ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

EXPERIMENTAL ACTIVE VIBRATION CONTROL OF AN IN-AIR OR WATER-LOADED PLATE: INFLUENCE OF TYPOLOGY AND LOCATION OF THE ERROR SENSORS

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Abstract

Broadband active vibration control of a thin-walled rectangular plate representing a flexible wall of a Plexiglas container is experimentally investigated in case of empty and water-filled tank.

The plate has boundary conditions close to those of clamped edges. Five piezoelectric PZT actuators are glued on its surface in order to apply the secondary control input.

The filtered-x Least Mean Square adaptive feedforward algorithm and the Direct Velocity Feedback technique are experimentally tested and their effectiveness is compared while using different kinds of error signals and different conditions of collocation.

The influence of the phase lag of the control system on the stability properties of the feedback algorithm is also experimentally evaluated.

INTRODUCTION

The use of active control techniques to suppress vibrations of very light structures is a very important target in many applications, since it allows to avoid the introduction of additional masses of stiffeners or dampers. Moreover, aeronautical and space structures often present thin walls containing fuel, where the fluid-structure interaction must be considered. For these reasons, the study of active vibration control of a panel in air and totally or partially wet on one side by a liquid is of interest.

In the present study, broadband active vibration control of a rectangular plate, representing a flexible wall of a thick Plexiglas container, is experimentally investigated for both empty and water-filled tank. Five piezoelectric PZT patches are used as control actuators, as firstly done by Dimitridis et al. [5] for two-dimensional structures.

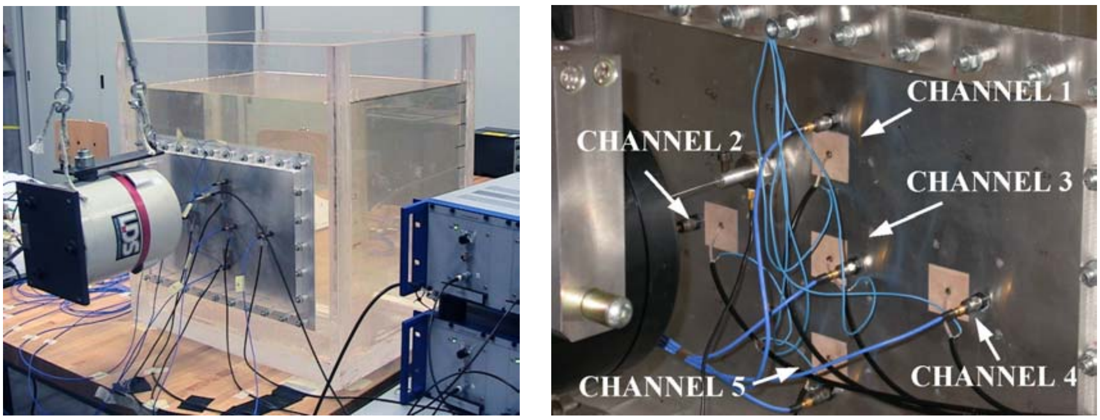
The presence of water increases the modal mass of the system and free surface waves complicate the system dynamics, as reported by Amabili [1] and Morand and Ohayon [14]. For this reason, several studies have been dedicated to the active control of sound and vibrations on fluid-loaded structures: in particular, Gu and Fuller [11], Lee and Park [12] and Fein et al. [7] investigated the case of a fluid-loaded plate.

The choice of the relative position between actuators and sensors is also a very important point, as explained by Preumont [15]. In particular, Direct Velocity Feedback (DVF) control, which has been also recently applied by Gardonio et al. [9] to a smart panel in air, is a theoretically unconditionally stable algorithm only if the sensor-actuator pairs are collocated and dual. Several solutions for real cases have been proposed, as by Gardonio et al. [10], Lee et al. [13] and Cole and Clark [4].

