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Active Engine Mount

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ABSTRACT

Conventional consumption and weight reduction measures aimed at an optimization of modern engine suspension systems, usually lead to an increase in vibrations acting on the powertrain suspension mounts. By application of active engine mounts, these vibrations, which are limited to special engine orders, are decoupled from the subframe. The design and operating principle of the active engine mount are explained. Particular focus is on the selection criteria for the actuator as well as the interaction and coordination with the characteristic mount parameters. Another focal point of this representation is the description of the control system including the necessary boundary conditions. The operating principle and effect of active engine mounts in the complete system is demonstrated by taking results obtained from measurements in the vehicle into account.

SUMMARY

Well-known measures to optimize fuel consumption and reduce weight in modern powertrain suspensions generally lead to higher vibrations in the powertrain suspension mounts. With the aid of active engine mounts, these disturbing vibrations, which are limited to special engine orders, are isolated from the subframe. The structure and effect of an active engine mount are explained. Special consideration is given to the criteria for selecting the actuator as well as the interaction and coordination with the characteristic mount parameters. A further focus of this article is the description of the adaptive control with the necessary boundary conditions. The effect of active engine mounts in the overall system is shown by means of measurements in the vehicle.

Keywords: Sound, Insulation, Transmission

1. INTRODUCTION

The automotive industry is making many efforts to reduce fuel consumption and thus the CO2 emissions of its fleet. Different approaches are being pursued. One possibility is to reduce the moving masses by reducing the number of cylinders. Higher compression in the combustion chambers and the use of turbochargers counteract a reduction in performance. Another possibility is to dispense with the balancing shaft, where the missing moment of inertia also leads to a reduction in consumption. An interesting alternative is based on the possibility of automatically switching off cylinders in the lower performance range. Here, however, it is not the reduction of the moment of inertia that is in the foreground, but rather the shifting of the operating point with a low-consumption speed range.

Although all these measures are fuel-efficient, they lead to a deterioration in driving comfort, as disturbing vibrations are transmitted via the engine mounts and the subframe to the passenger compartment. Passive mounts are often unable to resolve the conflict between torque support and ride comfort. This is why switchable mounts are already being used in many vehicles today. The damping and thus the dynamic hardening of the mounts can be lowered electronically or pneumatically in order to guarantee a reduction in stiffness, especially when idling [1]. For the consistent implementation of a downsizing concept, mounts must offer the expected comfort even under load. This is, however, where switchable mounts reach their limits.

The use of active engine mounts is therefore increasingly being tested. The basic idea is to reduce the mount stiffness for those vibrations with which the engine excites the mount due to unbalanced engine torques. This reduction in stiffness thus leads to a reduction in vibrations transmitted to the subframe.

2. BASICS

Active engine mounts are based on the well-known hydraulically damping engine mounts and perform their basic function. These consist of an elastomer main spring component to absorb the static preload and to support the elastic mounting of the engine (see Figure 1, left). The engine is usually connected to the inner part via an engine support. On the outside, the main spring component is fixed to the subframe by means of a housing. For hydraulic damping, a working chamber filled with a hydraulic fluid is located below the main spring component, which is closed at the bottom by a channel plate. As a rule, the fluid used is a glycol mixture. The channel in the channel plate now connects the working chamber with a second, so-called compensating chamber, which is usually located below the channel plate and which is closed off by a bottom compliance of high resilience. This compensating chamber serves to accommodate the hydraulic fluid flowing through the channel and, due to its high flexibility, balances the static pressure in the mount. A decoupling membrane is located in the center of the channel plate to adapt the high-frequency stiffness of the mount.

