Moving Magnet Linear Actuator for Active Vibration Control


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Devices for automotive noise, vibration and harshness (NVH) control have been on the market for several years. More recent developments focus on active engine mounts or active absorbers with electrodynamic actuators as efficient solutions. Moving Magnet Technologies (MMT) has developed an electromagnetic actuator, whose benefits are discussed and compared with existing solutions in the context of this application.

ACTIVE VIBRATION CONTROL IN THE AUTOMOTIVE INDUSTRY

Driven by the need for fuel economy and emission restrictions, OEMs have put emphasis on different strategies which allow effective improvements in that field, such as engine downsizing, cylinder deactivation, start/stop system or hybridisation. But these new applications result in significant changes in the number of NVH occurrences, as well as in frequencies and amplitudes of vibrations generated by the engine. Therefore, vibration and noise characterisation and cancellation have become a key topic for the automotive industry [1].

As a consequence, the development and demonstration of efficient active vibration control (AVC) for the vehicle interior has materialised during the past few years. Actually, many solutions have been developed to cancel out vibrations, enhancing both driver comfort and component durability. The active management of unwanted vibrations has been reached thanks to different solutions based on electric systems, for example the use of electroactive polymer [2] to respond to issues created by modern lightweight vehicles, or piezo based actuators [3] dedicated to limit the sound transmitted into the passenger compartment.

More specifically, active vibration control strategies, using active engine mounts or active absorbers [4] as shown in **FIGURE 1**, are already on the market [5]. These active continuously controlled solutions which allow for optimum compensation of the current engine speed clearly outperform classic rubber mounts or even semi-active hydraulic mounts. They also help saving weight and space in the engine compartment when substituting the heavy and wear-prone balance shafts.

A technical solution that is often used [5, 6] consists of electrodynamic actuators, also called voice coil, due to their robust and commonly applied design in the field of loudspeakers. Their low inductance and the high force constant explain the relevance of this type of actuator. Nevertheless, one severe drawback, that is not often cited, is the necessity to use large quantities of high quality rare-earth magnets in order to reach the expected dynamic force levels. One can also find the use of variable reluctance actuators, being magnet-less, but with the severe drawback of a high and non-constant inductance, so that they can only be used for low frequencies.

MOVING MAGNET ACTUATOR VERSUS MOVING COIL ACTUATOR

Moving magnet (electromagnetic) actuators are based on the same principle as electrodynamic voice coil drives, both of them being ruled by Maxwell's well-known equations. Nevertheless, the

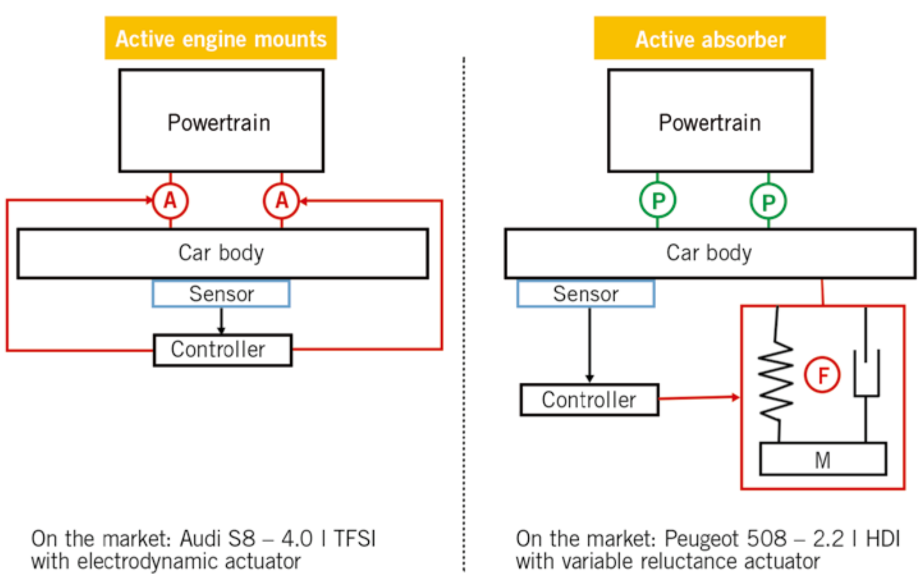

FIGURE 1 Two main strategies of active vibration control: on the left with active engine mounts (A) and on the right with passive engine mounts (P) plus active absorber (F) (© MMT)

