Effects of Winding Cylinder Materials on Dynamic Performances of a New MR Damper

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ABSTRACT In the semi-active control system based on magnetorheological (MR) damper, the separating arrangement of displacement sensor and MR damper is easy to reduce the reliability and increase system cost. Moreover, the detection accuracy of the sensor is not high due to the external disturbance. Based on this, a new displacement differential self-sensing magnetorheological damper (NDDSMRD) is developed to overcome these shortcomings. The structure design and working principle of NDDSMRD are expounded. In order to analyze the influence of winding cylinder materials for the developed MR damper on displacement self-sensing and damping characteristics, magnetic field simulations and experiments are conducted to investigate the relationship between the damping magnetic flux and self-sensing magnetic flux densities with two winding cylinders made from different materials. A finite element model was built with ANSYS software and magnetic field simulations in static and harmonic state were presented, respectively. Simulation results show that the damping magnetic flux density generated for winding cylinder made of No.10 steel material surpasses the one made of stainless steel material, and the self-sensing voltages are proportional to the damper displacement though the winding cylinders are different. A dynamic experimental test rig was built up to analyze the dynamic damping performances and self-sensing ability. Experimental results show that the damping force produced by NDDSMRD with No.10 steel winding cylinder is larger than that with stainless steel winding cylinder. The self-sensing voltages are also linear to the damper displacements even though the different winding cylinders. In addition, the self-sensing voltage generated by the stainless steel prototype is greater than the No.10 steel. Moreover, the self-sensing sensitivity of stainless steel winding cylinder can reach to 59mV/mm, which is 7.4 times greater than that the 8mV/mm for No.10 steel winding cylinder.

INDEX TERMS MR damper, winding cylinder, self-sensing voltage, damping performance.

I. INTRODUCTION
Magneto-rheological (MR) damper is a new type of intelligent buffered device, which applies MR fluid as working medium to produce the controllable damping force [1], [2]. Due to the rheological properties of MR fluids under magnetic fields, MR damper has a series of dramatic advantages such as fast response time, large adjustable range, low energy consumption and controllable damping force [3]. Based on these, MR dampers have been widely applied in vehicle semi-active suspension system, engineering construction, aerospace and other vibration control fields [4]–[7].

To make the best use of the damping force performances of the MR damper, the dynamic information of the MR damper needs to be fed back to the system controller, which is always equipped with some additional sensors, such as displacement sensor or velocity sensor, which can acquire the state information of the MR damper to achieve satisfactory effect [8], [9]. Nevertheless, the additional sensors will result in the high cost, complex control system, low reliability and occupy large installation space, which also restricts the further development and application of MR damper [10], [11]. Based on this, a series of new MR dampers integrated with sensor monitoring capabilities were developed to overcome these limitations.

Jung et al. [12] proposed an electromagnetic induction (EMI) system based on an MR damper. The EMI system, consisting of permanent magnets and coils, can convert reciprocal motions (kinetic energy) of the MR damper into electrical energy (electromotive force), which can serve as an
alternative power source for the MR damper control system. Furthermore, this device has a sensing ability to eliminate a conventional velocity sensor being used to implement control policies for MR damper based on vibration control systems. An alternating voltage signal produced from the EMI is proportional to the motion velocity. Therefore, the EMI can act as a relative velocity sensor for common control methods in MR damper. Wang and Bai [13], [14] designed an MR damper combing the relative displacement sensing ability with controllable damping performance together into one device. The developed MR damper was tested on the test rig, the experimental results showed that the developed MR damper cannot only achieve the ability of the relative displacement sensing, which can serve as displacement sensor, but also produce large controllable damping force. Chen and Liao [15], [16] designed a type of function-integrated MR damper, which integrated a power source, a displacement sensor and a damper into one device. This structure would produce the electrical energy from the working environment and can feedback the dynamic data to the control system. Nevertheless, the self-sensing part and the MR damper are arranged separately. In addition, the additional magnetic flux shield layer and flux guided layer were arranged to solve the magnetic field isolation, which increased the whole volume of the device. Chen et al. [17] developed a self-sensing MR damper, integrating one MR damper with the piezoelectric force sensor. The piezoelectric signal can change with the variation of the external pressure, and can reflect the damping force. Nevertheless, the processing technology of the piezoelectric force sensor is more complex. Sapiński [18]–[20] developed a functional-integrated MR damper combining the velocity sensing capability with power source axially connected with the MR damper. The experimental research was conducted to investigate the velocity sensing capability, the results showed that the velocity varies linearly with the voltage output, and can reflect the damper state information for better control. However, the power source was separately arranged with the damper, this separate configuration would enlarge the size and weight of the MR damper. Guan et al. [21] designed a velocity self-sensing magnetoreheological damper based on the numerical circuit technology and optical tracking technology. The velocity sensing circuit was integrated into a hollow upper cover of the MR damper to monitor the speed of damper piston.

