DEVELOPMENT OF ACTIVE ENGINE MOUNTS BASED ON PIEZO ACTUATORS

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In vehicles, engines cause vibrations that are transferred from the mounts and the adjacent structures to the interior where they typically result in unwanted sound emissions. Passive hydro mounts have asserted themselves as one response to dampening noise levels. However, current developments in the automotive industry such as three-cylinder engines and the use of cylinder deactivation are leading to an increase in vibration levels that passive systems can no longer compensate for. The implementation of active systems show more promise in improving vibration comfort and the acoustic impression. A systematic approach was taken to develop such a system at the Fraunhofer Institute LBF and subsequently test it in a real vehicle.

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1 MOTIVATION

In addition to various noise sources such as wind and rolling noise, the dominant sound emission is still caused by the engine and drivetrain. To minimise the excitation of the vehicle body, the engine is attached by resilient mounts to ensure a good isolation. The engine mount fulfils a multitude of functions that are often contradictory. On the one hand they ensure a high level of dampening for the resonances of the rigid-body, which normally falls within the 7 to 15 Hz range. On the other hand, it is ideal to maintain a low level of damping to provide good isolation at higher frequencies and rotational speeds. For this reason compromises are made at very low and high frequencies in the design of engine mounts. The conventional engine mount, consisting of an elastic casing to hold the engine in place, differs from hydro mounts that use an additional damping medium. This increases the dampening effect at low frequencies and thus solves the aforementioned conflict of engine mount dampening. These hydro mounts have therefore become standard as they provide for a smooth ride and a high level of comfort.

Key policy objectives and a general rise in public environmental awareness have led to several breakthroughs in engine design to address growing concerns. Among others, downsizing, cylinder shut-down and hybrid powertrains are the most relevant automotive industry trends being implemented to reduce fuel consumption and CO_2 emissions. These concepts have introduced new challenges to automobile-makers with regard to passenger comfort. These can no longer be addressed with conventional engine mounts and will need additional approaches to these new developments. One approach to the increased demand is to use adaptive or switchable engine mounts [1]. These behave similarly to the well-known hydro mounts with the addition of being adaptable to the different engine-modes of a vehicle. This technology has reached maturity and is already being used in vehicles to change engine mount properties according to RPM.

2 MORE COMFORT WITH ACTIVE SOLUTIONS

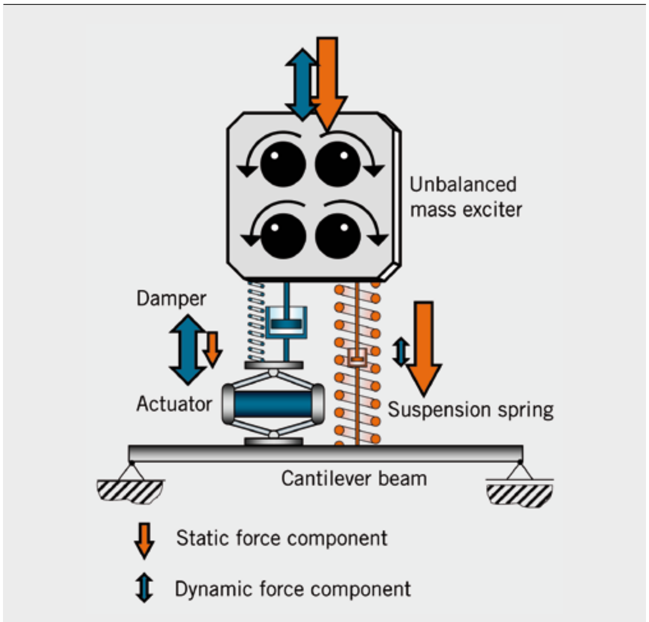
In addition to adaptive mounts, active concepts for approaching vibration control have swung into focus with recent research efforts. Active techniques use phase shifted counter vibrations to minimise unwanted vibrations emanating from the engine. Not only can active methods counteract vibrations, they also offer the possibility to provide the vehicle with a desired acoustic profile by dampening or emphasising specific frequencies. This offers sound designer new latitudes for the acoustic development of a vehicle and can even be implemented in accordance to engine torque and speed.

