Simulation, design and experimental validation of a passive magnetic damper for ultra-fast actuators

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Abstract

A contact system driven by a high energetic Thomson actuator requires to be decelerated from full speed down to zero. The forces originated from the interaction between a stationary copper tube and a moving array of magnets combined with plastic or ferromagnetic material are used to generate eddy-current damping. Five different configurations of small but strong (N52) neodymium magnets and spacers were benchmarked for simple free-fall damping. A comparison between experimental results and simulations (using COMSOL) has shown that the most effective damping is reached by two consecutive permanent magnets with opposite magnetization directions, separated by low-carbon content steel concentrators (SN - Fe concentrator- NS).

The proposed damper design is the result of the balance between various parameters such as magnet orientation topology in the array, spacer material and its dimensions, copper tube thickness and the air gap between copper tube and array.

Furthermore, the design was scaled up and an actuator-drive system was added to perform more realistic tests, which demonstrated the damping effectiveness on a fast moving armature actuated by a Thomson coil energized by a capacitor bank. All models in the simulation predicted the damping effect in advance. Investigations were conducted with two cases: (1) A solid copper rod was supposed to pass through the magnet array; (2) A plastic shaft was applied to support the magnet array.

Finally a damping prototype with a plastic shaft was built for completing damping tests. The results of these tests validated the numerical model with a high degree of accuracy.

Keywords: Damping, Thomson actuator, eddy currents, magnets, ferromagnetic materials, magnetic flux concentrators.
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1 Introduction

Recent research has led to rapid progress regarding various types of high-energy actuator designs. Improvements in numerical computation allowed the design of devices with ultra-fast displacement of the actuator’s moving part. Yet, after the contact system is accelerated to attain the desired steady state velocity, it should be decelerated down to zero upon the application of a controllable force within a specific and short period of time. Otherwise, a collision might lead to excessive mechanical stresses exceeding the ultimate yield stress of fragile components and permanent deformation.

1.1 Actuators

Actuators are the intermediate apparatus that transfer power to working devices. In vehicles, the motor acts an actuator, converting energy from current, hydraulic or pneumatic pressure into motion. The main function of an actuator is to change an object’s moving state, which means they initiate movement or control a mechanical installation or system.

At present, there are several types of actuators, such as hydraulic, pneumatic, electric and mechanical actuators. Compared to hydraulic and pneumatic actuators, electric actuators are more cost-efficient on operating control. An electric actuator benefits from simpler structures and more energy-efficient power transmission, avoiding dissipation in mechanism.

A Thomson-coil actuator is composed of a coil with a conductive aluminum disc armature on top. The coil is connected to a capacitor bank in order to form a circuit. When the capacitor bank is being discharged, it generates an electrical current impulse in the coil, inducing high eddy currents in the aluminum plate. Thus, a large force is exercised on this armature and causes it to move [20].

1.2 Dampers

A damper is a device that mitigates mechanical vibration by dissipating its kinetic energy, fulfilling the requirements of safety and reliability. In the dynamic operation devices, such as circuit breakers, if a circuit breaker is short circuit, overload, or any other problem happens, it will activate a contact system (e.g. vacuum interrupt) to be open, causing a capacitor to discharge, generating a high repulsive force on an actuator, and then this actuator will move with an ultra-fast speed. Thereby, a damper is required to be installed in the system to damp its speed; otherwise it will damage the entire system. In addition, dampers are applied to
vehicle suspension systems in order to ensure the safety of the passengers by minimizing the transferred forces on them [4]. In [21], the damper was installed with an electromagnetic actuator, suppressing a mechanical flexure in a levitation condition of transportation, which was propelling vehicles with applications of magnets.

1.3 Types of Dampers

There are two types of dampers, linear and rotary dampers. A linear damper is defined by its stroke, while a rotary damper is specified by having a damping coefficient in torque per angular velocity, which can be obtained directly from the manufacturers. These two kinds of dampers have been used for e.g. vehicle, relays and motors. Magnetic dampers have been created using principles from both kinds of dampers.

1.4 Magnetic Dampers

A simple demonstrative experiment of a permanent magnet going through a solenoid is illustrated in Figure 1 which shows the principle behind the damping mechanism when a magnet is passing through a solenoid.

![Figure 1: Four steps of a magnet passing through a solenoid.](image)

As shown in Figure 1, a solenoid is connected to an amperemeter to track the change of the current induced by the varying magnetic field of a falling magnet. Before the magnet is dropped (a), the current is zero. When the magnet is dropped and starts entering the solenoid (b), the pointer turns to the left until it reaches the middle of the solenoid, where the current peaks, and then it turns to zero (c) immediately. Afterwards, as it leaves the solenoid, the current changes its direction (d), reaching a maximum and then decaying to zero when the magnet is far away. By Faraday and Lenz law, when the magnet is in the upper part of the solenoid, the induced current generates a counter field that tries to reduce the magnet’s field. Then, when the magnet is leaving the solenoid, a current is induced which tries to increase the field to avoid the magnet’s departure.
In the given example there is little or no opposition of the system to the falling magnet. However if we increase the amount of conductive material, the speed of the magnet or the magnetic strength of the falling magnet, noticeable forces will start to appear. The latter is precisely the concept of magnetic damping.

### 1.5 Examples and Applications of Eddy Currents

Many different kinds of electromagnetic dampers (EMDs) have been applied in reality, e.g. shunt damping, passive damping and semi-passive damping. They all motivate the damping movement through variation of the magnetic fields in conductive objects. S. Behrens et al. [5] presented an approach for electromagnetic shunt damping, and it brought plenty of benefits, such as a smaller shunt voltage required and a larger mechanical structure compared to the traditional piezoelectric shunt damping, while this shunt damper would have a larger travelling range. Po Li et al. [6] studied an eddy current pattern applied in a high-speed train, which could improve the controllability, save energy and provide more modes of operations.

When two permanent magnets are getting closer to a conductive spinning disc, rotating with a very high angular speed $\omega$ in both sides (see Figure 2(a)), the flux density across the disc is changing. This is due to the fact that the shadows of both projecting magnets are not directed centrally to the disk. To explain this, the changes in the flux density can be divided into several flux areas, seen from the lateral side of the disc (see Figure 2(b)). The circles 1 to 7 are assumed to be shadows of the magnets' surface at different times. As the magnets move towards the disc, the air gap between the magnet and the disc is reduced. Since the disc rotates very fast, the area 1 is replaced by area 2, area 3, area 4, and so on very quickly, the disc is affected by different flux, as both magnets and disc move on a temporary scale. Due to the relative motion between the disc and the magnets, the spinning disc will start to generate currents in form of eddies which produce their own magnetic field. According to Lenz's law, this field is such that it opposes the change of the magnetic flux around the disc. The interaction (repulsion for flux increase and attraction for flux decrease) of these two magnetic fields causes the spinning disc to move slower and eventually to stop.
Figure 2: Eddy current brake in a spinning disc: (a) two magnets move towards a conductive spinning disc from both sides of this disc; (b) specification of flux change on the left side of the spinning disc.
In amusement parks, the freefall ride is a very popular attraction (see Figure 3). The physics in this free fall tower is closely related to the concept of magnetic damping. Permanent magnets are installed on the gondolas and vertical bars are mounted on the tower. The flux is shielded by iron plates in such a way that the magnetic field is guided to the interior of the cylinder and not outwards, which is why people and their ferromagnetic belongings will not be affected by the strong magnetic field when they are sitting on the gondolas. The lower part of the tower is made of two stages with a copper cylinder in each one of them. During the free falling, the peak speed of the gondolas can reach 100km/h. In the bottom part of a cylindrical copper bar, eddy currents are induced by the relative motion between the magnets and the copper, generating a damping force to reduce the gondolas’ speed to zero in a few meters. This design in the free-fall ride shares several features with the work presented in the thesis.