Hu and his coauthors designed and developed a displacement differential self-sensing MR damper (DDSMRD). In this proposed MR damper, there was one excitation coil wound around the piston head, the alternating currents (ACs) with different frequencies and direct currents (DCs) can be input simultaneously, and two differential self-sensing coils were wound around the winding cylinder to obtain a higher accuracy of self-sensing voltage that is proportional to the damper displacement. A series of experimental tests were carried out to evaluate the self-sensing ability and damping performance [22]–[25]. However, the amplitude of the generated self-sensing voltage is only 0.1V in the static and dynamic experimental tests. It is too small due to the coupling effects between DC and AC circuits in the excitation coil, which decreases the measurement accuracy.

To solve the above-mentioned problems, a new displacement differential self-sensing MR damper (NDDSMRD) with different materials of the winding cylinder and winding ways of piston head coil was designed and fabricated. By changing the winding cylinder material, a new improvement method for self-sensing ability is proposed. In this paper, the materials of the winding cylinder relating to the damping performance and self-sensing characteristics are discussed. Moreover, for the structure improvement, there are two concentrical coils winding around the damper piston head instead of one excitation coil used in the prior works [22]–[25]. The inner coil serves as the traditional damping excitation coil, generating the damping magnetic fields, while the outer coil serves as the self-sensing excitation coil, generating the self-sensing magnetic fields. This specific arrangement of the excitation coils can avoid the coupling effects between DC and AC circuits effectively. The structural design and the simulation of damping performances and self-sensing ability are presented, the static and dynamic experiments are carried out to investigate self-sensing performances, the dynamic damping performance is also tested experimentally, and the influence of winding cylinder materials on displacement self-sensing and damping characteristics is mainly analyzed.

II. STRUCTURAL DESIGN AND MAGNETIC CIRCUIT ANALYSIS OF THE PROPOSED MR DAMPER

A. STRUCTURAL DESIGN AND SELF-SENSING PRINCIPLE OF THE PROPOSED MR DAMPER

Figure 1 presents the structure and working principle of the designed NDDSMRD. This proposed MR damper is mainly composed of a piston, a piston rod, a winding cylinder around where two differential self-sensing coils are wound, a floating piston, two end covers, and an outer cylinder. Different from the developed MR damper studied by our prior works that DC and AC are simultaneously applied to the same excitation coil [22]–[25], the NDDSMRD has different distribution of the excitation coils for piston head, there are two concentrical coils wound around the piston, in which the inner coil through direct current serves as damping excitation coil, when the inner damping excitation coil powered with direct current, it will produce the damping magnetic field at the effective damping gaps in which MR fluid flowing can be magnetized, and generate the shear yield stress. So, the damping force can be generated with the piston moving up and down. Meanwhile, the outer coil through alternating current serves as sensing excitation coil, when a relative motion between piston and winding cylinder is occurred, the self-sensing coil l and coil 2 will generate the self-sensing voltage under the alternating magnetic field provided by the sensing excitation coil with high frequency alternating current. In addition, the frequency of self-sensing voltage is same as the alternating current. This specific arrangement of the two excitation
FIGURE 1. Working principle of NDDSMRD. (1) Piston rod (2) Upper end cover (3) Outer cylinder (4) Winding cylinder (5) Self-sensing coil 1 (6) Piston (7) Sensing excitation coil (8) Damping excitation coil (9) Self-sensing coil 2 (10) Floating piston (11) Lower end cover.