There exist different technologies for active vibration control systems. Using proof mass actuators or active vibration absorbers, the actuators are connected to an additional mass [2]. The advantage here is the flexibility in its position within a vehicle. The disadvantage is a limited frequency range. To provide the necessary counterforce, the device must be operated beyond its natural frequency, at lower frequencies it is almost useless. Thus, proof mass actuators add both, additional mass and unwanted resonances to the equation. In order to reach a low operation frequency band a larger mass is required. In case of active mounts the actuators are placed at the interface between the engine and the car body, such that no additional mass is required.

Hence, active mounts are most advantageous for active vibration control for a wide frequency range including low frequencies. For both mentioned vibration reduction measures the implementation of electro-dynamic actuators, such as those commonly found in loudspeakers, could be of use. For instance in [3] an active engine mount based on a voice coil is presented that has found its way into production. Next to electro-active polymers [4], which are an interesting alternative but still in a relatively early stage of development, piezo actuators show great potential for active vibration control [5]. They are able to generate high forces within very little space. Thus, they are a promising alternative to voice coils. The following report presents a novel active engine mount concept that uses stroke amplified piezo actuators as well as the corresponding test results.

3 FUNCTIONAL PRINCIPLE OF THE ACTIVE MOUNT

In vehicles the loads acting on the mounts can be divided into dynamic and static or quasi-static components. The quasi-static components consist of the engine-mass as well as the driving torque. These loads may exceed the dynamic loads, which are most significant in terms of driving comfort and primarily result from the combustion process as well as inertia forces, by orders of magnitude. However, the static loads do not have any effect on the vibration of the car body. Existing active mounting systems often utilise a serial arrangement of an actuator and a passive elastic coupling element. However, such a serial arrangement of the actuator with the suspension spring carries the disadvantage that the actuator is fully exposed to the static loads. This usually results in both, an unnecessarily large actuator and high power requirement.



❶ Topology of the active mount and the flux

A smart arrangement of the suspension components that divides the loads into two separate paths enables the decoupling of the actuator from the static load. In the case of the presented engine mount, ❶ the decoupling is realised by means of a serial arrangement of the actuator and a viscous damper. The counteracting force is introduced to the structure through the viscous damper whose dynamic stiffness increases as the frequency rises. The majority of the static and quasi-static loads are carried by a second elastic coupling element that keeps the engine in its position. This ensures that almost no static and quasi-static forces are transmitted to the actuator. In case of actuator failure the passive isolation effect remains. This allows for both, minimising the actuator loads and transferring the dynamic counterforces to the vehicle body efficaciously. Since piezoelectric actuators feature the capability to introduce high forces but only little strokes, the use of a stroke amplification mechanism is envisaged. Both prototypes, the active mount used for the preliminary test in the test bench and the active mount implemented in the vehicle, are designed to compensate the dynamic forces in the vertical direction, since the excitation in this direction dominates. However, the extension to other directions is basically feasible.

