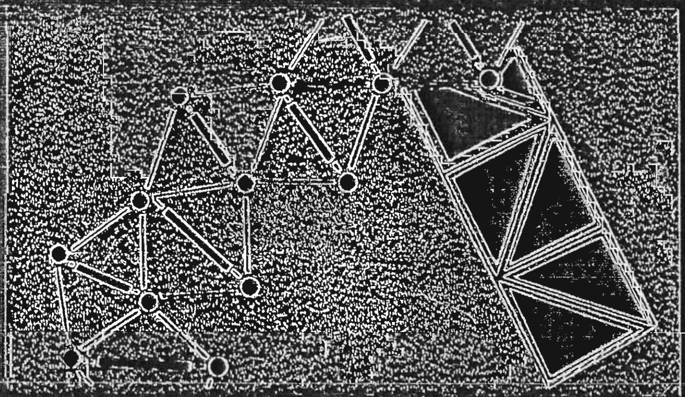
SIXTEENTH INTERNATIONAL CONFERENCE ON ADAPTIVE STRUCTURES AND TECHNOLOGIES



Edited by

MICHEL BERNADOU
JOHN CAGNOL
ROGER OHAYON

SIXTEENTH INTERNATIONAL CONFERENCE ON ADAPTIVE STRUCTURES AND TECHNOLOGIES

October, 9–12, 2005
Paris, France

Edited by
MICHEL BERNADOU
JOHN CAGNOL
ROGER OHAYON

DES*tech* Publications, Inc.

Sixteenth International Conference on Adaptive Structures and Technologies

DEStech Publications, Inc.
1148 Elizabeth Avenue #2
Lancaster, Pennsylvania 17601 U.S.A.

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Main entry under title:
Sixteenth International Conference on Adaptive Structures and Technologies

A DEStech Publications book
Bibliography: p.

ISBN No. 1-932078-57-6

ADAPTIVE FEEDFORWARD CONTROL OF VIBRATION OF A BEAM WITH ACTIVE-PASSIVE DAMPING TREATMENTS: NUMERICAL ANALYSIS AND EXPERIMENTAL IMPLEMENTATION

C. M. A. Vasques, J. Dias Rodrigues

ABSTRACT

This paper concerns the adaptive feedforward control of vibration of a freely supported beam with active-passive damping treatments using the filtered-reference LMS algorithm. Two distinct damping treatments are bonded on the beam and the aim is to compare the damping performances of the control configurations when the beam is excited by a broadband voltage disturbance applied into another piezoelectric patch. The first configuration concerns the use of an *Active Constrained Layer Damping* (ACLD) patch alone, where the piezoelectric constraining layer is actively utilized to increase the shear deformation of the passive viscoelastic layer and at the same time to transmit efforts to the structure, which will balance the power flows into the structure, and is denoted by ACLD configuration. The second configuration regards the use, as an active element in the control, of the piezoelectric patch alone, denoted by *Active Damping* (AD), and since the constraining layer of the ACLD treatment also bonded on the beam is not actively utilized, a *Passive Constrained Layer Damping* (PCLD) treatment is utilized in combination with AD, yielding an AD/PCLD configuration. A finite element (FE) model is used for the simulation of the adaptive feedforward controller which is also implemented in real-time.

INTRODUCTION

Over the past decades active control in conjunction with hybrid active-passive damping treatments has been applied to attenuate structural vibration and sound radiation from structures. The principle behind active control is being able of producing some kind of secondary (cancellation) control action upon the structure that will cancel the effects of a primary (disturbance) excitation. Hybrid active-passive damping treatments are composed by blends of piezoelectric and viscoelastic damping capabilities. A review on hybrid active-passive damping treatments can be found in [1]. *Active Damping* (AD) treatments comprise only piezoelectric material patches that are mounted (or embedded) on a structural system, which inject "negative" power flows to cancel the effects of the disturbance. A pioneer work concerning AD is the one presented by Bailey and Hubbard [2] in 1985, and over the following decades several works appeared in the open literature (e.g., [3]) with further developments. Passive damping treatments consider viscoelastic layers sandwiched (or not) between a host structure and an elastic constraining layer. They add damping to the system due to heat dissipation mainly caused by the shearing of the viscoelastic layer If an elastic constraining layer is considered, the configuration

