Active control of the sound transmission through a double-glazing window

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Introduction

Within the framework of the European Integrated Project "InMAR – Intelligent Materials for Active noise Reduction" [1] possibilities for the active control of the sound transmission through a double-glazing window by means of piezoelectric patch actuators were researched. The vibration behavior of the double-glazing window was experimentally analyzed and numerically simulated. Based on the results, favorable positions for the placement of the piezoelectric patch actuators were determined. Various control approaches were tested and compared with each other.

The passive window: vibration analysis

The test stand used for the vibration analysis of the passive window consists of a double-glazing window integrated into a frame structure made of aluminum profiles (see Fig. 1).

Figure 1: test stand with passive double-glazing window (red dot marks laser spot).

The double-glazing window in turn was custom-made to the material and geometrical specifications agreed upon by the project partners: width 600 mm, length (height) 1200 mm, thickness of outer window pane 6 mm, thickness of inner window pane 4 mm, distance between window panes 20 mm. The surface of the inner window pane (4 mm) was covered with white paint such that the laser spot of the laser vibrometer is better reflected (see red dot in Fig. 1). An electrodynamic shaker was attached to the outer window pane (6 mm) in order to excite vibrations of the outer window pane that are transmitted to the inner window pane by means of the gas-filled cavity between the two panes. The vibrations of the inner window pane were measured by means of a scanning laser vibrometer, and an experimental modal analysis of the vibration behavior of the inner, sound radiating window pane was performed.

The vibration behavior of the passive double-glazing window was also simulated numerically by means of a finite element model. As can be seen from Figs. 2 and 3, the results of the experimental modal analysis and of the numerical modal analysis agree very well.

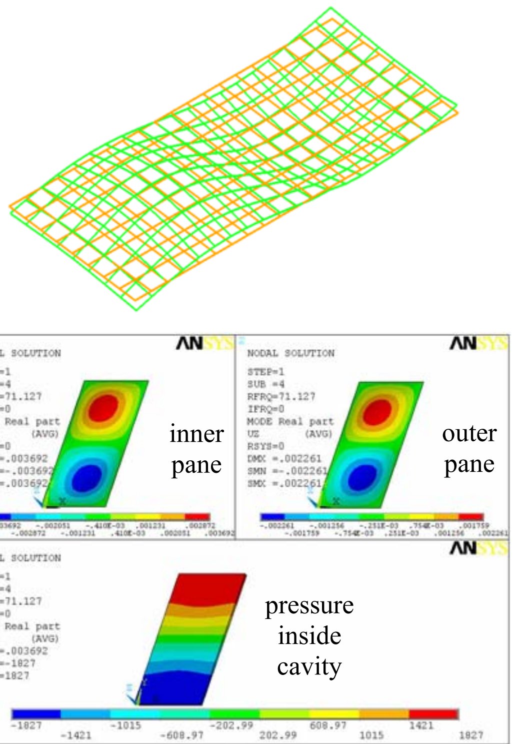

Figure 2: 1-2 structural mode shape of the window pane: experimental modal analysis (72.1 Hz, top), numerical modal analysis (71.1 Hz, bottom).

