Active Reduction of Car Interior Noise

Fig. 1:
Experimental setup of the active windshield with piezo-electric d_{31}-patches, electrodynamic shaker, accelerometers and laser-scanning grid (reflecting points).

Fig. 2:
Measured operational deflection shape (magnitude) at 116Hz without active control (shaker excitation).

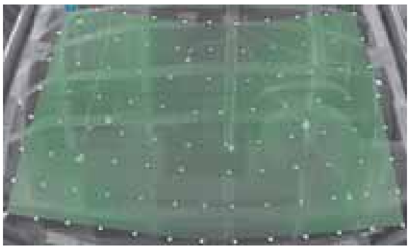

Fig. 3:
Measured operational deflection shape (magnitude) at 116Hz with adaptive feedforward control (shaker excitation).

Increase of driving comfort by means of active structural acoustic control (ASAC)

Active Structural Acoustic Control (ASAC) is an effective measure to reduce the windshield-vibration-induced interior noise in an automobile passenger compartment . The related research of the Institute is based on former work conducted within the framework of the EU-IP InMAR. An existing test-car equipped with an active windshield is used for the investigations. The active windshield consists of the passive structure equipped with optimally placed piezo-electric transducers. The main focus of the subsequent work is the development and evaluation of different control strategies (H2, FxLMS) designed with regard to either local or global performance metrics. Due to the lack of a roller test bench the structural excitation is realized by an electrodynamic shaker located at the roof brace between the A-pillars (cp. Fig. 1). This setup enables the emulation of the broadband structural excitation of the windshield due to rolling and motor force harmonics.

Optimized definition of sensors and actuators improves control performance

The kernel of the real-time system is a dSPACE-DS1005 board used for rapid control prototyping. The signals are conditioned by low-pass filters with a cutoff frequency of 240Hz. Six accelerometers are placed for vibration sensing at heuristically optimized positions on the inner side of the windshield. The sound pressure level (SPL) at different positions in the interior is sensed by a microphone. The reference signal for the adaptive feedforward controller is generated from a force sensor placed in the load path of the shaker near the excitation point at the roof brace. Fig. 1 shows the accelerometer positions (S1 to S6) as well as the selected piezo actuators (1||2, 3||4 and 13||14). The number and positions of sensors are determined heuristically using results from modal analysis of previous investigations and applying the principle of maximum modal observability. The selection process of the control actuators is guided by the evaluation of control-path frequency response functions (FRF). The number of actuator channels was restricted to three in order to achieve a reasonable trade-off between model complexity and control authority. A further increase in control authority is obtained by operating adjacent transducers in parallel.

Efficient System identification and modeling for real-time control

A suitable system model is needed for the design and implementation of a feedback or feedforward controller. A time-discrete state-space-model is calculated for the coarse accelerometer grid (3 control inputs, 1 disturbance input and 6 outputs) from multiple-reference test data. In order to obtain the global system dynamics in terms of a finer grid of 101 points, a subsequent least-squares fit is performed using the obtained state-space model and measurement data from the laser-scanning vibrometer. The final result is an augmented state-space system of the same order, yet with 101 outputs.