---

C. M. A. Vasques, PhD student, FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
J. Dias Rodrigues, Associate Professor, FEUP, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

is usually denoted by *Passive Constrained Layer Damping* (PCLD). However, in order to increase the shearing and energy dissipation of the viscoelastic layer, an active constraining piezoelectric layer may be used to actively increase the shearing in a convenient way. That was originally proposed by Plump and Hubbard [4] in 1986 and later further developed and studied by Baz and his co-workers (e.g., [5, 6]) and many others. These treatments are so-called *Active Constrained Layer Damping* (ACLD) and combine the high passive capacity of viscoelastic materials to dissipate vibratory energy at high frequencies with the active capacity of piezoelectric materials at low frequencies. In the open literature several works can be found where feedback theories are applied in vibration control of beams with AD and ACLD treatments. Usually it is shown that ACLD treatments have better performances than AD ones, with higher damping values being obtained with lower control voltages. Several works utilizing adaptive feedforward control theory in AD applications can be found (e.g., [7, 8]). However, only a few utilizing ACLD treatments, concerning harmonic *Active Structural Acoustic Control* (ASAC) [9] or broadband [10] and harmonic vibration reduction [11], are found.

The damping achieved with ACLD involves three damping mechanisms: (1) the shearing of the viscoelastic layer in open-loop, (2) the increase of shearing in the viscoelastic layer due to the convenient motion of the active piezoelectric constraining layer, (3) and the decrease of total input power into the structure due to the forces applied by the active piezoelectric constraining layer through the viscoelastic layer. Obviously, the latter mechanism for ACLD treatments has a reduced importance since the viscoelastic layer usually reduces the transmissibility of efforts to the host structure. In fact, usually the transmissibility (stiffness) increases with frequency. Thus, in order to dissipate energy also at low frequencies, the aim would be to actively increase the shearing in the viscoelastic layer. However, due to the loss factor behavior of viscoelastic materials (usually smaller at low frequencies), the treatment is usually more efficient for frequencies with higher loss factors, if we have also significant shearing strains. (The energy released is related with the loss factor times the shearing strain.) Regarding the AD treatment, the transmissibility of efforts to the host structure is higher, since the patch is bonded to the structure, and the aim is actively reducing the input power coming into the structure. Of course, some energy may also be lost due to the boundary conditions or the internal damping of the host structure, or even radiated into the ambient medium, which usually are neglected.

The aims of this paper are to give new contributions to the understanding of how AD and ACLD treatments behave and to know which one is best and easily implemented in practice. To this end a finite element (FE) model previously developed by the authors [12] is used for the simulation and succinctly described. A beam is excited by a piezoelectric patch, and AD and ACLD patch treatments, with the same dimensions and mounted on opposite sides, are compared in their capacity to attenuate the effects of a broadband disturbance voltage into the piezoelectric patch. The adaptive feedforward filtered-reference LMS algorithm considered to attenuate the vibration effects of the broadband disturbance is also succinctly described. First the damping treatments are assessed by simulation and later experimentally.

MATHEMATICAL MODEL

When designing hybrid active-passive damping treatments it is important to know the configuration of the structure and treatment that gives optimal damping. For simulation the designer needs a model of the system in order to define the optimal locations, thicknesses, configurations, control law, etc. The task of modeling beams with arbitrary ACLD treatments often requires the development of a piezo-visco-elastic coupled model of the structure, which comprises piezoelectric, viscoelastic and elastic layers. In the development of FE models different assumptions can be taken into account in the theoretical model when considering the mechanical model, the damping introduced by the viscoelastic materials and the electro-mechanical coupling.

A 1D FE model of a beam with active-passive damping treatments is utilized here in order to simulate the real system The FE model considers an arbitrary number of elastic, piezoelectric and viscoelastic layers attached to both sides of the beam, and a partial layerwise theory is used to define the displacement field. Furthermore, a fully coupled electro-mechanical theory is considered to model the piezoelectric layers, where a non-linear electric potential distribution is utilized. The temperature and frequency dependent material properties of the viscoelastic materials cause some difficulties for the mathematical model, increasing its complexity. Usually the temperature is assumed constant and only frequency dependent models are utilized. Thus, the damping behavior of the viscoelastic layers is considered by a Laplace transformed *Anelastic Displacement Fields* (ADF) method. For the sake of brevity the reader is referred to [11, 12] for further details about the FE and viscoelastic materials modeling.