![Figure 3: ‘Fritt Fall Tilt’ in Gröna Lund, Stockholm and a drawing of its principle [19].](image)

In order to generate a higher damping force on the moving part, the utilization of a linear Halbach array in an eddy-current braking system with high speed [7] had been suggested earlier by Seok-Myeong et al. (Figure 4). A Halbach array is a special arrangement of permanent magnets that makes the magnetic flux concentrate in one of the six sides and reduces it in the remaining five sides [14]. For this array, the magnetization direction of each magnet is perpendicular to the next one (Figure 4 (a) and (b)). If all five sides of magnets are shielded with iron steel plates except one side (Figure 4), the magnetic field in this side becomes even more concentrated.
Ebrahimi et al. [11] proposed a similar eddy current damper (ECD) design that exploits the relative motion between the permanent magnets and the conductive pipe. This idea was later refined and double copper layers of the Halbach construction were integrated in the system in order to further increase the damping effect [12]. An iron layer can be attached to the outer copper tube to cancel the field to near zero in one side which is outside of the copper. In case of even higher damping requirement, it can be further developed by using high-quality, low-weight magnets, as well as conductors with higher conductivity [13]. The Halbach structure can be especially used for linear system damping.

The eddy current concept was also utilized for the permanent-magnet machine [8] in order to achieve higher force capability according to the relative movement between the stator and the armature. Another application of ECDs is in levitation systems, for example in micromanipulation [9], a device consisting of copper plates was implemented to reduce the
positioning error of this system to a level of more than one third of its original value and thus increment significantly the precision of this device. In addition, Sodano et al. [10] improved the ability of suppressing the vibration of a cantilever beam by inducing eddy currents in the copper layers mounted on the beam. The simplified structure of this vibration system in a 2D aspect is drawn in **Figure 5**. As the cantilever beam is deflected in the vertical direction, the magnetic flux density produced by the magnet and going through the conductor changes, inducing circulating currents inside the conductive plate, creating a repulsive force that minimizes the vibration of the beam.

![Figure 5: Magnetic field and eddy current induced in a cantilever beam [10].](image)

Finally, Lei Zuo et al. [15] presented a new design of ECDs with magnet arrays and conductive plates in order to achieve a high damping efficiency. The proposed configuration consists in distributing the magnets into several groups in order to increase the eddy current by interchanging the magnetic poles (**Figure 6**). A small air gap is left between each magnet and the corresponding copper plate. Again, this is an example of eddy current damper that is a consequence of the relative movement between the copper plates and the permanent magnets leading to the generation of retarding forces on a moving object attached to the set of copper plates.
Figure 6: Prototype and configuration of a ECD consisting of a magnet array and a set of conductive plates [15].

From the given examples we can observe that an increasing number of dampers are being recently designed based on the eddy current concept. Consequently, several advantages are attributed to these types of magnetic dampers when compared to conventional mechanical dampers.

- **Non-contact performance**
  Magnetic dampers can easily damp an object’s motion without any contact (Figure 1). When the magnet is falling down, the magnetic field generated from this magnet impacts the field distribution in the solenoid. The solenoid then produces an extra field to resist the change of the inner field, according to Faraday’s Law. This generates a repulsive force on the moving magnet. During the whole moving process, there is no contact between the magnet and the solenoid to avoid frictional losses.

- **High efficiency, higher life-span in utilizations and low mechanical losses**
  Permanent magnets are used in magnetic dampers. If the damper is well-designed, it is a robust mechanism with a long lifetime (neodymium magnets are expected to last over hundred years). This is of course a highly cost efficient solution. Elbukken et al. [22] studied a magnetic levitation of micro objects. In their work, power was supplied from a magnetic drive component, activating electromagnets to generate a magnetic field. Thereby, friction between the levitation objects and the electromagnets as well as adhesion forces were eliminated, which avoids mechanical losses.

- **Reliability and controllability**
  This kind of damper benefits from a cleaner, simpler and more effective power transmission. The power source can be integrated with a programmable control or even be generated from a relative motion only.
1.6 Aim and Objectives

The goal of this project is to design a dedicated damper for a contact system driven by a Thomson actuator, which is based on the use of a permanent magnet array and eddy current induction in a copper tube.

As a first objective, simple and small-scale models of a magnet array are built, based on the educational demonstration of a magnet falling in a copper tube [1-3]. Then, larger-scale models of the magnet array are simulated by using the Finite Element Method (FEM) commercial called COMSOL Multiphysics. Two different magnets of large sizes were investigated. The different conditions with different numbers of magnets in one array were simulated, bearing the limitations of manufacturing a prototype in mind. After the completion of the simulation, a full scale prototype was constructed by choosing four N38 magnets to investigate experimentally the damping effect. By changing the armature’s initial activated moving speed, the experiment was performed varying stepwise the energizing voltage. The damping movement was recorded by a high speed camera, validating the predicted results from the simulation.

1.7 Definitions

List of Abbreviations
ECD: Eddy current damper
EMD: Electromagnetic damper
FEM: Finite Element Method

List of Symbols
\( B \) : Magnetic flux density
\( B_r \) : Radial magnetic field flux density
\( B_r \) : Remanent flux density
\( E \) : Electric field strength
\( J \) : Current density
\( J_e \) : External current density,
\( J_i \) : Induced eddy current density
\( A \) : Magnetic vector potential
\( \sigma \) : Electric conductivity
\( \mu \) : Magnetic permeability of ferromagnetic material
$F_z$: Lorentz force

$f$: Lorentz force density in $z$ direction

1.8 Structure

This report has the following structure:

Section 1, **Introduction**: describes actuators, dampers and their state-of-the-art designs, presenting the aim and objectives of this project.

Section 2, **Theory**: analytical description of eddy currents and computation of damping forces.

Section 3, **Modelling**: depicts the modelling procedure in COMSOL, including instructions on how to define each object in the model.

Section 4, **Numerical Verification from References**: verifies the experimental results of one permanent magnet falling through a copper tube which comes from similar experiments in references by using numerical model built in COMSOL.

Section 5, **Initial Prototype for Model Verification**: various configurations with different but simple damper designs in COMSOL, identifying the optimal construction of the damper in a small scale.

Section 6, **Potential Damper Modelling**: introduces an array with larger magnets to the most effective configuration in a small scale.

Section 7, **Real-scale Experimental Prototype**: validates the feasibility of the damper by building a real prototype and performing experiments. The obtained data and results are presented in the form of plots. A discussion and interpretation of these results follows.

Section 8, **Conclusions**: summarizes the thesis work, discussing factors that affect the results and making suggestions for future research.

Section 9, **References**: specifies sources and relevant material on the application of the eddy currents.
2 Theory

A retarding force will be generated on a moving permanent magnet when it passes through a static and conductive object. A changing magnetic field traverses the surface of the conductor and eddy currents are induced inside the conductor, producing the damping force.

2.1 Generation of Eddy Currents

When a permanent magnet is falling inside a copper tube, it is in an accelerating state. But due to the retarding force, it is slowing down. Eddy currents are induced in each infinitesimal segment of this conductive tube. The changes of the eddy currents in the entire tube can be divided in two areas and their directions are shown in Figure 7.

*Figure 7: Eddy currents in a cooper tube induced by a magnet dropping down.*

The current induced in the upper area is to produce a magnetic field in order to prevent the reduction of the flux as the magnet moves away. The induced current in the lower area is to generate a field, opposing the increasing magnet field.

