Experimental investigation on a colloidal damper rendered controllable under the variable magnetic field generated by moving permanent magnets

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Abstract. In this work, a colloidal damper rendered controllable under variable magnetic fields is proposed and its controllability is experimentally evaluated. This absorber employs a water-based ferrofluid (FERROTEC MSGW10) in association with a liquid-repellent nanoporous solid matrix, consisted of particles of gamma alumina or silica gel. Control of the dynamic characteristics is obtained by moving permanent neodymium annular magnets, which are placed either on the piston head (axial magnetic field) or on the external surface of the cylinder (radial magnetic field). In order to properly select these magnets, flow visualizations inside of a transparent model damper were performed, and the quantity of the displaced liquid by the magnets through the damper’s filter and through the nanoporous solid matrix was determined. Experimental data concerning variation of the magnetic flux density at the magnet surface versus the height of the magnet, and versus the target distance was collected. Based on such data, the suitable magnet geometry was decided. Then, the 3D structural model of the trial colloidal damper obtained by using Solidworks, and the excitation test rig are presented. From excitation tests on a ball-screw shaker, one confirmed larger damping abilities of the proposed absorber relative to the traditional colloidal damper, and also the possibility to adjust the damping coefficient according to the excitation type.

1. Introduction
Controllability of traditional hydraulic dampers can be achieved by adjusting viscosity of an oil-based rheological liquid under magnetic or electric fields, as in the case of magneto- or electro-rheological absorbers. As an oil-free environmental friendly alternative absorber, recently, colloidal dampers have been proposed [1-5]. They are based on the dissipative effect obtained at the cyclical penetration/exudation of a working liquid in/from the nanopores of a liquid-repellent solid matrix. Dissipation is not depending on viscosity, but on the surface tension $\gamma_L$ of the working liquid. Thus, not the hydraulic pressure, well-known to develop inside the oil dampers, but the capillary pressure $p = -2\gamma_L \cos \theta / r$ is responsible for achieving the damping force. For this reason, by adding a device able to control the capillary pressure inside the cylinder, controllability of colloidal dampers can also be achieved [6, 7]. E.g., by using silica gel particles as liquid-repellent nanoporous matrix, water as working liquid, and an electro-hydro-pneumatic apparatus as the pressure controlling device, a controllable colloidal damper, to be used for autovehicle suspension, was proposed [8]. Although such
controllable absorber was able to provide a damping ratio fluctuation larger than required change of damping for usual automobile suspensions, due to the large volume occupied by the electro-hydropneumatic apparatus, it was unable to accommodate practical applications. A more effective way to adjust pressure inside the cylinder is to control the capillary pressure at penetration/exudation of liquid in/from the solid matrix, by changing the surface tension of the liquid [6, 7]. E.g., by applying a variable magnetic and/or electric field, the surface tension of the working liquid, and implicitly the contact angle $\theta$ of the solid-liquid interface can be adjusted [9]. Thus, using quite a compact apparatus, dissipative and elastic properties of colloidal dampers can be controlled. Such absorbers, rendered controllable under electromagnetic fields, occur as complementarily to the classical magneto- and electro-rheological dampers, with the difference that the applied field affects the surface tension and not the viscosity of the working liquid.

In order to amplify the effect of the applied magnetic field, water was replaced by a magneto-rheological liquid (e.g., FERROTEC MSGW10), consisted of iron nanoparticles dispersed in water [9]. By using micro-drops with a volume varying between 1-10 micro-litters, and by applying a magnetic field, it was experimentally observed that the micro-drops elongate along the magnetic field, producing a considerably larger apparent contact angle [9]. Moreover, when a certain critical magnetic flux density is exceeded, micro-drop is pulled along the magnetic field, and jumps towards the magnet [9]. Proposed semi-empirical equations to describe dependence of the ferrofluid surface tension on the applied magnetic field, as well as on the drop volume, were found to be in good agreement with various theoretical and experimental results reported in literature [10-13].

