

Noise Reduction Potential of an Engine Oil Pan

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Abstract Considering automobiles with internal combustion engines, the power train represents one of the main noise sources, especially during idling and slow driving speeds. One major contributor to the overall power train noise emission is the engine oil pan. The objective of this paper is to evaluate the noise reduction potential of an oil pan with a combined use of passive and active methods. The passive approach is best suited for a frequency range above 1,000 Hz and is implemented in this study using different substitute materials. Active noise control techniques are efficient in a frequency range below 1,000 Hz. In the present study piezoceramic patches are used as actuators as well as sensors. By means of FE simulations a smart system is designed to reduce passively and actively the structural vibrations and consequently the resulting sound radiation. Therefore, optimal locations of piezoelectric actuators are computed. A control algorithm with respect to a collocated design is used to obtain high active damping effects. With control, attenuations up to 15 dB in vibration level are achieved at the resonance frequency regions of the most dominant modes of the oil pans in laboratory. It is shown that significant reductions up to 4 dB are achieved on the engine test bench in a frequency range up to 1,000 Hz and at engine speeds below 2,000 rpm, where a multi-discrete excitation characteristic exists. Due to the use of a low-mass plastic oil pan, improvements at several engine operating points are

F2012-J03-018

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measurable. Drawbacks of this material substitution are the higher temperature dependency and the lower electromechanical coupling of the piezoelectric patches due to the elasticity of the plastic ground material. An oil pan made of sheet steel has shown the worst acoustical properties.

Keywords Oil pan · FEM · Material substitution · Active control · Engine test bench

1 Introduction

Over the past years an increasing attention has been paid to acoustic noise control in automotive engineering. The use of light-weight materials in parts of a car has a direct influence on the radiated sound intensity of these parts. There are two different approaches to achieve noise and vibration attenuations. On the one hand, there is the widely used passive approach. Passive control techniques mostly reduce vibration and sound emission of structures by modifying the structural geometry, by applying additional damping materials or by a complete material substitution [1, 2]. These methods are best suited for a frequency range above 1,000 Hz. The active control approach can effectively support passive noise treatments as an alternative way to minimize unwanted structural vibration and noise. This technique is usually employed in a frequency range between 50 and 1,000 Hz. In active noise reduction piezoelectric ceramics can be attached to structures as actuators and sensors. An often used concept for noise reduction is active structural acoustic control (ASAC). In this concept the surface attached actuators are used to change actively the dynamic behavior of the structure in order to reduce the sound radiation from the surface.

One major contributor to the overall power train noise emission is the engine oil pan. Over the past years, researchers have already applied active noise reduction of a car oil pan [2] as well as a truck oil pan [3] by using distributed piezoelectric actuators. However, in these studies the oil pan was treated separately and no attempt was made to consider interactions between the crankcase and the oil pan. Furthermore, no investigations on an engine test bench or with a passenger car were done so far. In recent years, we have studied active noise reduction of a car oil pan on a dynamic acoustic engine test bench [4–7]. In these studies, we have investigated a smart aluminum oil pan. The objective of this paper is to assess the noise reduction potential of an oil pan with a combined use of passive (three different materials) and active (piezoelectric actuators) methods.

The paper is organized in the following way. First, numerical FEM simulations of a smart stripped car engine comprised of a crankcase and two types of oil pans (an aluminum and a plastic one) are performed. After identifying the most dominant mode shapes, suitable actuator and sensor positions at the bottom of the oil

pans are selected. In a next step, the control problem of the smart system is considered. A feedback control technique is chosen to compute input signals for the actuators that are bonded on the outer surface of the oil pan bottoms. Additionally, piezoelectric sensors are placed at the inner surface of the pans. Finally, in order to evaluate the quality of the designed system and to investigate the simultaneous use of passive and active reduction, experimental tests are carried out in laboratory at the stripped car engine and on a dynamic engine test bench. The experiments on the fired engine with different oil pans involve stationary engine operating points and engine running-ups. In the experimental investigations the uncontrolled behavior of a sheet steel oil pan is used as a worst-case reference.

2 Design of a Smart Stripped Car Engine

In the following, the development of a smart stripped car engine is discussed to understand the interactions between the crankcase and the oil pans as well as to prepare an oil pan configuration for entire engine tests.