The generation of induced eddy currents can be described in further detail by choosing any
small strip of the induced eddy currents in the copper tube (see Figure 8). Before less than half of the magnet passes by this infinitesimal segment of the copper tube, the magnetic field produced by the induced eddy currents is opposite to the field generated from the magnet. When more than half of the magnet passes by this strip of the copper tube, the currents induced inside the copper tube reach their maximal intensity. When the magnet moves further down, the direction of the eddy currents in this strip of the copper tube is changed immediately.

![Diagram of eddy currents before and after half of the magnet passes through a small strip of the copper tube.](image)

**Figure 8:** Longitudinal indication of the flux density generated from a permanent magnet falling through a copper tube: before and after half of the magnet goes through a small strip of the copper tube.

### 2.2 Damping Force on the Magnet

When a cylindrical permanent magnet falls down axisymmetrically in a vertical direction [16]. As it moves, eddy currents in a conductive tube will be induced, due to the change of flux density traversing the pipe wall. Therefore, the current density can be obtained by the magnet’s moving speed $\vec{v}$, $\vec{J} = \sigma (\vec{v} \times \vec{B})$ (2.1)

Where $\sigma$ is the copper conductivity. The schematic of this moving process in a two dimensional description is presented in Figure 9.
A variable damping force is exerted on the magnet as it falls down, while this force is computed corresponding to the eddy current, flux density and vertical velocity. Therefore, the next step is to compute magnetic flux density at any point \( P(R, \theta, z) \) away from magnet by using a cylindrical coordinate (Figure 10) [3].

Assuming that the magnet’s velocity and its magnetic flux are expressed in vectors

\[
\mathbf{v} = 0\mathbf{i} + 0\mathbf{j} + v_z\mathbf{k}
\]  
(2.2)

\[
\mathbf{B} = B_r\mathbf{i} + B_\theta\mathbf{j} + B_z\mathbf{k}
\]  
(2.3)

The magnetic flux density is defined according to Biot-Savart’s law

\[
d\mathbf{B} = \frac{\mu_0 M_0}{4\pi} \int_0^\Phi \frac{d\mathbf{l} \times \mathbf{R}}{R^3} d\phi
\]  
(2.4)
Where \( \mu_0 \) and \( M_0 \) are the permeability and the magnetization per unit length, and \( d\vec{l} \) is an infinitesimal current strip, while \( \vec{R}_1 \) is a vector quantity to define the distance between the point P and the current strip.

The relations among all vector quantities in Figure 10 are written as [3, 10]:

\[
\vec{R}_1 = \vec{R} - \vec{r}
\]  

(2.5)

Where

\[
\vec{R} = y\hat{j} + z\hat{k}
\]

(2.6)

\[
\vec{r} = b\cos \phi \hat{i} + b\sin \phi \hat{j}
\]

(2.7)

Thus the length vector \( d\vec{l} \) of the infinitesimal strip is obtained by

\[
d\vec{l} = \frac{d\left(\vec{r}\right)}{d\phi} = -b\sin \phi d\hat{i} + b\cos \phi d\hat{j}
\]

(2.8)

Where \( b \) is the radius of the circular magnet.

Taking equations (2.5) and (2.8) into equation (2.4), the flux density can be derived:

\[
\begin{align*}
\frac{dB_y}{dz} &= \frac{\mu_0 M_0 b z}{4\pi} \int_0^{2\pi} \frac{\sin \phi}{\left(b^2 \cos^2 \phi + y^2 + z^2 - 2yb\sin \phi + b^2 \sin^2 \phi\right)\frac{3}{2}} d\phi = \frac{\mu_0 M_0 b z}{4\pi} I_y(b, y, z) \\
\frac{dB_z}{dz} &= \frac{\mu_0 M_0 b z}{4\pi} \int_0^{2\pi} \frac{b - y\sin \phi}{\left(b^2 \cos^2 \phi + y^2 + z^2 - 2yb\sin \phi + b^2 \sin^2 \phi\right)\frac{3}{2}} d\phi = \frac{\mu_0 M_0 b}{4\pi} I_z(b, y, z)
\end{align*}
\]

(2.9) (2.10)

Where \( I_y \) and \( I_z \) are composed of the elliptic integrals, and here we do not make a complete integration over their boundaries.

The damping force is then expressed by:

\[
\overline{F}_z = \int_J \bar{J} \times \bar{B} dV = 2\pi \sigma \delta v_1 \int yB^2_z dz
\]

(2.11)

Where \( \delta \) is the thickness of the copper tube and \( B_y \) is the radial flux density.

The magnet’s movement obeys Lenz law of the damping force always resisting the magnet’s moving direction. The free-body diagram is shown in Figure 11.
Figure 11: Free-body diagram for a magnet falling down inside a copper tube.

Hence, the resultant force on the magnet with a variable velocity is expressed by

\[ F_g - F_z = m \frac{dv_z}{dt} \]  \hspace{1cm} (2.12)

Where \( F_g \) is a gravitational force on the falling magnet and \( m \) is the magnet’s mass
3 Modelling

A two dimensional axisymmetric simulation model was developed based on the finite element method (FEM). It was modeled in an r-z plane where the heights of the copper tube and the magnets are illustrated in z-direction, while the r-direction defines the radius of both objects. The magnets were fastened around a shaft, separated by the same spacers. The magnets were assumed to be completely immersed in the copper tube at the beginning of the damping movement.

A basic framework in COMSOL was constructed by cutting this 3D magnet array model transversely, achieving a 2D axisymmetric cross section (Figure 12).
Figure 12: Geometries of permanent magnets and copper tube in COMSOL: (a) magnets arrangement in 3D; (b) magnets modelling in COMSOL.

The copper tube is divided into three domains where the middle one will be in a more complicated mesh, as this domain is mainly influenced by the movement of those magnets.

This model is composed of the Magnetic Fields (mf) and Global ODEs and DAEs (ge) modules in COMSOL. The permanent magnets are defined by setting remanent flux density values in z-direction in the Ampere’s Law selection. If each two consecutive magnets are in opposite magnetization directions, the remanent flux density values have to be defined by opposite values. Accordingly, the remanent flux density values are set the same under the condition of each two consecutive magnets having the same magnetization direction. The Lorentz force in z-direction is computed by integrating the copper tube in r direction.

\[ F_z = \oint_{tube} (f) dV \]  

(3.1)

Where \( f \) is the Lorentz force density.
The relation between forces and the damper’s velocity in a varied period of time is expressed by:

$$\frac{dv}{dt} = \frac{F_g - F_z}{m}$$  \hspace{1cm} (3.2)

Where $m$ is the total mass of a moving object, $F_g$ is the gravitational force of this moving part, and $v$ is the magnets’ velocity in $z$-direction. A time-varying relation between a magnets’ displacement and its velocity is derived:

$$\frac{ds}{dt} = v$$  \hspace{1cm} (3.3)
The concept of the eddy currents being induced by a varying magnetic field was researched for different applications all over the world, and it has been used for manufacturing dampers over decades. Jae-Sung et al. [3] and Derby et al. [17] observed the damping effect by performing a test of a permanent magnet going through a copper tube and verifying the damping movement by simulations. Dimensions of both the magnet and the copper tube could affect the damping results. A similar test carried out for this project, was to simply drop a magnet down through a copper tube. The height of the copper tube was 100mm and its thickness was 10mm (Figure 13).

The distance between the magnet and the inner wall of the copper tube (air gap) was set to 0.5mm and 0.05mm, respectively. The dimensions of the magnet and the copper tube were:

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>100mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>Air gap=0.5mm</td>
<td>10.025mm</td>
</tr>
<tr>
<td></td>
<td>Air gap=0.05mm</td>
<td>9.575mm</td>
</tr>
</tbody>
</table>

Figure 13: Geometries of falling magnet and copper tube.
The displacement of the magnet moved is
\[ s = 100\text{mm} - 19.05\text{mm} = 80.95\text{mm} \]

The moving time of the dropping the magnet was recorded and compared to the simulated results (Table 2 and Figure 14).