In this work, one investigates how the above-described wetting phenomena can be applied to render the colloidal damper as controllable under variable magnetic fields simply generated by moving permanent neodymium magnets. Proposed colloidal damper employs a water-based ferrofluid working against a liquid-repellent nanoporous matrix of gamma alumina or/and silica gel. Control of the dynamic characteristics is obtained by moving permanent annular magnets, which are placed either on the piston head (axial magnetic field) or on the external surface of the cylinder (radial magnetic field). In order to properly select these magnets, flow visualizations inside of a transparent model damper are performed, and the quantity of the displaced liquid by the magnets through the damper’s filter and through the nanoporous matrix are determined. Experimental data concerning variation of the magnetic flux density at the magnet surface versus the height of the magnet, and versus the target distance is collected. Based on such data, the suitable magnet geometry is decided. Then, the 3D structural model of the trial colloidal damper, obtained by using Solidworks, and the excitation test rig are presented. From excitation tests on a ball-screw shaker, one evaluates the damping characteristics of the proposed controllable colloidal damper.

2. Structure of the proposed controllable colloidal damper

Figure 1 illustrates a schematic view of the colloidal damper rendered controllable under magnetic fields created by neodymium magnets. Such damper employs a traditional cylinder-piston structure. Nanoporous solid matrix is introduced in the right-side of the cylinder, inside a chamber closed by a liquid permeable membrane (filter). Water-based magneto-rheological liquid (FERROTEC MSGW10 type ferrofluid) is introduced inside the main cylinder, i.e., inside the left-side chamber, in which the piston executes its reciprocating movement. Piston is magnetized by fixing a neodymium annular magnet on its head. This magnet produces a magnetic field along the axial direction of the damper. Hence, during the reciprocating movement of the piston, such magnetic field occurs as variable both in space and time. During the compression phase of the damper, ferrofluid pressurized by the magnetized piston is able to pass through the orifices of the filter with a certain fluid flow resistance, and to produce a colloidal mixture together with the solid particles of the nanoporous matrix. At higher level of pressurization, ferrofluid is further able to penetrate the nanopores of the liquid-repellent solid matrix, and consequently, to produce the dissipation effect. On the other hand, during the extension phase of the damper, ferrofluid which exudes from the nanopores is able to pass in opposite direction the orifices of the filter, and to return inside the main chamber of the cylinder. In this way, the
magnetized piston is able to assist the penetration/exudation (adsorption/desorption) of the liquid in/from the nanopores of the solid matrix. Filter has the role of preventing solid particles, which suffered fatigue fracture, to escape inside the main chamber of the cylinder, and eventually, to damage the seals. By such liquid-permeable encapsulation of the solid matrix, a certain desired lifetime of the colloidal damper can be achieved [14].

Additionally, in order to control dynamic characteristics of the colloidal damper, at the external part of the cylinder, a second annular neodymium magnet is used. This magnet produces a magnetic field along the radial direction of the cylinder, which can be moved along the axial direction of the damper. Thus, during a controlled reciprocating motion of the outer magnet, this second magnetic field occurs also as variable both in space and time, and consequently, it has also the ability to displace a certain amount of ferrofluid inside the cylinder, through the filter and nanoporous matrix.

Accordingly, concerning the spatial and temporal variable magnetic fields created by moving the magnetized piston and the outer magnet, in the following sections, one visualizes the fluid flow inside a transparent cylinder, and measures the quantity of ferrofluid displaced by these annular magnets.

**Figure 1.** Schematic view of the colloidal damper rendered controllable under magnetic variable fields created by moving annular neodymium permanent magnets.

### 3. Visualization of the ferrofluid flow induced by the magnetized piston

As magneto-rheological liquid was used a black colloidal solution, called FERROTEC MSGW10, consisted of a mixture of iron nanoparticles dispersed in water, with the following properties: density of 1,190 kg/m³, surface tension of $\gamma_s = 0.057$ N/m, dynamic viscosity of 0.005 Pa·s, and saturation magnetic flux density of 0.0185 T. Nanoporous solid matrix was rendered as liquid-repellent through a chemical reaction of hydrophobization for all the inner and outer surfaces of the solid particles, by using chains of alkyl-chloro-silanes. Nanoporous solid matrix was consisted of either particles of gamma alumina with a mean diameter of 2 mm, and a mean diameter of the pores of 15 nm, or silica gel particles with a mean diameter of 20 µm, and a mean diameter of the pores of 15 nm.

