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COMPARISON OF VARIOUS ACTIVE VIBRATION AND NOISE REDUCTION APPROACHES APPLIED TO A PLANAR TEST STRUCTURE

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Abstract

Various approaches for active vibration and noise control based on velocity feedback are tested against each other. The test setup consists of several piezoelectric patch actuators, which are applied to a thin rectangular aluminum plate, an electrodynamic shaker, an accelerometer, and analog control electronics. The vibration modes of the plate are measured using a scanning laser vibrometer. Based on the measurement results, favorable positions for the application of four pairs of piezoelectric patch actuators are determined by superposing the plate curvatures caused by the first four vibration modes. By measuring the transfer functions between the piezo patches, the excitability and measurability of certain vibration modes is checked. Then, several different active vibration and noise control approaches are tested. The vibration and sound pressure amplitudes at certain modes can be reduced by up to 20 dB.

INTRODUCTION

The vibrations and the sound radiation of a structure can be reduced by means of damping treatments or adding stiffening elements such as ribs. While this is generally applicable for mid-range and high frequencies, damping of low frequency noise and vibrations requires a lot of additional material, which ads some substantial mass to the structure. Active approaches [1, 3] are a means to avoid this mass increase, which is a serious drawback particularly in lightweight design, e.g., in aerospace applications. This paper describes the design, application, and testing of various active vibration control (AVC) and active structural acoustic control (ASAC) approaches based on favorably placed piezoelectric patch actuators and analog velocity feedback. These active approaches are applied to a baffled aluminum plate.

Eds.: J. Eberhardsteiner, H.A. Mang, H. Waubke

EXPERIMENTAL SETUP

The baffled aluminum plate has a size of 635 mm × 335 mm and a thickness of 2 mm. It is clamped into a steel frame by means of 48 bolts. Figure 1 shows the plate with its four pairs of piezoelectric patches (each 50 mm × 25 mm × 0.5 mm) on the front side (left) and an electrodynamic shaker, a force sensor, and an accelerometer on the back side (right).

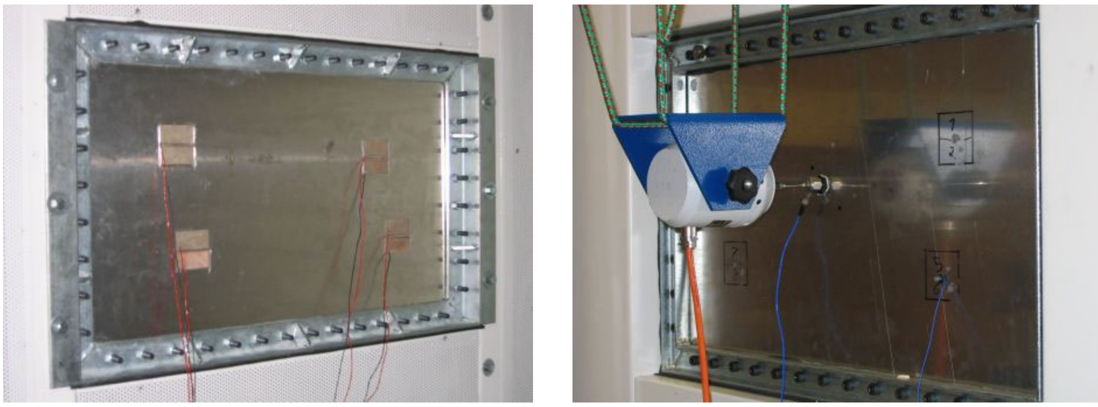

Figure 1: Front side (left) and back side (right) of the aluminum plate

The active vibration and noise control approaches are based on analog velocity feedback. The output of the accelerometer, which is collocated with one of the piezo actuators (see Fig. 1, right), is band-pass filtered and integrated using an analog integrator/filter/amplifier unit, which is able to control two separate control loops independently. A schematic representation of the experimental setup is shown in Fig. 2.