Based on the electromagnetic induction principle, it can produce a large self-sensing voltage with the more number of coils kept in the alternating magnetic field. In addition, due to the differential connections of two self-sensing coils, the self-sensing voltages are same because of the same length of the two self-sensing coils kept in magnetic field when the sensing excitation coil lies in the middle position of the two self-sensing coils. Therefore, the summation of the self-sensing voltages is zero and this point is regarded as zero reference position. When the damper piston moves up and down relative to the zero reference position, the numbers of turn of the self-sensing coil 1 and coil 2 which in the alternating magnetic field decrease and increase respectively by both $\Delta N$ (turns of coil 1 is $N_1$, turns of coil 2 is $N_2$, here $N_1 = N_2$), the relative displacement voltage signal of the piston is twice than that of the variation in each self-sensing coil. In consequence, the change of piston displacement can be reflected on the variation of voltages in two self-sensing coils. Furthermore, the total voltage is proportional to piston displacement.

In order to obtain a good damping performance and better displacement self-sensing ability, the self-sensing alternating magnetic field must not disturb the damping force magnetic field, and the leakage flux should be as small as possible. Good damping performance requires that the working magnetic field be concentrated in the effective damping gap, so magnetic material for the winding cylinder may be more suitable because of its low magnetic resistance. In addition, the large magnetic resistance can avoid the leakage of the alternating magnetic in the winding cylinder which can effectively improve the displacement self-sensing performance. To some extent, the non-magnetic material seems a better choice for the winding cylinder. In summary, the choice of winding cylinder material has a crucial impact on both damping performance and self-sensing ability of damper.

In order to further explore the influence of the winding cylinder materials on damping and self-sensing ability of the proposed MR damper, the materials of the winding cylinder were chosen stainless steel and No.10 steel, respectively. The structure specifications of the NDDSMRD are listed in Table 1. Here, some key parameters, including the turn numbers of damping excitation coil and the sensing excitation coil, were designed to obtain a larger self-sensing voltage in our present work.

B. MAGNETIC CIRCUIT OF THE PROPOSED MR DAMPER

Figure 2 shows the simplified magnetic circuit of the NDDSMRD with different materials for winding cylinders. In this progress, the $R_i$ and $R_s$ represent the magnetic resistance of the $i$th path that magnetic flux pass through the winding cylinder and the sum of rest paths of magnetic circuit, respectively, the magnetic resistance can be calculated as:

$$R_i = \frac{l_i}{\mu_0\mu_iS_i}$$  \hspace{1cm} (1)
TABLE 1. Specifications of the NDDSMRD.

| Parameter                          | Values  |
|------------------------------------|---------|
| Piston rod diameter                | 16 mm   |
| Piston head diameter               | 42 mm   |
| Piston left wing length (b)        | 8 mm    |
| Piston right wing length (c)       | 8 mm    |
| Gap thickness                      | 1 mm    |
| Winding cylinder inner diameter    | 44 mm   |
| Winding cylinder region length     | 45 mm   |
| Outer cover outside diameter       | 64 mm   |
| Winding cylinder thickness         | 2 mm    |
| Outer cover thickness              | 8 mm    |
| Piston head groove width           | 10 mm   |
| Piston head groove length (w)      | 30 mm   |
| Damping excitation coil width      | 6 mm    |
| Signal excitation coil width       | 4 mm    |
| Damping excitation coil turns (Nz) | 570     |
| Sensing excitation coil turns (N)  | 280     |
| Self-sensing coil 1 turns (Ni)     | 295     |
| Self-sensing coil 2 turns (N2)     | 295     |
| Excitation coil diameter           | 0.6 mm  |
| Self-sensing coil diameter         | 0.33 mm |

where \( l_i \) is the length of the \( i \)th path that the magnetic flux through, \( \mu_0 \) is permeability of vacuum, \( \mu_i \) is the relative permeability of the \( i \)th path, and \( S_i \) is the cross-sectional area of the \( i \)th path.

