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ACTIVE STRUCTURAL ACOUSTIC CONTROL ON FACADES

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Abstract

Nowadays noise exposure is considered one of the main environmental pollutions. Hence, a significant number of research projects are promoted throughout the European Union and worldwide that treat with the attenuation of ambient noise in daily life. Supported by the German ministry of Education and Research the object of the research project “Active Facades for Reduction of Sound Immissions in Buildings” is the investigation of the possibilities of reducing structure borne sound and radiated noise using active techniques. In modern architecture, facades serve as the outer skin of buildings and have to fulfill the demand of static strength. However, if facades are planned in a suitable way, they can also act as a barrier of incident sound fields. Active techniques on the basis of multifunctional materials can overcome the problems of increasing weight and volume, which the passive noise attenuation methods possess. In the present work a facade specimen consists of double-glazed windows and panels, implemented in a stiff frame. With Active Structural Acoustic Control (ASAC), the active system consists of distributed sensors and piezoceramic actuators attached to the laminar elements of the facade. By inducing anti-vibrations the structural vibrations caused by the surrounding airborne noise are minimized, thus reducing the radiated noise efficiently. Furthermore, with piezoceramic stack actuators integrated into the frame, an adaptive interface is designed preventing structure borne sound from being transmitted. With that configuration active damping and uncoupling effects can be investigated. The performance of both setups strongly depends on an effective control system. Therefore different control concepts including adaptive algorithms and model based control are designed and tested in the numerical environment. The reduction of the noise radiation achieved by the active System is estimated by BEM calculations. Utilizing a DSP-System the results can directly be validated at the demonstrator facade at Darmstadt University of Technology.

INTRODUCTION

The actual research project "Active Facades for Reduction of Sound Immissions in Buildings" is promoted and financed by the German ministry of education and research. At Darmstadt University of Technology, along with the project partner Schüco Int. KG, international supplier of facade elements and systems, possibilities are investigated to improve the noise attenuation properties of facades by active means. Besides visual facets facades have to fulfill various tasks like the demand of static strength. However if facades are planned in a suitable way, they can also act as a barrier to incident sound fields thus reducing the noise levels inside buildings. Examples for classical passive methods for reduction of sound immissions are double- or triple glazed windows and sound proofing materials. Especially in the low frequency domain (below 1000 Hz) passive means possess the drawback of increasing volume and weight of the facade construction and are therefore inapplicable in many cases. Moreover the structure borne sound which is transmitted over the support of the facade into the building or neighboring elements is difficult to handle by passive methods.

With an active system designed applying the principles of Active Structural Acoustic Control (ASAC), it is possible to construct light facade elements providing equal or even better noise attenuation than the passive counterparts. With ASAC, actuators shaped of multifunctional materials are placed at determined positions on the laminar elements of the facade. If an appropriate control system is provided, energy is introduced into the system damping the structural vibrations of the sound radiating eigenmodes.. The design of the active system is realized by utilizing the numerical simulation environment of Matlab/Simulink (M/S). With M/S it is possible to simulate and test different control strategies. An accurate model of the facade is needed in order to design the layout of the active system. Later on this model is also needed for filtering purposes. The model is derived by reducing a previously developed finite element (FE) model of the facade to only a few degrees of freedom. Special effort is thereby laid upon the adoption of a special model order reduction technique. The aim is to provide a reduced model of the facade that is applicable in real-time applications. Thus the reduced system must contain as less degrees of freedom as possible, providing a still accurate description of the dynamic properties.