2.1 *Finite Element Analysis and Definition of Actuator Positions*

In order to design an active system to reduce the vibrations of the stripped car engine in a noise reducing manner, it is essential to identify the most dominant mode shapes. This step is carried out by means of an eigenvalue analysis using a three-dimensional FE model meshed with quadratic 10 node tetrahedral elements. The FE model is refined enough to include the irregular-shaped geometry of the crankcase and the oil pan accurately. The FE formulation for modeling the stationary behavior of the uncoupled stripped car engine is given in [5]. More details about the modeling of the configuration with the aluminum oil pan are also presented in [5]. The detailed modeling approach of the plastic oil pan as well as some additional details regarding the overall configuration is published in [6].

A force excitation by an actuator placed on the inner side panel of the oil pan is chosen to excite all eigenmode in a frequency range up to 1,000 Hz. Figure 1 shows exemplarily the frequency response functions (FRFs) of the aluminum configuration between the structural displacement at the center of the oil pan bottom calculated from an acceleration sensor signal and the excitation force. It can be seen that the measured data and the computational prediction agree very well. Since the FE model is stiffer than the real object, the simulated eigenfrequencies are slightly higher. It can be observed that the first (580 Hz) and the third (960 Hz) eigenmode are pure bending modes of the oil pan bottom [4]. The second mode is a global bending mode of the whole stripped car engine. Under real

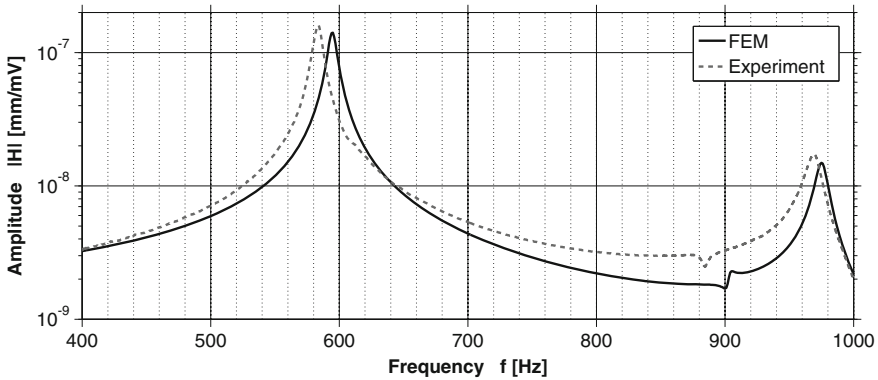


Fig. 1 Frequency response functions (FRFs) of the uncontrolled stripped car engine with an aluminum pan

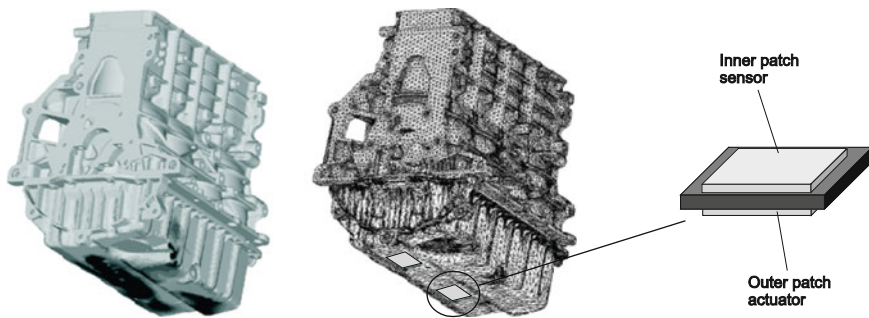
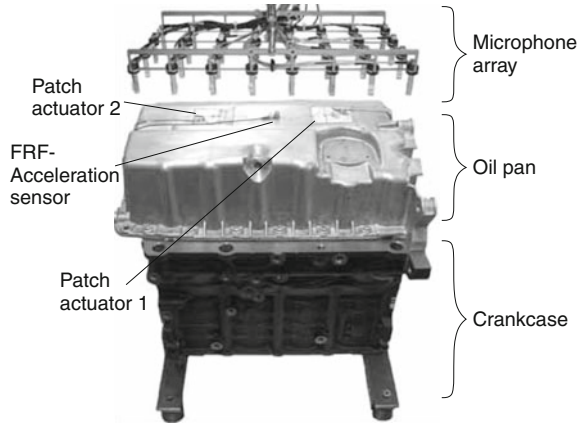


Fig. 2 Contour plot of the superposed modal strain field (*left*) and FE mesh with selected actuator and sensor positions (*right*) of the aluminum configuration

operating conditions the bottom modes are the main contributor to the overall noise emission. Due to this fact, the present approach aims to control these two modes only.