FEEDFORWARD CONTROL THEORY

The *filtered-reference LMS* algorithm is the most widely accepted feedforward control algorithm because of its ease of implementation and remarkable performance. In Figure 1 a schematic diagram of the discrete-time (digital) generalized plant for a feedforward controller is presented. It is assumed that a detection system, which produces a signal correlated with the primary disturbance, exists (or not, and in that case the true excitation signal is utilized), and produces a reference signal $r(k)$ correlated with the excitation. This signal is then adaptively filtered to generate the necessary control action, $u_\phi(k)$, to cancel the effect of the primary excitation (disturbance), $u_u(k)$. The control filtering process utilizes an adaptive *Finite Impulse Response* (FIR) filter whose i th coefficient at the k th sample time, $h_i(k+1)$, is given by

$$h_i(k+1) = h_i(k) - \alpha y(k)\hat{r}(k-i), \tag{1}$$

where α is a convergence coefficient parameter that determines the speed and stability of adaptation, $\hat{r}(k-i)$ is the estimated filtered reference signal, which is the output of a FIR or *Infinite Impulse Response* (IIR) filter estimating the true impulse response of the cancellation path $P_\phi(z)$, and $y(k)$ is the measured output (error) which is minimized. The convergence properties of the filtered-reference LMS algorithm are similar to those of the normal LMS algorithm and the reader is referred to [13] for further details.

EXPERIMENTAL AND SIMULATION SETUP

The filtered-reference LMS algorithm was tested on a freely supported aluminum beam measuring $380\times15\times2$ mm, with two piezoelectric patches of material PXE-5 (Phillips Components, PLT 30/15/1-PX5-N) measuring $30\times15\times1$ mm mounted each one 52 mm from the free ends, and an ACLD patch, with a constrained layer made of the same piezoelectric material and a viscoelastic layer 3M ISD112, measuring $30\times15\times0.127$ mm mounted on the same location but opposite side (Figure 2). Furthermore, the piezoelectric patches were bonded on the beam by means of a non-conductive cianoacrilate adhesive (Loctite – 496) with high rigidity.

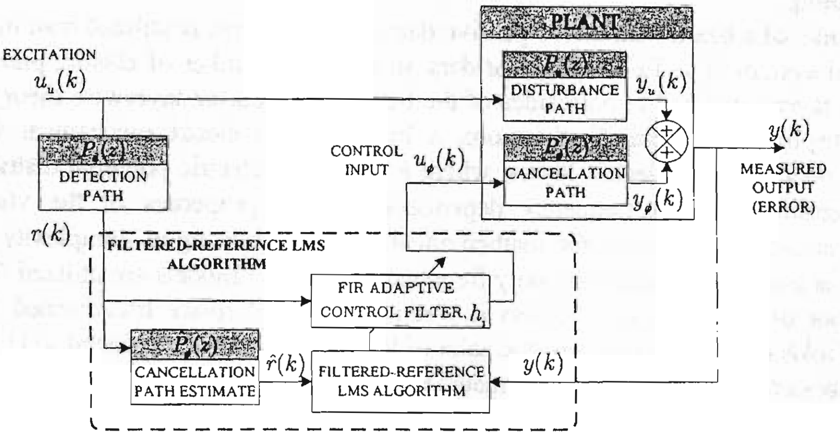


Figure 1 Schematic diagram of the discrete-time (digital) generalized plant for a feedforward SISO controller.

For the simulation the previously referred FE model was used with a spatial discretization of 190 FEs, and a piezo-visco-elastic structural coupled modal model with 20 modes plus 3 rigid body modes was considered. The material properties of aluminum, PXE-5 and 3M ISD112 at 27°C and the parameters of the three-series ADF model utilized in the simulation are the same used in [11] and for the sake of brevity the reader is referred to the reference for further details.

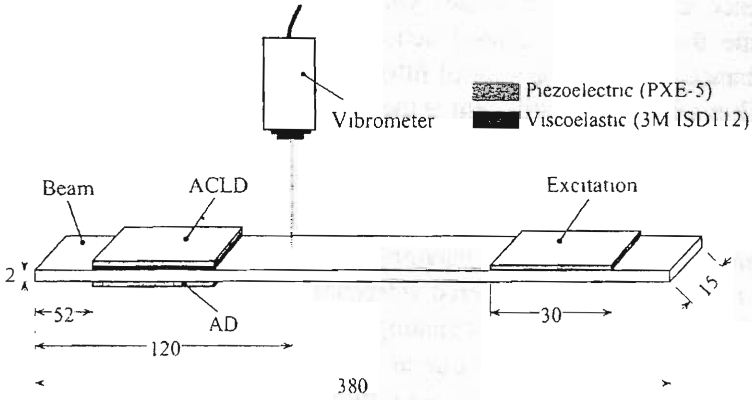


Figure 2 Freely supported test beam configuration (dimensions in mm) with the AD, ACLD and excitation patches.