**Table 2**: Moving time of a single falling magnet through a copper tube with different air gaps

<table>
<thead>
<tr>
<th></th>
<th>Air gap=0.5mm</th>
<th>Air gap=0.05mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.86s</td>
<td>7.44s</td>
</tr>
<tr>
<td>2</td>
<td>5.80s</td>
<td>7.40s</td>
</tr>
<tr>
<td>3</td>
<td>5.93s</td>
<td>7.45s</td>
</tr>
<tr>
<td>4</td>
<td>5.97s</td>
<td>7.45s</td>
</tr>
<tr>
<td>5</td>
<td>5.83s</td>
<td>7.44s</td>
</tr>
<tr>
<td>Average moving time</td>
<td>5.876s</td>
<td>7.436s</td>
</tr>
<tr>
<td>Moving time in simulation</td>
<td>6.443s</td>
<td>7.425s</td>
</tr>
<tr>
<td>Relative error</td>
<td>9.65%</td>
<td>0.148%</td>
</tr>
</tbody>
</table>
Figure 14: Displacement of a single magnet falling down inside a copper tube with different air gaps.

It is obvious that the damping effect will be stronger as the air gap is narrowed, inducing more eddy currents inside the copper wall and causing the magnet to move slower.
5 Initial Prototypes for Model Verification

Neodymium magnets are a kind of rare earth magnets and are the most powerful permanent magnets in the world until now. They are graded by the material they are made of. The higher the grade (the number following the 'N'), the stronger the magnet.

The experimental model for the small scale consisted of an array of neodymium ring magnets (N52). A plastic shaft is used to mount the fixture of the magnet array with minimum tolerance. The experiments tested the free fall of the described array while the number of permanent magnets was varied.

The same copper tube was used for all tests. The dimensions of the tube were measured and are described in Table 3.

Table 3: Dimensions of the copper tube

<table>
<thead>
<tr>
<th></th>
<th>Outer diameter (mm)</th>
<th>Inner diameter (mm)</th>
<th>Length of the tube (mm)</th>
<th>Electrical conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper tube</td>
<td>38</td>
<td>22</td>
<td>255</td>
<td>$5.998 \times 10^7$</td>
</tr>
</tbody>
</table>

The dimensions of the magnets were provided by the manufacturer (Table 4).

Table 4: Dimensions of the permanent magnet (N52)

<table>
<thead>
<tr>
<th>Magnet composition</th>
<th>Remanent flux density (T)</th>
<th>Outer diameter (mm)</th>
<th>Inner diameter (mm)</th>
<th>Magnet thickness (mm)</th>
<th>Magnet weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N52</td>
<td>1.48</td>
<td>19.05</td>
<td>6.35</td>
<td>19.05</td>
<td>36.2</td>
</tr>
</tbody>
</table>

5.1 Free-fall Movement with Different Amounts of Magnets

The experiment was carried out with different numbers of magnets while all of them had the same magnetization direction. This allowed for the verification of the COMSOL models. The
two-magnet array, three-magnet array and four-magnet array were tested 13 times, respectively.

The parameters of the spacers and the plastic shaft were measured manually (Table 5).

Table 5: The parameters of the spacers and the plastic shaft

<table>
<thead>
<tr>
<th>Spacer thickness (mm)</th>
<th>Spacer weight (g)</th>
<th>Shaft weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.67</td>
<td>8.6</td>
</tr>
</tbody>
</table>

The structure of the setup is presented in Figure 15. 125mm of the shaft’s height was retained inside the copper tube before starting the falling test.

Figure 15: Experimental setup, validation of the magnets’ falling process (N52).

The moving distance of the four arrays equals

\[ s = 255\,mm - 125\,mm = 130\,mm \]

1) Test with two magnets

The magnets’ movement was timed and recorded in the following list (Table 6):

Table 6: Moving time with two magnets (N52)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>4.2</td>
</tr>
<tr>
<td>3</td>
<td>4.2</td>
</tr>
<tr>
<td>4</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>4.2</td>
</tr>
</tbody>
</table>
The magnets’ moving distance in the simulation is presented in **Figure 16**

![Figure 16: Two-magnet array displacement in FEM model (N52).](image)

According to the preceding simulations, it should take the magnets 4.15s to reach their final position. This result was compared with the moving time recorded in the experiment. The relative error is expressed by

\[
\text{error} = \left| \frac{t_{\text{test}} - t_{\text{ideal}}}{t_{\text{ideal}}} \right| \times 100\%
\]

Where \( t_{\text{test}} \) refers to the experimental moving time and \( t_{\text{ideal}} \) refers to the moving time in the simulation

The relative error therefore equals
\[
error = \frac{|4.223 - 4.15|}{4.15} \times 100\% = 1.759\%
\]

2) Test with three magnets

For this test, one spacer and one magnet were added to the array.

**Table 7: Moving time with three magnets (N52)**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td>2</td>
<td>3.4</td>
</tr>
<tr>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>3.4</td>
</tr>
<tr>
<td>7</td>
<td>3.4</td>
</tr>
<tr>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>9</td>
<td>3.5</td>
</tr>
<tr>
<td>10</td>
<td>3.4</td>
</tr>
<tr>
<td>11</td>
<td>3.4</td>
</tr>
<tr>
<td>12</td>
<td>3.5</td>
</tr>
<tr>
<td>13</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Average moving time (s) 3.454

The simulation predicted a moving distance as presented in **Figure 17**.
Hence, the relative error is given by:

\[
\text{error} = \left| \frac{3.454 - 3.46}{3.46} \right| \times 100\% = 0.173\%
\]

3) Test with four magnets
Another spacer and another magnet were added to the array.

**Table 8: Moving time with four magnets (N52)**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.1</td>
</tr>
<tr>
<td>2</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>3.1</td>
</tr>
<tr>
<td>4</td>
<td>3.1</td>
</tr>
<tr>
<td>5</td>
<td>3.1</td>
</tr>
<tr>
<td>6</td>
<td>3.1</td>
</tr>
<tr>
<td>7</td>
<td>3.1</td>
</tr>
<tr>
<td>8</td>
<td>3.2</td>
</tr>
<tr>
<td>9</td>
<td>3.1</td>
</tr>
<tr>
<td>10</td>
<td>3.1</td>
</tr>
<tr>
<td>11</td>
<td>3.1</td>
</tr>
<tr>
<td>12</td>
<td>3.1</td>
</tr>
</tbody>
</table>
The ideal magnet displacement in COMSOL is presented in Figure 18.

This results in a relative error of

\[
\text{error} = \left| \frac{3.1077 - 3.06}{3.06} \right| \times 100\% = 1.559\%
\]

As the computed errors are relatively small, it can be said that the designed models are reasonable both in the simulations and in principle. The simulations predicted performance of the damper with an accuracy of 98%. The higher the number of magnets, the stronger the damping forces. As the magnet's mass dominates the movement in such small scales, the moving time decreased with an increasing number of magnets.

### 5.2 Five Models in a Free-fall Movement

In the next step, five damper configurations with varying magnetization directions were tested: (A) Two magnets having the same magnetization direction without spacers; (B) Two magnets having the same magnetization direction with plastic spacers; (C) Two magnets having opposite magnetization directions with plastic spacers; (D) Two magnets having the same
magnetization direction with ferromagnetic spacers (made of low-carbon content steel) that act as flux concentrators; (E) Two magnets having opposite magnetization directions and ferromagnetic concentrators. These five configurations of magnet topologies are presented in Figure 19. Each configuration was tested five times to compute the average displacement time of the magnets. The results validated the displacement predicted by the simulation.