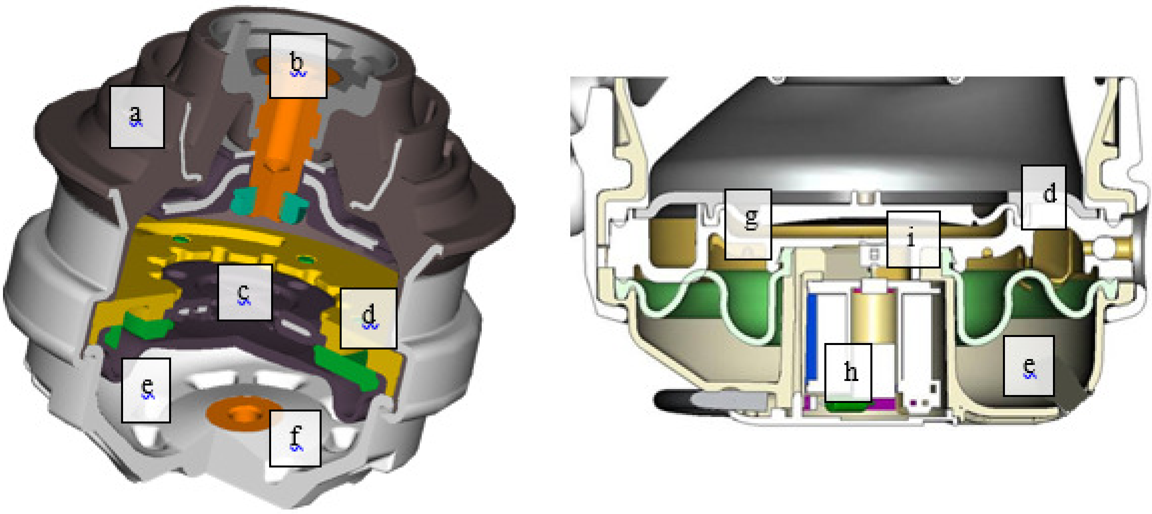


Figure 1 – Sectional view of a conventional hydraulic engine mount: - LH: Design with main spring component (a), inner part (b), channel plate with lower compliance (c), channel plate (d), bottom compliance (e), housing including screwing (f) – RH: Switchable version with membrane and air chamber (g), tractive electromagnet (h) and lock with seal (i).

The deflection of the main spring component reduces the volume V of the working chamber. A characteristic measure for the displacement potential of the main spring component is the so-called effective area $A = dV / dz$, where z is the deflection of the mount. With harmonic excitation at low frequency, hydraulic fluid is pumped through the channel between the working chamber and the compensating chamber. Due to the viscosity η of the fluid, hydraulic damping occurs in the channel due to the internal friction according to Hagen and Poiseuille [1]. A measure for the hydraulic damping is the phase shift occurring between displacement excitation z and reaction force F, which is also referred to as the loss angle. With increasing frequency, an oscillating system becomes more important, which consists of the elastic deformation of the main spring component and the mass of the liquid in the channel. When the mount is excited in the resonance range, the amplitude of the liquid movement in the channel increases significantly, and with it the damping. The elastic properties of the mount also change considerably here. The resonance system can be adjusted by channel length and diameter and adapted to the axle natural frequency as well as to the resonance of the engine mass with the mount stiffness.

For frequencies above the resonant frequency, the inertia of the amount of liquid in the channel

prevents a liquid exchange between the chambers. When the main spring component deflects, the pressure in the working chamber changes because the volume changes have to be absorbed by the internal deformation of the main spring component and the decoupling membrane. A measure of the volume absorption dV of the main spring component without its own deflection when the pressure changes dp is the volumetric flexibility = dV / dp = A dz / dp. This pressure fluctuation at deflection z finally causes an additional stiffness over the effective area, which is referred to as buckling strength or dynamic hardening.
In the case of a switchable mount for idle decoupling, there is an additional membrane with an air chamber on the side of the working chamber instead of the decoupling membrane in the channel plate (see Figure 1 right). With the volume of the air chamber, an additional flexibility is created in the working chamber and thus dynamic hardening according to customer requirements is provided. This air chamber is now connected to the environment via an opening, which is closed by a tractive electromagnet. In this condition, the mount shows hydraulic damping and thus dynamic hardening. The open air chamber, on the other hand, takes over the fluid displaced by the deflection of the main spring component without changing the pressure in the working chamber. Without pressure changes, however, no liquid is pumped through the channel. As a result, the hydraulic damping and the dynamic hardening are missing. This decoupling in particular has a positive effect on smooth running at idling speed and increases comfort.