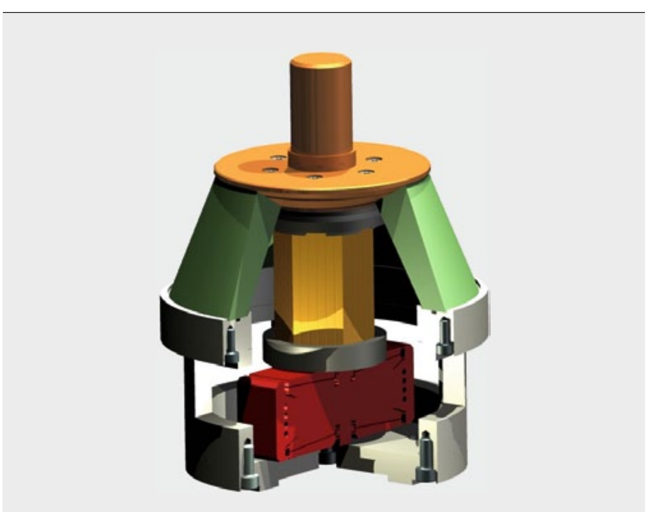
4 EVALUATION OF THE MOUNT CONCEPT

Based on the results of an overall-system simulation with Matlab, a prototypical realisation of the mount, ❷, was brought into a test environment shown in the cover picture to validate the numerical results of the previous simulations. The test environment ① consists of the following three basic components: an unbalanced mass exciter, ❸, which includes the static preload on the mount, as well as the excitation through the dominating second engine order of the motor, a cantilever beam that represents the flexible and resonant structure and lastly, the active mount that isolates the resonant structure from the exciter by being placed between them.

With four-cylinder operation, every crankshaft revolution contains two ignitions. Therefore it is typical for four-cylinder engines to find the dominance in the second engine order, as depicted here by the unbalanced mass exciter. The displacement amplitude is set according to the previously recorded oscillations of the engine in the test vehicle, ❹.

5 USED CONTROL SYSTEM

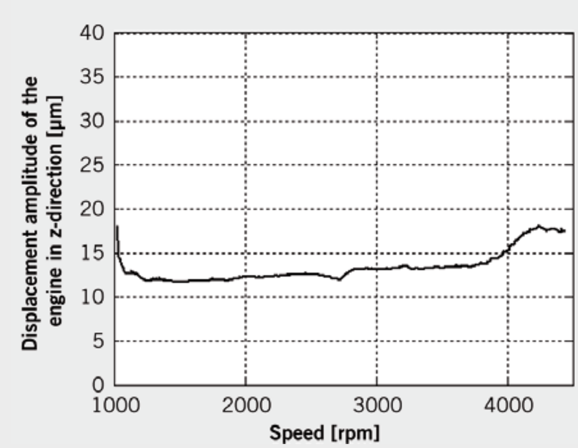
An adaptive control concept is used to generate an appropriate signal for the actuator. In order to reduce or synthesise harmonic signals the use of feed forward control concepts is common. The Filtered Reference Least Mean Squares Algorithm (FxLMS) is well known [6, 7] and implemented in the present case. In order to compute the control signal the actual rotational speed is measured. Based on this information a synthetic and harmonic reference signal is generated by an oscillator. Knowledge of the rotating system's angular position is not required. The filter weights are



❷ Active mount in cross-sectional view

❸ The unbalanced mass exciter of the test bench in cross-sectional view adapted according to the gradient based FxLMS method, which requires information about the dynamic behaviour of the system to be controlled. This system identification can be easily realised by means of adaptive FIR-filters, too [8]. For experimental testing the control algorithm was implemented on a rapid control prototyping system. However, the algorithm has been successfully tested on embedded control platforms in previous studies, too [9].

❺ shows the experimental setup comprising the actively mounted unbalanced mass exciter with the flexible and resonant structure as well as the schematic of the control algorithm. The excitation due to the unbalanced mass exciter is already reduced via passive isolation of the resilient mount. Counteracting forces due to the actuator allow an additional reduction. Either the acceleration of the car body or the sound pressure can be used as error signals for adapting the filter weights of the control algorithm. To ensure an optimal performance with changing rotational speed or ambient conditions, the filter is readjusted in every single sampling step. The novel active mount topology has been successfully tested in the test bench. For the presentation of the results please refer to [10].