A schematic of the experimental setup of the real-time feedforward controller is depicted in Figure 3. The velocity at one point of the beam was measured with a Doppler vibrometer transducer Polytec – OFV 303 with a laser vibrometer controller unit Polytec – OFV 3001. A Krohn-Hite dual channel (model 3362) and single channel (model 3550) low-pass filters with four-pole Butterworth characteristics with the cut-off frequency set to 1200 Hz were utilized as anti-aliasing and reconstruction filters. Furthermore, two power amplifiers were used, one LDS PA100E with a maximum output voltage of 20 V rms for the excitation, and another constructed in the lab with a maximum output voltage of 150 V for the control voltage. All real-time processing was carried out with a National Instruments Lab-PC+ DAQ board with 12-bit analog resolution, and the sampling rate was set to 3600 Hz both for simulation and real-time.

In the simulation and real-time implementation of the control system a *Single-Input Single-Output* (SISO) configuration, with the input being the velocity at one point of the beam and the output being the voltage applied into the piezoelectric constraining layer, for the ACLD configuration, or the piezoelectric patch, for the AC/PCLD configuration, is considered here. Assuming that the designer has access to a reference signal that is correlated with the disturbance, the filtered-reference LMS algorithm is employed to cancel the effects of the disturbance on the plant at the chosen output location. The simulation and all real-time processing were performed using Matlab® and Simulink® software, incorporating the Real-Time Workshop® and the Real-Time Windows Target®.

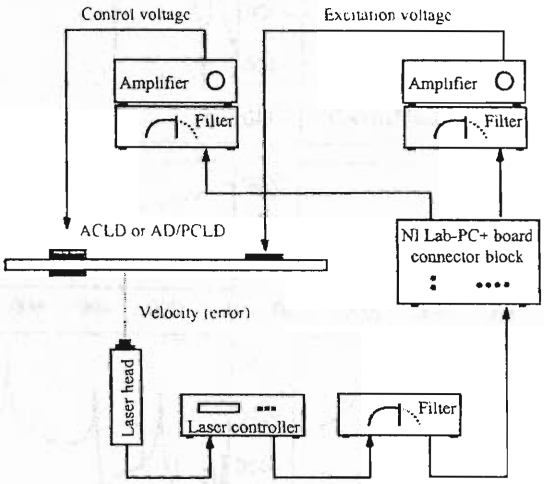


Figure 3 Schematic of the experimental setup of the real-time feedforward controller

SYSTEM IDENTIFICATION

The first step in operating the control is to perform the off-line system identification. Thus, a band-limited random noise from 10 to 1200 Hz, which was generated by Simulink®, was fed into the two piezoelectric patches of the AD and ACLD treatments and the FRFs between the voltage applied and the measured velocity were estimated in Matlab®. An IIR filter was used to identify the measured and simulated FRFs using the Matlab® *invfreqz.m* routine and the identified coefficients were utilized as coefficients of the IIR discrete filters of the cancellation paths. The results are presented in Figure 4. Note that the identified FRFs of the discrete filters match the predicted and measured FRFs in magnitude and phase, with the exception of some parts of the phase of the measured FRFs, however presenting the same trend. The phase has been "unwrapped" so that the reader can see that the phase does not remain within a $(-90°, 90°)$ boundary and therefore the control loops are indeed non-minimum phase in the bandwidth of interest. The resulting nearly linear decreasing trend in the phase verified in the measured FRFs is due to a combination of the delays from the DSP system, analog filters, amplifiers, etc, and demonstrates the "non-causality" of the controller. Furthermore, it's also worthy to mention that the predicted FRFs match the measured ones for both AD and ACLD treatments, and that there is almost two orders of magnitude of difference between the actuating capacity of the AD and ACLD patches, where the viscoelastic layer decreases the transmissibility of efforts, mainly in the low stiffness range (low frequencies). That is evident in the measured FRF of the ACLD patch, were in the range from 0 to more or less 150 Hz (first mode) the measured results show a very low transmissibility.

