euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Electromagnetic dampers in precision machines

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Abstract
In high precision machines, lightly damped structural resonances can often deteriorate performance when excited by e.g. floor vibration or positioning forces. Adding damping to a system can often alleviate this issue. Rubber however suffers from problems regarding stiffness and cleanliness. As such electromagnetic dampers can be an alternative to obtain the desired damping.

This paper focuses on the working of electromagnetic damping. As a first approximation, electromagnetic dampers can be considered ideal dampers since their force is proportional with only the velocity. The link between electromagnetic dampers and actuators is made and the limits of the dampers are explored. With regards to the design of electromagnetic dampers, the trade-off between damping requirement and volume claim is addressed and an optimization based on finite element simulations is presented. Furthermore some design rules are derived. Finally some practical examples of dampers are given and compared to the theoretical damping prediction.

Electromagnetic damper, eddy current damper, electromechanical system, resonance attenuation

1. Introduction

In high precision machines, lightly damped structural resonances can often deteriorate performance when excited by e.g. floor vibration or positioning forces. Adding damping to a system can often alleviate this issue. Rubber damping however suffers from problems regarding stiffness and cleanliness. As such electromagnetic dampers can be an alternative to obtain the desired damping of resonances.

Several damper designs exist in literature (see the introduction of [1] for an overview), usually with the aim of maximizing the damping by volume.

This paper first links the damping constant to the an actuator constant sometimes called the steepness or speed/force constant which is similarly optimized. Secondly it uses a finite-element approach to find an optimal design for the damper. Finally some theoretical prediction are compared to the measured damping values.

2. Working Principle of the Electromagnetic Damper

The principle of an eddy current damper is based on the Lorentz force, where instead of a current driver, the current is sourced from the motion of a conducting element. In Fig. 1 a typical damper design is presented, the similarity to an ironless linear motor is clear.

As such, a typical Lorentz-force based actuator can be short-circuited and turned into a magnetic damper. This transformation can be described by the steepness equation (given in Eqn. 1). With d the damping coefficient, S the motor steepness, F_B the blocking force, $\dot{x}_n$ the no-load speed, K_M the motor- and back-emf-constant, R the coil resistance and u the excitation voltage which goes to zero for a short circuited actuator.

$$d = S = \frac{F_B}{\dot{x}_n} = \frac{K_M u R^{-1}}{u K_M^{-1}} = \frac{K_M^2}{R} \qquad \left[\frac{\mathrm{N}}{\mathrm{m/s}}\right] = \left[\frac{\mathrm{N}^2}{\mathrm{W}}\right] \qquad \text{Eqn. 1}$$

Since the steepness is a measure for how efficient a motor can produce a DC force, it is often maximized in optimization procedures. Similarly a short-circuited actuator provides a useful indication for the maximum damping that can be achieved in a certain volume, e.g. ~1 N/(m/s)/cm^3 (see [2]).

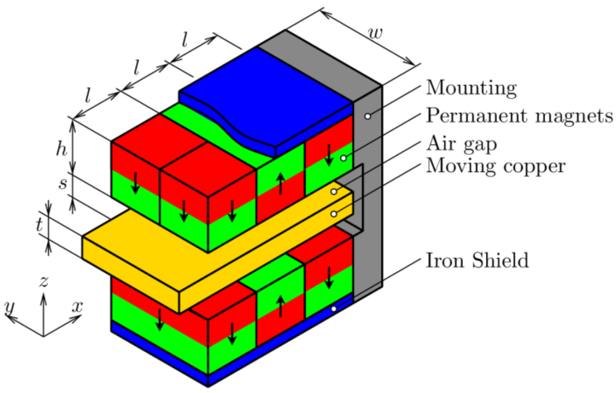

Figure 1. Typical layout of an electromagnetic damper.

It should be noted that the resistance R in Eqn. 1 can be replaced by an impedance Z for the dynamic case. As such the damper will have a limited bandwidth of around 100 Hz due to the inductance L.

3. Optimization Strategy

The optimization strategy calculates the damping by volume using a 3D finite-element-simulation implemented in GetDP (see [3]). At first, an infinite array with periodic is simulated to simplify calculation. Such a checkerboard pattern achieves damping in both planar directions (x and y). Optimization of the copper plate thickness t and magnet height h is done using the fmincon() routine in Matlab. The simulation parameters are given in Table 1.

Table 1 Effect of in-plane boundary condition on damping by volume.

Parameter	Value	Unit
Magnet height	see Figure 3b	mm
Copper thickness	see Figure 3b	mm
Air gap	1.5	mm
Velocity	1	mm/s
Magnet size	see Figure 3a	mm
Frequency	1	Hz
NdFeB magnet / H_c	1000	kA/m
Moving copper / σ	59	MS/m

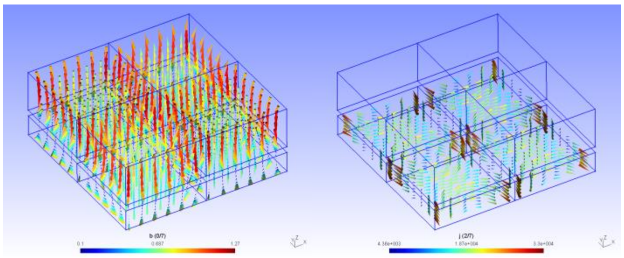

Figure 2. Field and eddy-current distribution in considered geometry.