During flow visualization experiments, a piston with a diameter of 10 mm was used. On the piston head a cylindrical permanent neodymium magnet was fixed by using a metal bonding adhesive. Six types of neodymium N35 magnets having a diameter of $2R = 9$ mm, a remanent magnetic flux density of 1.19 T, and a thickness (height) of $t = 1, 2, 3.5, 6, 12$, and 30 mm were used in construction of the magnetized piston. Quantity of ferrofluid to be displaced by the piston is presumably depending on the surface magnetic flux density of the neodymium magnet used to magnetize the piston. For this reason, the magnetic flux density of the permanent magnets was measured by using a Gauss-meter.

Figure 2 illustrates the variation of the surface magnetic flux density versus the height of the permanent magnet, and figure 3 presents the variation of the magnetic flux density along the axial direction of the magnet versus the target distance, i.e., the distance between magnet surface and the testing point. On figure 3, magnet with the height of 60 mm was obtained by joining together two magnets, each having a height of 30 mm. Results obtained agree quite well with the catalogue data
concerning the magnetic flux density (see figure 2). At augmentation of the magnet height the surface magnetic flux density monotonically increases and then saturates. Thus, for magnet heights exceeding a saturation height of about 12 mm, the rate of increase for the flux density becomes extremely low. In conclusion, although the quantity of ferrofluid displaced by the magnetized piston is likely to increase at augmentation of the magnet height, in order to avoid waste of neodymium material, the magnet height can be reasonably limited at the corresponding saturation height. Such saturation height generally depends both on the material and the radial geometry of the selected magnet.

Figure 2 illustrates that magnetic flux density abruptly decreases as distance between the magnet surface and the testing point increases. Decreasing rate is higher for magnets of smaller height. Since rate of the magnetic flux density is considerably lower for distance (1), and experimentally by using a Gauss-meter, for \( t = 30 \text{ mm} \) and \( R = 4.5 \text{ mm} \). Although theoretical and experimental results display graphs of similar shape, theoretical model predicts considerably lower decreasing rate for the magnetic flux density. Thus, although for small distances \( \bar{x} \) the experimental and theoretical results appear as superposed, for large distances \( \bar{x} \) the theoretical model predicts too optimistic results. Therefore, correction of the theoretical results against the target distance should be considered during the design of the controllable colloidal damper.

Next, in order to determine the amount of liquid displaced by the magnetized piston, firstly the piston head was submerged inside of a beaker filled with ferrofluid. Then, the piston head was pulled

\[
\frac{B}{B_{\text{max}}} = \frac{B(\bar{x})}{B(\bar{x} = 0)} = \frac{1 + \bar{t}^2}{\bar{t}} \left( \frac{\bar{t} + \bar{x}}{\sqrt{1 + (\bar{t} + \bar{x})^2}} - \frac{\bar{x}}{\sqrt{1 + \bar{x}^2}} \right),
\]
out from the beaker and the quantity of ferrofluid adhered to magnet was measured by using an electronic balance (see figure 5). Figure 6 shows variation of the adhered quantity of liquid versus the height of the permanent magnet. Similar to variation of the surface magnetic flux density (figure 2), at augmentation of the magnet height, the adhered mass of ferrofluid monotonically increases and then saturates. For the magnet of interest, having \( t = 30 \text{ mm} \), the adhered quantity of liquid was of 6.4 g.