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 an in-plane actuator should be placed at positions on the surface of the structure where the strains and the corresponding electric potentials are the highest. In case of the stripped car engine, the first and the third eigenmode are considered. In contrast to an additive superposition, the multiplicative superposition makes sure that the actuators are not placed on the node line of an eigenmode which should be controlled. A contour plot of the superposed field allows the definition of optimal actuator positions. Two actuator positions have been selected according to the contour plot visible in Fig. 2. The light gray areas of

Fig. 3 Actuators and sensors of the stripped car engine attached to the aluminum pan



the FE mesh mark the two selected positions. Additionally, two sensors are placed on the opposite side of the oil pan. The collocated design of the piezoelectric actuator/sensor pairs guarantees control stability.

It should be noted that also more collocated actuator/sensor pairs could be applied. The method explained has also been applied to choose suitable actuator positions for the plastic oil pan [6].

2.2 Implementation and Verification of a Suitable Control Strategy

The design of a smart stripped car engine requires the implementation of a suitable control algorithm. Feedback control has several advantages over feedforward control. For instance, feedback control is able to take into account unexpected disturbances. Another advantage of feedback control is the capability to stabilize unstable processes. For that reason the robust and widely used velocity feedback control is applied [4, 7]. This algorithm combines high performance control with robustness against time variance of the operating parameters such as oil temperature and excitation frequencies. An important requirement for a successful feedback is the availability of appropriate feedback points. Using a separate sensor for each actuator leads to a decentralized feedback control strategy with independent local feedback loops.

The experimental setup, shown in Fig. 3, has been developed to measure the uncontrolled and the controlled behavior of the stripped car engine with the different oil pans. By means of an actuator placed at the inner side panel of the oil pan, the stripped car engine is excited harmonically with white noise and also with real engine spectra resulting from combustion engine measurements. It should be noted that the force amplitudes of the excitation are smaller than under real operating conditions.

Table 1 Material parameters of the crankcase and three types of oil pans

	Density (g/cm ³)	Elastic modulus (N/mm ²)
gray cast iron crankcase	7.2	135,000
Aluminum pan	2.7	70,000
Glass fiber reinforced polyamide plastic pan	1.3	6,000
Sheet steel pan	7.85	210,000

The obtained results show that a significant damping of the dominating resonance frequencies can be achieved with help of the implemented velocity feedback control. Amplitudes are reduced by about 15 dB at 580 Hz and by about 10 dB at 960 Hz on the aluminum configuration [4]. Amplitude reductions up to 6 dB at the dominating resonance frequencies are achieved on the plastic configuration [6]. The active reduction potential of the stripped car engine with the plastic oil pan is lower because of the lower electromechanical coupling of the piezoelectric patches due to the elasticity of the plastic ground material.

2.3 Passive Behavior of the Stripped Car Engine with Three Types of Oil Pans

The passive reduction potential of an engine oil pan is investigated in this study using three oil pans of different type material. The material parameters of the used components of the stripped car engine are shown in Table 1. The die cast aluminum oil pan (see Fig. 3) has a mass of 2,600 g and a wall thickness of 3 mm. In comparison, the low-mass plastic one (1,790 g) with a wall thickness of 3.5 mm has higher passive damping characteristics [1, 6]. By means of reinforcing ribs on the inner surface of the plastic oil pan bottom, improvements of the stiffness have been achieved. The thinnest oil pan of the three examples is the sheet steel one (1.9 mm, 1,950 g) without any reinforcing ribs. The low production costs are the main advantage of the steel oil pan.