In this study, broadband active vibration control is experimentally applied to a fluid-coupled system, using the filtered-x LMS (FXLMS) feedforward technique and the Direct Velocity Feedback (DVF) control. In addition to other recent experiments realized by the authors [2] [3], the FXLMS and DVF control algorithms are compared while using different kinds of error signals and different conditions of collocation. The effects of fluid-structure interaction on the control are also investigated.

THE SYSTEM AND ITS DYNAMICS

The system to be controlled is constituted by a rectangular Aluminium plate (400 × 283 × 0.8 mm), which is bolted to the thick wall of a Plexiglas tank (Figure 1(a)).



(a) (b)

Figure 1- Experimental set-up (water-filled tank): a) the system; b) the control channels

The plate has boundary conditions close to those of clamped edges and it is positioned on the wall in correspondence of an opening of dimensions 350 × 233 mm at a distance of 70 mm from the bottom of the tank. The Plexiglas walls are quite thick (30 mm) and they are reinforced with stainless steel bars at the opening, so they can be considered quite rigid in the low-frequency range.

In the past, modal analyses were carried out on the system, for empty tank and in presence of different levels of water. It has been observed that the progressive increment of the fluid gives a significant reduction of the natural frequencies.

The control components are constituted by five piezoelectric PZT patches (25mm x 25mm x 0.2mm, capacity 50 nF), glued on the dry surface of the plate, and five accelerometers, which are positioned close to the PZT actuators in a nearly-collocated configuration. Every couple accelerometer-piezoactuator represents a SISO (Single Input Single Output) channel of the control system and it is numbered as in Figure 1(b). The position of the PZT patches has been optimised by calculating the deformation energy of the plate for the first natural modes in case of empty tank.

Additional tests in presence of different environment conditions have shown that the studied structure is very sensitive to temperature [3]. Thus, the control techniques should take into account the extreme variability of the system dynamics.

THE CONTROL SYSTEM: HARDWARE AND ALGORITHMS

For every SISO channel of the control system, the acceleration signal is sent to a real-time digital controller (dSPACE DS1104 processor board) passing through a 12-bit A/D converter. The controller generates the command input for the correspondent collocated PZT actuator; such signal is reconstructed by a 16-bit D/A converter. Every actuator receives the command signal from a high-voltage power amplifier. Smoothing and antialiasing filters (eighth order filters, with cut-off frequency at 400Hz) have been used. Some amplification gains have been opportunely introduced into the control-loop in order to increase the signal/noise ratio. The control algorithm has been implemented working in a Matlab-Simulink environment.

The complete control system (Figure 2(a)) also includes a laser doppler vibrometer Polytec OVF-5000 for direct measurement of velocities and displacements, which is shown in Figure 2(b).

(a) *(b)*

Figure 2 – The control system: a) global view; b) laser doppler vibrometer

The primary disturbance is given by an electrodynamical shaker, driven with random signal, which excites the plate in eccentric position through a thin stinger. A piezoelectric force transducer is glued to the plate in correspondence of the excitation point in order to measure the actual force given to the plate by the shaker.

The active control is experimentally applied to the studied system in presence of broadband disturbance using the filtered-x Least Mean Square (FXLMS) adaptive feedforward technique and the Direct Velocity Feedback (DVF) control, in Single Input Single Output (SISO) approach, for both empty and completely water-filled tank.

In the case of FXLMS control, a reference signal is derived from the primary excitation and it is used directly to drive the secondary control input [8]. In Figure 3(a), *H* is a Finite Impulse Response (FIR) filter that acts on the reference signal *x* in order to generate the secondary control input *u*. The coefficients of such filter have to be continuously calculated by a LMS adaptive filter *F*.