As a result, the magnetic resistance \( R_{n1}, R_{n2}, R_{n3} \) and \( R_{m1}, R_{m2}, R_{m3} \) that magnetic flux passes through the two different winding cylinders can be present respectively as follows:

\[
R_{n1} = \frac{t}{\mu_0 \mu_n S_{n1}}
\]

\[
R_{n2} = \frac{c + w + b}{\mu_0 \mu_n S_{n2}}
\]

\[
R_{n3} = \frac{t}{\mu_0 \mu_n S_{n3}}
\]

\[
R_{m1} = \frac{t}{\mu_0 \mu_m S_{m1}}
\]

\[
R_{m2} = \frac{c + w + b}{\mu_0 \mu_m S_{m2}}
\]

\[
R_{m3} = \frac{t}{\mu_0 \mu_m S_{m3}}
\]

Based on the same size of two kinds dampers, it can be seen that the cross-sectional area of the magnetic flux passing through the winding cylinder: \( S_{n1} = S_{n3} = S_{m1} = S_{m3} \), \( S_{n2} = S_{m2} \), \( \mu_n \) is the relative permeability of stainless steel winding cylinder, \( \mu_m \) is the relative permeability of No.10 steel winding cylinder, due to the No.10 steel has higher magnetic characteristics than stainless steel, it can be seen that \( \mu_n \leq \mu_m \). So the \( R_{n1} = R_{n3} \geq R_{m1} = R_{m3} \), \( R_{n2} \geq R_{m2} \). In addition, the dampers with different winding cylinder materials have the same rest magnetic resistance, that is \( R_{sn} = R_{sm} \). As shown in figure 2(c) and (d), the total magnetic resistance of two assembly structures can be presented as follows:

\[
R_{sum}^n = 2 \cdot R_{n1} + R_{n2} + R_{sn}
\]

\[
R_{sum}^m = 2 \cdot R_{m1} + R_{m2} + R_{sm}
\]

According to the mentioned above, it can be seen that the magnetic resistance \( R_{sum}^m \) for stainless steel winding cylinder is larger than that \( R_{sum}^n \) for No.10 steel winding cylinder. Therefore, Under the same exciting current loaded on the damping excitation coils, the magnetic flux density passes vertically through the damping gaps for No.10 steel winding cylinder is larger than that of stainless steel winding cylinder, which leads a larger damping force to the NDDSMRD with No.10 steel.

Besides, the magnetic resistance \( R_{m2} \) of the No.10 steel winding cylinder is far less than \( R_{n2} \) of the stainless steel
winding cylinder. When the alternating current loaded on
the sensing excitation coils, the alternating magnetic field
forms a closed magnetic circuit inside the No.10 steel wind-
ing cylinder, which causes decrement of the magnetic flux
density go vertically through the self-sensing coil, therefore,
the self-sensing voltage generated by self-sensing coils for
stainless steel winding cylinder is larger than that for No.10
steel winding cylinder.

III. MODELING AND SIMULATION OF NDDSMRD WITH
FINITE ELEMENT METHOD

A. DAMPING MAGNETIC FIELD SIMULATION

In order to analyze the influence of the different winding
cylinders on the displacement self-sensing and damping char-
acteristics, the 2D finite element models of the NDDSMRD
were built with ANSYS/Emag software. The symmetry of the
model structure determines the performances of NDDSMRD
in each sides of symmetry axis are same, the 1/2 cross sec-
tions of NDDSMRD were selected as simulation object to
reduce the calculated amount, as shown in Figure 3(a) and
3(b). The modeling approaches are all the same except the
choice of winding cylinder material. Those two FEA models
were divided into 12 regions which included three material
properties, respectively. In these areas, A1 area is the piston
rod, A2 area is MR fluids, A3 area is the piston, A4 and
A5 area are damping excitation coil and sensing excitation
coil, respectively, A6 area is winding cylinder with material
of stainless steel or No. 10 steel, A7 and A8 areas are self-
sensing coil 1 and coil 2, A9 area is the outer cylinder,
A10 and A11 area are end covers, A12 area is the floating
piston. Piston rod, floating piston and two end covers are
made of non-magnetic stainless steel, all coils are copper coil,
and piston, outer cylinder are made of magnetic No.10 steel.