123mm of the shaft’s height was retained inside the copper tube before starting the falling test. Thus the moving distance equals

\[ s = 255\text{mm} - 123\text{mm} = 132\text{mm} \]

The relative errors were computed by comparing the average values of the experimental data with the simulation results.

![Figure 19: Benchmark between various magnet arrays falling in a copper tube; the arrays are displayed from left to right according to their damping efficiency.](image)

The main difference among these five models is the total mass (see Table 9), since the spacers’ materials were varied in order to investigate the different damping efficiencies.

### Table 9: Parameters for five configurations

<table>
<thead>
<tr>
<th>Total mass of model A, B and C (g)</th>
<th>Total mass of model D and E (g)</th>
<th>Distance between each two consecutive magnets (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>164</td>
<td>12</td>
</tr>
</tbody>
</table>

- Model A: Two magnets having the same magnetization direction without spacers
The moving time was recorded in the following list

**Table 10: Moving time with two magnets (Model A)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.37</td>
</tr>
<tr>
<td>2</td>
<td>3.36</td>
</tr>
<tr>
<td>3</td>
<td>3.39</td>
</tr>
<tr>
<td>4</td>
<td>3.36</td>
</tr>
<tr>
<td>5</td>
<td>3.36</td>
</tr>
<tr>
<td></td>
<td>Average moving time (s)</td>
</tr>
</tbody>
</table>

The magnets’ displacement curves are shown in **Figure 20**.

![Figure 20: Magnets’ displacement (same magnetization directions, no spacers).](image)

The blue line in **Figure 20** is the estimated magnets’ moving track according to the experiment. The curve predicted for ideal circumstances by the simulation is presented by the red line. Therefore the relative error is given by

\[
error = \left| \frac{3.368 - 3.717}{3.717} \right| \times 100\% = 9.39\%
\]

- Model B: Two magnets having the same magnetization direction with plastic spacers

The following list displays the moving time in the experiment.
Table 11: Moving time with two magnets (Model B)

<table>
<thead>
<tr>
<th>No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8</td>
</tr>
<tr>
<td>2</td>
<td>3.83</td>
</tr>
<tr>
<td>3</td>
<td>3.78</td>
</tr>
<tr>
<td>4</td>
<td>3.81</td>
</tr>
<tr>
<td>5</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>Average moving time (s) 3.804</td>
</tr>
</tbody>
</table>

The array’s displacement curves are presented in Figure 21.

![Figure 21: Magnets’ displacement (same magnetization directions, plastic spacers).](image)

Thus, the relative error for this test equals

\[
error = \left| \frac{3.804 - 4.356}{4.356} \right| \times 100\% = 12.67\%
\]

- Model C: Two magnets having opposite magnetization directions with plastic spacers

The magnets’ moving times in this experiment were recorded as follows.

Table 12: Moving time with two magnets (Model C)

<table>
<thead>
<tr>
<th>No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this case, experiment and simulation led to very similar displacement curves (Figure 22).

![Figure 22: Magnets’ displacement (opposite magnetization directions, plastic spacers).](image)

The relative error is therefore

\[
error = \left| \frac{5.9 - 5.92}{5.92} \right| \times 100\% = 0.3378\%
\]

- Model D: Two magnets having the same magnetization direction with ferromagnetic spacers (made of low-carbon content steel) that act as flux concentrators

For this model, the moving times were recorded as follows.

**Table 13: Moving time with two magnets (Model D)**

<table>
<thead>
<tr>
<th>No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.05</td>
</tr>
<tr>
<td>2</td>
<td>2.05</td>
</tr>
</tbody>
</table>

average moving time (s) 5.9
Since we cannot precisely determine the material of the ferromagnetic spacers, the relative permeability was defined as 250 in COMSOL.

The curves of the magnet displacement in the experiment and in the simulation are shown in Figure 23.

![Graph showing magnet displacement over time](image)

**Figure 23:** Magnets’ displacement (same magnetization direction, ferromagnetic concentrators).

Hence, the relative error is

$$\text{error} = \frac{2.024 - 1.948}{1.948} \times 100\% = 3.9\%$$

- Model E: Two magnets having opposite magnetization directions and ferromagnetic concentrators

*Table 14* shows the recorded moving time of Model E.
Table 14: Moving time with two magnets (Model E)

<table>
<thead>
<tr>
<th>No.</th>
<th>Moving time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.04</td>
</tr>
<tr>
<td>2</td>
<td>5.05</td>
</tr>
<tr>
<td>3</td>
<td>5.04</td>
</tr>
<tr>
<td>4</td>
<td>5.06</td>
</tr>
<tr>
<td>5</td>
<td>5.04</td>
</tr>
<tr>
<td></td>
<td>Average moving time (s) 5.046</td>
</tr>
</tbody>
</table>

The magnets’ displacement curves of this model are presented in Figure 24.

![Figure 24: Magnets’ displacement (opposite magnetization directions, ferromagnetic concentrators).](image)

The moving time was 5.046s in the simulation; therefore the relative error is given by

\[ error = \frac{5.046 - 4.489}{4.489} \times 100\% = 12.4\% \]

The results from these tests lead to the following conclusion:

- The relative errors for model A, B and E are not small. The main factors contributing to those errors are: the variation of the air gap between the array and the copper tube, the relative permeability of the ferromagnetic concentrators and the uncertainty about the exact value of the applied copper’s electric conductivity.
- Ferromagnetic materials can strengthen the magnetic field around magnets and develop a
larger damping effect as this material acts as a magnetic flux concentrator. In this experiment, the damping force was maximized by Model E. Yet the moving time is lower than for Model C. This is due to the fact that ferromagnetic concentrators are heavier than plastic ones, thereby decreasing the magnets’ dropping time.

- The configuration of two consecutive magnets having opposite magnetization directions, separated by the same ferromagnetic concentrators will produce maximal fringe fields. This will lead to maximal eddy currents and thus larger damping forces.

5.3 Summary

By testing the damping efficiencies of the five configurations in small scale experiments, we found Model E produce optimal damping forces.

The relative errors can be explained by the following factors.

- Operational errors could not be avoided as all the data had to be recorded manually.
- The air gap between the array and the copper tube was altered. A larger air gap reduces the stability of magnets passing through the copper tube.
- The measurement was not precise enough to make sure that the experimental results do not deviate from the results of the simulation.
- The field computed numerically around the magnets and the concentrators (spacers) is not precisely the one provided by the magnet manufacturer’s data as the latter is not an exact value but a range. Moreover, the relative permeability values of the concentrators had to be estimated.
- The degree of purity in the copper used for this experiment is unknown. This may of course lead to relative errors as the simulation is based on the assumption that all parameters are ideal.
6 Potential Damper Modelling

The small-scale experiments verified that the most effective free-fall damping setup is an array of two consecutive permanent magnets with opposite magnetization directions, separated by concentrators (South (S) North (N) – Fe concentrators – NS). Two larger sizes of ring permanent magnets (N42 and N38) were thus used to build models based on this configuration. The copper tube’s size had to be adjusted accordingly. Two kinds of shafts were selected and analyzed: (1) a solid copper rod; (2) a plastic shaft (only for N38). These arrays were no longer tested for a free fall. Instead, they were moved in an upward direction, driven by an actuated aluminum armature. The damper’s total mass is composed by the magnets’ mass and 3kg of extra load, representing either the armature only (with a copper rod) or both the armature and the shaft (with a plastic shaft). The simplified structure of the magnet array with a copper rod is illustrated in Figure 25.