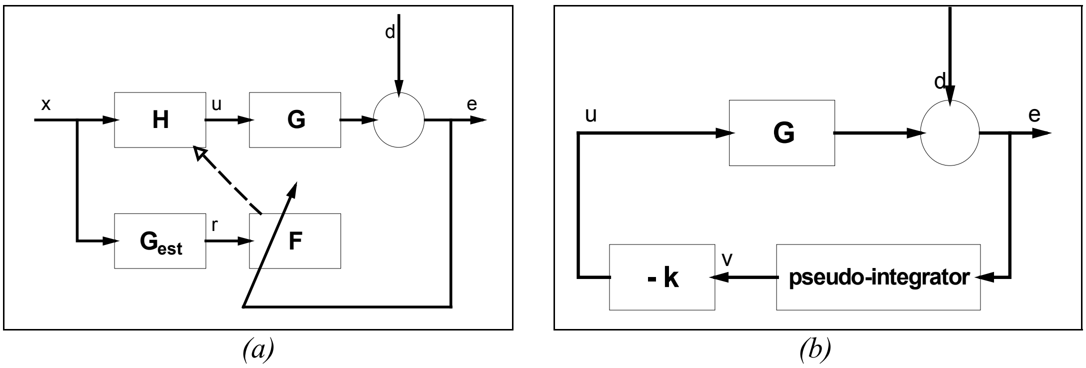


Figure 3 - Block diagrams of the tested algorithms: a) FXLMS control; b) DVF control

The reference signal *x* must be also filtered with an appropriate filter G_{est}, which represents a model of the secondary control path.

Other tests have been performed by applying the DVF technique [15], where the velocity signal *v* from the sensors is multiplied by a feedback gain *k* and it is sent back to drive the secondary PZT actuators with changed sign (Figure 3(b)).

EXPERIMENTAL ACTIVE CONTROL RESULTS

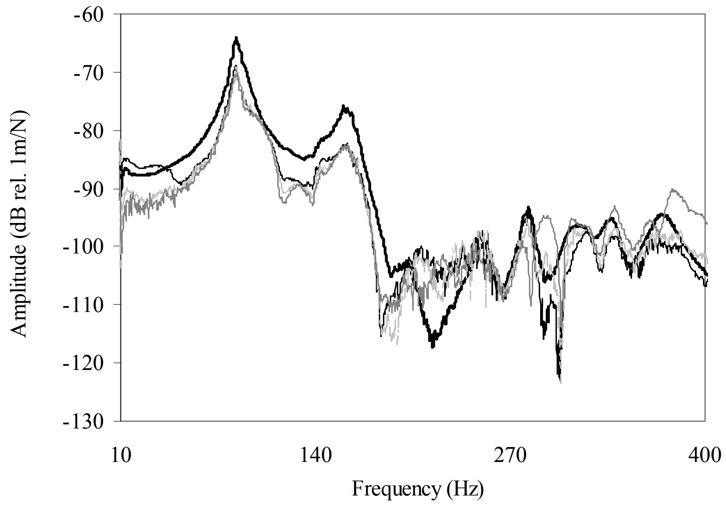
Active control has been experimentally applied to the plate in linear behaviour (small vibration amplitudes) in presence of broadband disturbance on 10-400 Hz (in case of empty tank) and on 10-200 Hz (in case of water-filled tank), testing filtered-x Least Mean Square adaptive feedforward control and Direct Velocity Feedback control.

The level of the primary excitation, produced by the shaker, has been chosen high enough to guarantee a good signal/noise ratio, but also low enough to avoid to reach large vibration amplitudes (nonlinear behaviour).