After assigning the material property for each area,
the magnetic field boundary conditions without magnetic
leakage are applied, and then input current density in the
coil area to simulate the excitation load. By finishing the
above operation, distribution of the magnetic flux lines of
NDDSMRD with two different winding cylinders under the
excitation current of 1.0A are shown in Figure 3(c) and 3(d).
It can be seen that the magnetic flux lines is mainly embodied
in the effective damping gap, a low level of flux leakage
path appears on the upside and downside of piston which
the No. 10 winding cylinder is larger than the stainless steel.
In other word, the NDDSMRD with No. 10 winding cylinder
has more concentrated flux path in the piston than that one
with stainless steel material. Furthermore, In figure 3(d),
the magnetic flux lines goes axially through the winding
cylinder that leads a high-level magnetic flux in the effective
damping gap which can magnetize working magnetorheologi-
cal fluid better.

Figure 4 shows the variations of the average magnetic
flux density with each corresponding excitation current at
the middle path of the effective damping gaps for two dif-
f erent winding cylinders. It can be seen that the magnetic
flux densities of two kinds of winding cylinders increase
with the increment of excitation current. The magnetic flux
densities are proportional to the currents when the excitation
current doesn’t exceed 1A, and then the magnetic flux density
changes slowly and reaches saturation at 1.5A. In addition, the magnetic flux density of No.10 steel winding cylinder is larger than that of stainless steel winding cylinder under the same excitation current, and the maximum magnetic flux density of No.10 steel is 0.425T, while the stainless steel is 0.345T.

Considering the change of the relative position between the winding sections of the winding cylinder and the piston may affect the magnetic field intensity distribution in the effective damping gap, the simulations of the influence of the different displacement on magnetic flux density for different winding cylinders were carried out. Figure 5 shows the relationship between the damping force and piston displacement from −15mm to 15mm under different currents. The simulation results show that the damping forces of both the positive displacement and the negative displacement increase with increment of the excitation current, and the increase trend of damping force stay the same with the trend of average magnetic flux density shown in figure 4 which is faster firstly and then slower. Besides, the maximum simulated damping force of stainless steel winding cylinder is 712N, while the No.10 steel winding cylinder is 1068N.

Table 2 shows the average magnetic flux density of damping channel at different positions with the excitation current of 1.0A. It can be seen that the average magnetic flux density at different positions is approximate to 0.342T for stainless steel winding cylinder and 0.452T for No.10 steel winding cylinder, which indicates that the magnetic winding cylinder can produce more concentration flux than non-magnetic winder cylinder. According to Table 2, the deviation rates of average magnetic flux density at different positions are calculated and is shown in Figure 6. Observing figure 6, the flux reduction rates of No.10 steel are lower than stainless steel, which means the No.10 steel winding cylinder has more excellent damping magnetic circuit. But even the maximum deviation rate of stainless steel is kept within 4%, and the whole deviation rates are still small, therefore, the magnetic flux density of different winding cylinder is less influenced by different positions.

B. HARMONIC MAGNETIC FIELD SIMULATION

In order to investigate the displacement self-sensing performance of NNDSMRD for different winding cylinder materials, the simulation models of harmonic magnetic field and the coupling of circuits are established, as shown in Figure 7.

In Figure 7, the voltage source U1 is built to represent the excitation voltage which is a sinusoidal signal with amplitude of 10V and a frequency of 1KHz. The current-control-voltage units W1, W2 and W3 are built to represent the
self-sensing voltages for sensing excitation coil, self-sensing coil 1 and self-sensing coil 2, respectively. The units RW1 and RW2 (RW1=RW2=1 \times 10^{10} \Omega) are created to simulate the resistances of self-sensing coil 1 and self-sensing coil 2. In addition, the analysis circuits are connected with model of NDDSMRD by element nodes.

Figure 8 shows the distribution of magnetic flux lines of NNDSMRD with different winding cylinders on harmonic simulation. We can see that a closed magnetic circuit is only formed between the piston and the outer cover for stainless steel winding cylinder, but there are two closed magnetic circuits for No.10 steel winding cylinder, which one formed between the piston and outer cover and the other formed between piston and the winding cylinder. The distribution of harmonic magnetic field is similar to that of damping magnetic field. But the harmonic magnetic flux goes axially through the winding cylinder means a high-level magnetic leakage for self-sensing coil which can greatly decrease the differential self-sensing performance.