❹ Dynamic second order displacement of the engine (left-hand side, in vertical direction)

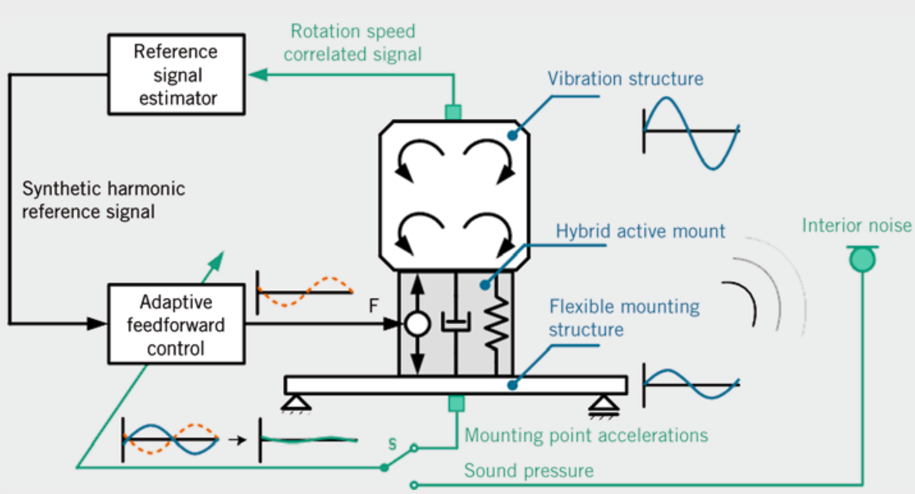
6 IN-VEHICLE MEASUREMENTS

Following the successful testing of the concept at the test rig, the mount is adapted to meet the requirements of in-vehicle conditions by being integrated into a vehicle for testing under close to reality conditions. Thus in comparison to the prototypical test rig, the mount is subjected to actual excitations and needs to account for constraints such as available space, temperature influences, and mechanical loads. To assess the experiment trials of the mount a vehicle test bench at the Fraunhofer Institute LBF was used [11]. The vehicle is attached and the wheels are driven by additional asynchronous motors. 60 s run-up measurements are taken throughout a 1500 to 4500 rpm cycle in second gear and with the gas pedal at 30 %. The control algorithm previously described can be adjusted to target various inputs depending on the given objective. In the present case the acceleration of the car body, the interior noise in the driver's cabin and a combination of both were targeted in the experiments.

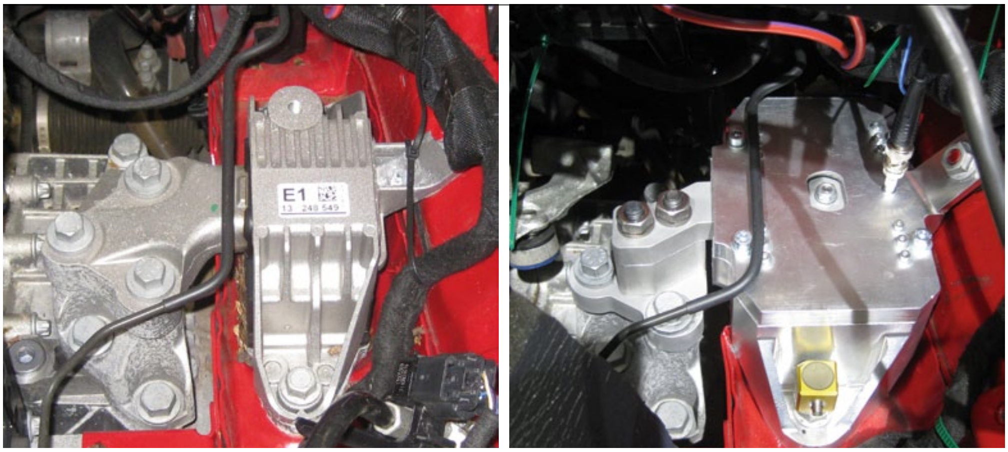
7 MEASUREMENT RESULTS

For comparison of the different configurations, measurements were taken for the serial mount, for the uncontrolled active mount and the controlled active mount as well. Accelerations were measured at the chassis side of the engine mount, ❻ (right), whilst the sound pressure was measured in the passenger cabin at driver's ear position. The acceleration and sound pressure signals were collected by a LMS data acquisition system.

