of the Institute of Acoustics, 1993.
9. L. Håkansson, "Adaptive Active Control of Machine-Tool vibration in a Lathe", Doctoral Dissertation, Division of Production and Materials Engineering Lund Institute of Technology, Lund University, Sweden, 1999.
10. M. Morani, E. Zafiriou, "Robust Process Control", Prentice Hall, 1989.