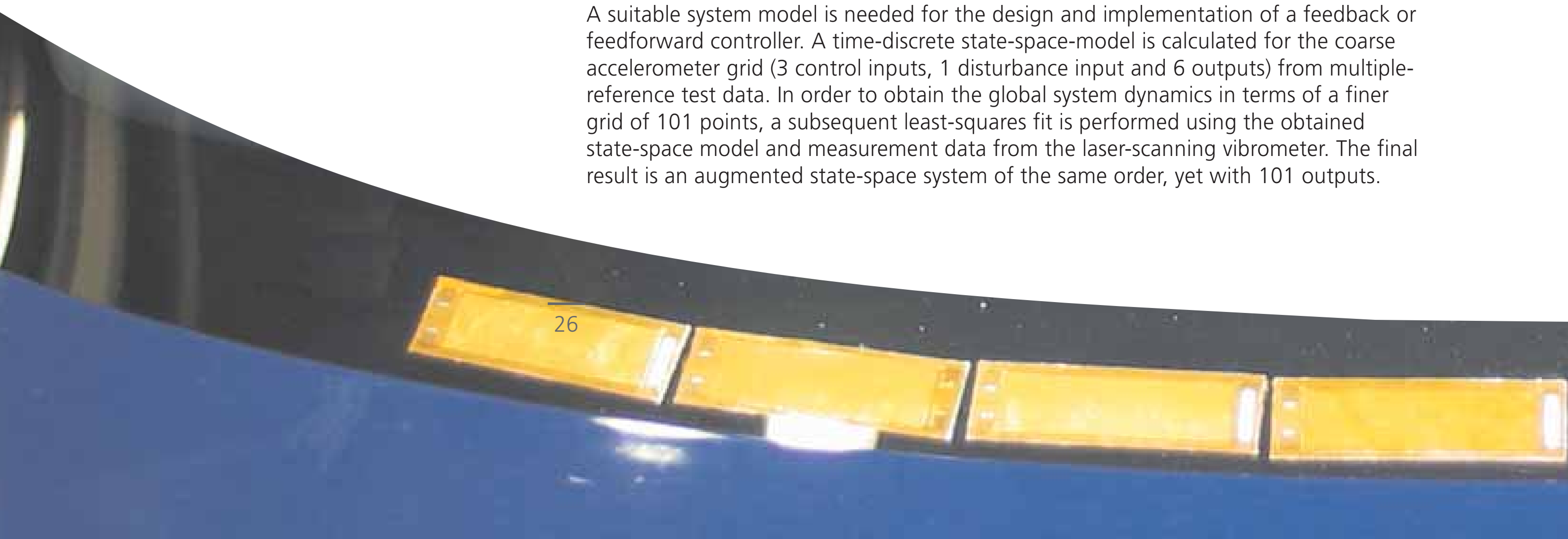

Fig. 4 compares the singular values of the identified system model with measurement data. The comparison confirms, that the use of just 60 states is a numerically efficient and accurate modeling of the 404 transfer paths.

Control of acustically relevant modes

The second eigenfrequency of the windshield is most relevant for low-frequency interior noise which has been proven in previous acoustic investigations performed by our industrial partner Volkswagen AG. The experimental results of the active feedforward control of this mode are presented exemplary.

The applicability of adaptive feedforward control depends on the existence of a reference signal that is sufficiently time-advanced and highly correlated with the sensor signals. If these constraints are fulfilled, a very powerful and robust control system can be designed. In contrast to an observer-based state-feedback control scheme, the implemented FxLMS algorithm performs no post-processing of the sensor signals and can thus only process local information based on the coarse sensor grid. The adaptive filtering is performed with 200 FIR-filter taps for each control channel, a leakage factor equal to one and a normalized step size of 0.1% of the theoretical maximum value.

The SPL shown in Fig. 5 was measured at six arbitrarily chosen points about 0.1m from the inner surface of the windshield. These results give a initial impression of the potential sound reduction demonstrating the capability of active methods. The realization of profound intensity or sound power measurements was beyond the scope of these experiments and remains a topic for further investigations.

Significant reduction of interior SPL

Different control strategies for the active reduction of windshield-vibration-induced interior noise are developed, experimentally validated, and now available. The comparison of the vibration levels in open and closed loop show a global reduction of 5dB to 7dB in the acoustically relevant frequency band containing the second and third eigenmode of the windshield system (100Hz to 150Hz). The acoustic effects, though not yet entirely scrutinized, are reflected in a reduction of up to 15dB in SPL at 145Hz. Moreover, the results are obtained in a realistic environment.

These promising results encourage future work on this topic. Possible questions for subsequent research activities concern the implementation of piezo-electric transducers for a structurally integrated sensing and the use of a larger number of low-voltage piezo actuators in order to handle the observed complex operational deflection shapes. Also, a further development of sound power estimation based on structural information or a frequency-selective post-processing of sensor data might be a focus of prospective research activities.

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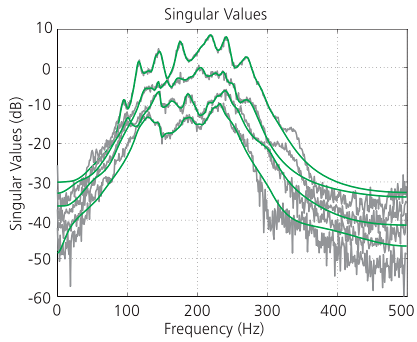

Fig. 4:
Singular values of control- and disturbance-path FRF-matrix. Identified state-space model (green) and measurement data (grey).

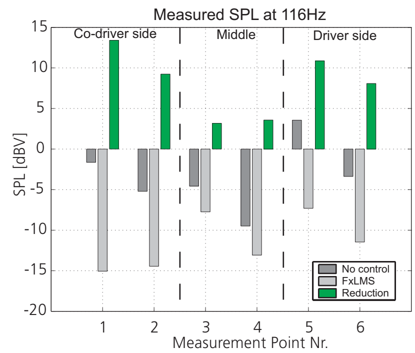

Fig. 5:
Reduction in sound pressure level (SPL) at 116Hz achieved by the adaptive feedforward controller (FxLMS).