EXPERIMENTAL SETUP

Using the ASAC method, the identification of the lower natural frequencies and corresponding structural modes as well as the exact knowledge of the structural properties is of high importance. Therefore, structural tests and acoustic measurements have been performed in order to determine this data as exactly as possible. This was done using the facade test facility of Schüco Int. KG with a 2.8 by 3.0 m facade specimen assembled out of standard components. It included three double-glazed windows and six aluminum panels in a stiff frame, commonly used in facade construction. This specimen is referred to as 'reference facade' and has been measured extensively. The results of these measurements have been used in the construction of a down-scaled model. The physical dimensions are 1710 by 1260 mm and are chosen in such a way that it is possible to integrate the demonstrator into the semi anechoic chamber at TUD (Darmstadt University of Technology) (see fig. 1) [1]. The demonstrator can either be used with double glazed windows or aluminum panels. For both options, the demonstrator has been measured using loudspeakers (for airborne noise) and electro-dynamic shakers (for structure borne noise) as sources. Focus was given on the natural frequencies and vibration modes, the boundary conditions of the laminar elements as well as on the support between frame and wall. Besides the structural characteristics, the sound radiating behavior of the demonstrator near the resonant frequencies was examined, also. The areas in the receiving room showing the maximum sound pressure for each critical frequency have been located, too. This data was used for an acoustical rating of the critical modes. It turned out that only a part of the natural frequencies is of acoustical relevance.

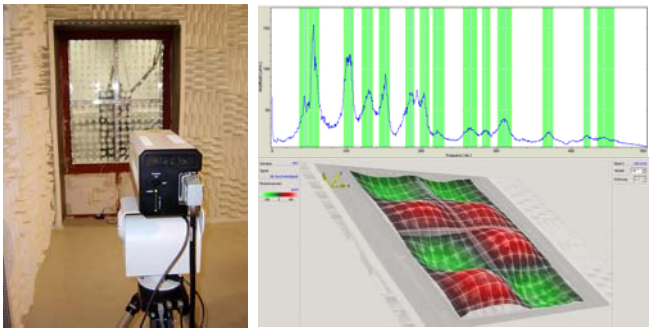

Figure 1 – Left: experimental setup with facade specimen,
right: results of structural vibration measurements

It depends on several factors whether a resonant frequency of a structure leads to sound radiation or not. First of all, the frequency must occur in the excitation signal with sufficient strength. Furthermore, the magnitude of resonant vibrations of a structure depends on the system properties (geometry, material, etc.). Other factors are the acoustic short-circuit as well as people's hearing sensitivity. The interaction of all these factors makes it difficult to predict the acoustical relevance of the structural modes of the facade; thus, they must be confirmed by experiments. Resonant frequencies between 200 and 300 Hz have been identified as the 'loudest' noise emitters of the glass elements of the demonstrator facade.

POSITIONING OF ACTIVE ELEMENTS

The results derived by the structural and acoustical measurements were used as a data basis for a reconstruction of the demonstrator facade with the FE program Ansys. The laminar elements are thereby connected to the frame applying spring elements for all six degrees of freedom (three translatory, three rotatory) thus providing a maximum flexibility for examination of the effects of fully clamped and free bearing conditions.

Calculations of variation were performed and the results were compared with the experimental data. It was determined that boundaries close to fully clamped meet the real boundary conditions best. In the design of the active system for the laminar elements of the demonstrator facade piezoceramic plate actuators (patches) are used. Since the actuators are meant to excite as many sound radiating modes as possible, investigations about their positioning on the surface of the laminar elements have to be performed. One criterion to determine optimized actuator positions is the controllability index ξ [2] which is derived by modal strains ε_x and ε_x in plain directions of the plates:

$$\xi_{total}(x,y) = \prod_i \frac{\varepsilon_{x_i}(x,y) + \varepsilon_{y_i}(x,y)}{\varepsilon_{i,\max}}; \qquad \varepsilon_{i,\max} = \max\left(\varepsilon_{x_i} + \varepsilon_{y_i}\right) \tag{1}$$

The modal strains are calculated for each flexural mode i and at every position x,y on the plate. The benefit of the description in eq. (1) is that single modes that show no acoustical relevance can easily be excluded. Thus, the flexural modes can be weighed according to the results of the acoustical measurements. For the double glazed window of the demonstrator facade the 'loudest' noise emitting modes were found between 200 and 300 Hz. Hence in fig. 2 only these modes were considered in the evaluation of the controllability index ξ (1).