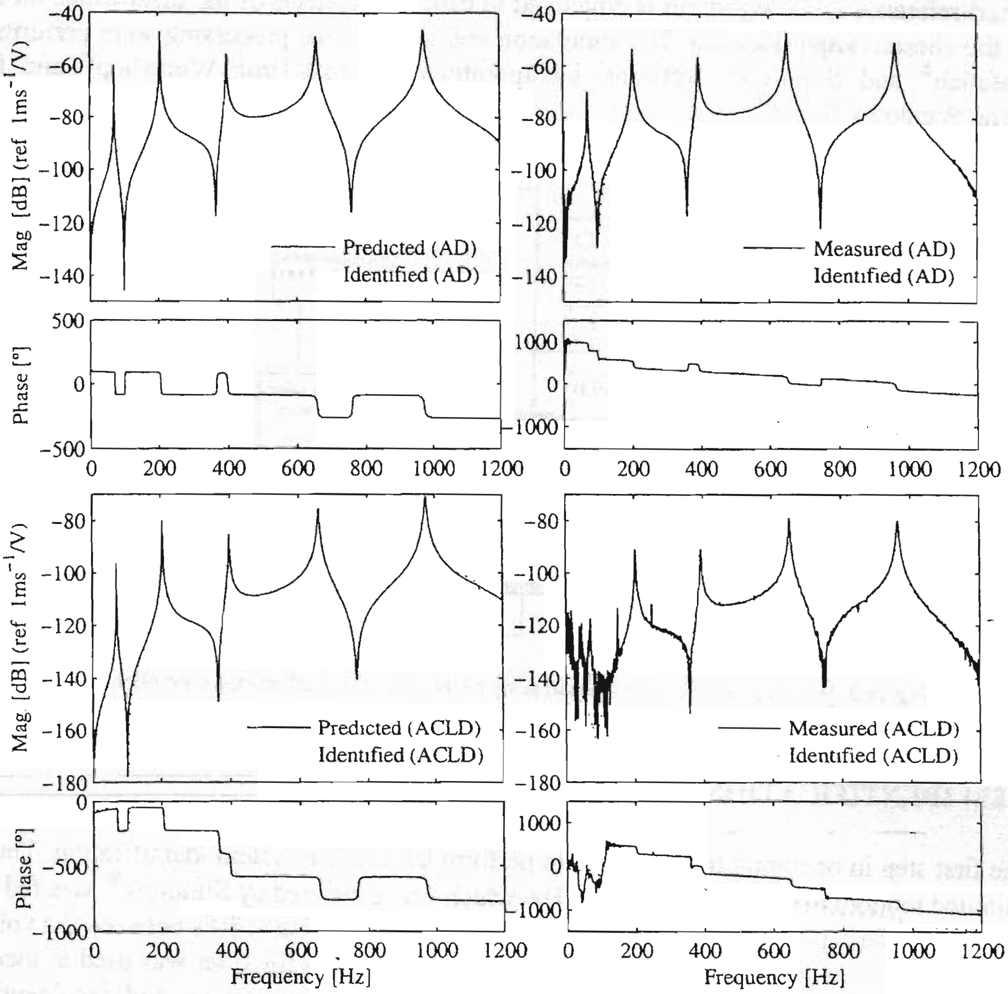


Figure 4 Comparison of the predicted and measured AD and ACLD cancellation path FRFs with the identified ones.

RESULTS

All controlled measurements have been obtained with the adequate adaptation rates for the different damping treatments. A filtered-reference LMS algorithm with 50 adaptive coefficients was considered both in the simulation and real-time control. The time responses after convergence of the adaptive feedforward algorithm were saved and post-processed to obtain the measured and predicted FRFs of the open- and closed-loop control systems for the two damping configurations, namely AD/PCLD and ACLD, as presented in Figure 5. The open-loop FRFs show again a good match between the predicted and measured FRFs at all modes. It's shown that the closed-loop response with the AD/PCLD treatment is more effective than with the ACLD treatment. Both measured and predicted FRFs show that, and a similar trend in the AD/PCLD results is achieved. However, the predicted results for the ACLD are too optimistic when compared with the measured ones, where the control was inefficient. That is justified by the fact that the control voltage of the simulation doesn't have any constraint and can increase indefinitely. However, in practice, the real-time controller was limited to a 150 V range output, and since ACLD requires higher voltages to have a similar actuating capacity to AD (recall