A sinusoidal signal with amplitude of 10V and a frequency of 1KHz was loaded onto the sensing excitation coil, the amplitudes of the self-sensing voltages of self-sensing coil 1 and coil 2 for different winding cylinders

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**TABLE 2. Average magnetic flux density of damping gaps at different positions.**

| relative displacement Δx /mm | -15 | -10 | -5  | 0   | 5   | 10  | 15 |
|------------------------------|-----|-----|-----|-----|-----|-----|-----|
| average magnetic flux density B/T | stainless steel | 0.348 | 0.343 | 0.347 | 0.342 | 0.342 | 0.345 | 0.342 |
|                              | No.10 steel    | 0.426 | 0.426 | 0.426 | 0.425 | 0.426 | 0.426 | 0.426 |

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**FIGURE 7.** Harmonic simulation model of the NDDSMRD.

**FIGURE 8.** Distribution of magnetic flux lines for different winding cylinders on harmonic simulation: (a) stainless steel and (b) No. 10 steel.

**FIGURE 9.** Amplitude of the self-sensing voltages for different winding cylinders under different damper displacements: (a) self-sensing coil 1 and (b) self-sensing coil 2.
under the different damper displacements were obtained, as shown in figure 9. Because of the imaginary solution amplitude of the self-sensing voltage of the two self-sensing coils is much lower than the real solution, approximate to zero, which can be ignored, the real solution of the self-sensing voltage is taken as its amplitude. In figure 9(a) and (b), the self-sensing voltage amplitudes of self-sensing coil 1 for different winding cylinders decrease gradually with the variation of the damper displacements from $-15\text{mm}$ to $15\text{mm}$, while the self-sensing voltage amplitudes of self-sensing coil 2 increase gradually with the increment of the relative displacement. In addition, the amplitudes of self-sensing voltage of coil 1 and coil 2 for stainless steel winding cylinder are larger than that for No. 10 steel winding cylinder.

Due to the differential connection between the self-sensing coil 1 and coil 2, the self-sensing voltage amplitude is the difference of the self-sensing voltage amplitude of two self-sensing coils according to the displacement differential self-sensing principle. Figure 10 shows the variation of the self-sensing voltage amplitude of NDDSMRD at different positions for two different winding cylinders. It is obvious seen that the amplitudes of the self-sensing voltage are proportional to the relative displacement between piston and winding cylinder, though the winding cylinders are different. However, the self-sensing voltage signal strength of the stainless steel winding cylinder is 2.7 times than that of the no.10 steel winding cylinder.

**IV. STATIC EXPERIMENTAL TEST OF SELF-SENSING PERFORMANCE**

To verify the self-sensing voltage of NDDSMRD is proportional to the damper displacements, and analyze the self-sensing performance with different winding cylinders, a static signal acquisition system was built, as shown in figure 11. The test system was generally composed of data acquisition card, LabVIEW testing interface, the NDDSMRD and signal generator. Both a voltage signal acquisition module and a displacement analysis module were programmed with LabVIEW software. The position of sensing excitation coil is in the middle of the self-sensing coil 1 and coil 2, regarded as zero reference point. In the static experiments, the AI1 channel was used to simulate the input differential mode, the sampling frequency was 10KHz, and the sample of the single
channel was 100. A sinusoidal excitation signal generated by signal generator with frequency of 1KHz and voltage amplitude of 10V was loaded on the sensing excitation coil of NDDSMRD with different winding cylinders, and then a static self-sensing voltage of the same frequency as the sinusoidal excitation signal was obtained with the variation of relative displacements set at 5, 10, 15mm, respectively, which is shown in Figure 12.

Figure 12(a) shows the self-sensing voltage of the NDDSMRD with stainless steel for winding cylinders at special positions. It can be seen that the static self-sensing voltage increases with the increase of the piston displacement, and a similar trend appears in figure 12(b) for No.10 steel winding cylinder, especially. When the relative displacements is set to 0mm, 5mm, 10mm and 15mm, the amplitudes of self-sensing voltages will reach to 0V, 0.3V, 0.6V and 0.9V, while
the No.10 steel winding cylinder are 0V, 0.04V, 0.08V and 0.12V, respectively. It is obvious seen that the self-sensing voltages changes equivalently with the same change of the relative displacements, which indicates the amplitude of self-sensing voltage is proportional to the relative displacement between piston and winding cylinder. Moreover, the self-sensing voltage of the stainless steel winding cylinder is larger than that of the No. 10 steel winding cylinder at the same position, which means the damper with stainless steel winding cylinder has more excellent displacement self-sensing performance.