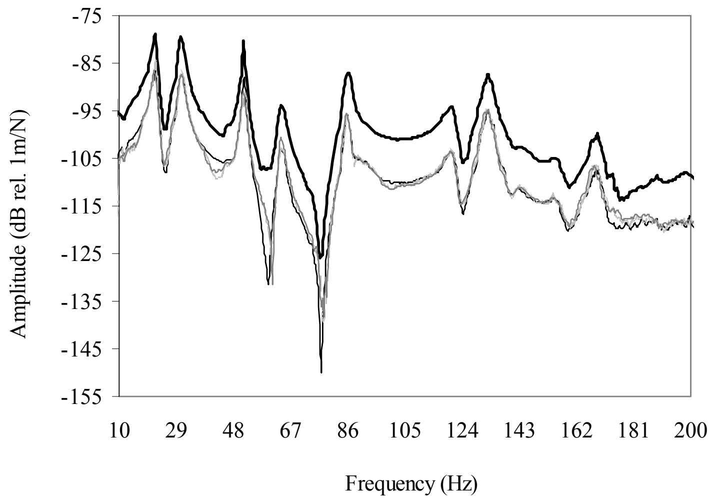
Experiments have been repeated by using different kinds of error signals and in different conditions of collocation.

Filtered-x Least Mean Square (FXLMS) experiments

Satisfactory reductions have been obtained by using the FXLMS algorithm for both empty and water-filled tank, as shown in Figure 4. The control effectiveness is well distributed on both resonances and antiresonances, expecially in the case of water-filled tank. Tests have been repeated while using different kinds of nearly-collocated error signals (acceleration, velocity, displacement), but no significant differences in the control effectiveness have emerged. Velocities and displacements are calculated by digital pseudo-integrators or directly measured by the laser doppler vibrometer.



(a)



(b)

Figure 4 – FXLMS control effectiveness on the measured frequency response function on Channel 3 in case of a) empty tank and b) water-filled tank: no control (——), acceleration control (——), velocity control (——), displacement control (——)

In case of fluid-structure interaction, satisfactory reductions can be obtained anyway only by stopping the convergence of the algorithm at about one third of the optimal control effort, in order to avoid the saturation of the piezoelectric patches. The introduction of effort constraints, as suggested by [6], could be therefore advisable.

Additional experiments have been performed in case of perfectly-collocated control, measuring velocities in the centre of the piezoelectric patches with the laser vibrometer. Results are comparable with the ones obtained in case of nearly-collocated control. A possible negative influence of the in-plane deformation of the piezoactuators on collocated control has been also excluded. Similar results have been obtained by using a subminiature accelerometer, located on the inner side of the plate.

In all FXLMS experiments, the primary excitation (measured by the load cell) is adopted as reference signal and an off-line identification of the secondary control path is realized. The causality of the control system was verified by the authors in [3].

Direct Velocity Feedback (DVF) experiments

In case of DVF control, the effects of the system phase lags have been evaluated, observing that stability cannot be guaranteed in all the studied frequency range.

In particular, the phase lag introduced by the antialiasing filters reduces significantly the control performances. Figure 5 shows that, in absence of antialiasing filter, on Channel 4, very satisfactory results can be obtained on the second peak (at about 170 Hz), that is in fact optimally controlled by Channel 2 and 4 [3].

The residual delays on the secondary path cause anyway, even in absence of the filter, amplifications of other peaks at higher frequencies, expecially when very high values of the control gains are adopted. This effect is more evident in case of empty tank, since the studied bandwidth is larger. The use of perfectly-collocated control seems anyway to avoid the risk of such amplifications, as shown in Figure 5.