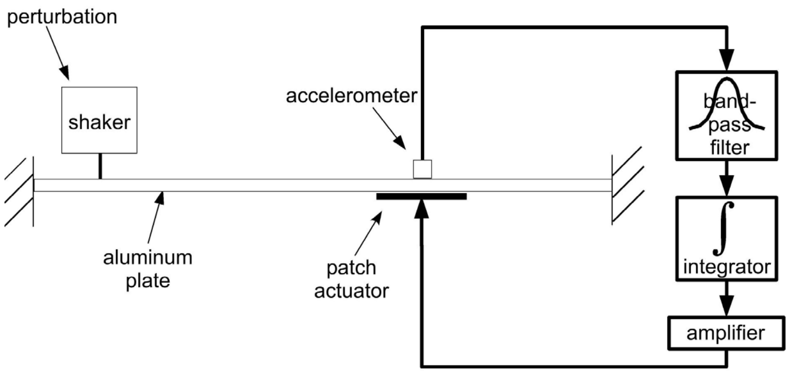

Figure 2: Schematic representation of the experimental setup

The plate is excited by a sine sweep signal or white noise in the frequency range 0–1000 Hz by means of the shaker. On the front side of the plate a measurement microphone is placed at a distance of 3.5 m to measure the reductions of the radiated sound pressure level. Figure 3 shows a photograph of the complete test setup including an FFT analyzer, a signal generator, and two piezo power amplifiers.

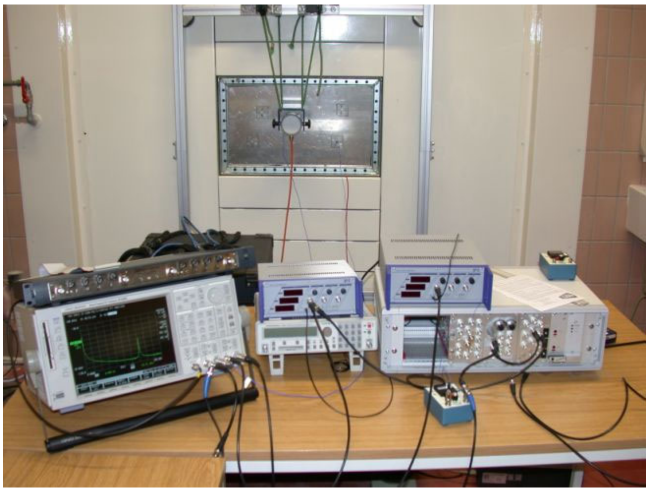

Figure 3: Complete experimental setup

FAVORABLE ACTUATOR PLACEMENT

As a first step, the vibration mode shapes of the baffled plate are determined by means of an experimental modal analysis using a scanning laser vibrometer and Cada-X software by LMS. Based on the results, four vibration modes are selected: mode 1 (1-1, 87.5 Hz), mode 3 (3-1, 187 Hz), mode 4 (2-2, 262 Hz), and mode 7 (3-2, 325 Hz). The piezo patch actuators are to be placed on the plate in such a way that they can influence and control the vibrations of these four vibration modes.

The displacement values z of the measured mode shapes are imported into Matlab. The plate's curvature (see Fig. 3 for examples) is determined by differentiating the displacement z twice [3]

$$w'' \approx \frac{\partial^2 z}{\partial^2 x} + \frac{\partial^2 z}{\partial^2 y} \quad . \tag{1}$$