![Figure 25: Basic structure of a damper with large magnets (N42 and N38).](image)

In the simulation, ten-magnet arrays and four-magnet arrays (only for N38) are used to predict the damping movement. Assumptions on the relevant parameters of the damper are displayed in Table 15.
Table 15: Relevant parameters of the damper in the simulation

<table>
<thead>
<tr>
<th>Maximal velocity (m/s)</th>
<th>Relative permeability of the ferromagnetic concentrators</th>
<th>Thickness of the copper tube (mm)</th>
<th>Distance between the magnets and the copper rod (mm)</th>
<th>Distance between the magnets and the copper tube (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2500</td>
<td>15</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

As Table 15 shows, the maximal velocity is the speed of the armature when hitting the shaft. The concentrators between each two consecutive magnets were assumed to be made of high ferromagnetic materials. In the simulation with a plastic shaft, magnets were assumed to be fastened on the shaft without any tolerance. Thus, the magnet array movement will not be distorted during the damping movement. While in the other simulation, there will be a small air gap between the magnets and the copper rod. The utilization of the copper rod in the simulation aims to generate additional Lorentz forces apart from the copper tube due to the relative motion between the magnets and the two copper elements (copper tube and copper rod).

### 6.1 Simulation with Largest Size Magnets (N42)

The parameters of the N42 magnet, the copper tube and the copper rod are displayed in Table 16 and Table 17.

Table 16: Dimensions of the magnets (N42)

<table>
<thead>
<tr>
<th>Magnet composition</th>
<th>Maximum remanent flux density (T)</th>
<th>Outer diameter (mm)</th>
<th>Inner diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N42</td>
<td>1.32</td>
<td>76.2</td>
<td>38.1</td>
<td>6.35</td>
<td>163</td>
</tr>
</tbody>
</table>

Table 17: Dimensions of the copper tube and copper rod

<table>
<thead>
<tr>
<th></th>
<th>Inner radius (mm)</th>
<th>Outer radius (mm)</th>
<th>Thickness (mm)</th>
<th>Air gap (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper tube</td>
<td>38.6</td>
<td>53.6</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>Copper rod</td>
<td>18.55</td>
<td>18.55</td>
<td>15</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The dimensions of the magnet array and the copper tube are decided already. The damping effect will be investigated by changing the distance between each two consecutive magnets (spacer thickness) in the simulation. After the simulation, the variations of damping forces on the moving magnet array, the magnet array’s velocity and its displacement during the deceleration process are observed. Thus, the damping movement can be analyzed from those related results.
The different flux density distributions around magnets of different topologies can be seen in Figure 26: (a) all magnets having the same magnetization direction; (b) each two consecutive magnets having opposite magnetization directions. It becomes clear that configuration (b) has more fringe fields around the corners of the magnets and the copper elements. Therefore, more eddy currents and larger damping forces will be exercised on the moving magnets.
Figure 26: Distribution of the fringe fields around magnets when (a) two consecutive magnets have the same magnetization direction; (b) two consecutive magnets have opposite magnetization directions.

The variations of the flux density and the eddy currents during the movement depend on the magnets’ velocity and are shown in **Figure 26 (b)** and **Figure 27**.
Figure 27: Eddy-current density in the azimuthal direction (copper rod, ten-magnet array, N42).

As the magnets move in a direction parallel to the $z$-axis, the time derivative of the axial component of the magnetic field (Figure 26(b)) will induce azimuthally directed eddy currents in the copper tube (Figure 27). The product of the radially oriented magnetic field with the induced currents in the copper tube results in an axially directed body force known as the Lorentz force. All the forces induced in the copper tube will be distributed in such a way as to decelerate the moving magnet array. The force felt by the copper tube will also be felt by the magnet array but in the opposite direction as stated by Newton’s third law, the action-reaction law.

The Lorentz force, the velocity and the magnets’ displacement are observed by varying the height of the ferromagnetic concentrators.
Figure 28: Lorentz forces in z-direction for different spacer thicknesses vs. time (copper rod, ten-magnet array, N42).

Figure 29: Magnets’ velocity for different spacer thicknesses vs. time (copper rod,
ten-magnet array, N42).

In principle, when the magnet array’s speed is slowed down to zero, it reaches the maximal distance and then it will go back without being stopped. That’s why in Figure 30, after the magnet array reached the maximal displacement value, the curves go down subsequently.

Based on Figure 28, Figure 29 and Figure 30, the deceleration time, maximal displacement of the magnets and the peak Lorentz force were estimated in Table 18.

Table 18: The deceleration time, displacement and Lorentz force data when the spacer thicknesses was varied from 5mm to 12mm (copper rod, ten-magnet array, N42)

<table>
<thead>
<tr>
<th>Spacer thickness (mm)</th>
<th>Deceleration time (ms)</th>
<th>Maximal displacement (mm)</th>
<th>Peak Lorentz force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>18</td>
<td>52.95</td>
<td>5186</td>
</tr>
<tr>
<td>6.35</td>
<td>17</td>
<td>53.16</td>
<td>5063</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>53.79</td>
<td>4926</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>54.97</td>
<td>4793</td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>56.04</td>
<td>4691</td>
</tr>
</tbody>
</table>

In Table 18, the maximal displacement represents the distance that the magnet array moved.
during the deceleration process.

Figure 28 to Figure 30 and Table 18 demonstrate the following results:

- The moving magnet array will accordingly go towards the location where it starts moving after its speed is decelerated to zero in the simulation as the magnet array is then dominated by its own gravity effect.
- With the same maximal speed, the moving time decreases with increased thickness of the spacers between the magnets. However, the magnet displacement is decreasing during the deceleration process as the spacer thickness between each two consecutive magnets is reduced.
- The maximal value of the Lorentz force in the copper tube occurs when the spacer thickness is 5mm when spacer thickness is chosen between 5mm and 12mm.
- The moving curves with different spacer thicknesses are very similar; however, the damping effect is improved as the spacer thickness is reduced in the decided range of thickness values. The damping movement can be stopped in a short period of time, thus the performances of the dampers can be regarded as very good.

6.2 Simulation with Medium Size Magnets (N38)

After carrying out the simulation with N42 permanent magnets, N38 magnets were applied in order to observe the magnet array’s damping effect.

The dimensions of the permanent magnet (N38), the copper tube and the copper rod are listed in Table 19 and Table 20.

Table 19: Dimensions of the permanent magnet (N38)

<table>
<thead>
<tr>
<th>Magnet composition</th>
<th>Remanent flux density (T)</th>
<th>Outer diameter (mm)</th>
<th>Inner diameter (mm)</th>
<th>Thickness (mm)</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N38</td>
<td>1.22</td>
<td>50</td>
<td>20</td>
<td>10</td>
<td>123.07</td>
</tr>
</tbody>
</table>

Table 20: Dimensions of the copper tube and copper rod

<table>
<thead>
<tr>
<th></th>
<th>Inner radius (mm)</th>
<th>Outer radius (mm)</th>
<th>Thickness (mm)</th>
<th>Air gap (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper tube</td>
<td>25.5</td>
<td>40.5</td>
<td>15</td>
<td>0.5</td>
</tr>
<tr>
<td>Copper rod</td>
<td>9.5</td>
<td>0.5</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>

Although the ferromagnetic materials are attracted to magnets, the force between two repelling N38 magnets dominates over the attractive force for small spacer thicknesses. Thus the concentrator’s height should be decided accordingly beyond a certain value. Only 8mm to 20mm of spacer thicknesses are investigated in the simulation.
6.2.1 Simulation with a Solid Copper Rod

The first simulation was based on the condition that a solid copper rod would be the shaft in the model. In this case, the total number of magnets was 10. The force, the velocity and the magnets’ displacement vary with different spacer thicknesses:

![Graph showing Lorentz forces in z-direction for different spacer thicknesses vs. time (copper rod, ten-magnet array, N38).](image)

**Figure 31:** Lorentz forces in z-direction for different spacer thicknesses vs. time (copper rod, ten-magnet array, N38).
Figure 32: Magnets’ velocity for different spacer thicknesses vs. time (copper rod, ten-magnet array, N38).