Figure 4. Variation of the dimensionless magnetic flux density versus the dimensionless distance between the magnet surface and the testing point, \( \bar{x} = x/R [\cdot] \)

Next, quantity of ferrofluid displaced by the magnetized piston through orifices of the filter used in construction of the colloidal damper (figure 1) is evaluated. Thus, figures 7 and 8 illustrate the results obtained for filters with diameters of the orifices of 5 and 2 \( \mu \text{m} \), respectively. At augmentation of the magnet height the amount of ferrofluid displaced by the piston increases monotonically. Also, the quantity of ferrofluid able to pass through the filter decreases as diameter of the filter orifices reduces. This can be explained by the increase in the hydraulic resistance of the filter relative to the ferrofluid flow. Unexpectedly, the quantity of liquid remanent inside the filter, which is of about 0.2 g, seems to be unaffected by the height of the magnet or by the diameter of the filter’s orifices.

Concerning the magnet of interest (\( t = 30 \text{ mm} \)), in comparison with the amount of liquid adhered on the whole surface of the magnet (6.4 g, on figure 6), for the filter with diameter of orifices of 5 \( \mu \text{m} \), quantity of liquid displaced by the cross-sectional surface of the magnet through the filter reduces by 4.3 times, down to 1.5 g (see figure 7). Moreover, effective quantity of liquid displaced by the piston reduces to \( 1.5 \text{ g} - 0.2 \text{ g} = 1.3 \text{ g} \) (see figure 7) due to the remanent liquid inside the filter, which leads to a calculated piston stroke of about 17 mm.

In order to check this result, a flow visualization test was performed, by using a transparent cylinder consisted of two parts linked together through a screwed ring (figure 9). Either pure ferrofluid
or a mixture of nanoporous gamma alumina particles dispersed in ferrofluid was introduced in the left chamber of the cylinder, which was then covered by a filter with the diameter of the orifices of 5 µm. Magnet of interest (\( t = 30 \text{ mm} \)) was bonded on the piston head. During extension phase of the damper, the magnetized piston was able to extract a certain quantity of ferrofluid from the left chamber and to steadily displace it along the right part of the cylinder (figure 9). Relatively good agreement was found between the measured (about 16 mm) and the calculated (about 17 mm) values of the piston stroke.

4. **Visualization of the ferrofluid flow induced by the movement of the external magnet**

A tube made in transparent glass, having the outer diameter of \( 2b = 18 \text{ mm} \) and the inner diameter of \( 2a = 16 \text{ mm} \), was used as model cylinder of the controllable colloidal damper (figure 11). This tube was closed at one end and opened at the other. Note that the relative magnetic permeability \( \mu_r \) of the material used to manufacture the tube, as well as the ratio \( a/b \) of the inner radius to outer radius are parameters which decisively influence the degree of shielding of the external magnetic field produced by the permanent magnet. E.g., for the hollow cylinder shown in the left side of figure 10, the degree of shielding \( \eta \) of the external magnetic field can be calculated as [15]:

\[
\eta = \frac{t}{t^*},
\]

where \( t^* \) is the thickness of the cylinder wall.
\[ \eta = \frac{B_{\text{inner}}}{B_{\text{outer}}} = \frac{4\mu_r}{(\mu_r + 1)^2 - (\mu_r - 1)^2 \left( \frac{a}{b} \right)^2}, \]  

where \( B_{\text{inner}} \) and \( B_{\text{outer}} \) are the magnetic field densities at inner and outer parts of the tube, respectively.

As shown in the right side of figure 10, maximal value of the degree of shielding (\( \eta = 1 \)) is found for \( \mu_r = 1 \), regardless the value of ratio \( a/b \). Moreover, thin walls, i.e., large ratios \( a/b \), are preferable in order to avoid the degradation of the magnetic field inside the tube. For this reasons, in the present section a tube made in transparent glass (\( \mu_r = 0.999987 \approx 1 \)), and in construction of the controllable colloidal damper, a cylinder made in aluminium alloy (\( \mu_r = 1.000023 \approx 1 \)) were selected. Note that, since for stainless steels SUS 630 and SUS 440, which were previously used in construction of the colloidal damper [1-3], the relative magnetic permeability is on order \( \mu_r = 700-1,000 \), the magnetic field inside of the cylinder completely degrades. Therefore, such materials are not desirable candidates for the cylinder fabrication of the proposed controllable colloidal damper.