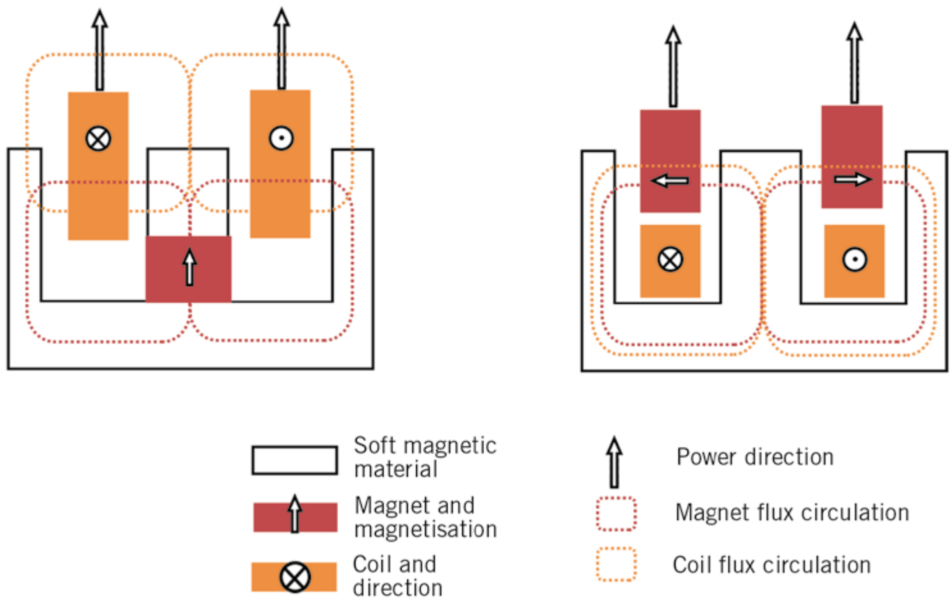

FIGURE 2 Schematic differences between electrodynamic (left) and electromagnetic (right) actuators (© MMT)

magnetic flux flowing within the magnetic circuits is quite different between both cases, **FIGURE 2**.

In an electrodynamic actuator, the magnetic flux is generated by the magnet and the coil in two quite different ways, while these magnetic circuits are closely linked in a moving magnet actuator. These physical conditions are the reason for the main features and differences between these two technologies: low inductance and high resistance for the first one while the second technology has a higher inductance but lower resistance and less stray magnetic field. But as a consequence of their physical features, voice coil types need a dramatically higher magnet volume to ensure an equivalent force constant as reached by moving magnet actuators.

Because of the low electric time constant and the well-known principle, the electrodynamic actuator may initially be considered as a logical solution for an application when high dynamics are required. On the other hand, since the principal force developed by the actuator must typically cancel out the vibration created by the second and fourth order of the engine speed, the actuator will therefore need to create its force output in the frequency range of 20 Hz to 200 or even 250 Hz [5]. In this important frequency range, a moving magnet actuator constitutes a very advantageous alternative to the actuator topologies used so far. Customised magnetic circuit designs can be implemented, depending on the design space and required force levels. An efficient topology consisting of four alternating ring magnets has been studied [7] and released by MMT, **FIGURE 3**, for the realisation of an active absorber. It has an axisymmetric design with a mass suspended between two springs, moving axially inside a soft ferromagnetic part, which has two integrated coils and three stationary magnetic poles. The mechanical resonance frequency of the system must be tuned to a frequency lower than the usable bandwidth. One important feature is that, thanks to the efficient magnetic circuit, the moving magnet can even be made of low grade ferrite material, while electrodynamic actuators require very costly sintered magnets made from neodymium, iron and boron (NdFeB) instead. The magnet mass is moreover drastically reduced in such a moving magnet type actuator.