Figure 4 where a two order magnitude difference between the actuating capabilities of AD and ACLD is shown), the real-time controller produces low damping. Of course, in order to be able to increase the excitation to actuating voltage ratio one can decrease the magnitude of the excitation. However, if the values are too low, the signal to noise ratio increases and the controller may become unstable. Other alternative to increase ACLD performance is trying to implement a controller that can specifically increase the shearing of the viscoelastic layer, instead of trying to reduce the input power into the structure. (That is something that requires further study which is still in progress.) The measured and predicted ACLD to AD control voltage spectral density ratios are presented in Figure 6. It's shown that the predicted ratio is well above the measured one, showing that the real-time controller hasn't been able to feed the ACLD patch with the required control voltage to achieve a similar behavior to the simulated controller.

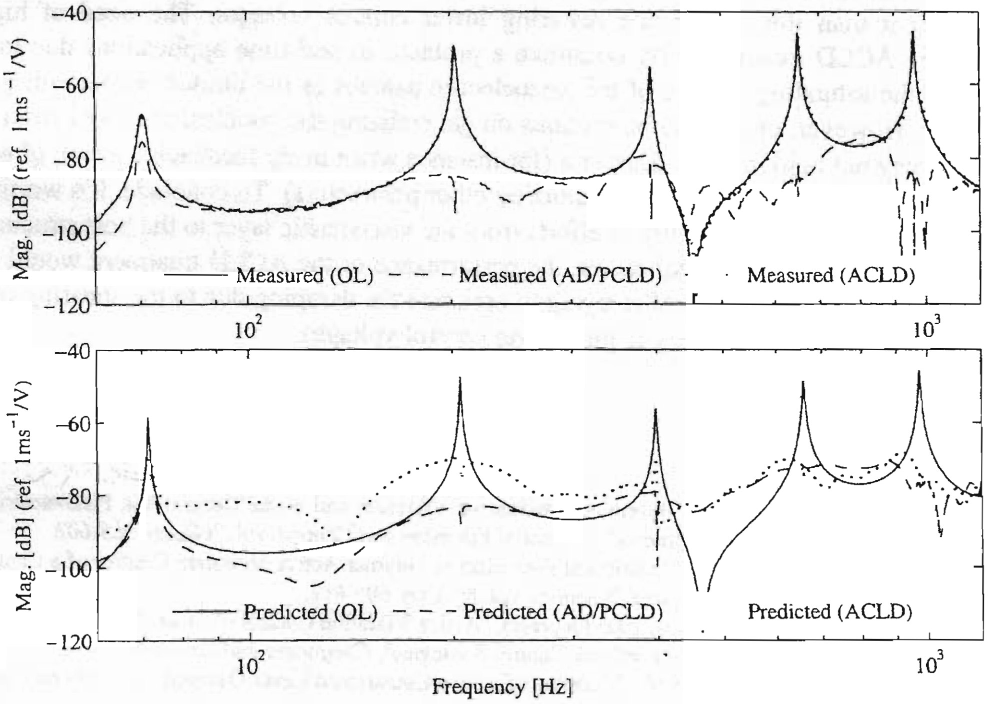


Figure 5. Measured and predicted open-loop (OL) and closed-loop FRFs of the SISO control system

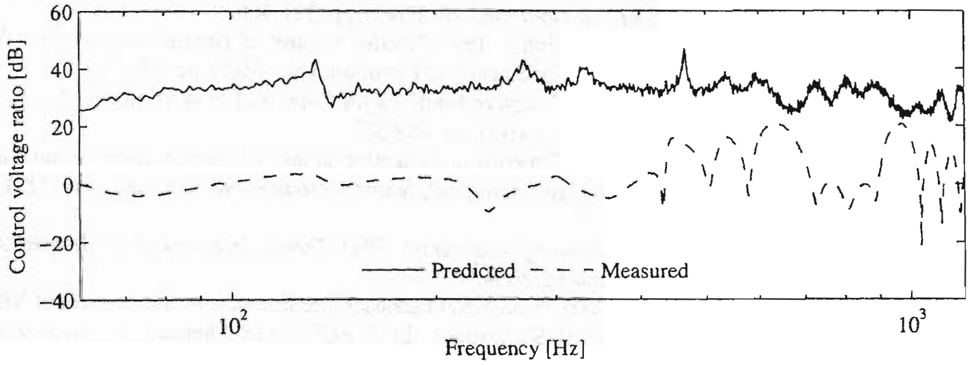


Figure 6. Measured and predicted ACLD to AD/PCLD control voltage spectral density ratios.