For comparison purposes, investigations of the passive behavior of the different oil pans are carried out using the experimental setup, shown in Fig. 3. Only the point force excitation has been realized by means of an impulse hammer at the oil pan flange instead of applying the piezoelectric actuator placed on the inner side panel of the oil pan. Figure 4 shows the frequency responses in terms of the structural displacement at the center of the oil pan bottom due to an excitation force at the flange.

It is clearly visible that the sheet steel configuration has the highest frequency peaks in the presented frequency domain. The amplitudes are also the highest due to the thin wall thickness. The amplitudes of the dominating resonance frequencies of the aluminum and plastic oil pan are at about the same level. Since the plastic pan has superior material damping properties compared to the aluminum pan, wider frequency regions can be seen (blue function graph in Fig. 4).

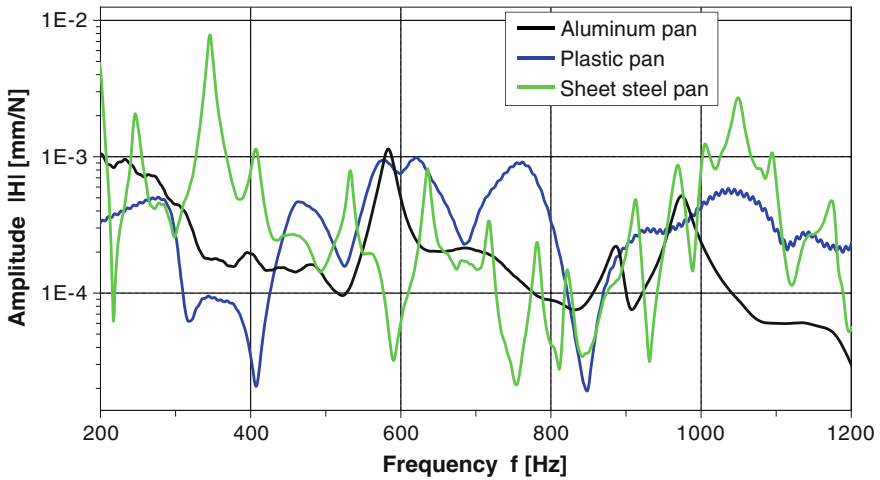


Fig. 4 FRFs measured of the uncontrolled stripped car engine with three different types of oil pans

3 Modification of the Oil Pans for Engine Tests

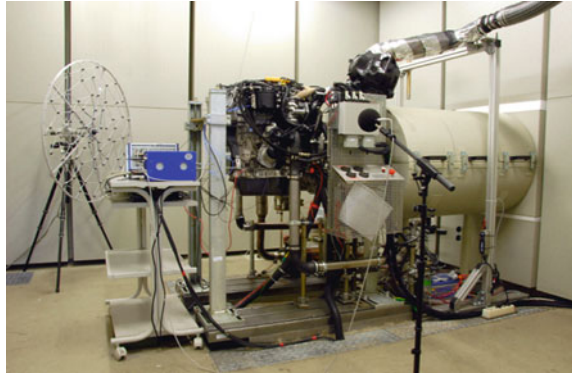
Before analyzing the developed smart car oil pans on a diesel engine, the configuration has to be protected against the oil and the high temperature. The jacket of the cables connecting the piezoceramic patches consists of polyolefin copolymer isolation. This chemical composition is heat- and oil-resistant until 145 . Furthermore, the cables have been fixed with two-component gluten. The single-layer piezoelectric ceramics attached on the inner surface of the oil pan have been protected with elastic packing material [7].

4 Measurements on a Dynamic Acoustic Engine Test Bench

In order to evaluate the quality of the designed oil pans, several experimental tests on an acoustic engine test bench have been carried out. In Fig. 5 the altered four-cylinder common rail diesel engine is shown.

First, investigations of the separately excited engine without combustion are made to determine the potential of the active system. After that, tests of the uncontrolled and controlled behavior of the oil pans on a fired engine have been performed.

Fig. 5 Four-cylinder diesel engine with the polyamide plastic oil pan in an anechoic room



4.1 Analysis of the Separately Excited Entire Engine

By means of an actuator placed at the inner side of the oil pans, the diesel engine has been excited with white noise signal that excites all eigenmode in a frequency range up to 1,000 Hz. Figure 6 exemplarily shows the frequency responses of the aluminum configuration in terms of the structural displacement at the center of the oil pan bottom due to the excitation force. The given results show a damping effect at the dominating resonance frequencies due to the implementation of a velocity feedback control algorithm. Amplitudes are reduced by about 4 dB at 640 Hz and by about 1.5 dB at 880 Hz.