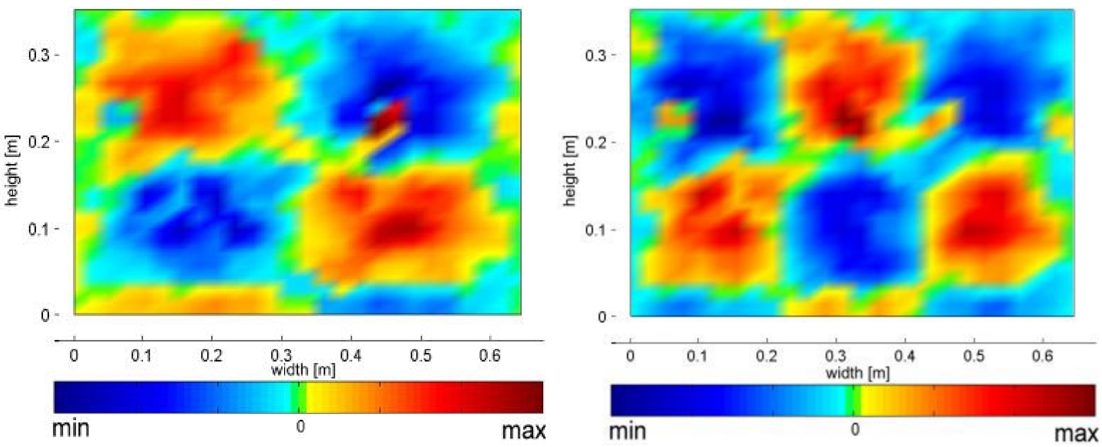

Figure 4: Curvature of the plate for the 2-2 mode (left) and the 3-2 mode (right)

The total curvature of the plate due to the four vibration modes mentioned above (see Fig. 5) is obtained by multiplying the respective curvatures calculated by means of Eq. (1). The piezo patches (numbered 1–8) are placed at these high-curvature (i.e., high-strain) regions. The white line indicates the sign change of the curvature of the first bending mode.

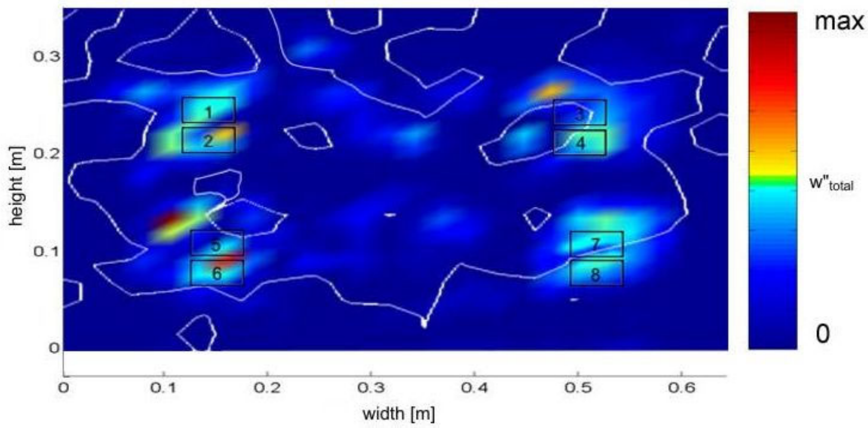

Figure 5: Total curvature of the plate considering modes 1-1, 3-1, 2-2, and 3-2

Figure 6 shows the frequency response functions between two adjacent piezo patches. The plot indicates that the actuators are able to excite most of the desired vibration modes. However, the patches 7 and 8 are obviously not able to excite the first mode (1-1) since they are located on opposite sides of the white line in Fig. 5, which indicates the curvature sign change of the first mode.