V. DYNAMIC EXPERIMENTAL TEST OF DAMPING PERFORMANCE AND SELF-SENSING ABILITY OF THE PROPOSED MR DAMPER

A. DYNAMIC PERFORMANCE TEST SYSTEM SETUP

A dynamic performance test system is set up, which is shown in Figure 13. When the damper piston moves in the magnetic field generated by sensing excitation coil and damping excitation coil, the damping force signal, self-sensing voltage signal and displacement signal can be acquired by DAQ card and are displayed on the LabVIEW test interface, respectively.

Figure 14 shows the key components and prototype of the proposed NDDSMRD. In this structure, the materials of the winding cylinder are chosen stainless steel (non-magnetic) and No.10 steel (magnetic), as shown in Figure 14(c), the structure of the winding cylinder which has two separate slots, in which the self-sensing coil 1 and coil 2 are wound around, respectively. In addition, the number N1 of turn of self-sensing coil 1, is same as N2 of self-sensing coil 2. Figure 14(d) shows the assemble of the two layers excitation coils wound around the piston, in which the inner coil serves as damping excitation coil, and the outer coil serves as sensing excitation coil.

B. ANALYSIS OF DYNAMIC DAMPING PERFORMANCES

The proposed NDDSMRD is installed on the test rig to investigate the damping performance with different winding cylinders. Figure 15 shows the variation of damping force with piston displacement under different direct currents of 0, 0.5, 1, and 1.5A when the exciter is loaded with sinusoidal signal with frequency of 0.5Hz and displacement amplitude of 15mm. As shown in Figure 15(a) and (b), when the excitation current exceeds 1.0A, the damping force changes slowly which illustrates that the damping forces tend gradually to saturation. Furthermore, because of the gravity of the damper piston itself, the magnitude of the damping force is not exactly equal when damper piston moves up and down with the same displacement.

Figure 16 shows the maximum damping forces of NDDSMRD with different winding cylinders under different direct currents, the damping forces with stainless steel winding cylinder increase from 50N of 0A to 400N of 1.5A, which surpass 10% over stainless steel winding cylinder. Moreover, the damping forces of the NDDSMRD with two different winding cylinders are same when the applied current is 0A, which indicates that the material of the winding cylinder can’t influence the viscous damping force.

Figure 17 shows the damping force performance index of the NDDSMRD with different winding cylinder under the different currents, the equivalent damping and dynamic damping adjustable coefficient are shown in figure 17(a) and figure 17(b), respectively. It can be seen that the equivalent damping coefficient increases with increase of the damping excitation current, and the adjustable coefficient is
proportional to the applied currents when the current doesn’t exceed 1.0A. Meanwhile, the maximum adjustable coefficient of the NDDSMRD with stainless steel and No.10 steel winding cylinder are 6.0 and 7.0, respectively, and the maximum equivalent damping coefficients is 9.0 and 10.2 Ns/mm with excitation current of 1.5A, respectively, which means both of proposed MR dampers have a good damping performance. Furthermore, the experimental damping forces are lower than that of simulation calculation when the current applied. The possible reason is that the simulation results are obtained in ideal situations and the shear thinning effect of the MR fluid is not considered in the simulation based on the Bingham model, the leakages of the magnetic flux and the sedimentation of MR fluid will also affect the experimental results. On the other hand, the relationship between the yield stress and the magnetic flux density is obtained under the assumption that the magnetic particles in the MR fluid form a single-chain structure. However, the structure formed by the magnetic field is a column-like structure. Therefore, the saturated yield stress will be smaller in the actual experiment tests, which also makes the experimental damping forces smaller than the simulated results. Nevertheless, the change trend of damping forces from experiment measurement is in accordance with the simulation results.

