Design of a Smart Stripped Engine for Active Noise and Vibration Control Using Numerical Methods

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Introduction

The objective of this paper is to design a smart stripped car engine comprised of a cylinder block and an oil pan with surface-attached piezoelectric actuators and sensors for active noise and vibration reduction using numerical methods. In the analyses the FEM is applied to model the structural behavior of the cylinder block and the oil pan as well as the surface-attached piezoelectric patches. At first structural FE simulations of the stripped engine are presented, which are aimed to identify the most dominant mode shapes within a frequency range of 0-1200 Hz. Based on these results the actuator positions are calculated. Then a fully coupled electromechanical FE model is derived, which includes additionally the piezoelectric actuators and sensors into the structural model. With such a model it is also possible to simulate the controlled behavior of the engine as well. For that purpose a controller has to be implemented into the electromechanical coupled FE analysis. As an example in the paper a velocity feedback control algorithm is applied to provide a closed loop model of the controlled engine. The model is used to carry out simulations of the uncontrolled and the controlled behavior of the engine in the frequency domain, which demonstrate the performance of the designed system. The numerical results are also successfully compared with measurements. Finally, the exterior noise radiation of the stripped engine is numerically analyzed by applying the BEM. These results are also in a good agreement with noise measurements, and demonstrate the noise reduction efficiency of the designed system.

FE Analysis of the Dominant Mode Shapes

In order to design an active system to reduce the vibrations of the stripped engine in a noise reducing manner, it is essential to identify the most dominant mode shapes. This step is carried out by means of harmonic FE simulations. A point force excitation at the oil pan flange is chosen to excite all eigenmodes in a frequency range up to 1200 Hz.

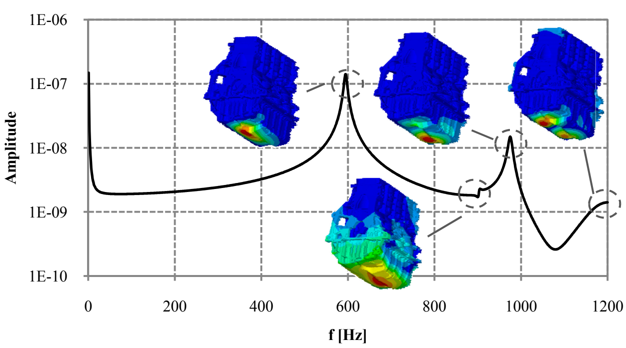

Figure 1: Computed FRF of the stripped car engine.

Figure 1 shows the frequency response function (FRF) between the structural displacement at the center of the oil pan bottom and the excitation force. In addition, the mode shapes that are associated with the respective resonance frequencies are illustrated. It can be seen that the first, the third and the fourth eigenmode are pure bending modes of the oil pan bottom. The second mode is a bending mode of the whole stripped engine. Under real operating conditions the bottom modes are the main contributor to the overall sound emission. Due to this fact, the present paper aims to control these modes only.

Definition of the Actuator Positions

The choice of suitable actuator positions depends on many factors, such as the employed control and the vibrational behavior of the structure. An often used method for the actuator placement is based on the assumption that an actuator is placed well when it is able to influence significantly the shape of the structural modes. This means that a patch actuator should be placed at positions on the surface of the structure, where the strains are the highest [1]. In case of the stripped engine, the modal strains of the first, the third and fourth eigenmode are computed. A contour plot of the multiplicatively superposed modal strains allows the definition of optimal actuator positions and makes sure that the actuators are not placed on node lines.

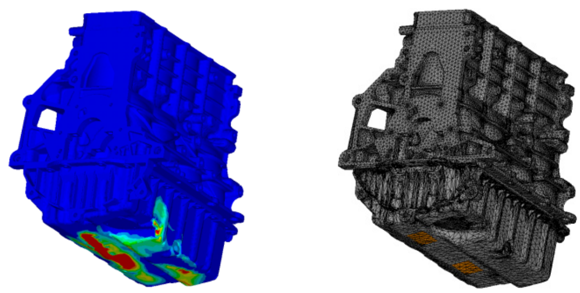

Figure 2: Contour plot of the superposed modal strain field and chosen actuator positions.

Two actuator positions have been chosen according to the contour plot visible on the left-hand side of Figure 2. On right-hand side of Figure 2 the orange areas mark the selected positions.

Controller Design

The design of a smart stripped engine requires the implementation of a suitable control. In the present study, the robust and widely used velocity feedback control is applied. Collocated piezoelectric actuators and sensors are utilized to form the closed-loop control system. The collocated design of an actuator/sensor pair is important to guarantee control stability. In the considered feedback-control system, the sensor output voltage is differentiated, amplified by a constant gain and directly fed back to the collocated actuator. Due to the feedback, the collocated actuator generates counteracting moments which suppress the vibrations, and consequently, the resulting sound radiation. In order to evaluate the performance of the designed system, test simulations are carried out and the results are compared with experimental data. For the comparison, uncontrolled and controlled FRFs are considered.