Figure 33: Magnets’ displacement for different spacer thickness vs. time (copper rod,
ten-magnet array, N38).

The relevant results of Figure 31, Figure 32 and Figure 33 are collected in Table 21.

**Table 21**: The deceleration time, displacement and Lorentz force when the spacer thickness was varied from 8mm to 20mm (copper rod, ten-magnet array, N38)

<table>
<thead>
<tr>
<th>Spacer thickness (mm)</th>
<th>Deceleration time (ms)</th>
<th>Maximal displacement (mm)</th>
<th>Peak Lorentz force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>18</td>
<td>66.85</td>
<td>3556</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>68.8</td>
<td>3443</td>
</tr>
<tr>
<td>12</td>
<td>18</td>
<td>70.62</td>
<td>3353</td>
</tr>
<tr>
<td>15</td>
<td>18</td>
<td>73</td>
<td>3249</td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>76.13</td>
<td>3127</td>
</tr>
</tbody>
</table>

Some conclusions can be directly drawn from Table 21:
- It is evident that the maximal Lorentz force is high enough to damp the movement in a short period of time from the results of the simulation.
- The maximal displacement is increasing with increasing spacer thickness. Yet, the longest moving distance during the deceleration process under the measured circumstances is only about 10mm longer than that shortest one.

### 6.2.2 Simulation with a Plastic Shaft

In this simulation, a plastic shaft replaced the copper rod, and the shaft’s diameter is presumed to be the same as the magnet’s inner diameter. The force, velocity and magnet displacement are presented in Figure 34, Figure 35 and Figure 36.
Figure 34: Lorentz forces in z-direction for different spacer thicknesses vs. time (plastic shaft, ten-magnet array, N38).

Figure 35: Magnets’ velocity (plastic shaft, ten-magnet array, N38).
Figure 36: Magnets’ displacement (plastic shaft, ten-magnet array, N38).

The relevant data from Figure 34 to Figure 36 are presented in Table 22.

Table 22: The deceleration time, displacement and Lorentz force when the spacer thickness was varied from 8mm to 20mm (plastic shaft, ten-magnet array, N38)

<table>
<thead>
<tr>
<th>Spacer thickness (mm)</th>
<th>Deceleration time (ms)</th>
<th>Maximal displacement (mm)</th>
<th>Peak Lorentz force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>21</td>
<td>84.04</td>
<td>2655</td>
</tr>
<tr>
<td>10</td>
<td>21</td>
<td>86.08</td>
<td>2576</td>
</tr>
<tr>
<td>12</td>
<td>21</td>
<td>87.97</td>
<td>2516</td>
</tr>
<tr>
<td>15</td>
<td>21</td>
<td>90.64</td>
<td>2450</td>
</tr>
<tr>
<td>20</td>
<td>22</td>
<td>93.45</td>
<td>2375</td>
</tr>
</tbody>
</table>

As Table 22 shows, the damping effect will be stronger as the separation between each two consecutive magnets is decreased meanwhile the magnets will move in a shorter distance when their speed was slowed from maximum down to zero. Considering that this moving time is on a millisecond scale, the deceleration time of the moving magnets is almost the same in different spacer thicknesses due to the limited accuracy in COMSOL.
6.2.3 Simulation with Four Magnets and Plastic Shaft

In the experiment, the number of magnets had to be reduced, due to the limited height of the manufactured copper tube. Therefore, an array of four magnets was simulated. This exact design was later validated in experiments. The damping movement according to COMSOL is described in Figure 37 to Figure 39 and Table 23.

Figure 37: Lorentz forces in z-direction for different spacer thicknesses vs. time (plastic, four-magnet array, N38).
Figure 38: Magnets’ velocity for different spacer thicknesses vs. time (plastic, four-magnet array, N38).

Figure 39: Magnets’ displacement for different spacer thickness vs. time (plastic,
four-magnet array, N38).

**Table 23:** The deceleration time, displacement and Lorentz force when the spacer thickness was varied from 8mm to 20mm (plastic, four-magnet array, N38)

<table>
<thead>
<tr>
<th>Spacer thickness (mm)</th>
<th>Deceleration time (ms)</th>
<th>Maximal displacement (mm)</th>
<th>Peak Lorentz force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>45</td>
<td>172.4</td>
<td>1038</td>
</tr>
<tr>
<td>10</td>
<td>45</td>
<td>175.8</td>
<td>1010</td>
</tr>
<tr>
<td>12</td>
<td>45</td>
<td>178.9</td>
<td>988.6</td>
</tr>
<tr>
<td>15</td>
<td>44</td>
<td>182.9</td>
<td>965.1</td>
</tr>
<tr>
<td>20</td>
<td>44</td>
<td>188.1</td>
<td>938.8</td>
</tr>
</tbody>
</table>

Assuming there are five spacers and four magnets in the array, the maximal height of the copper tube should be more than:

\[ H = 5 \times 20\, \text{mm} + 4 \times 10\, \text{mm} + 188.1\, \text{mm} = 328.1\, \text{mm} \]

In reality, the maximum height of the copper tube was 300mm. Considering expenditure, setup space and moving part’s total mass, a spacer thickness of 10mm was decided for the manufacturing of the ferromagnetic concentrators.
7 Real-scale Experimental Prototype

The damping prototype built for the real-scale experiments was driven by the Thomson-coil actuator, employing the principle of eddy currents [18].

The array consisted of four permanent magnets (N38), an aluminium armature, a fiberglass shaft, a cap made of Teflon, and a copper tube, five ferromagnetic spacers, and four plastic screws; all mounted in a steel and Bakelite frame (Figure 40). Two discs made of polyoxyethylene, on the top and bottom of the copper tube were installed to act as guides in order to center the shaft’s moving direction and to minimize friction between the magnets and the inner wall of the copper tube. A Teflon cap placed on the bottom part of the shaft acts as the interface which the aluminium armature collides with.

![Figure 40: Prototype of an eddy current damper in the experiment.](image)

The relevant parameters of the experimental setup are shown in Table 24.

<table>
<thead>
<tr>
<th>Setup parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

Table 24: Parameters of the experimental setup
Copper tube’s inner diameter | 52mm
---|---
Copper tube’s outer diameter | 81mm
Capacitor bank | 33mF
Height of the shaft | 500mm
Weight of the moving part in the damper | 1.5kg
Weight of the aluminum armature | 1.494kg
Cap’s dimension | 40mm in height
| 30mm in width
| 17mm inner diameter

By varying the initial voltage of the capacitor bank, the armature was actuated with different initial speeds. After the discharge of the capacitor, the armature is actuated. It attains a steady state velocity and travels freely for 40 mm until it collides with the shaft. The damping movement was recorded with a high speed camera with 5000 fps.

### 7.1 Experiment I

First, the capacitor banked initially charged to 200V was discharged. The damping effect recorded with a high speed camera can be seen in Figure 41 and Figure 42.

![Figure 41: Measured velocity of the armature and the magnets (200V).](image-url)
Figure 41 shows the velocity profiles of the armature and the magnet. Initially, while the magnets are at stand still, the armature is accelerated from 0 m/s up to 4.4 m/s in just 1ms. At 20ms, the armature and the shaft collide, exchanging velocities. The velocity of the armature drops to 0.7 m/s while the magnets rapidly accelerate to 3.8 m/s. Afterwards, the magnets decelerate slowly due to eddy currents and the kinetic energy of the armature is dissipated in the form of heat. In Figure 42, it is clear to see that the shaft part moved farther than the armature after the collision between the armature and the magnet array.

