Key factors in Optimal Design of MR Device except Magnetic Circuits

LIKANG YANG[1,2], FUBIN DUAN[1], E. ANDERS[2]
(1 College of Mechanical and Automotive, Zhejiang University of Science and Technology, Hangzhou, 310023, China)
(2 Department of Mechanics, the Royal Institute of Technology (KTH), Stockholm, SE-100 44 Stockholm)

Abstract: - Most of design processes of the MR device only focus on their magnetic circuit analysis. During the exploring of Magnetorheological(MR) fluid applications, the design method is getting important to MR devices in developing primary products. Based on the usual magnetic circuit design, the MR Adaptive structure design method was presented according to the whole requirement of Adaptive structure characteristics. In other words, the Adaptive structures design methods do not just execute optimization according to magnetic circuit requirement, and it can customize the whole system's key requirements. Besides usual magnetic circuit design analysis, by utilizing the structural parameters, the response time of MR devices was considered by analyzing the time constant of electromagnetic coils inside the MR devices too. Additionally, power consumption relevant to transient useful power was analyzed for structure design. Finally, based on the computation of magnetic field in finite element analysis method (COMSOL multiphsics), all these factors were illustrated respectively in a MR fluid valve based on the results of magnetic circuit design.

Key-Words: : - Megnetorheological devices, Optimal design, Adaptive structure

1 Introduction

During recent years the report about MR fluid commercial employment began increasing. This indicates that the design methods which can decrease the cost, manufacture period and improve the performance will be more important. Though the structure of MR device is simpler than its counterpart hydraulic devices, it needs efficient design method.

The main design method of MR devices is optimization. For example, some researches on the optimal design of magnetic circuit were studied[1, 2, 3]. These design method didn't directly involve the response time of MR devices.

One important fact to keep in mind is that while an engineering system consists of various components, the optimal individual component that makes up a system does not lead to an optimal system. MR Adaptive structure includes smart material properties and mechanical structure. In the design procedure of a MR device, there are three key domains should be considered: (a) the design of mechanical structure which should satisfy the motion demand; (b) the design of magnetic circuit which should confine the magnetic flux saturation at part of the circuit; (c) the whole MR devices' respond time should satisfy the controllable dynamic requirement.

In this paper, not only the optimal design method will be analyzed, but also the MR devices' response time and electric power consumption will be investigated based on the optimal design results of magnetic circuit saturation design.

2 the factors affecting the respond time

The MR devices must depend on their driving electronics (or its controller) to regulate the MR fluid dynamic yield stress. Though less than 1ms the MR fluid can be shifted from fluid state to semi-solid under the control current, which issued by Lord Corporation[4], the circuit itself needs response time to reach the command current. In other words, in most MR fluid devices the overall response time is limited not by the MR fluid but by the inductance of the electromagnet and the output impedance of the driving electronics. The practical response time can be got from some experimental results. For example, the response time of a rotor system on a magnetorheological(MR) fluid squeeze film damper was measured experimentally. It indicates that the response time of MR fluid devices is 0.05~0.7s in applying voltage, and 0.01~1.225s in dropping voltage respectively, including all kinds of the effect[5].

The inductance of the electromagnet also play a significant role in the performance of MR dampers' response time[5,6], however, the MR devices controller usually is designed independently of its structure design. Parameters in structures affecting the response time of MR devices were not considered during the design phase, and they don't ensure the rapid response time for real-time control applications. For the structure designer, it's difficult to consider the characteristics of the driving electronics used for activating the damper in structure design, but the electromagnetic coil's, which is equivalent to an inductance in series with a resistance in circuit, can be considered easily in structure design phase.

To quantify the effect on the circuit response time resulting from the inductance of the electromagnet inside the MR damper, it needs to refer to the behavior of the simplest circuit shown in Figure 1, which composed of resistance and inductance [30]. When an excitation (such as step or impulse current) is applied to this circuit, the steady state reached after a decaying exponential response.

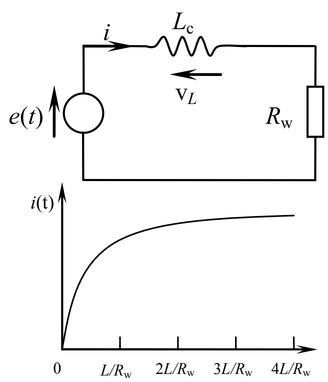


Figure 1. The series R-L circuit and its step response

The rate of decay depends on the electrical parameter resistance(R_w) and inductance (L_c), i.e. time constant of the circuit

$$T = L_c / R_w \tag{1}$$

For step current input, assuming that no current flow before the step is applied, continuity of current in circuit is

$$i(t) = I[1 - \exp(-t/T)] \tag{2}$$

where I is the supplied current, L_c is the inductance and R_w is resistance, t is the time needed to reach i(t).

And the schematic illustration of the step response of this kind of R-L circuit is shown in figure 1. Here define the response time as the time required to transition from the initial state to 95% of the final state, then the response time t will be 2.9957T. If the required response time is 10ms, the time constant T should be near 3.33ms. To satisfy this requirement, the designer needs to calculate the inductance and resistance. Resistance can get easily by computing the coils' wire length and multiplying with resistance-per-unit-length.