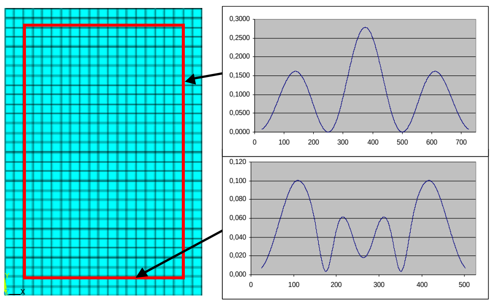

Figure 2 – Controllability-index 50 mm from the margin

Fig. 2 shows the distribution of the controllability index near the boundaries because of a restriction to the project. The active elements applied to the window have to be placed at the margin, so they can be hidden behind faceplates without covering the view. But as shown in fig. 2, the index near the boundary still shows good results which was also proven by experiments. A second method considered for actuator positioning utilizes the coupling effects between a plate and a piezoceramic plate actuator attached to it. The electromechanical coupling coefficient K [3] is expressed by

$$K_{ijn}^2 = \left(\frac{\left(\omega_n^D\right)^2 - \left(\omega_n^E\right)^2}{\left(\omega_n^E\right)^2} \right) \tag{2}$$

with n as the modal order. In (2) the coupling coefficient weighs the eigenfrequencies of the structure with opened ω^E and shorted electrodes ω^D of the plate actuator and can be interpreted as a criterion for the transformation of mechanical oscillation energy into electrical energy. As laminar piezoelectric strain actuators are utilized, only the 31-effect [3] is considered and the coupling coefficient of interest is K_{31}.

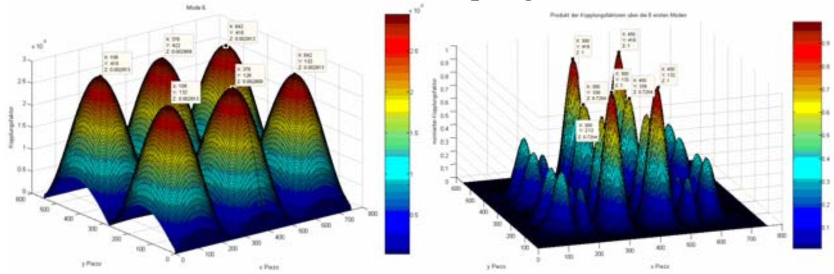

Figure 3 – Coupling coefficient K_{31}, left: single mode (3,2), right: index for first 8 modes

In fig. 3 left the distribution of the coupling coefficient K_{31} for a single Mode of the aluminum panel of the demonstrator facade is shown. The plot is derived by multiple modal Analyses with Ansys. Between the calculations the position of the piezo-patch is altered with a predefined step size thus moving the patch all over the panel and calculating coupling coefficient at each position (2). On the right an index over the first 8 structural modes is shown with the red peaks indicating the positions of best controllability i.e. good actuator positions. Comparing the two considered methods for determination of actuator positions the coupling coefficient seems to be the more practicable approach. The stiffening effects caused by the piezoceramic actuator attached to the panel are considered in (2) whereas they are neglected in (1). However, because the physical dimensions of the piezo-patch are small compared to the panel, its stiffening influence is low. Hence both methods lead to similar results

MODEL ORDER REDUCTION

Matlab/Simulink (M/S) is an ideal simulation tool for the development and design of active control systems. Within the simulation environment, closed loop control concepts can be created and tested in a virtual computer environment. By application of adaptive Filters, the complete signal path of an active system can be identified i.e. control path and connected hardware. The system response can be determined also for complex load cases as for random unique incidents. The basic condition to completely simulate an experiment in the M/S environment is the exact modeling of the mechanical and dynamical properties of the structure. The system matrices of the finite-element model of the facade are used for that purpose. However, regarding the sizes of the system matrices (> 60.000 degrees of freedom) their use in a real-time application is not practicable; hence the order of the model has to be reduced. The FE program Ansys uses the modal reduction strategy by Guyan [4]. Before the reduction procedure is performed so-called master degrees of freedom (mDOF) have to be chosen by hand which yields good knowledge of the dynamic properties of the structure. Although the Guyan reduction provides satisfactory results at least in the lower frequency range, other approaches exist that lead to models of smaller order providing better modal consistency.