C. SELF-SENSING PERFORMANCE TEST UNDER DYNAMIC EXPERIMENTS

Figure 18 shows the variation of the self-sensing voltages for stainless steel and No.10 steel winding cylinder under three different positions with the damping excitation current of 1A. Here the exciter is loaded with sinusoidal signal with frequency of 0.5Hz and amplitude of 5mm, 10mm and 15mm, respectively, and the sensing excitation coil is loaded with the same sinusoidal signal as static experiment. Observing Figure 18, it is noted that the amplitudes of self-sensing voltages for two kinds of winding cylinder increase with the increase of the displacement. In Figure 18(a), the amplitudes of the self-sensing voltages for stainless steel winding cylinder can reach to 0.3V, 0.6V and 0.9V at three different positions, while for No.10 steel winding cylinder is 0.04V, 0.08V and 0.12V, respectively, as shown in figure 18(b). Comparing both figures, it is obvious seen that the self-sensing voltages for stainless steel winding are in agreement with the simulation results.

Figure 19 shows relationship between the amplitude of self-sensing voltage and damper displacement with different winding cylinder, which indicates that the dynamic self-sensing voltages of different winding cylinders are all proportional to the piston displacement under the excitation current of 1.0A. However, the self-sensing voltage signal strength of the stainless steel winding cylinder is 7.4 times than that of the
No.10 steel winding cylinder, which means the NDDSMRD with stainless steel winding cylinder has better self-sensing performance, and it can be reasonably considered as the No.10 steel winding cylinder is magnetic steel, which makes the magnetic leakage of the alternating magnetic field more serious than stainless steel winding cylinder, thus weakens the self-sensing performance of NDDSMRD. It is noted that the amplitude of dynamic self-sensing voltage in the zero reference point is 0.001V, which is not strictly zero. However, the amplitude is small enough to ignore. Moreover, the experimental self-sensing voltages of different winding cylinders are slightly lower than simulated results, the possible reason is that the magnetic flux leakage and external disturbance are not considered in harmonic magnetic field simulation.

The self-sensing performance indexes of the proposed NDDSMRD with different winding cylinder under different direct currents are presented in Figure 20. From Figure 20(a), the linearity of stainless steel is far lower than No.10 steel, which means that the differential displacement signal is more accurate, and even the maximum linearity of stainless steel is kept within 0.21%, therefore, the linearity of stainless steel is less influenced by different direct input current. From Figure 20(b), the sensitivities of self-sensing voltage of the stainless steel winding cylinder can reach to 59mV/mm, which is 7.4 times than that of 8mV/mm for No.10 steel one, which indicates the NDDSMRD of the stainless steel has higher relative displacement measurement accuracy, and can better achieve the displacement self-sensing ability.

VI. CONCLUSION

In this paper, a novel MR damper with displacement self-sensing and damping characteristics was developed. The innovative structures of the NDDSMRD were two self-sensing coils wound on the winding cylinder, and two concentrical coils winding around the damper piston, which the inner one served as the damping force excitation coil and the outer one served as the sensing excitation coil.

The electromagnetic simulation results indicated that the magnetic flux density generated by damping excitation coil distributed in the effective damping gaps of the No.10 steel winding cylinder exceeded that of the stainless steel one, and the maximum simulated damping force of stainless steel winding cylinder was 712N, while the No.10 steel winding cylinder was 1068N. The amplitudes of the self-sensing voltage were proportional to the relative displacement between piston and winding cylinder, though the winding cylinders were different and the self-sensing voltage signal strength of the stainless steel winding cylinder was larger than that of the No.10 steel winding cylinder.

In the static experiments, the self-sensing voltages changed equivalently with the same change of the relative displacements, and the amplitude of self-sensing voltage was proportional to the damper displacement. Moreover, the self-sensing voltage of the stainless steel winding cylinder was larger than that of the No.10 steel winding cylinder at the same position.

In the dynamic tests, the maximum damping forces with stainless steel winding cylinder was 360N of 1.5A, while the stainless steel winding cylinder was 400N, which surpassed 10% over stainless steel winding cylinder. The self-sensing voltages for stainless steel winding cylinder exceeded that for No.10 steel winding cylinder by almost one order of magnitude that was in agreement with the simulation results. Besides, the self-sensing voltage signal strength of the stainless steel winding cylinder is 7.4 times than that of the
No.10 steel winding cylinder, which means the NDDSMRD with stainless steel winding cylinder has better self-sensing performance.

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