As external magnets were used two types of annular magnets made in N40 neodymium material (figure 11). Both magnets have the outer diameter of \( 2R = 22 \text{ mm} \), the inner diameter of \( 2r = 18 \text{ mm} \), the height of \( 2t = 30 \text{ mm} \), and the surface magnetic flux density of 0.4 T. One magnet produces a magnetic field along the radial direction, and the other magnet along the axial direction of the glass tube. A certain amount of ferrofluid was introduced inside the glass tube, as shown by figure 11.

**Figure 10.** Degree of shielding of the external magnetic field produced by a hollow cylinder.

**Figure 11.** Visualization of the displaced ferrofluid by annular magnets, which produce either axial or radial magnetic fields, when placed outside a glass tube.
When moved along the glass tube, magnets producing the axial and radial magnetic fields were able to displace a quantity of 3.8 and 8.6 g of ferrofluid, respectively (see figure 11). Thus, by changing the action line of magnetic field from axial to radial direction, the amount of displaced ferrofluid increased more than 2 times. For this reason, on figure 1, the magnet moving at external part of the cylinder was adopted with the magnetic field acting along the radial direction. In order to further concentrate the magnetic field at internal surface of the magnet towards the glass tube, i.e., in order to avoid dissipation of magnetic field at the external surface of the magnet, a yoke (not shown in figure 11) should be used. As discussed in connection with the degree of shielding (figure 10), such yoke should be made in a material with high relative magnetic permeability.

In order to explain the experimental results shown by figure 11, one compares the dimensionless magnetic flux density $B = 2B/(\mu_0M_0)$ obtained along the axial coordinate $x$ (see figure 12), for the annular magnet that produces a magnetic field along the radial direction [18, 19]:

$$B_{\text{radial}} = \frac{1}{\sqrt{1 + (x-R)^2}} - \frac{1}{\sqrt{1 + (x+R)^2}} - \frac{\bar{r}}{\sqrt{\bar{r}^2 + (x-R)^2}} + \frac{\bar{r}}{\sqrt{\bar{r}^2 + (x+R)^2}},$$

and for the annular magnet that produces a magnetic field along the axial direction [18, 19]:

$$B_{\text{axial}} = \frac{x-R}{\sqrt{1 + (x-R)^2}} - \frac{x+R}{\sqrt{1 + (x+R)^2}} - \frac{\bar{t}}{\sqrt{\bar{t}^2 + (x-R)^2}} + \frac{\bar{t}}{\sqrt{\bar{t}^2 + (x+R)^2}},$$

where $\bar{r} = r/R = 9/11$ is the dimensionless radius of the magnet, $\bar{t} = t/b = 15/11$ is the dimensionless height of the magnet, $\bar{x} = x/R$ is the dimensionless axial coordinate, $\mu_0$ is the magnetic permeability of vacuum, and $M_0$ is magnetization density. Figure 12 shows that the radial magnetic field is asymmetric but stronger than the axial magnetic field, which is symmetric but weaker.

These theoretical results support the experimentally observed feature, i.e., the radial magnetic field is able to displace a larger amount of ferrofluid than the axial magnetic field.

**Figure 12.** Variation of the dimensionless magnetic flux density versus the dimensionless axial coordinate for annular magnets producing magnetic fields along the axial and radial directions.

4. Trial colloidal damper, vibration test rig and experimental procedure
The 3D design model of the controllable colloidal damper, obtained by using Solidworks Premium 2013, is illustrated in the left upper part of figure 13. A photo of the manufactured colloidal damper is shown in the left lower part of figure 13 and the vibration test rig is presented in the right side of figure 13. Details concerning the construction and performances of the made-in house ball-screw...
A load cell placed at the piston end of the colloidal damper is used to measure the compressive damping force $F$ [kN]. In order to measure the piston displacement $S$ [mm] and the amplitude of vibration $S_{\text{max}}$ [mm], a laser displacement sensor is employed. Dissipated energy $E$ of the colloidal damper can be calculated as the area of the hysteresis loop (the loop-like graph showing variation of the damping force versus the piston displacement, see figure 14):

$$E = \int F(S) dS.$$  

(5)

On the other hand, the equivalent damping coefficient can be calculated as (see figure 15):

$$C = 2E / (\pi^2 f S_{\text{max}}^2),$$  

(6)

where $f$ is the excitation frequency, which has been fixed to $f = 1$ Hz during vibration tests. Amplitude of vibration was considered as a variable parameter, varying from 8 to 56 mm (see figures 14 and 15).