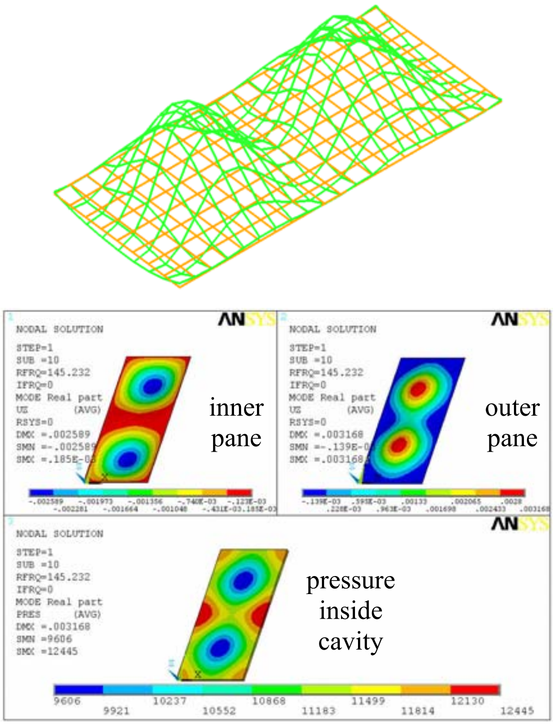

Figure 3: mode shape of the cavity: experimental modal analysis (153.0 Hz, top), numerical modal analysis (145.2 Hz, bottom).

Figure 2 depicts the 1-2 mode shape of the window. The two panes are in phase, indicating a structural mode of the window pane. Figure 3, however, obviously shows a mode shape of the gas-filled cavity between the window panes as can be seen from the fact that the two panes are out of phase (bottom part of Fig. 3) and that the two "hills" in the top part of Fig. 3 are in phase.

Favorable actuator positions

Unfortunately, reference [2] does not give any information on why the piezoelectric patch actuators used in that paper where placed at the given locations. The actuators (DuraAct) and sensors (piezoceramic patches) used in the present paper were carefully placed according to certain criteria. In order to determine such favorable actuator and sensor positions, so-called controllability and observability indices were calculated from the measured modal strain for certain combinations of various mode shapes [3, 4]. The mode shapes to be considered for these calculations were selected based on their contribution to the total vibration of the inner window pane and to the total radiated sound pressure level (SPL) in front of the window. Four actuators and four sensors were to be distributed on the inner window pane such that each of them is able to control or observe three mode shapes, respectively, which is achieved by multiplying the controllability or observability indices of the mode shapes to be considered. The sensors and actuators are to be placed at the locations with the highest index values. Figure 4 shows as an example the distribution of the controllability index for a combination of the modes 16 (112.1 Hz), 20 (157.7 Hz), and 22 (204.8 Hz) on the left hand side and of the observability index for a combination of the modes 10 (42.6 Hz), 27 (290.3 Hz), and 31 (400.6 Hz) on the right hand side.

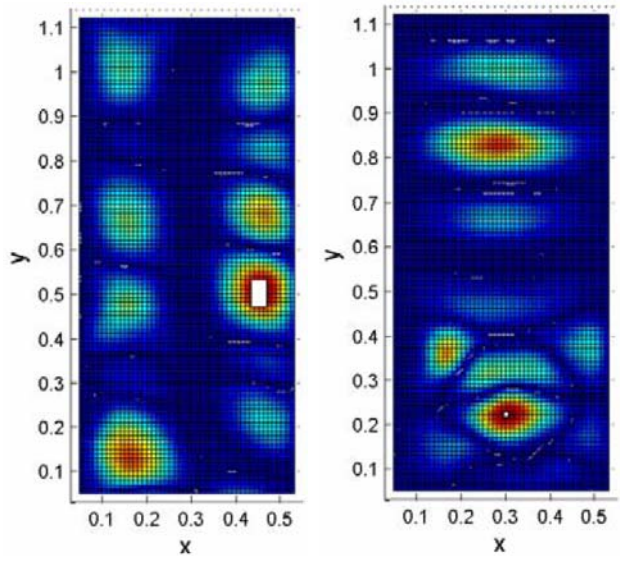

Figure 4: controllability index (left) und observability index (right) for certain mode shape combinations.

Active control of the sound radiation

First, some preliminary experiments with the active window (see Fig. 5) were performed. Besides other approaches (e.g., a simple analog feed-forward control or a positive position feedback control), an FxLMS algorithm using adaptive FIR filters and implemented on a dSpace system [5] was used as the control system in order to reduce vibrations induced by an electrodynamic shaker on the outer window pane while the sound pressure was measured at the inner window pane. Various signals were used as error signals or reference signals (e.g., microphone signals, piezo patch voltage signals, output signal of the function generator).