3. ACTIVE ENGINE MOUNT

This chapter describes the specific features of the active engine mount. In addition to the overall tuning of the mount, the selection and design of the actuator is of central importance and will be summarized below. The description of the overall system includes the mount and the control unit with the algorithm to map an adaptive control system. The chapter concludes with a consideration of the effect in the vehicle.

3.1 Design

With active engine mounts, the variation of the pressure in the working chamber is modified in a similar way to switchable mounts. In contrast to the switchable mounts, where stiffness and damping characteristics can be changed in two states, here the influence on stiffness is frequency-selective. Instead of the membrane with the air chamber, there is an elastically suspended actuator plate in the channel plate, which is moved by the armature of an actuator. **Figure 2** shows a sectional view of an active engine mount. The stator of the actuator, like the outside of the main spring component and the channel plate, is connected to the housing shell and thus firmly to the subframe. The frequency range in which the active engine mounts operate is above the hydraulic resonance. We, therefore, consider the case that no fluid is exchanged by the channel.

The following consideration is decisive for understanding the mode of action of an active engine mount: The stiffness of a rubber mount, more precisely the transfer stiffness, causes a force fluctuation on the output side due to a deflection on the input side. Engine mounts support with their main spring component on the subframe side when the main spring component is excited on the engine side. In addition, the buckle strength becomes effective due to the pressure fluctuation. Active mounts are now able to considerably reduce the force fluctuations on the subframe side for certain adjustable frequencies. This practically means a frequency-selective reduction of the mount stiffness. The frequency in question is derived from the unbalanced engine torques to the instantaneous engine speed. This is known from the evaluation of the crankshaft sensor, but changes permanently during operation.

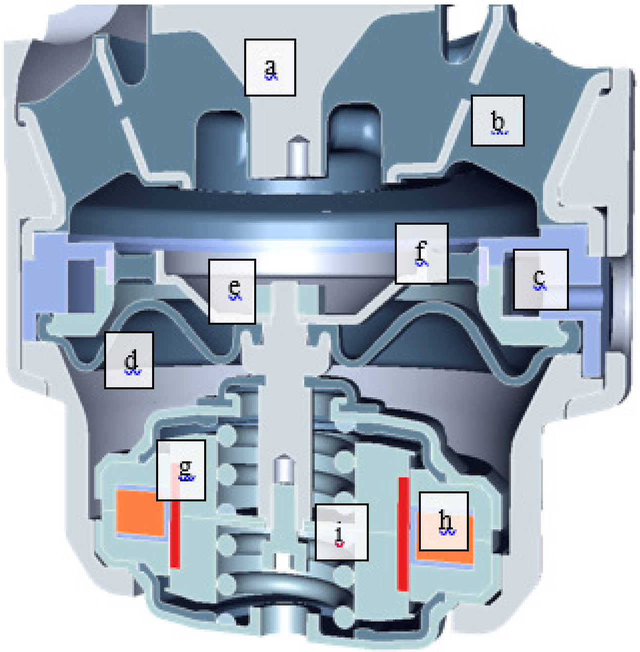


Figure 2 – Schematic representation of an active engine mount : Inner part for travel excitation (a), main spring component with effective area AT and volume compliance κT (b), channel plate with channel (c), decoupling membrane (d), actuator disk with cross section area AA (e), actuator membrane with compliance κA (f), armature of actuator with mass mA (g), stator of actuator (h), set of springs with stiffness cA for elastic connection of armature (i).

An active engine mount is not only capable of compensating for the increase in pressure when the engine, but also of generating a negative pressure which compensates for the force effect of the main spring component via the effective surface. This is done by moving the actuator plate, which is attached to the actuator and elastically suspended in the channel plate, downwards. This enlarges the working chamber so that instead of an overpressure as with conventional mounts, a negative pressure is created. If, on the other hand, the engine pulls on the mount, the actuator disc is moved upwards so that not only the negative pressure is compensated but also an overpressure in the working chamber compensates the tensile forces exerted by the main spring component. If the actuator is excited in the correct phase, force fluctuations on the output side can be eliminated despite excitation on the engine side. This eliminates the stiffness of the mount for this frequency. The mount therefore does not counteract the deflection but avoids the movement. This is one of the most important findings and decisive for understanding.