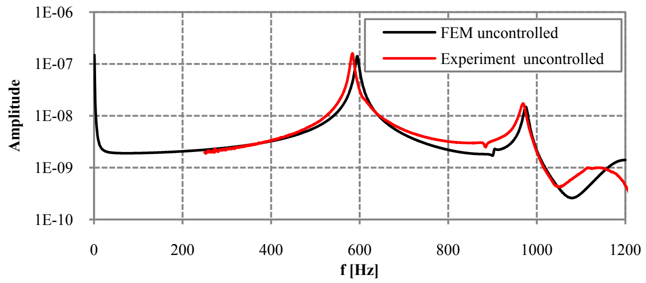

Figure 3: Uncontrolled FRFs of the stripped car engine.

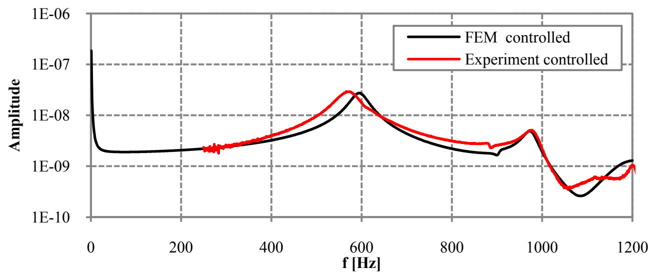

Figure 4: Controlled FRFs of the stripped car engine.

In both Figures, it can be observed that the measured data and the numerical predictions agree very well. Additionally, the results in Figure 4 show that a significant damping at the dominating resonance frequencies is achieved, due to the implementation of velocity feedback control. The amplitudes are reduced by more than 14 dB at 595 Hz and by about 10 dB at 975 Hz.

BE Analysis of the Surrounding Sound Field

The radiated sound field plays an important role by evaluating the performance of the designed system. In the present work, the BEM is used to characterize the acoustic field of the stripped engine. In order to perform a frequency response analysis, the structural displacements of the smart stripped engine obtained from the harmonic FE analysis have to be interpolated onto the grid points of the BE mesh and applied as boundary conditions. To be able to determine the sound pressure distribution, a considerable amount of field points is defined, which are located on a plane parallel to the oil pan bottom. After the acoustic pressure is calculated at all points, a contour plot allows to visualize its spatial distribution. In Figures 5 and 6 the computed sound pressure distribution of the uncontrolled and controlled stripped engine are plotted. The chosen plane is approximately 50 mm apart from the bottom surface. To test the noise reduction efficiency of the designed system and to verify the simulated data, near-field airborne noise measurements were carried out in a free-field room [2].

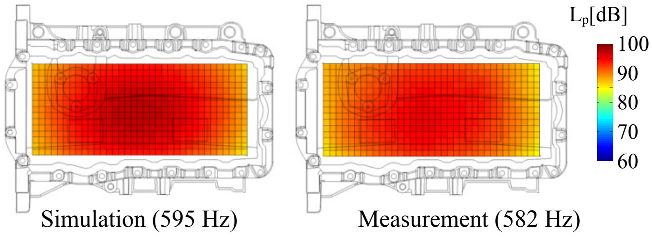

Figure 5: Sound pressure distribution of the uncontrolled Stripped Engine.

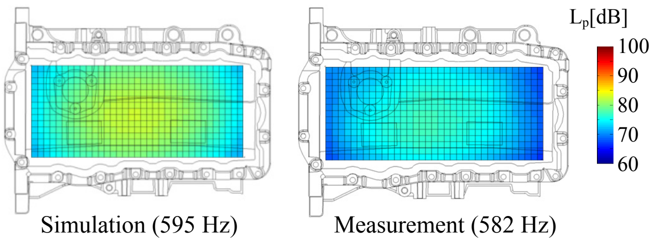

Figure 6: Sound pressure distribution of the controlled Stripped Engine.

In both Figures it can be noticed that the simulation results correlate well with the experimental results. Furthermore from Figure 6 can be seen that due to the controller influence the sound pressure level is reduced by approximately 16 dB, which indicates the noise reduction potential of the designed system.

Conclusions

On the basis of FE and BE simulations a stripped car engine is designed to reduce the structural vibrations in a sound reducing manner. For noise reduction, optimal locations of two piezoelectric actuators attached to the bottom surface of the oil pan have been studied. The FEM is applied to model the structural behavior of the stripped engine as well as the surface-attached piezoelectric actuators. The BEM is used to describe the exterior sound field. A velocity feedback control algorithm is implemented into the numerical model to obtain an active damping effect. With velocity feedback control, attenuations of about 14 dB in vibration level and 16 dB in sound pressure level at the resonance frequencies of the most dominant modes of the stripped engine have been achieved. In order to show that the designed system works also in reality experimental tests have been performed. A comparison between the experimental and numerical results shows a good agreement.

Acknowledgement

The work is financially supported by the German Federal State of Saxony-Anhalt and by the European Commission, in the frame of the research project ”COmpetence in MObility”. This support is gratefully acknowledged.

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