Additionally, it can be observed that the two bending modes of the oil pan bottom have suffered frequency shifts compared to the stripped car engine caused by mass and stiffness variations of the entire engine. The lower amplitude reductions primarily result from the smaller deformation of the pan because of the damping behavior of the sealing between the crankcase and the oil pan. Furthermore, the influence of the oil has also to be taken into consideration. The modified vibrational behavior of the pans due to the presence of oil is discussed in [8, 9]. Nevertheless, it can be seen in Fig. 6 that in spite of frequency shifts and amplitude variations, the velocity feedback control used in collocated design is robust against variances of the real control system.

This study considers also the robustness of the design with respect to the temperature. During the experimental tests it could be noticed that besides the wall thickness, the oil temperature influences the stiffness of the glass fiber reinforced polyamide plastic pan. The elastic modulus of the plastic material is very dependent on the temperature. Increasing the oil temperature, leads to a stiffness reduction. This dependency is shown in Fig. 7. The amplitudes of the hot oil pan have risen (red function graph). Additionally, FRF measured of the uncontrolled stripped car engine with the plastic oil pan without oil is plotted in Fig. 7. Thus it is visible that the oil presence in the pan shifts the frequencies of the system.

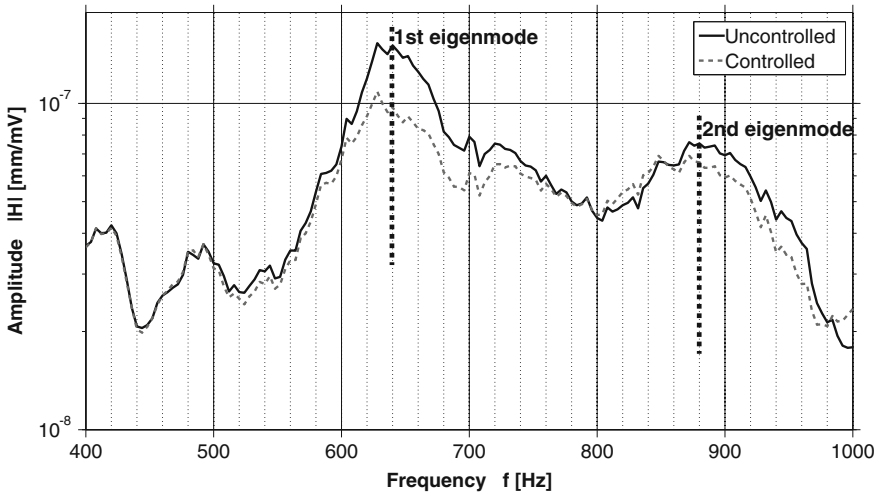


Fig. 6 FRFs measured of the uncontrolled and controlled aluminum oil pan on a diesel engine