The fact that a reduction in stiffness leads to a reduction in the force acting on the subframe is due to the type of excitation. Due to the high moments of inertia of the unbalanced engine orders, the engine generates an excitation by a displacement at the mounts. In the case of force excitations, which predominantly occur in the chassis area, a reduction in stiffness would only lead to an increase in the excitation amplitude. Therefore, the concept of active engine mounts cannot easily be transferred to mounting points in the chassis.

3.2 Actuator selection

The requirements analysis as a starting point for actuator selection and subsequent optimization of the actuator parameters is of decisive importance. Customer requirements are taken into account and own objectives need to be formulated. These include an upper limit for the total weight of the actuator as well as the frequency range in which the mount control is to operate. The maximum power consumption and the associated coil design are also of decisive importance for the design.

Beyond the total weight, the frequency range and the power limit, there are parameters, which can only be evaluated together with the installation situation in the mount. The force of the actuator and the linear stroke are such parameters, whose limit values can be determined by the ratio of the effective areas of the main spring component and actuator as well as by the volume compliance of the working chamber. Two values have to be distinguished, especially for the movement of the actuator: on the one hand, the stroke of the armature caused by the force effect, which determines the compensating capacity via the flexibility of the working chamber, and on the other hand the linear free travel of the armature. It must be taken into account that the forced movements may be superimposed by further movements due to pressure fluctuations in the working chamber which lead to displacements of the working point. Outside the linear clearance, the armature is slowed down elastically by end stops.

Finally, customer-specific overall optimizations are carried out with the help of the coil design. After defining the yoke geometry of the actuator and the winding window, the force spectrum, i.e. the force effect as a function of the frequency, can be adapted by varying the wire cross-section and the number of turns. However, it must be taken into account that the electrical cutoff frequency, which is determined by the inductance of the coils in the magnetic circuit, is well below the working range of the control system. The thermal properties can also be modified here.

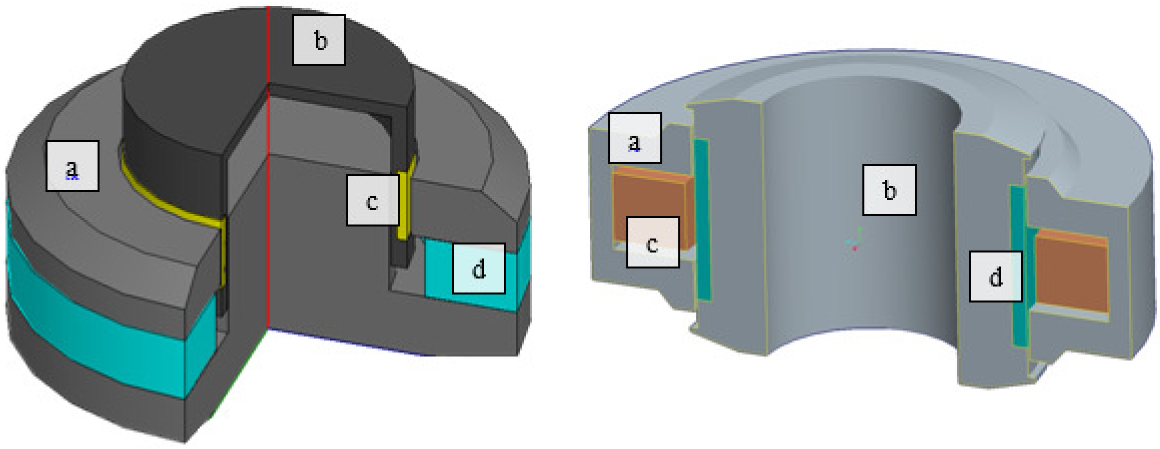


Figure 3 – Two actuators with different operating principles for power generation: Shown are stator (a), armature (b) , solenoid coil (c) and permanent magnet (d) – LH: Lorentz force with electro-dynamic mode of operation – RH: Reluctance drive with electro-magnetic mode of operation

In order to implement a linear drive with the boundary conditions described above, there are basically two principles of action that need to be narrowed down. The first is the electrodynamic drive, whose operating principle goes back to Hendrik Antoon Lorentz [1]. A possible implementation is shown in Figure 3 on the left. A coil dips into an annular gap containing a magnetic field. This is generated by a permanent magnet and guided through an iron yoke. This plunger coil is drawn into the iron annular gap by current (Lorentz force). The current/force characteristic curve is very linear, since saturation effects in the iron do not occur here when current is applied. If the plunger coil is longer than the height of the radial magnetic field, the force/displacement characteristic curve is also linear. A technological challenge that can be overcome is the contacting of the moving coil. On the other hand, the power yield, which is not achieved under the described general conditions, is problematic.