The main constructive characteristics of the manufactured colloidal damper are as follows: piston diameter of 8 mm, diameter of the corresponding cylinder hole of 11.5 mm, and the outer diameter of the cylinder of 36 mm.

On the piston head was fixed an annular (tubular) permanent magnet made in neodymium N40, with the following characteristics: external diameter of 11 mm, internal diameter of 4 mm, height of 20 mm, and surface magnetic flux density of 0.478 T. Magnetic field is produced in the axial direction of the magnet. Note that an annular magnet was preferred here, instead of the cylindrical magnet selected in section 3 (diameter of $2R = 9$ mm and height of $t = 30$ mm), for the following reasons: an annular magnet can be firmly fixed and better aligned on the piston head; the magnetized piston becomes shorter, and more stable to the action of shock and vibration. External diameter (11 mm) of the magnet was selected in correlation with the diameter of the cylinder’s hole (11.5 mm). Internal diameter (4 mm) of the magnet was decided to allow for the necessary strength. Height (20 mm) was selected to obtain the same variation of the magnetic flux density along the axial direction of the magnet versus the target distance (see figure 3 for $t = 30$ mm).

On the other hand, at external part of the cylinder was employed an annular (tubular) permanent magnet made in neodymium N45, with the following characteristics: external diameter of 50 mm, internal diameter of 37 mm, height of 20 mm, and surface magnetic flux density of 0.514 T. Magnetic field is produced in the radial direction of the magnet. Internal diameter (37 mm) of the magnet was selected in correlation with the outer diameter of the cylinder (36 mm). Height (20 mm) of the magnet was selected to be the same as that of the magnet attached to the piston head. At the outer part of the magnet a yoke made in a material with high relative magnetic permeability (SUS 440) was used. Its purpose is to concentrate the magnetic field at the internal surface of the magnet towards the cylinder, i.e., to avoid dissipation of the magnetic field at the external surface of the magnet.
5. Experimental results

Figure 14 illustrates the hysteresis characteristics of the proposed colloidal damper, obtained for an excitation frequency of $f = 1\text{Hz}$, and various functioning conditions, listed as follows: with pure water and water-based ferrofluid as working liquids; with and without annular magnet at the external part of the cylinder; with the outer magnet placed near to, and far from the filter and the nanoporous solid matrix. Figure 15 presents the variation of the damping coefficient versus the amplitude of vibration, in the same working conditions as those described in connection with figure 14.

![Figure 14](image1.png)

**Figure 14.** Hysteresis loop of the proposed colloidal damper.

![Figure 15](image2.png)

**Figure 15.** Damping coefficient of the proposed colloidal damper.

Figures 14 and 15 indicate that, in comparison with the traditional colloidal damper that employs water as working liquid, for the proposed colloidal damper that uses water-based ferrofluid, both area of the hysteresis loop (dissipated energy) and damping coefficient are increasing. In order to explain this, note that while the surface tension of the working liquid slightly decreases, about 22 %, from 0.0728 N/m in the case of pure water, to 0.057 N/m in the case of the ferrofluid used, the dynamic viscosity of the working liquid increases 5 times, from 0.001 Pa·s in the case of pure water, to 0.005 Pa·s in the case of MSGW10 ferrofluid. Thus, especially at the ends of piston stroke ($S = 0$ and 48 mm on figure 14) an increase of the frictional effect on the damper’s hysteresis can be observed.

Note that presence of the outer magnet in structure of the colloidal damper considerably influences the shape of the obtained hysteresis, producing both larger damping forces and dissipated energies. This can be explained by the considerable change in the surface tension of the ferrofluid, and more importantly, on modification of the apparent contact angle of the solid-liquid interface, under the action of the variable magnetic field.