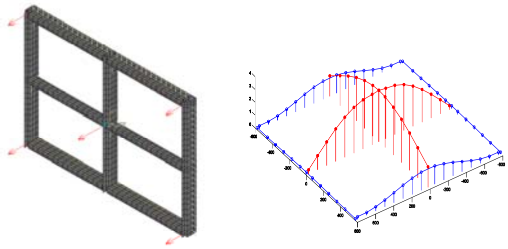

Figure 4 – Left: FE model of frame; right: outputs of the MOR4ANSYS reduced model

With MOR4ANSYS (“model order reduction for Ansys”) the Ansys FE model can be exported to other programs providing a powerful model reduction at the same time. MOR4ANSYS [5] is developed at the chair for simulation of the Alberg Ludwig University Freiburg and is distributed under the GNU- Public Licence. It extracts the systems matrices of the FE- model from certain ANSYS files and performs a model reduction. The matrices are saved as text files and can thus be easily read by other programs. The reduction method is based on the Arnoldi algorithm, which removes weakly controllable parts of the model. The reduction works almost automatic. The user only has to manually choose the order of the reduced system. MOR4ANSYS provides the reduced model as a second- order system:

$$\begin{gathered} M \cdot \ddot{x} + E \cdot \dot{x} + K \cdot x = B \cdot u \\ y = C \cdot x \end{gathered} \tag{3}$$

In the equations (3) the vector x includes all degrees of freedoms. M, E, and K are the mass, damping and stiffness matrices. B is the input, C the output matrix, u is the vector of inputs and y is the vector of outputs. In the following the model reduction with MOR4ANSYS is illustrated by the example of the frame of the facade (fig. 4 left). The original FE- model in ANSYS consists of over 60,000 degrees of freedom (DOF). Before the reduction can be executed, the inputs and outputs have to be defined for the reduced model.

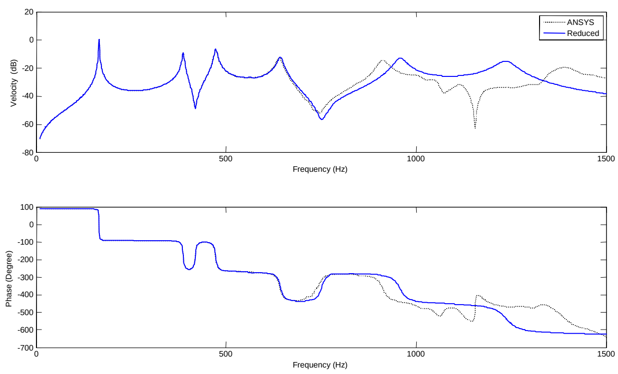

Figure 5 – Bode-plot: comparison of the frequency responses between Ansys and reduced model

Six independent forces are defined as inputs which are illustrated as vectors in fig. 4 left. A number of 85 displacement outputs perpendicular to the plane frame are chosen (fig 4 right). For the further processing the reduced model is read into the Matlab numerical environment. In fig. 5 a reduced model with 20 DOF is compared to the original Ansys model. The frequency response at one of the corners of the frame is displayed. The force in the middle of the frame (fig. 1 left) is used as excitation. The frequency response of the reduced model agrees almost exactly with the original model up to a frequency of 700 Hz. In order to accurately represent the entire frequency range of interest (up to 1500 Hz) the size of the model has to be increased to about 60 DOF. If other reduction methods like the balanced reduction are used an even higher accuracy of the reduced system can be achieved. One way to do that is to reduce the model with MOR4ANSYS in a first step to a multiple of the desired model size and then perform a second reduction step with a more exact reduction method (e.g. the balanced reduction provided by Matlab).