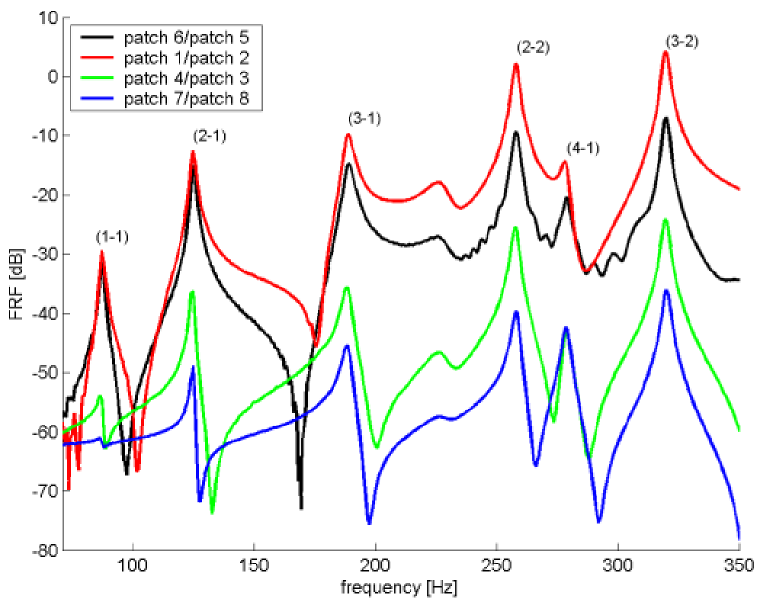

Figure 6: Frequency response functions of collocated piezo patches

MEASUREMENT RESULTS

Several different active vibration and noise control approaches are applied and tested. These include the narrowband control of different individual modes by using both a SISO and a SIMO method, the broadband control of several modes by using both a SISO and a Multi-SISO method, and the narrowband and broadband control of the sound transmission through the plate. Some selected results are presented below.

Narrowband control using one actuator (SISO)

First, the vibration amplitude of the third vibration mode (3-1) is reduced by means of narrowband control using a single acceleration sensor and a single piezo actuator (patches 3 and 4). This approach is called "single input, single output" (SISO). Sensor and actuator are collocated.

Figure 7 shows the acceleration levels with the control switched off and on. The vibration amplitude of mode 3-1 is reduced by approximately 6 dB. As a side effect, the amplitudes of some other modes are reduced as well. Apparently, the natural frequencies of other modes below or above mode 3-1 are shifted towards lower or higher frequencies, respectively, as a result of the virtual mass and stiffness changes due to the band-pass filter/integrator combination.

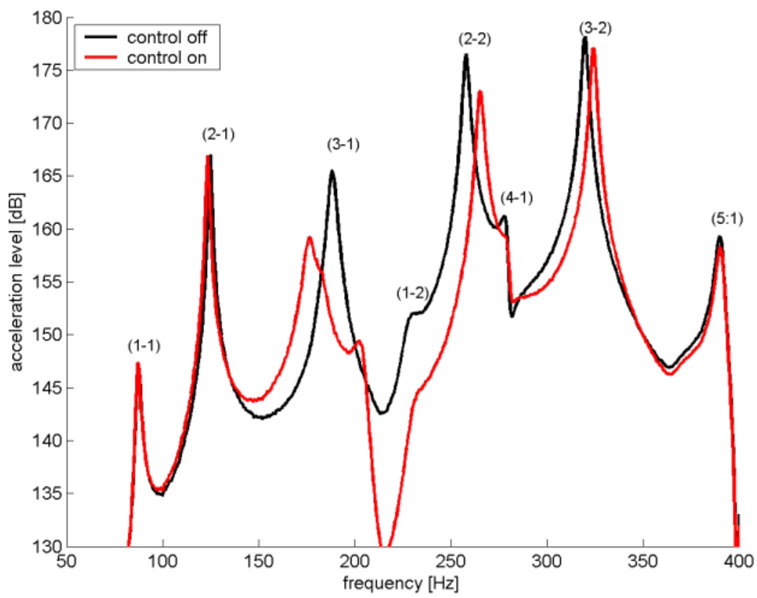

Figure 7: Acceleration level, narrowband control of mode 3-1 (SISO)

The sound pressure level (SPL) in front of the plate with the control switched off and on is depicted in Fig. 8. The SPL at mode 3-1 is reduced by 6 dB as well. At other frequencies (e.g., mode 1-2 or 2-2), however, it is slightly increased. The same frequency shift as for the acceleration level in Fig. 7 can be observed. The subjectively perceived noise reduction is negligible, only the sound characteristics change.