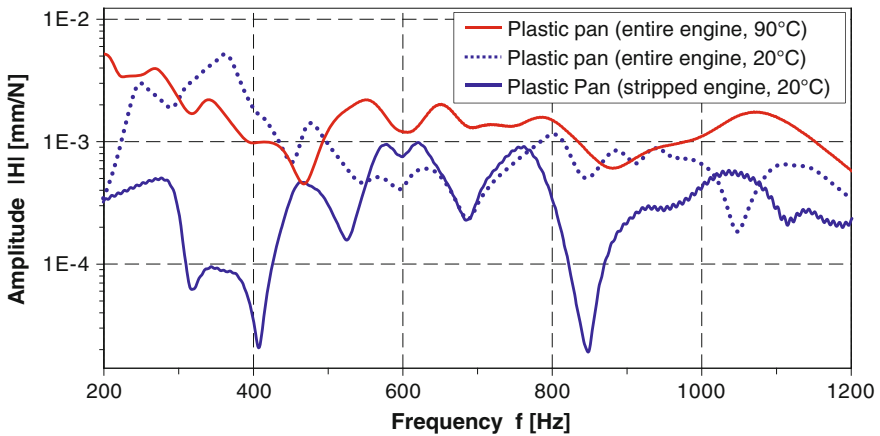
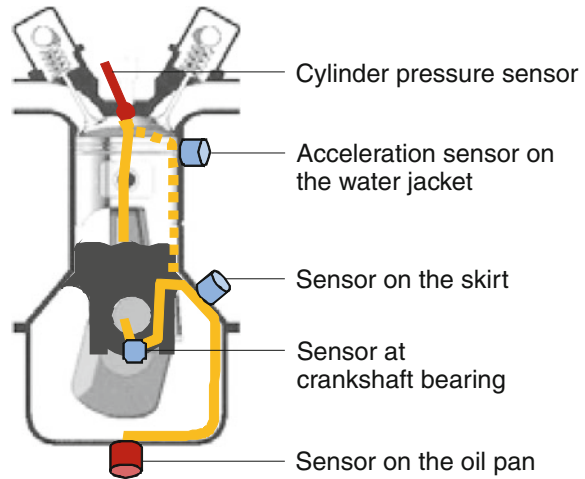


Fig. 7 FRFs measured of the uncontrolled plastic oil pan on a diesel engine at different oil temperatures in comparison to FRF measured of the uncontrolled stripped car engine with the plastic oil pan

4.2 Oil Pan Vibrations on a Fired Engine

The following experimental engine investigations involve stationary engine operating points and engine running-ups (900–4,000 rpm) for different loads (20, 50, 100 and 150 Nm). The four cylinder pressure signals are measured using an indicating system.

Fig. 8 Inner (*solid yellow line*) and outer (*dashed yellow line*) structure-borne noise path of one cylinder



The total combustion noise of a diesel engine which dominates over mechanical noise at low and middle revolutions per minute (less than 3,000 rpm) and at low and middle loads is mainly radiated by the crankcase and the oil pan. To separate the direct combustion noise from the indirect combustion noise, the coherence criterion between combustion pressure and acceleration signals measured at the oil pan bottom is used. To check how the oil pan bottom responds to the excitation of the combustion pressure, all cylinder pressures have to be considered since the excitation is caused simultaneously by each cylinder moved by the particular firing interval. The cylinder pressure signal in the frequency domain has peak amplitudes with a periodicity defined by the cylinder firing. Coherence analyses revealed that in the low frequency region up to 1,500 Hz linear direct combustion noise dominates over the non-linear indirect combustion noise without respect to the engine operating point [7]. Physically, a direct combustion noise source is generated internally. Consequently, the cylinder walls are excited and the sound is transferred into the pan by an inner and outer structure-borne noise path as shown in Fig. 8.

4.2.1 Passive Behavior of the Fired Engine with Three Types of Oil Pans

In order to get an overview of the uncontrolled behavior of the oil pans on a fired diesel engine, engine running-ups were made and evaluated. The acceleration sensor at the center of the oil pan bottom is used to generate the diagram of Fig. 9, because this sensor represents the entire vibration characteristics of the oil pans.

The analysis of these graphs indicates significant improvements in the vibration level by using a polyamide plastic oil pan because of the higher damping properties compared to the other pans. As it can be seen in Fig. 4, the sheet steel oil pan graph shows the highest acceleration levels from 1,300 up to 3,000 rpm because of the thin-walled structure and the missing reinforcing ribs.