In ❼ and ❽ acceleration and sound pressure data measured during an engine run-up is compared for all three configurations. The active mount was designed to have a comparable dynamic stiffness to the serial mount. By comparison of the serial engine mount with the uncontrolled active engine mount the difference of the amplitude is mostly between -5 and 5 dB. This indicates

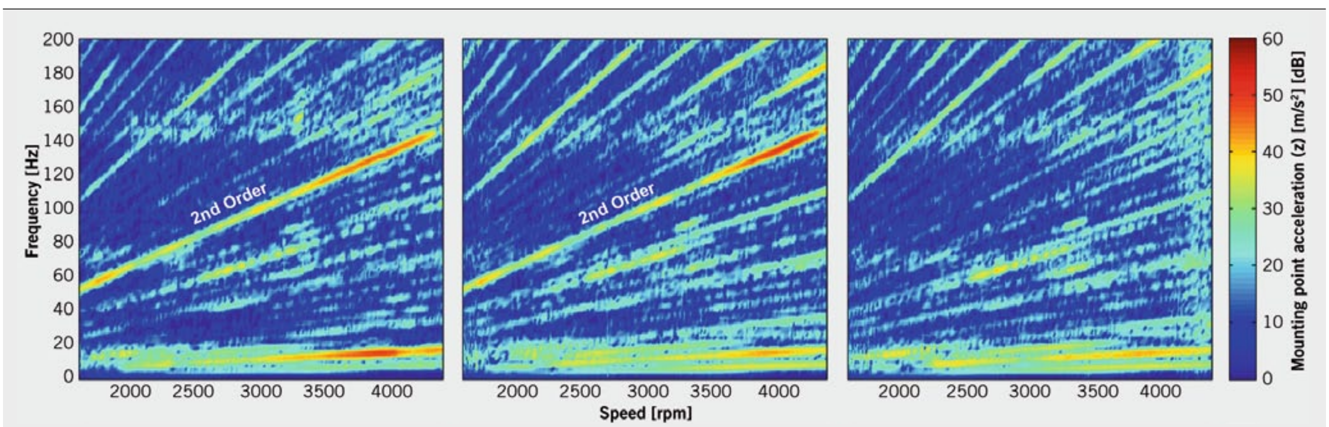


❺ Schematic of the adaptive control concept

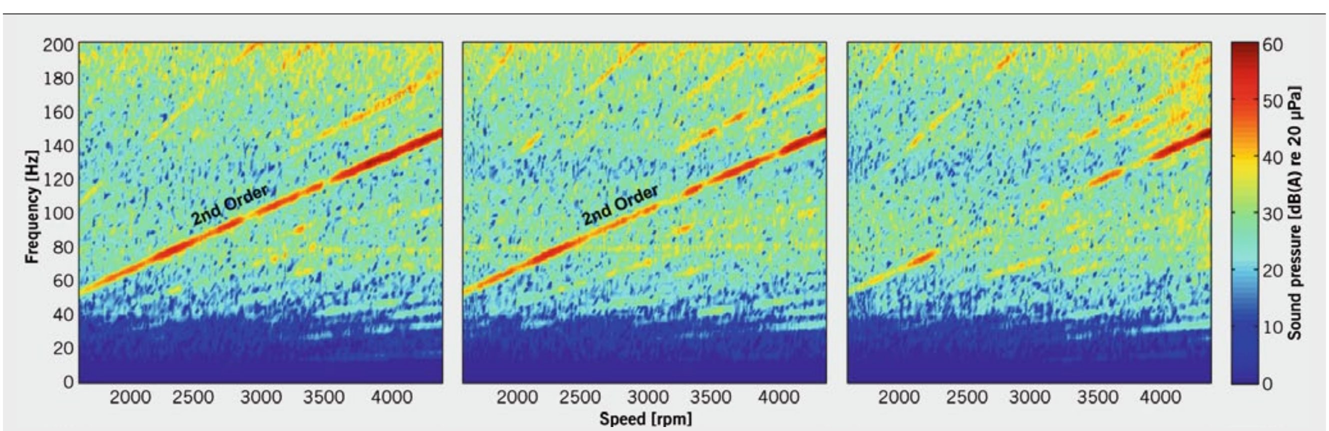


❻ Schematic of the adaptive control concept

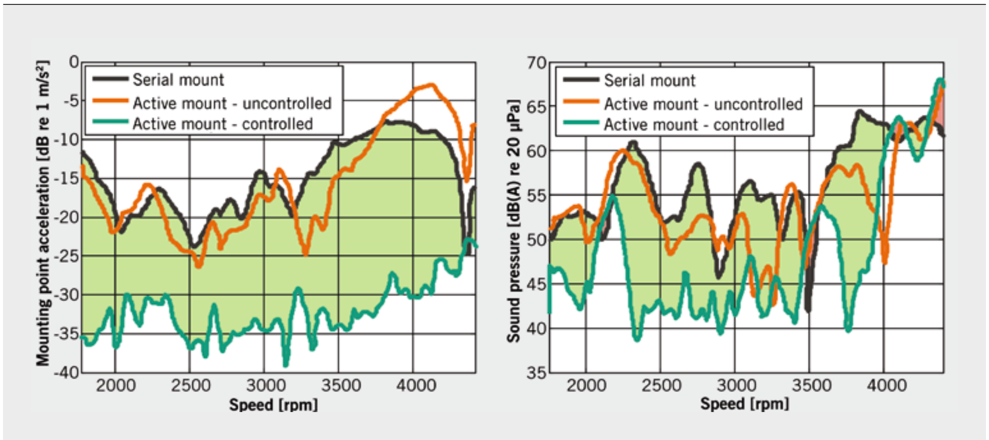
that the passive behaviour of the serial mount in the vertical direction is comparable to the behaviour of the developed active mount in passive condition. Because of the fact that the second engine order represents the dominating harmonic distortion, the controller is adjusted to reduce the disturbance of this particular order. Thus, the second order in the acceleration signal is significantly reduced in the active condition. In the experiments only one active mount is implemented. However, the engine is attached by several mounts. Therefore the vibrations are transmitted into the passenger compartment by a variety of transfer paths where they are emitted as airborne sound. On this account it is comprehensible that better results are achieved at the car body vibrations than at the interior sound pressure. Nevertheless using the sound pressure as error signal significant reductions can be obtained, too.



❼ Spectrograms of the mounting point acceleration (left: serial mount; middle: active mount uncontrolled; right: active mount controlled)



❽ Spectrograms of the sound pressure at the driver's ear (left: serial mount; middle: active mount uncontrolled; right: active mount controlled)



❾ Reductions of the second engine order (left: body acceleration on the motor bearings; right: sound pressure in the cabin)

These results could be enhanced by the use of more than one active mount.

To illustrate the influence on the second order the order cuts for the car body vibration and the sound pressure measured during the engine run-up are shown in ❾. With respect to the serial mount, a significant reduction of the acceleration of the second order amplitude up to 20 dB is achieved by the active mount. Referring to the sound pressure, noise reductions up to 10 dB are achieved. The improvement is highlighted by a green coloured background.

8 SUMMARY

Current trends in the field of vehicle engine development bring forth new challenges in respect to driving comfort. The introduction of active engine mounts that address unwanted vibrations directly at the source are most certainly a promising solution to the challenges ahead. At the Fraunhofer Institute LBF an active mount incorporating a piezo actuator was developed using an existing engine mount test bench before being tested in an actual vehicle. The mount is unique in that the actuator has been decoupled from the majority of the static load. This enables the dimensions of the actuator and the power requirements to be greatly reduced. The technology has proven its worth in an experimental setting and in a real vehicle. Vibration reductions of up to 20 dB were measured within the car body. Not to mention the potential applications for projects outside of the motor-vehicle sector that could benefit from active mounts in vibrating units.

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