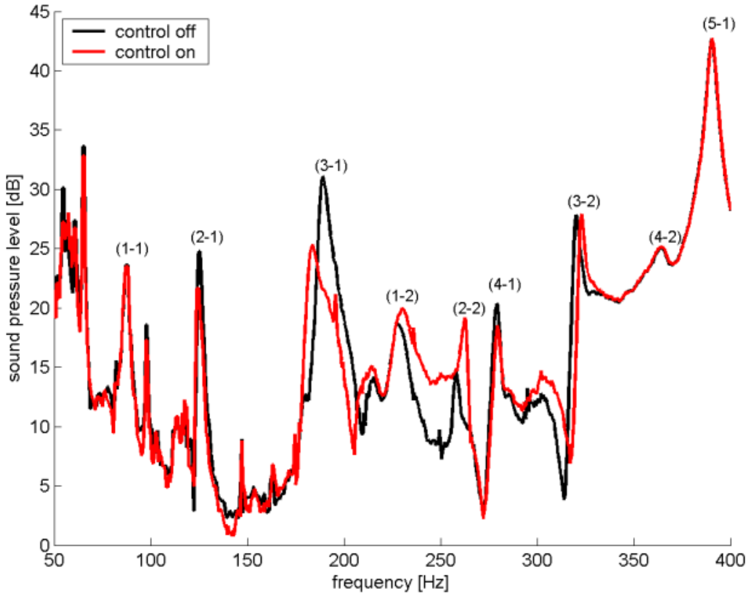

Figure 8: Sound pressure level, narrowband control of mode 3-1 (SISO)

Broadband control using two sensors and two actuators (Multi-SISO)

In this example, two pairs of collocated sensors and actuators (patches 1/2 and 5/6) are used to achieve a broadband control of the vibration amplitudes. As can be seen from Fig. 9, this broadband control is quite effective. All of the peaks (except for the one of mode 1-1) are substantially reduced by up to 20 dB (e.g., modes 2-2 or 3-2).

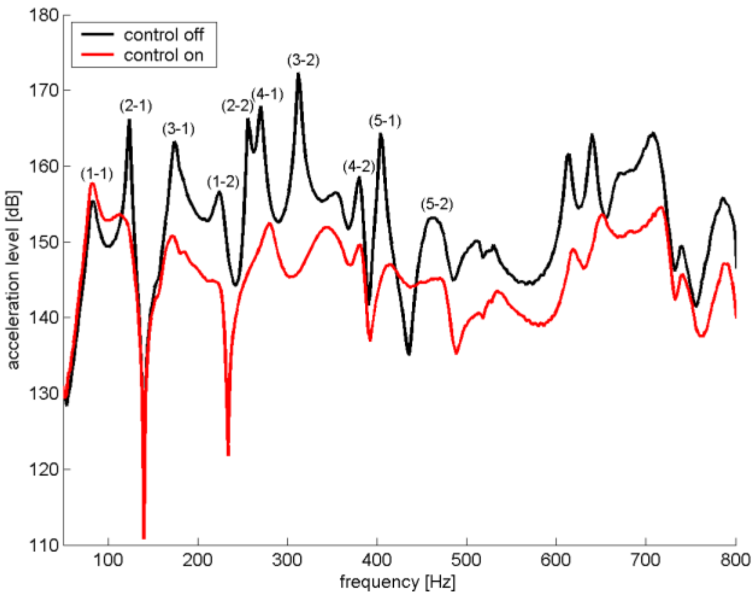

Figure 9: Acceleration level, broadband control (Multi-SISO)

The corresponding SPL spectrum at a distance of 3.5 m in front of the plate is shown in Fig. 10. The SPL reductions are not quite as impressive as those of the acceleration level in Fig. 9. The SPL amplitudes of mode 2-2 and 3-2 are reduced by 10 dB and 12 dB, respectively. Again, one can barely hear any change in the perceived loudness as the control is switched on and off; just the timbre of the noise changes somewhat.