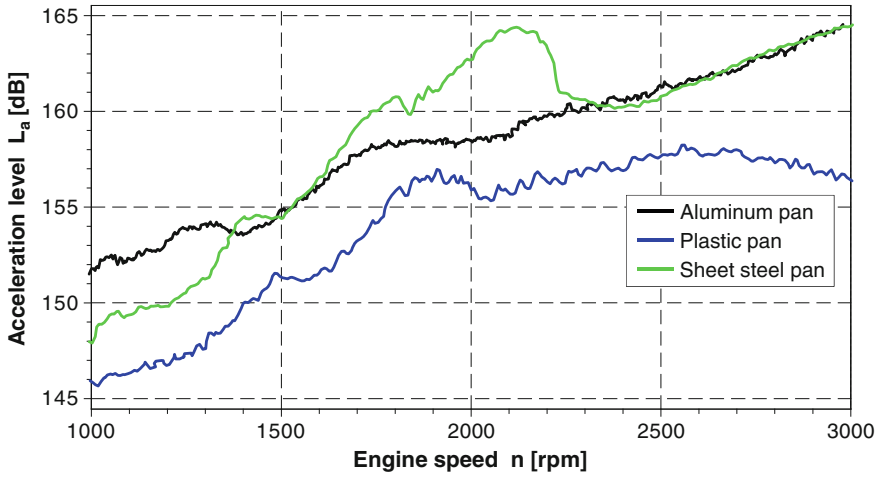


Fig. 9 Acceleration level of the uncontrolled oil pans at engine running-ups (engine load 100 Nm)

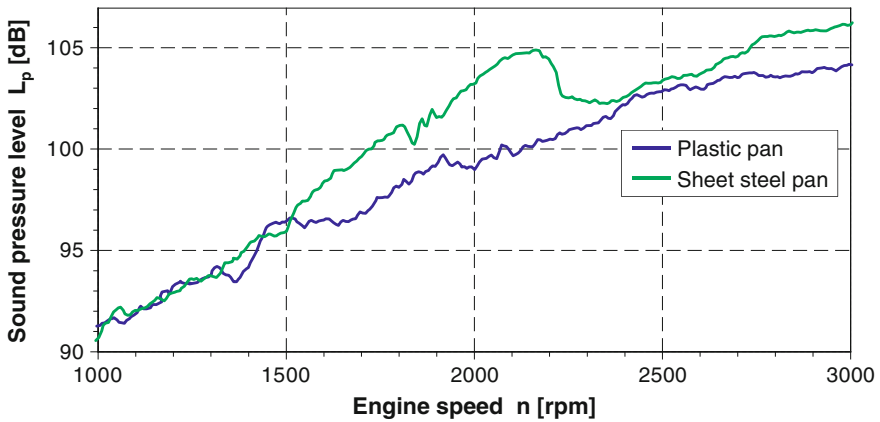


Fig. 10 Sound pressure level of the uncontrolled plastic and the sheet steel oil pan 150 mm apart from the oil pan bottom at engine running-ups (engine load 100 Nm)

A similar trend can be noticed by comparing the sound pressure levels of the plastic and the sheet steel oil pan given in Fig. 10. However, up to 1,500 rpm the sound pressures are at about the same level. It has to be taken into account that the microphone recognizes the surface integral of the vibrational behavior of the oil pan bottoms.

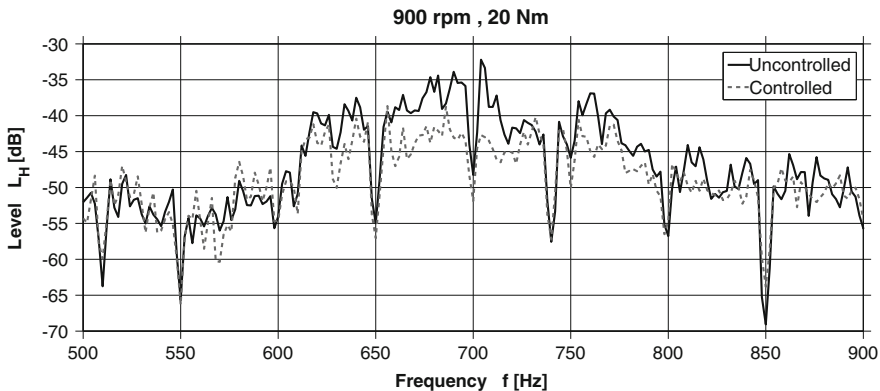


Fig. 11 Transfer functions between the acceleration of the aluminum oil pan bottom and the energetically averaged cylinder pressure

4.2.2 Active Behavior of the Fired Engine

For a further validation of the smart active systems, a stationary engine operating point with minimal real excitation forces is chosen. At 900 rpm, multiples of the half engine order cause excitations in a frequency interval of 7.5 Hz and multiples of the second engine order cause excitations in a frequency interval of 30 Hz.

