An Efficient and Optimal Moving Magnet Actuator for Active Vibration Control

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Abstract:
The need for fuel economy and emission restriction has led OEMs to put emphasis on different strategies which allow effective improvements in that field (engine downsizing, cylinder deactivation ...). These new applications imply significant vibration increase, created by the engine and transmitted to the chassis and the vehicle interior, such that their cancellation is a key topic for the automotive industry. The use of active engine mounts, acting directly on the fluid of the hydromount, or active absorber, acting as an inertial mass-spring system, are very effective solutions, particularly when using actuators working on electromagnetic principles. Nevertheless, when it comes to concrete solutions, the choice of such actuators must be considered, taking into account the full performances and overall cost of the solutions. This paper deals with the presentation of an electromagnetic actuator, up to a realistic demonstration stage, showing that it can be considered as the most convenient solution, particularly by saving several tens of grams of magnets compared to the electrodynamic ones currently proposed by automotive suppliers.

Keywords: NVH, Vibration Cancellation, Electromagnetic Actuator, Demonstrator, Transfer Function

Introduction
The need for fuel economy and emission restriction have led OEMs to put emphasis on different strategies which allow effective improvements in that field, such as engine downsizing, cylinder deactivation, start/stop system or hybridization (Fig.1). As a consequence, these new applications imply significant changes on noise, vibration and harshness (NVH) occurrences. Particularly, several unwanted vibrations appear, created by the engine and transmitted to the chassis and the vehicle interior, such that their cancellation has been a key topic for the automotive industry [1].

Comparison between moving magnet and moving coil actuators
Because of their intrinsic principle, electrodynamic and electromagnetic actuators, even though working on the same magnetic equations, have different magnetic flux paths (Fig. 2) that lead to various designs with inherent benefits. As for example, the first cited depicts better dynamics ability thanks to a low inductance and a low electrical time constant, while the second cited implies a better coil thermal dissipation and a generally higher force constant per magnet mass.

In the particular application of active vibration control, and although high current dynamic is requested, it can be shown that electromagnetic actuators with moving magnet can be considered as a best solution in order to save tens of grams of magnet, keeping high dynamic ability within realistic specifications.
Moving magnet actuator design

Moving Magnet Technologies (MMT) has proposed an active absorber solution based on a moving magnet actuator (Fig. 3) [6].

This actuator is made up of a two coils / three poles stator unit and the rotor holds a ring magnet having four poles alternation, the magnet being made of ferrite or bonded NdFeB. This design allows high force density with a minimum magnet mass and the magnet can be easily magnetized, once mounted on the rotor yoke, by a dedicated magnetizing fixture. Such an actuator has typical force and inductance (or coil permeance) profiles very constant as a function of the position and the current (similar behavior than a voice-coil actuator) such that the drivability is very easy: driving the actuator with a sinusoidal current will ensure that the position oscillation is also sinusoidal with insignificant harmonic content.

The magnetostatic force (without current) can also be molded so as to participate to the mechanical axial stiffness.

The moving part is guided by spring blades also acting as a mechanical stiffness element contributing, with the moving mass, to the resonant frequency of the system that must be precisely set.

The elastic blade is a very important element allowing a frictionless guiding, an axial mechanical stiffness, along with a compact flat design. The privileged design we have chosen deals with a frame having two or three beams following Archimedean spiral mathematical law. Other types of mathematical laws and blades may be investigated and chosen as a function of the needs in terms of dimensions, stiffnesses and lifetime, as for example in [7].

Both the axial and radial stiffnesses of the blades have been studied with energetic analytical approaches thanks to the energetic and Castigliano theorems allowing fast and precise optimization of both parameters with quite simple numeric tools (Excel or Matlab for examples) without the need for Finite Element Method during the dimensioning process.

The radial stiffness is as important as the axial one because the efficient guiding of the actuator relies on it. Actually, because of the strong magnetic interaction between the stator and the rotor, a small radial offset can create an attraction force that the spring radial stiffness must overcome.

At the end of the process, the results of the theoretical calculations have been confronted to the finite element analysis and shown good accordance with the theory.
Transfer function and response time

A first important requirement for the application is the ability to switch from a frequency to another (the response time) to ensure that the actuator will follow the dynamic of the engine vibrations. Despite the notably higher electric time constant of the moving magnet actuator, the response time stays in the same range of the electrodynamic one, because of the poles $p$ of the transfer function $g(p)$ of the position $X$ over the command voltage $U$, that can be written as:

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

with $\gamma n$ being the force factor of the actuator (constant over the stroke), $R$ the electric resistance of the coil, $L$ the inductance, $m$ the moving mass, $b$ the damping coefficient, $k$ the spring stiffness.

Actually, the response time of the system (third order) is mainly dictated by the “slowest” pole of this transfer function. Due to its complexity, this one is not depicted here but involves all the parameters described above and is, for realistic specifications of an active vibration cancellation device, of the same order of magnitude for both electromagnetic and electrodynamic actuators.

Bandwidth

Of course, the achievable frequency bandwidth will be smaller with the electromagnetic design (because of a higher inductance) but, as it is shown just afterwards, frequencies up to 200-250 Hz may be achievable, still considering realistic specifications. At the end of the day, the upper current/voltage limitation (typically 5 to 10 Amps rms / 12 Volts) will limit, in regard to the impedance of the actuator, the achievable bandwidth.

Comparison of performances

On the basis of realistic specifications coming from the automotive field, MMT has dimensioned two different actuators, an electrodynamic one and an electromagnetic one, and compared the performances. In both cases, the actuators have been prototyped and have the same dimensions.

As it can be seen (Fig. 8), for given dynamic performances, the moving magnet actuator has an important gain on the overall magnet mass as well as on the magnet grade.

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Real Demonstrator mock-up

To demonstrate the full viability of moving magnet actuators for the active vibration application, MMT has built a full size mock-up that was exposed in several automotive events, such as IAA Frankfurt 2015. The audience could feel the benefit of the active vibration cancellation by taking place on this demonstrator, with or without the actuator in action.

![Fig. 8: demonstrator of an active absorber with MMT electromagnetic actuators](image)

The mock-up demonstrator is made up of a chassis with a seat, an exciter actuator, emulating the vibrations generated by an engine, and an active absorber actuator, compensating the created disturbances. It includes an electronic hardware and a control panel allowing the user to activate or to deactivate the active control and to change between different vibration modes. Indeed, several scenarios are displayed, including, for example, a frequency ramp from 20 to 200 Hz in few seconds or a randomized noise. The absorber is driven in response to the signal coming from accelerometers situated near the exciter and near the control panel. Actually, it has been demonstrated that the attenuation on the chassis is up to 20 dB on the main frequency spectrum of the studied [20Hz; 200Hz].

![Fig. 9: Power spectrum of vibrations without and with active absorber (measurements)](image)

Conclusions

Active automotive vibration cancellation is a very promising application, demonstrating a real comfort for the driver despite the increased NVH issues due to the latest developments of the OEM (downsizing, lightweight material, start-stop,…). The implementation of an electromagnetic actuator, with a moving magnet is, to our opinion, an optimal solution, allowing good performances over the frequency range, with the main benefit being the low magnet mass and the potential use of low magnet grades when compared to the classic solution of the electrodynamic actuator. The current MMT’s internal developments involve low cost designs with some design simplification, use of ferrite magnet and show some good potential. They will be developed in a near future.

References