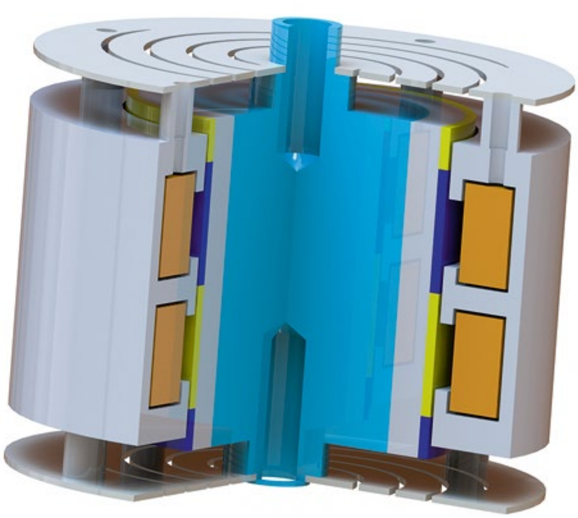

FIGURE 3 Cut view of an electromagnetic actuator dedicated to active vibration control (© MMT)

COMPARING MOVING MAGNET ACTUATORS FOR ACTIVE VIBRATION CONTROL

Both electromagnetic and electrodynamic actuators are composed of the same intrinsic features and can thus be compared as follows: the mechanical

Parameters	Voice-coil actuator	MMT moving magnet actuator
Br at 20 °C	1.2 T	0.6 T
Magnet mass	350 g	60 g
Actuator mass	1400 g	1200 g
Electric time constant	1 ms	8 ms
Response time (at 2 %) given by the transfer function	60 ms	100 ms
Km (force/√power)	10 N/√W	12.5 N/√W

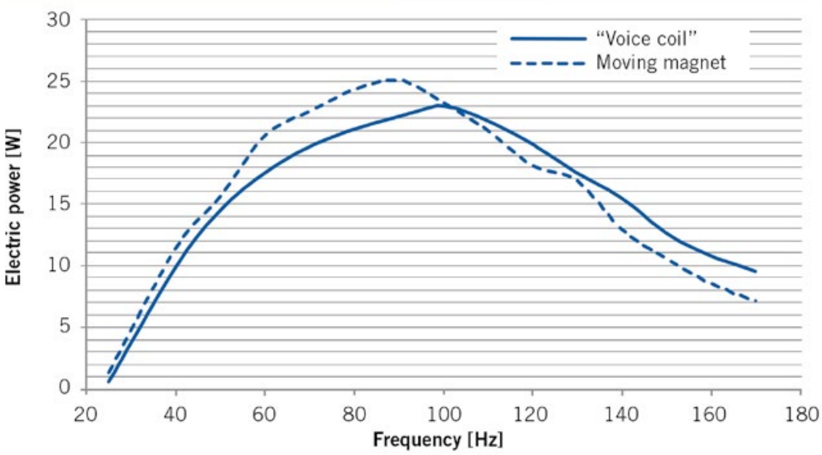

FIGURE 4 Comparison between voice coil actuator and moving magnet actuator for a realistic AVC active absorber dimensioning (© MMT)

parameters being the moving mass m and the spring stiffness k with a given damping coefficient b; the electrical ones being electric resistance R and inductance L, these two domains being linked by the force constant γn. MMT has established dimensioning definitions for both of them, based on typical specifications of an active absorber: These realistic conditions require a constant dynamic force of up to 50 N in the frequency range of 20 to 200 Hz. Actually, to achieve the same force level for the same given electric power, the electrodynamic actuator needs more than 300 g of sintered NdFeB magnets whereas the electromagnetic actuator only needs 60 g of much cheaper bonded NdFeB. Even though the electric time constant is considerably lower for the electrodynamic actuator, providing theoretically much better global dynamics, the system is in fact determined by a transfer function g(p) of position X over voltage supply U:

Eq. 1

$$g(p) = \frac{X}{U} = \frac{\gamma n}{(R+Lp)(mp^2+bp+k)+(\gamma n)^2 p}$$

The relevant response time actually has very similar frequency characteristics, **FIGURE 4**, for both actuators – namely the slowest pole of the transfer function – in the range of several tens of milliseconds. That means that both actuators will have comparable dynamic responses to sudden changes in frequency or amplitude of the unwanted vibration. The electric consumption of both actuators is comparable, so that, finally, what will objectively limit the use of an electromagnetic actuator is only its lower power factor at high frequencies. Nevertheless, for typical frequencies up to 250 Hz and a power supply of 12 V and 6 A, the limits of these actuators will not be reached. And the decisive advantages of the moving magnet actuators for the same given dynamic force are the significantly lower magnet mass (and thus cost), lower overall mass and lower stray field. Actually these advantages are clearly linked to the more confined low-loss magnetic circuit of moving magnet actuators as compared to the rather open magnetic circuit of electrodynamic actuators.