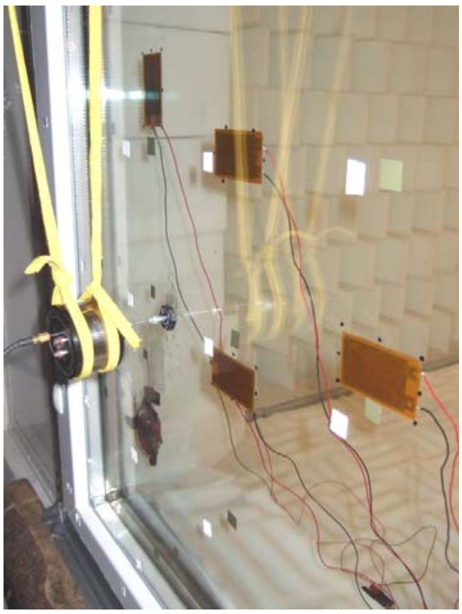

Figure 5: test stand for the active window: shaker, piezoelectric patch actuators, reflecting dots for laser vibrometer measurements.

The shaker signal, which was also used as the reference signal for the FxLMS control algorithm, was bandlimited white noise (40–440 Hz), the microphone signal of one of the microphones in front of the inner window pane was used as the error signal. The goal of this active control approach was the broadband reduction of the SPL in the given frequency band 40–440 Hz. However, due to the fact that the piezo actuators were placed in such a way that the controllability of certain modes reaches a maximum, the control algorithm seems to focus on certain peaks of the SPL spectrum. Figure 6 shows the SPL reduction at the error microphone due to the active control: The maximum SPL reduction is approximately 20 dB at 390 Hz, the highest SPL peak at 152 Hz is reduced by approximately 16 dB.

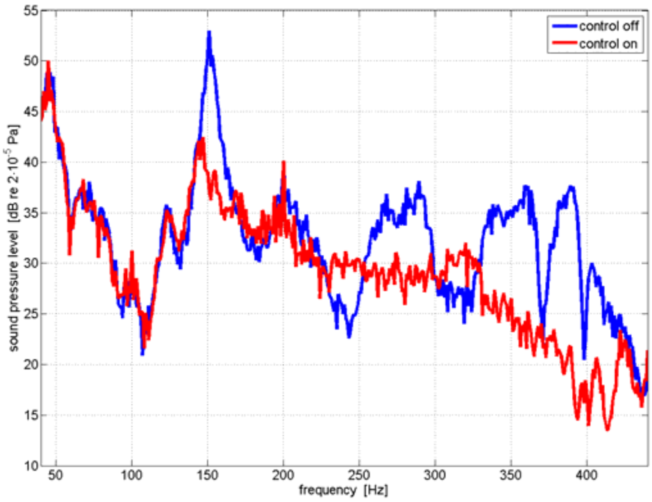

Figure 6: sound pressure level spectrum of the radiated sound at the error microphone location: control off (blue line), control on (red line).

Active control of the sound transmission

Next, the sound transmission through the double-glazing window was actively controlled. For that purpose a large loudspeaker, driven by bandlimited white noise (0–500 Hz), was placed approximately 40 cm in front of the outer window pane. A microphone array consisting of 64 microphones (8×8) was placed in front of the inner window pane to capture the radiated sound pressure across the whole window. Figure 7 shows the test stand with the patch actuators, the microphone array (in this picture placed in front of the outer window pane), and the loudspeaker.

Again, an FxLMS control algorithm was used to reduce the SPL in a wide frequency range (40–440 Hz), but the algorithm focused on certain peaks due to the placement of the patch actuators. In this configuration, not the signals from the array microphones were used as error signals, but rather the signals from six additional microphones at other locations close to the inner window pane were used. Therefore, the SPL reduction due to the active control system is not only measurable at the error microphone location but also clearly audible inside the receiving room.

Figure 7: test stand for the active window: piezoelectric patch actuators, microphone array, reflecting dots for laser vibrometer measurements, loudspeaker in the background.