In Fig. 11, the dependency between the structural vibration and the cylinder pressure in uncontrolled and controlled case can be seen exemplarily for the aluminum pan. Additionally, the results show significant damping effects in the frequency region of the first eigenmode. Amplitudes are reduced up to 8 dB. This demonstrates the advantage of the developed control which benefits from the multi-discrete characteristics of the real excitation signals.

To evaluate the quality of active control of the plastic and aluminum oil pan at higher engine speeds and loads, several engine running-ups are carried out. The measurements, shown in Fig. 12, revealed that the piezoelectric actuators generate counteracting forces which suppress the sound pressure level 150 mm apart from the oil pan bottom of the two pans.

The active reduction potential of the stripped car engine with the plastic oil pan (on the left-hand side of Fig. 12) is lower because of the lower electromechanical coupling of the piezoelectric patches due to the elasticity of the polyamide plastic ground material. As explained, the higher the oil temperature is, the higher the material elasticity becomes. Although the uncontrolled sound pressure level of the plastic pan is slightly better, the aluminum pan shows nearly linear behavior over the speed range. This is an important advantage for the subjective sound perception. In a previous paper [7] it is shown for an aluminum pan that with control, attenuations up to 4 dB are achieved at the resonance frequency regions of the most dominant modes at engine speeds below 2,000 rpm. The main reason for

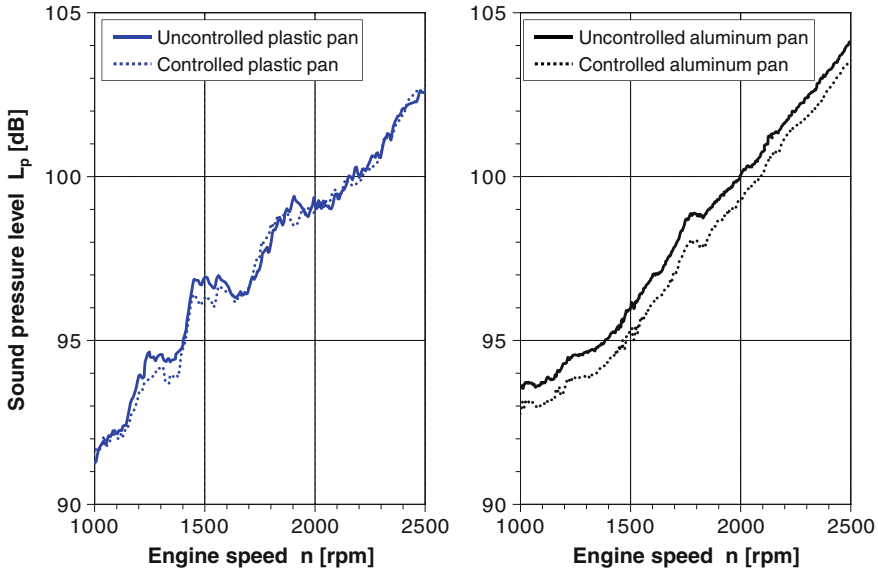


Fig. 12 Sound pressure level up to 10 kHz of the uncontrolled and the controlled plastic (*left*) and aluminum (*right*) oil pan 150 mm apart from the oil pan bottom at engine running-ups (engine load 100 Nm)

performance limits of the developed control system at higher engine speeds is the higher firing frequency at these engine operating points. For that reason, the developed control needs a roughly multi-discrete excitation characteristic.

5 Conclusions

In the paper the application of a combined passive and active vibration control of oil pans on a four-cylinder diesel engine has been presented. The passive approach includes the investigation of different materials of the oil pans. Due to the use of a low-mass glass fiber reinforced polyamide plastic pan, improvements at several engine operating points are measurable. Drawbacks of this material substitution are the higher temperature dependency and the lower electromechanical coupling of the piezoelectric patches. A sheet steel oil pan has offered the worst acoustical properties. The active approach has been implemented by using piezoceramic patches. It is shown that significant reductions up to 4 dB are achieved on the engine test bench if the oil pan is made of aluminum. The performance of the designed control system could be improved by using more efficient piezoceramic patch actuators.

Acknowledgments The work is financially supported by the German Federal State of Saxony-Anhalt and by the European Commission as a part of the research project “Competence in Mobility”. This support is gratefully acknowledged.

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