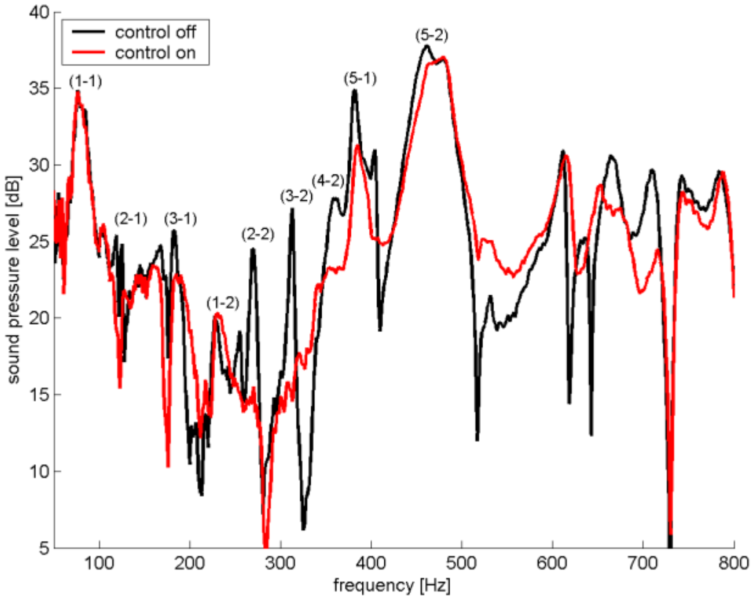

Figure 10: Sound pressure level, broadband control (Multi-SISO)

SUMMARY AND CONCLUSIONS

Various control strategies for active vibration and noise control based on active structural acoustic control (ASAC) are tested against each other. These control strategies are applied to a baffled rectangular aluminum plate. The acceleration measured by one or two accelerometers is band-pass filtered and integrated and is used as the input signal for one or several piezoelectric patch actuators (analog velocity feedback control). The actuators should be capable of efficiently exciting certain acoustically relevant vibration modes of the plate. Thus, favorable actuator positions are determined from experimental modal analysis results by means of numerical analyses. The excitability of certain vibration modes by certain patch actuators is checked. Then, several narrowband and broadband control strategies using one or multiple sensors and actuators are tested. The plate vibrations at certain modes can be reduced by up to 20 dB, the corresponding sound pressure level in front of the plate drops by up to 12 dB.

From the measurement results it is obvious that the vibration reduction does not necessarily lead to a comparable SPL reduction as well. This might be due to an increase of the plate's radiation efficiency, to a change of the acoustic short circuit, or to a change of the plate's radiation characteristics as a result of the applied control. Furthermore, the subjectively perceived noise reduction is barely audible. This might be due to the low sensitivity of the human hearing at low frequencies and to the fact that most often only a narrowband instead of a broadband SPL reduction can be achieved. Therefore, further research in this field should focus on larger SPL reductions at low frequencies and on broadband control, possibly by using digital control.

Approaches similar to those presented in this paper have been successfully tested in real-world applications such as vibration and noise control in buildings using active windows and facades [2].

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The numerical analyses and the measurements presented in this paper were performed by Christian Schmid-Schönbein as part of his master thesis [4], which was supervised by the authors of this paper. Furthermore, the financial support by the Fraunhofer Gesellschaft in the framework of an internal research project titled "SEF 'Adaptive Lärmminderung an flächigen Strukturen auf Basis piezoelektrischer Sensor-Aktormodule mit anisotroper Charakteristik' " ("Adaptive noise reduction applied to planar structures based on piezoelectric sensor/actuator modules with anisotropic characteristics") is gratefully acknowledged.

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