Figure 8 depicts the SPL spectra averaged over all 64 array microphones with the control switched off (blue line) and the control switched on (red line). At 156 Hz the averaged SPL is reduced by 11.5 dB, at 191 Hz it is reduced by 6.6 dB. The corresponding third-octave band SPL spectra are shown in Fig. 9.

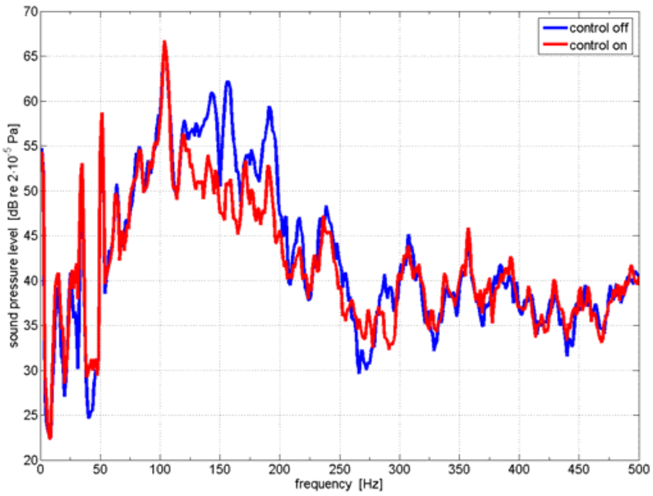

Figure 8: narrowband averaged sound pressure level spectrum of the transmitted sound: control off (blue line), control on (red line).

The total sound power level in the frequency range from 0 Hz to 500 Hz is reduced by 3.5 dB(A).

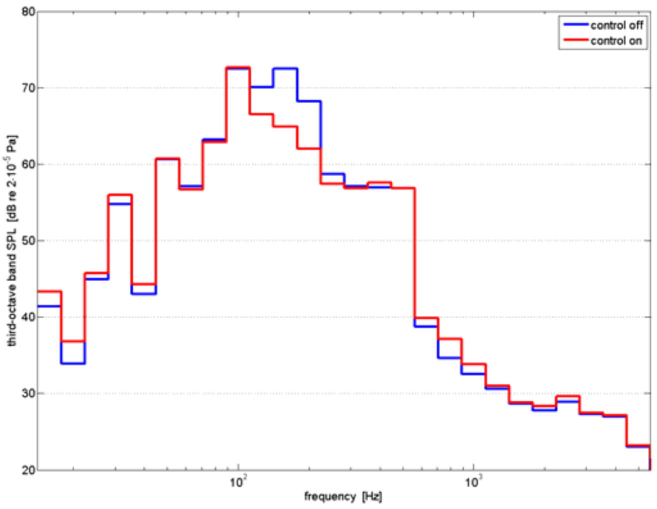

Figure 9: third-octave band averaged sound pressure level spectrum of the transmitted sound: control off (blue line), control on (red line).

Summary and conclusions

Various active control approaches for the reduction of the sound radiation from and the sound transmission through a double-glazing window were tested. The piezoelectric patch actuators were placed at locations where they can effectively influence several mode shapes. Depending on the test setup and on the choice of error and reference signals for the FxLMS algorithm narrowband SPL reductions of up to 20 dB were achieved for the sound radiation and of up to 11.5 dB for the sound transmission. In the 150 Hz third-octave band the SPL was reduced by 7.6 dB. The broadband total sound power level in the frequency range 0–500 Hz was reduced by 3.5 dB(A).

At first sight, these level reductions appear somewhat disappointing. However, one must consider that even the passive window has a high sound reduction index. Its weighted sound transmission loss was determined to be $R_w \approx 39$ dB, which is at the upper limit of the noise insulation class 3 – the noise insulation class 4 starts at $R_w = 40$ dB. Therefore, for this particular double-glazing window active control measures can only cure weak spots of the acoustic behavior such as the increased sound radiation and transmission due to the cavity mode at approximately 150 Hz.

Acknowledgments

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