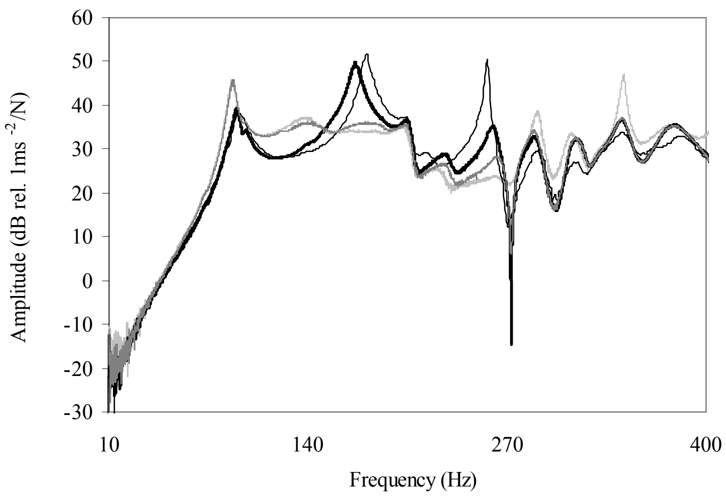


Figure 5 – DVF control effectiveness on the measured frequency response function on Channel 4, in case of empty tank: no control (▬), nearly-collocated control with filter phase lag (—), nearly-collocated control (▬), collocated control (▬)

Some amplified peaks (as the one at about 95 Hz in Figure 5) can be finally observed at low frequency in absence of water; this “positive feedback” effect is extended to almost one half of the studied frequency range in case of water-filled tank (Figure 6).

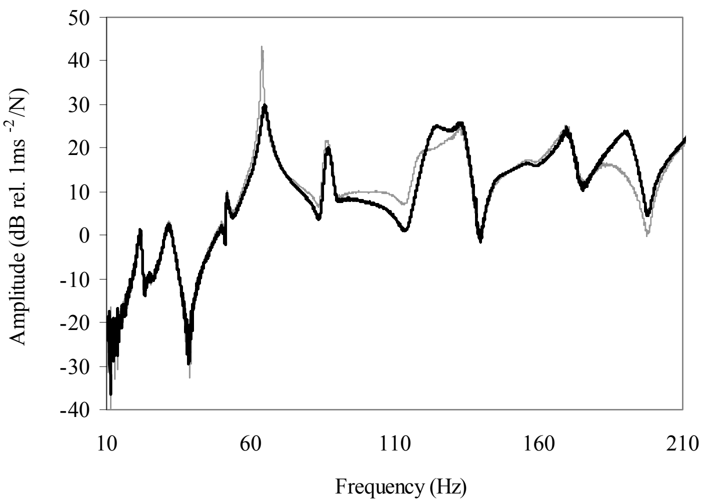


Figure 6 – DVF control effectiveness on the measured frequency response function on Channel 1, in case of water-filled tank: no control (▬), acceleration control (▬)

CONCLUSIONS

The active vibration control of a thin rectangular plate, representing a flexible wall of a rigid container, has been experimentally investigated in case of both empty and water-filled tank, testing the filtered-x Least Mean Square adaptive feedforward (FXLMS) algorithm and the Direct Velocity Feedback (DVF) technique.

Satisfactory reductions have been obtained using FXLMS control for empty and water-filled tank; in future, effort constraints could be introduced in the algorithm, in case of water-filled tank, in order to reduce the required actuation power.

Tests have been repeated while using different kinds of error signals (acceleration, velocity, displacement) but no important differences in the control effectiveness have emerged. A laser doppler vibrometer has been also used as error sensor in a perfectly-collocated configuration, obtaining similar satisfactory results.

In case of DVF control, the effects of the phase lag of the control system on the stability of the algorithm have been observed and evaluated. Significant vibration reductions are obtained in the stability region, but amplifications appear at higher frequencies. This effect, which is more evident in case of empty tank, is considerably reduced when a perfectly-collocated error sensor is used. The values of the control gains could be also optimized in future in order to reduce such amplifications.

Finally, some amplified peaks appear at low frequency in absence of water; this “positive feedback” effect is extended to almost one half of the studied frequency range in case of water-filled tank. Possible reasons, related to some components of the control system (high-pass filters, accelerometers), will be investigated in future.

ACKNOWLEDGMENTS

The present research is carried out within the Italian-French Vinci doctoral program, involving University of Parma and CNAM-Paris. It has been partially supported also by the Italian Ministry for Research (MIUR) through the FIRB 2001 and COFIN 2003 grants. A particular acknowledgement goes to Dott. Ing. Giovanni Zannoni for his participation to the realization of some of the experimental control tests.

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