CONCLUSION

In this paper an adaptive feedforward controller using the filtered-reference LMS algorithm was utilized in the active control of vibrations of a beam excited by a piezoelectric patch and damped by *Active Damping* (AD) or an *Active Constrained Layer Damping* (ACLD) treatment. The two damping treatments were simulated and experimentally implemented in real-time with the purpose of comparing their damping performance. It was shown that the FE with the viscoelastic damping model utilized here has a very good accuracy and it is a reliable and useful tool for the controller and treatment design. In this specific application the AD/PCLD treatment is more efficient than the ACLD one requiring lower control voltages. The need of higher voltages of the ACLD treatment may constitute a problem in real-time applications due to the constraints of the saturating voltage of the piezoelectric patches or the limited output voltage of the amplifiers. However, one has to be cautious on generalizing the conclusions taken from this work, which may not hold in other situations (for instance when using feedback control, or when other performance indexes are utilized minimizing other parameters). To conclude, it's worthy to mention that since the transmissibility of efforts from the viscoelastic layer to the host structure is usually reduced, mainly at low frequencies, the performance of the ACLD treatment would only be improved if one designs a controller trying to optimize the damping due to the shearing of the viscoelastic layer, which in turn may require lower control voltages.

REFERENCES

1 Benjeddou, A 2001 "Advances in Hybrid Active-Passive Vibration and Noise Control Via Piezoelectric and Viscoelastic Constrained Layer Treatments", *Journal of Vibration and Control*, vol 7(4), pp 565-602

2 Bailey, T and J E. Hubbard. 1985. "Distributed Piezoelectric Polymer Active Vibration Control of a Cantilever Beam", *Journal of Guidance Control and Dynamics*, vol 8(5), pp 605-611

3 Vasques, C. M A. and J D Rodrigues 2005 (in press) "Active Vibration Control of Smart Piezoelectric Beams. Comparison of Classical and Optimal Feedback Control Strategies", *Computers and Structures*.

4 Plump, J M and J. E J Hubbard. 1986 "Modeling of Active Constrained Layer Damped" In *12th International Congress on Acoustics*, Toronto, Paper No D4-1

5 Baz, A. 1993. "Active Constrained Layer Damping" In *Proceedings of Damping' 93*, San Francisco, CA, pp IBB 1-23.

6 Ray, M C and A Baz 1997 "Optimization of Energy Dissipation of Active Constrained Layer Damping Treatments of Plates", *Journal of Sound and Vibration*, vol 208(3), pp 391-406

7 Vipperman, J S, R A Burdisso and C R Fuller 1993. "Active Control of BroadBand Structural Vibration Using the LMS Adaptive Algorithm", *Journal of Sound and Vibration*, vol. 166(2), pp 283-299.

8 Vipperman, J S and R. A. Burdisso 1995 "Adaptive Feedforward Control of Non-Minimum Phase Structural Systems", *Journal of Sound and Vibration*, vol 183(3), pp 369-382.

9 Poh, S, A Baz and B Balachandran 1996 "Experimental adaptive control of sound radiation from a panel into an acoustic cavity using active constrained layer damping", *Smart Materials and Structures*, vol. 5(5), pp 649-659

10 Illaire, H., "A study of active-passive damping treatments" *PhD Thesis, Department of Applied Acoustics, Chalmers University of Technology*, Gotenborg, 2004

11 Vasques, C M A and J D Rodrigues 2005 "Combined Feedback/Feedforward Active Control of Vibration of Beams with ACLD Treatments Numerical Simulation" In *II ECCOMAS Thematic Conference on Smart Materials and Structures*, Mota Soares, C A. *et al* (Eds.), Lisbon, 12-15 July, CD Rom Edition, pp. 1-25

12. Vasques, C M A., B R. Mace, P. Gardonio and J D Rodrigues 2005 (in press) "Arbitrary Active Constrained Layer Damping Treatments on Beams Finite Element Modelling and Experimental Validation", *Computers and Structures*

13 Widrow, B. and S D Stearns 1985 *Adaptive signal processing* Englewood Cliffs Prentice-Hall