3.1. Simulation Results

The simulation results are given in Fig. 3. It is clear that in an infinite array, the damping by volume can exceed 1 (Ns/m)/(cm^3) for larger dimensions. Furthermore it can be seen that magnet height *h* increases approximately linear with the magnet length and that the copper plate thickness *t* should be approximately halve the magnet height.

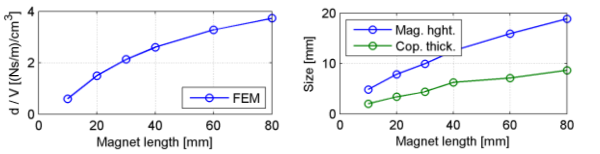

Figure 3. Damping by volume (left) and dimensions (right) for different magnet lengths *l*.

In Fig. 4 the normalized optimum for a 20 mm magnet is plotted. As is clear from the figure, the optimum is quite gradual. For example with halve the optimum copper plate thickness, still 90% of the maximum can be obtained.

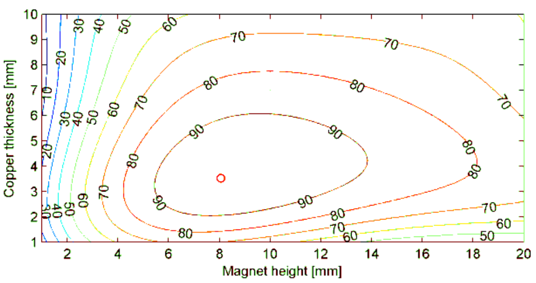

Figure 4. Normalized damping-by-volume for a magnet length of 20 mm.

3.2. In-Plane Boundary Effects

To account for the effects of the boundary, a variety of boundary cases were simulated as depicted in Fig. 5. The results are summarized in Table 2. Based on the results it can be stated that one row of magnets does not contribute significantly to the damping.

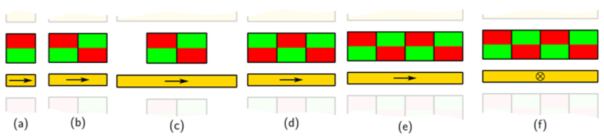

Figure 5. In-plane boundary conditions simulated.

Table 2 Effect of in-plane boundary condition on damping by volume.

Config.	Damp. [Ns/m]	Rel. Vol. [%]	Rel. d / V [%]
Periodic	38.3	100	100
(a)	3.5	50	18
(b)	21.4	100	56
(c)	29.9	200	39
(d)	40.3	150	70
(e)	59.4	200	78
(f)	78.8	200	100

3.3. Out-of-Plane Boundary Effects

Out-of-plane, a similar effect is observed, i.e. for *n* conducting plates, about halve a plate does not contribute to the damping due to edge effects.

3.4. Optimum

Since the damping-by-volume increases approximately with the square-root of the magnet length and one row does not contribute, for a given total length a maximum damping is reached at the maximum of (n-1)/($n\sqrt{n}$), which has a maximum at 3 for integer *n*, although 2 and 4 are within 90%.

Out-of-plane it is usually best to have as many copper plates as possible since the damping does not deteriorate as much with thinner copper and magnets (see Fig. 4). This however results in a more difficult construction due the amount of magnet stators, so usually a single plate is used as in Fig. 1.

4. Measurement Results

Several damper designs have been prototyped and qualified for use in e.g. test rigs. The designs are based upon the optimization in Section 3 with usually 3 magnets in the direction to be damped. Depending on available magnet size and volume also 2 or 4 magnets are sometimes used.

The resulting damping of the designs is derived from frequency response function measurements and given in Table 3. As can be seen from the table, the expected damping-by-volume of ~1 (Ns/m)/cm^3 is achieved. Errors up to 20% occurs between simulation and measurement which can be attributed to tolerances and resonance frequency mismatch.

Table 3 Measured damping coeficients compared to simulation

Design	Volume [cm^3]	Simulated [Ns/m]	Measured [Ns/m]
A	72	65	79
B	103	145	152
C	10	10	11
D	237	170	188

5. Conclusions

An eddy-current damper is similar to a Lorentz actuator in that they are characterized by the same performance metric, the steepness. As such similar rules of thumb can be applied in their design. Furthermore design rules are presented to come to an optimum design inside a constrained volume. Finally the simulation is compared to measured damping values and the results are within 20% for different designs.

It can thus be concluded that the performance of electromagnetic dampers can be derived from actuators and as such more volume helps in achieving an efficient component.

In the future the simulations will be extended to include dynamic effects such as the inductance and the skin-effect to estimate the frequency and velocity dependence of the damper.

References

[1] Zuo L, Chen X and Nayfeh S 2011 *J. Vib. Acoust.* **133(4)** 041006
[2] Toma A 2013 *Mikroniek* **1** 21-26
[3] Dular P, Geuzaine C, Henrotte F and Legros W 1998 *IEEE Trans. Magn.* **34(5)** 3395-98