Figure 43 and Figure 44 show the velocity and the displacement of the magnet array from the experiment and the simulation. The simulation predicts the velocity drop of the magnet with good accuracy as well as the displacement the magnets moved in comparison with the experimental results. However, in reality, the magnet decelerates faster due to the existence of several factors and thereby moved a distance less than expected, which may contribute to the relative errors.
Figure 43: Velocity of magnets measured by a high speed camera compared with simulations (200V).

Figure 44: Displacement of magnets measured by a high speed camera compared with
7.2 Experiment II

In the second test, the capacitor’s voltage was increased from 200V to 300V.

![Graph](image)

**Figure 45:** The measured velocity of the armature and the magnets (300V).
With higher discharging voltage, the armature and the magnets can reach higher initial velocities. At 14ms, the armature hit the shaft. In this case, the shaft was accelerated to the peak speed in 2ms (Figure 45) after the collision while the armature decelerated to 2.7 m/s. The moment they moved together, their velocities fluctuated between 2.5 m/s and 3.8 m/s in about 6ms. Subsequently, they decelerated quicker until the speed was around zero. This also indicated the presence of multiple collisions. In Figure 46, it is visible that the shaft part and the armature reached to their farthest position almost in the same time.

In Figure 47, the velocity of the magnets’ after collision was set as 3.53 m/s. The moving was then verified in COMSOL (Figure 47 and Figure 48).
Figure 47: Velocity of magnets measured by a high speed camera compared with simulations (300V).

Figure 48: Displacement of magnets measured by a high speed camera compared with
simulations (300V).

**Figure 47 and Figure 48** show the velocity and the displacement of the magnet array from the experiment and the simulation. The simulated curves of the magnets’ velocity and displacement can match the movement results obtained from the experiment in a good degree of accuracy.

### 7.3 Discussion

Comparing the experimental results with the simulations, it is crucial to know that the simulation model could only predict the experiment under strict conditions: low voltage supply, relatively light damper prototype, setup with less friction. Multiple collisions during the experiments were not predictable by the simulation, but they occurred in both experiments. For each collision, the exchanged velocity of the magnet array will be reduced according to law of conservation of momentum. In reality, the array’s moving speed is decreased much more with several collisions, having more obvious damping effect. However, if collision times are increased, the components in the damper will be easier to be damaged after a number of tests.

The model was valid for 8ms to 10ms in these two experiments.

The main factors influencing the results are listed below:

- The relative permeability of the ferromagnetic spacers and the uncertainty about the value of the applied copper’s electric conductivity
- The remanent flux density is not precise and is given as a range value from the manufacturer. This has a significant influence on the results.
- In the second experiment, the velocity when the shaft started to move is an estimated value so that the simulated curves mismatched the results of the experiment.
- Despite the use of the two discs for the large scale setup which acted as a guide for the shaft, friction could not be eliminated completely.

In general, this model is not adequate for experiments involving large kinetic energies and multiple collisions. However, the moving magnet array’s damping effect has its limitation as the array’s speed is increasing. The motion of the magnet array is decided by Newton’s law which is expressed by equation (2.12). The entire damping movement is explained in **Figure 49**.
In Figure 49, R is the resistance where eddy currents are induced. It’s related with eddy currents’ frequency, while this frequency is related with array’s velocity. The equivalent damping circuit is such a kind of LR series circuit, where L is defined as inductance since eddy currents are varying in the system. If the magnet array’s velocity is increased, its damping force is increased. The array’s speed variation is then changed more, increasing currents’ frequency. Thus, the value of resistance R is growing due to skin effect, reducing the currents in the circuit. Therefore, the damping force is decreased, achieving less damping effect, which states the kinetic energies can be large but it can’t be extremely high. Otherwise, the array’s movement will be underdamped.

Much more work has to be done, such as to reduce or eliminate friction, increase the discharge voltage of the capacitor bank or reduce the total mass of the damper setup.

8 Conclusions

This project has shown that it is possible to decelerate and stop a fast moving Thomson actuator using an eddy-current damping mechanism and that the predictions made by FEM simulations matched the experimental test results within a reasonable approximation.

The small scale experiments were very useful not only to validate the numerical model but to select among a diversity of magnet arrangements the best choice for the final proposed large scale design.

The developed damper is a passive device having several advantages over other systems (e.g. mechanical, hydraulic or active). If well designed it becomes a robust mechanism with a long useful life representing a cost-effective solution. What is more, mechanical wear is eliminated between magnet and copper tube since there is no direct contact between them.
According to all results, many factors may contribute to the relative errors between the simulation and the experiment, such as electrical conductivity, air gap between the magnets and the copper tube, inertia (e.g. mass), magnet strength, magnets’ dimensions and the ferromagnetic materials.

- **Electrical conductivity**
The conductivity value is proportional to the Lorentz force generated on the moving magnets. Therefore, if the conductive material is changed, the damping force will be varied as well.

- **Air gap**
Through hundreds of simulation times, it is observed that the Lorentz force is very sensitive to the change of the air gap between the magnets and the copper tube, even 0.1mm difference. Doing the free-fall test with the small magnets, it is clear that the damping time will be increased as the air gap is narrowed.

- **Inertia**
The inertia here is mainly pointed to the mass, including the magnets’ mass, the spacers’ mass and the contact system’s mass. Those initial prototypes of small magnets being tested in a free falling aspect have confirmed that mass dominates the damping time besides the damping characteristics of the model itself.

- **Magnet strength**
Different grades of the magnets have different magnetic strength. The stronger the permanent magnet is the better damping effect it will achieve.

- **Magnets’ dimension**
In the project, it is easy to see that a larger magnet’s size enhances the flux density around the magnets is to be enhanced, the thicker the copper tube, the more eddy currents will be induced. Another point that may influence the damping outcome is the distance between each two consecutive magnets.

- **Materials for spacers**
The ferromagnetic material can strengthen the magnetic field around magnets which is applied to the prototype to improve the damping. Comparing the model of ferromagnetic spacers to the one of the plastic spacers, the damping force and the deceleration time are able to be developed twice; the maximal magnet displacement will be reduced significantly if the ferromagnetic material is applied.

Improvements of the present design are still possible by: increasing the number of magnets to enhance the damping force; narrowing the air gap between magnet and copper tube or improving the shaft guidance using dedicated bearings.

- **Future work**
In spite of having achieved great improvements in the current damper design, there is some
more work to be done in future research:

- Bearings will be applied to fix the moving shaft with an extremely little tolerance in order to make the shaft travel in a straight routing.
- The shape of the moving shaft will be optimized so that the magnet array will not be distorted during the damping process, reducing the friction as well.
- The total mass of the shaft can be lighter, so the material of the shaft can be replaced with a relatively low-density material, such as Teflon.
- The conductive armature plate can be manufactured to be a ring shape. A copper shaft can be suspended and is in the same static state as the copper tube. When the ring armature is actuated, it will no longer collide with the shaft. Instead, it will hit the last ferromagnetic concentrator, and then the armature is moving along with the concentrators and the magnets. More damping forces will be generated on this moving part, and a better damping effect can be achieved.
- A spring can be added between the armature and the bottom concentrator to make the shaft collision softer in case the concentrators and the magnets become brittle.
- A Moving Mesh method can be applied to the simulation to analyze the damping movement in the case of not all magnets being actuated to move inside the copper tube at the beginning of the movement. Thus, after the collision between the concentrator and the armature, the magnets’ moving is to be made softer.
- Permanent magnets’ thickness can be increased by stacking two magnets which can represent one larger and stronger permanent magnet., achieving much more damping effect,

The fact that the efficiency of the damper improves with the initial speed of the moving object as well as with the strength of the magnet array makes it possible to hope that solutions for ultrafast actuators could be found in the near future.
9 References