ADAPTIVE CONTROL STRATEGY

An adaptive controller is characterized by time-variant adaptive filters whose transfer functions are dynamically altered in order to follow changes in the control path and minimize the error. The filters are realized by adaptive finite impulse response (FIR) filters whose coefficients are adjusted permanently making use of the least mean square (LMS) algorithm. In the following the filtered-X LMS [6] control strategy (filtered reference LMS) is used in order to minimize the structural vibrations detected by the error sensor. For application of the filtered-X LMS, a model of the transfer path from the actuator to the error sensor is needed in the secondary path. This model can be obtained by applying another adaptive filter for system identification. Furthermore a reference signal of the disturbance must be available which can be realized by a microphone.

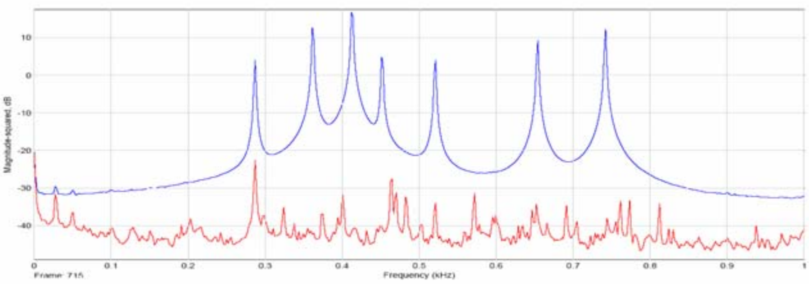

Figure 6 – Fourier transform of the detected signals at the error sensor with and without control

The controller is thus implemented as an adaptive feed forward control; hence system stability only depends on the stability of the controller itself [7]. The active system is designed in the Matlab/Simulink environment due to the principles explicated in the sections before. With the multichannel digital signal processing (DSP) system dSPACE, the adaptive controller can be transferred directly out of the Simulink environment onto the DSP processor board for use on the demonstrator facade test rig. Fig. 6 illustrates the adaptive feed forward control of the double glazed window of the facade. In this example the structure is excited by an electrodynamical shaker which is connected on the outside of the window. The disturbance is a mixture of seven sine signals that match the eigenfrequencies of the window between 200 and 800 Hz. The error sensor is placed near the point of excitation. For actuation, a piezo-patch is used which is attached at the inside of the window. The results in fig. 6 show that the vibration is completely canceled at the place of the error sensor. It has been determined that at least four sensor/actuator pairs are needed to efficiently reduce the structural vibrations of the complete window.

CONCLUSIONS

At Darmstadt University of Technology a simplified demonstrator facade element was constructed. The results of the measurements of the reference facade at Schüco testing facility were used for that purpose. The structural and dynamical properties of the demonstrator were determined. These data provided the basic information for the generation of a FE model of the facade. On the basis of this model investigations on actuator and sensor placement were performed. Two strategies were analyzed in that context. It was shown that both, the controllability index on basis of the modal strain and the electromechanical coupling coefficient are equally suited to provide optimized actuator positions. An adaptive control concept was developed in the Matlab/Simulink environment. Special effort was laid on the adoption of model order reduction techniques in order to achieve a model of the demonstrator that is suited for real-time applications. Utilizing the DSP system dSPACE the designed controller was transferred into the real-time environment. Applying the control to the double-glazed window of the demonstrator facade it was shown that the vibration detected at the error sensor could be canceled completely. Thus it has been proven that the feed forward control concept based on the adaptive filtered-X LMS algorithm is particularly suited for the facade application.

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