An alternative is the reluctance drive (see Figure 3 on the right). Here, too, two magnetic fields interact, one generated by a permanent magnet and one by a coil. Preferably, the permanent magnet is located as a ring on the inner armature and the coil in the outer stator. Variants of this are also known [4].

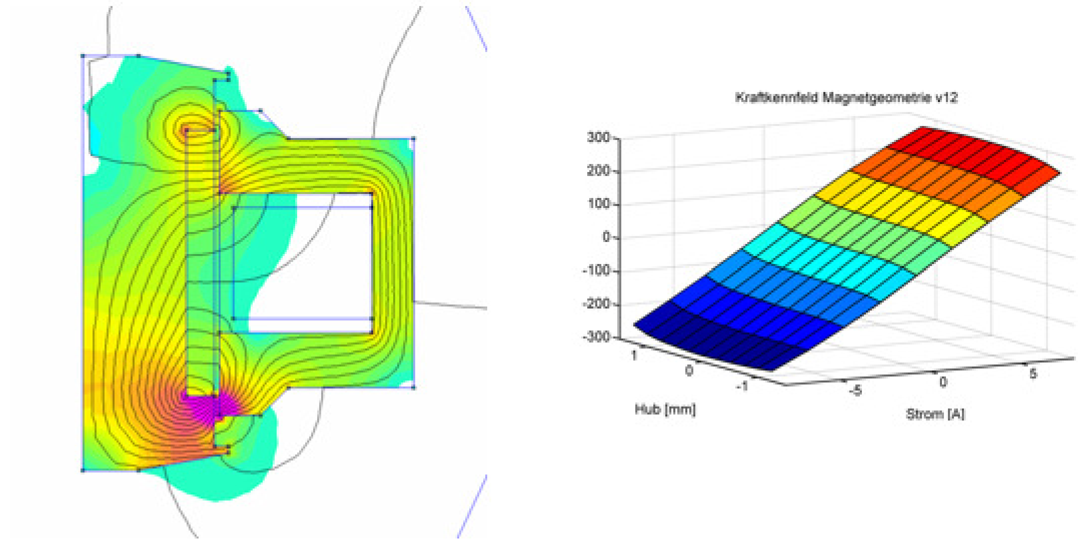


Figure 4 – Results of a simulation using Finite Element Analysis for optimization of the drive – LH: Field distribution when the solenoids are energized. The structural interference at the lower end and the destructive interference at the upper end can be identified. The action of force on the armature is here towards the top – RH: Force mapping after optimization. The force is applied as a function of the stroke and the coil current.

The force effect results from the only partial overlapping of the front surfaces of the yokes of stator and armature on the upper and lower side of the actuator. Without current, the fields generated by the permanent magnet in the annular gap between the yoke ends and thus the forces on both sides are the same. A second magnetic field is generated around the coil by current supply, which is superimposed constructively at one end with the magnetic field of the permanent magnet and destructively at the other end. On the side of the constructive superposition, the force increases which wants to reduce the resistance of the magnetic circuit by the yokes overlapping each other more strongly. On the destructive superposition side, the counterforce decreases. An example of a field distribution is shown in Figure 4 on the left. As a result, Figure 4 on the right shows the force field, i.e. the force as a function of the stroke and the coil current.

The superposition processes generally do not lead to linear characteristic curves. However, since two sub-processes compete in the reluctance drive shown here, linear characteristics can be set in a restricted stroke range. It is important that linearity and force can be adapted to the application. This means that the requirements agreed above can be implemented.