DEMONSTRATOR AND MEASUREMENT RESULTS

To demonstrate the effectiveness of the concept in a realistic configuration, MMT has realised an interactive mockup, **FIGURE 5**, and has displayed it during recent events [8]. This demo unit, aimed at exhibiting the capabilities of active vibration cancellation in the range of 20 to 200 Hz for a typical dynamic force of about 50 N, features a basic chassis frame with a car seat, modified to hold a first actuator generating vibrations, the exciter, emulating e.g. actual engine vibration, and a second actuator performing the

FIGURE 5 Interactive demonstrator (left) featuring moving magnet exciter and active absorber (right) (© MMT)

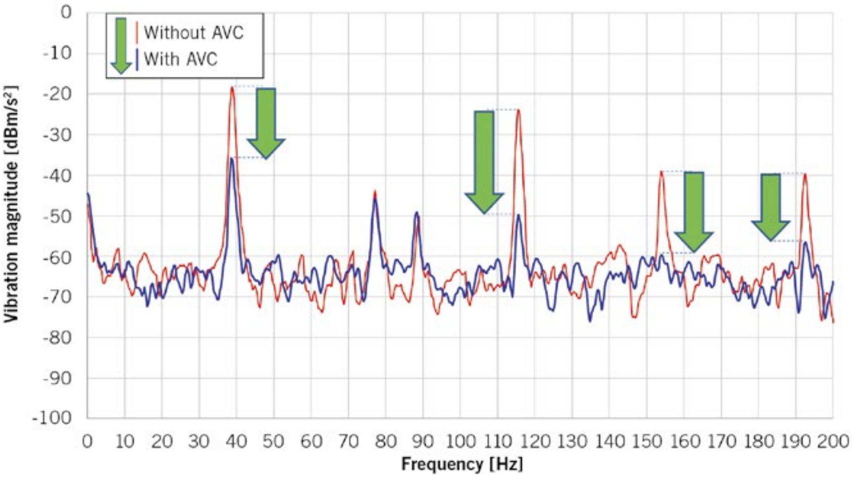

FIGURE 6 Measured performances with and without the moving magnet active absorber (© MMT)

vibration cancellation, the active absorber. Both of them have been realised with an external moving mass, so that the movement of the actuator can be seen by an outside observer, but the actuator can generally be designed with internal or external moving mass. Two main operating modes have been simulated: quick engine accelerations from 20 to 200 Hz (equaling 1200 to 12000 rpm) within a few seconds and a broadband noise profile composed of all frequencies from 20 to 200 Hz. Both of these scenarios have proven the instant reactivity and effectiveness of such moving magnet actuators. And the substantial vibration attenuation, as compared to the non-dampened condition, can clearly be felt by a person sitting on the demonstrator seat. This haptic sensation is very evident and it is even confirmed and quantified by an accelerometer measuring the actual chassis vibration. A vibration attenuation up to 20 dBm/s² on the chassis has been reached by the MMT actuator, **FIGURE 6**.

CONCLUSIONS

Active vibration control significantly improves the perceived comfort and helps increase component durability in vehicle applications. Electric vibration cancellation solutions include active engine mount and active absorbers. But the overall weight and magnet mass (and thus cost) could still be significantly reduced as compared to commonly used electrodynamic systems. MMT has shown that moving magnet actuators with their lower weight and magnet mass, and despite their higher intrinsic inductance, are perfectly suited to cancel out the entire relevant spectrum of automotive vibrations. An interactive demonstrator has proven the significant effectiveness of such actuators, measured by an accelerometer and empirically experienced and confirmed by many persons taking the test. Further developments are currently under way towards further design simplifications and increasing the overall capabilities of these moving magnet actuators.

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