Although the shape of the hysteresis only slightly modifies during the movement of the outer magnet from a position closed to, toward a position far away from the filter and nanoporous solid matrix, noticeable variation of the dissipated energy and more importantly, of the damping coefficient can be observed. Thus, figure 15 proves that the damping coefficient can be adjusted by modifying the position of the permanent magnet placed at the external part of the cylinder.

6. Conclusions

In this work, a colloidal damper rendered controllable under variable magnetic fields is proposed and its controllability is experimentally evaluated. Such absorber occurs as complementarily to classical magneto-rheological dampers, with the difference that the applied magnetic field affects the surface tension and not the viscosity of the working liquid. Proposed colloidal damper employed a water-based ferrofluid working against a liquid-repellent nanoporous matrix of gamma alumina or/silica gel. Control of the damping was obtained by moving permanent annular magnets, which were placed...
either on the piston head (axial magnetic field) and/or on the external surface of the cylinder (radial magnetic field). In order to properly select these magnets, flow visualizations inside of a transparent model damper were performed, and the quantity of the displaced liquid by the magnets through the damper’s filter and through the nanoporous matrix were determined. From experimental results obtained during horizontal vibration tests on a ball-screw shaker, the following conclusions were inferred.

1) At augmentation of the magnet height the surface magnetic flux density, the amount of liquid adhered on the whole surface of the magnet, and the quantity of ferrofluid displaced by the magnetized piston monotonically increased and then saturated. In order to avoid waste of neodymium material, the magnet height can be limited at the corresponding saturation height, which generally depends both on the material and the radial geometry of the selected magnet.

2) Magnetic flux density drastically degraded for damaged (fractured) magnets. For this reason, the magnetized piston should not receive during operation shocks which might exceed the impact resistance of the brittle neodymium material used in the fabrication of permanent magnets.

3) Theoretical model predicted too optimistic results for the variation of the magnetic flux density versus the target distance. Therefore, correction of the theoretical results should be considered during the design process of the controllable colloidal damper.

4) Effective quantity of ferrofluid displaced by the magnetized piston reduced due to the remanent liquid inside the filter, and also due to the increase in the hydraulic resistance of the filter. However, the magnetized piston was able to produce long enough strokes to accommodate applications for the proposed colloidal damper.

5) In order to avoid degradation of the magnetic field produced by the external magnet inside the cylinder with relatively thick walls, a material with the relative magnetic permeability close to 1, such as aluminium alloy, should be selected. Additionally, at the outer part of the external magnet a yoke made in material with high relative magnetic permeability, such as stainless steel, should be used. In this way, concentration of the magnetic field towards the cylinder is enhanced, by avoiding dissipation of the magnetic field at the external surface of the magnet.

6) For the external magnet, by changing direction of the magnetic action line from axial to radial direction, the amount of displaced ferrofluid considerably increased.

7) Both dissipated energy and damping coefficient of the proposed absorber (working liquid: water-based ferrofluid) were found largely increased in comparison with those of the traditional colloidal damper (working liquid: pure water). This was explained by augmentation of the frictional effect on the damper’s hysteresis, due to the 5 times increase in the dynamic viscosity of the working liquid, from 0.001 Pa·s for pure water, to 0.005 Pa·s for ferrofluid.

8) Presence of the outer magnet considerably influenced the shape of the obtained hysteresis, producing both larger damping forces and dissipated energies. This was explained by the considerable change in the surface tension of the ferrofluid, and more importantly, on modification of the apparent contact angle of the solid-liquid interface, under the action of the variable magnetic field.

9) Although the hysteresis suffered only minor shape changes during the movement of the outer magnet from a position closed to, toward a position far away from the filter and nanoporous solid matrix, noticeable variation of the dissipated energy and more importantly, of the damping coefficient was observed. Results obtained proved that the damping coefficient can be adjusted by modifying the position of the permanent magnet placed at the external part of the cylinder.

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