3.3 Control unit

In order to design an active mount from a hydraulically damping mount, the implementation of an actuator is not sufficient. In addition, a control unit is required which calculates a control signal on the basis of the acceleration signal together with other input variables and uses this to control the actuator via power electronics. The architecture of this ECU (electronic control unit) is shown schematically in Figure 5. The target frequencies for which the active mount is to isolate are first calculated from the signal from the crankshaft sensor. The signal supplied by the acceleration signal is filtered for harmonic components with these target frequencies. An algorithm then calculates the amplitude and phase of the current required to isolate the contributions at the target frequency and uses this signal to control the power electronics (H-bridge), which then supply the actuator with current. The force effect of the actuator influences the signal at the acceleration sensor, which provides its signal again for adaptation. In addition, the ECU performs diagnostic jobs and monitors the CAN (Controller Area Network) for communication with the vehicle ECU.

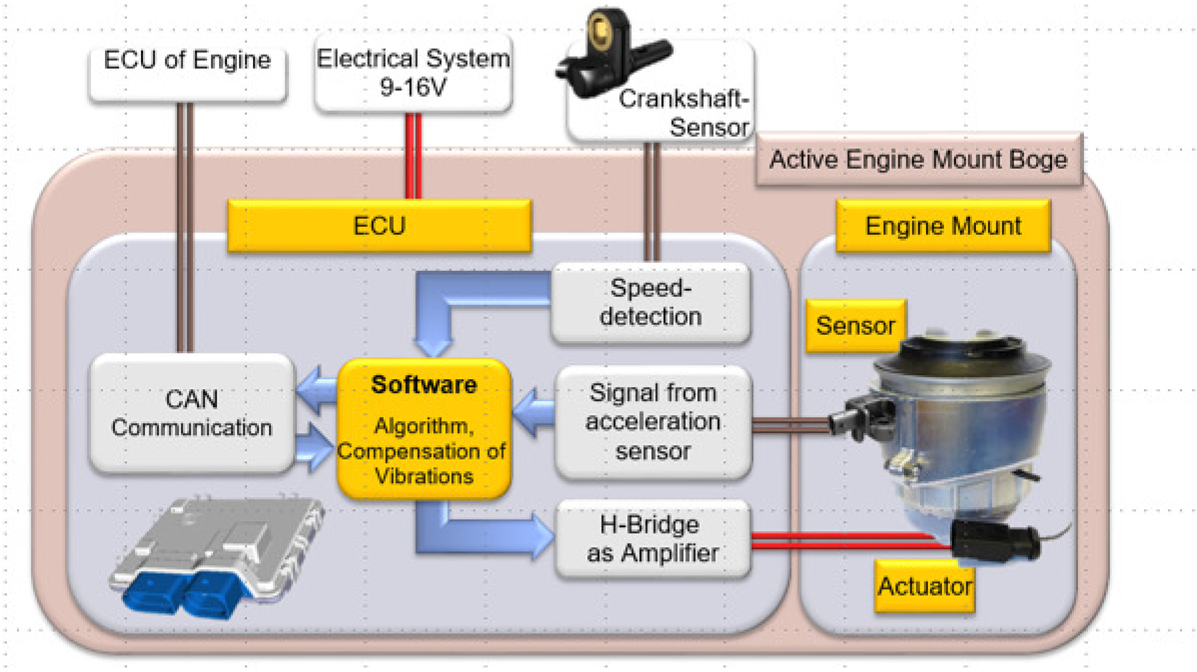


Figure 5 – System architecture of the active engine mount

3.4 Effect in the vehicle

To assess the functionality of the overall system, the mode of action in the vehicle is described below. In the following application, the active engine mounts carry an in-line four-cylinder engine. With this engine, the second engine order is the first order not balanced due to the ignition processes. Another unbalanced engine order is the fourth. The aim now is to eliminate the force fluctuations with the frequencies belonging to these orders on the mount housing despite the harmonious engine-side excitation. A measure for these force fluctuations is the signal transmitted by the acceleration sensor. Figure 7 on the left shows the signal from the accelerometer mounted on the housing as a function of the engine orders and the engine speed in the form of a Campbell diagram. The high acceleration values of the second and fourth engine orders can be seen. This diagram was created with the engine mounts deactivated. In contrast, Figure 7 on the right shows the same diagram with active engine mounts, where the system eliminates both orders. A reduction of the second and fourth engine orders to noise level can be seen.

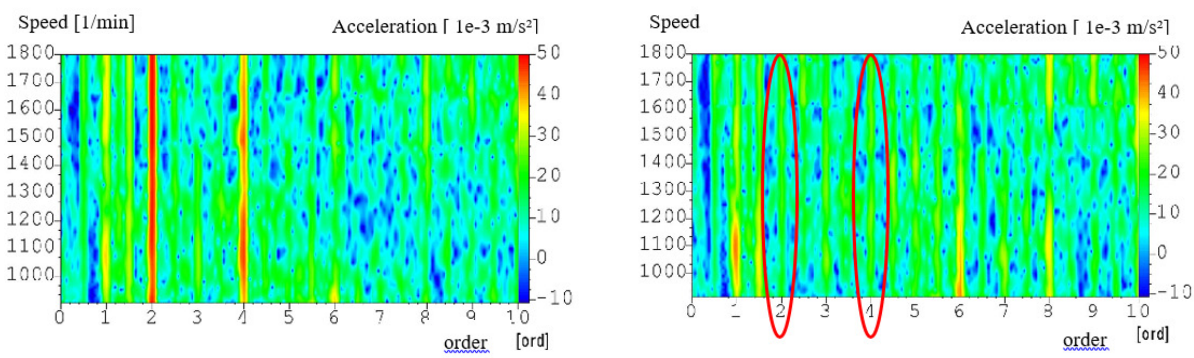
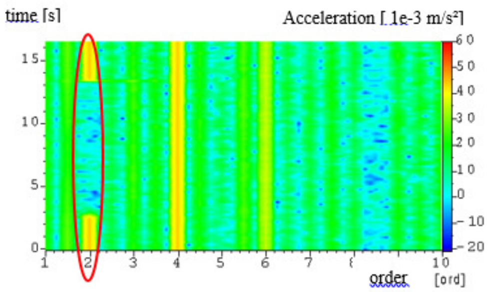


Figure 7– Acceleration as a function of revolutions per minute (speed), applied via the engine order of a four-cylinder engine. The color shows the acceleration according to the scaling RH. – LH: Recording with deactivated engine mounts – RH: Recording with activated engine mounts.

For the quantitative evaluation, the temporal course of the switch-on and switch-off of the mounts is to be considered. Figure 8 on the left shows the acceleration as a function of the engine orders at a speed of 2000 rpm during the switching operations of the second order. Here, too, the signal is reduced to the level of the noise.



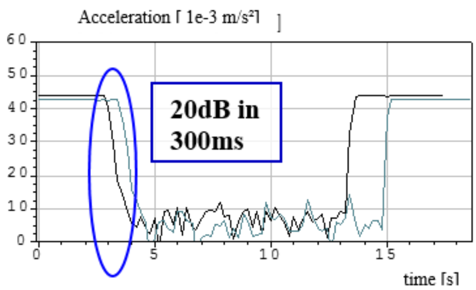


Figure 8– Acceleration as a function of speed, plotted over the engine order of a four-cylinder engine. The color shows the acceleration value according to the scaling on the right. - Left: Right: image with activated engine mounts.

Figure 9– Development over time of acceleration at a fixed speed of 2000 rpm during activating and deactivating of active engine mounts, applied via the engine order of a four-cylinder engine. – LH: The color shows the acceleration figure according to the scaling RH. – RH: The development of the second engine order is shown.

Finally, Figure 8 on the right shows the time course of the acceleration at a speed of 2000 rpm during the switching operations. A reduction of 20 dB within 300 ms and a total reduction of up to 30 dB can be seen.

4. Conclusions

Only by application of active engine mounts it is possible to eliminate the conflict of objectives between firm powertrain suspension systems on the one hand and isolation of disturbing vibration and noise on the other hand. Thus, the range of possible measures to reduce consumption in engine suspension systems increases significantly. A precondition is, however, a design that is tailored to the specific needs of the individual application case. This representation describes the structure and mode of operation of active engine mounts. In this respect, special aspects such as the selection of the appropriate operating principle for the actuator play a key role and are the precondition for the manufacture of tailor-made systems. Thus, active engine mounts enable the consistent implementation of the consumption reduction measures.

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