The inductance essentially depends on the parameters of the magnetic circuit, in term of the reluctance of the magnetic circuit and turns of wire in coils, the inductance in equation (1) can be defined as[7, 8]

$$L_c = N^2 / R_\Sigma \tag{3}$$

where R_Σ is the total reluctance of magnetic circuit.

3 the magnetic saturation analysis

Many researches had mainly focused on magnetic circuit saturation design[2,3,9,10]. Most devices that use MR fluids can be classified as having either fixed poles (valve mode) or relatively movable poles (shear mode). Examples of valve mode devices include servo-valves, shock absorbs and dampers, and shear mode includes clutches, brakes and chucking devices. One common feature of these devices is that the magnetic circuit is consisted of gaps filling MR fluids and other parts. The magnetic field intensity in these gaps influences the yield stress of MR fluid directly. The magnetic induction in the damping gap is limited by the minimum saturated magnetic flux of all the other parts, because the magnetic fluxes are the same in the magnetic circuit. Hence the actual maximum magnetic flux is[3]

$$\phi_{\max} = \min(B_1 S_1, B_2 S_2, \cdots, B_g S_g) \tag{4}$$

where B_1, B_2, … is saturation magnetic flux density of different part respectively. S_1, S_2, … is the cross section area of in different part magnetic circuit respectively, B_g and S_g are the magnetic flux density and cross section area of magnetic circuit in the gap,

So the maximum magnetic induction of damping gap is

$$B_{g\max} = \phi_{\max} / S_g \tag{5}$$

4 Ratio of Lost Power

The equation (1) and (2) show that decreasing the response time needs reduce the inductance and increase the resistance R_w, however, for steady current, larger resistance may lead to more electric power wasting

$$P_w = I^2 R_w \tag{6}$$

where I is the maximum current, R_w is the resistance of coils.

For magnetorheological devices, the useful power can be expressed as the produced damping force F (or torque) multiplying by corresponding velocity v (or angle velocity) at that moment. For the on-state MR devices, these two kinds of power grossly illuminate that part of the supplied energy is consumed producing resistance heat and the other part is converted into magnetic energy. The induced magnetic energy leads to micro-structure inside the MR fluid to resist the outside motion of piston or other moving parts. The relative power wasting can be expressed in term of ratio of lost power to useful power as

$$P_l = I^2 R_w / Fv \tag{7}$$

where F is the maximum force and v is the corresponding maximum velocity.

In MR devices design, the ratio of lost power can be limited by improving its damping function and restrict its power wasting.

5 the optimal design model

The main capacity of all the MR fluid devices, such as damper, clutch, brake and so on, is its controllable force. The force is composed of two parts which are viscous force and controllable force. The controllable force is usually far larger than the viscous force. During the structure design phase the designer can just focus on the controllable force structures which don't affect the viscous force structure. By the way, the viscous force must be considered during the controller design phase.

In the literature, it is found that characteristics of MR fluids can be described by a simple Bingham plastic model and Hershel-Bukley[11~13]. The Bingham model is adequate to structure design[13]. The force capacity can be computed based on the structural parameters, MR fluid property parameters, and mechanical motion dynamic parameters, details about this can be found in many literatures[13].

The whole optimization problem can be expressed as

Minimize $F(x)-F_t$ (8)

Subject to

$0<H(x, N)<H_{max}$

$0<T<T_t$ and $P_l<10\%$

$x \in X$

where F_t is the target force, φ_v is the volume fraction, T_t is the target time constant, X is the constraints of geometric dimensions, H_{max} is maximum the magnet field intensity in gap, N is numbers of the wire winding turns. The coil was chosen according to the maximum current value. P_l is the ratio of lost power.

6 the optimal design instance analysis

Considering the magnetic circuit design, many researches on optimal design have been done. To simplify the analysis procedure, except for the magnetic circuit, the other factors will be analyzed based the volume-constrained design of magnetic circuit results, in which the height(L)and diameter (D=2R) was specified by prescribing maximum values, they're shown in figure 2. This means that the magnetic circuit is the same as that in literature [2].

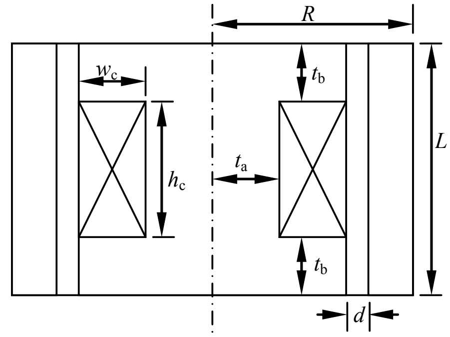
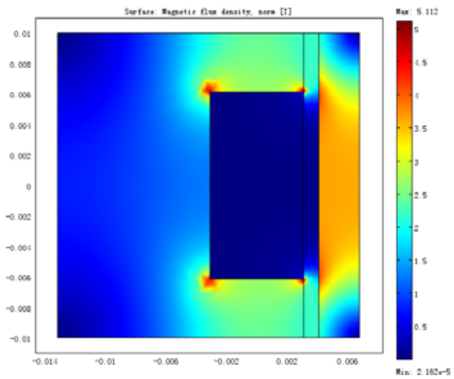


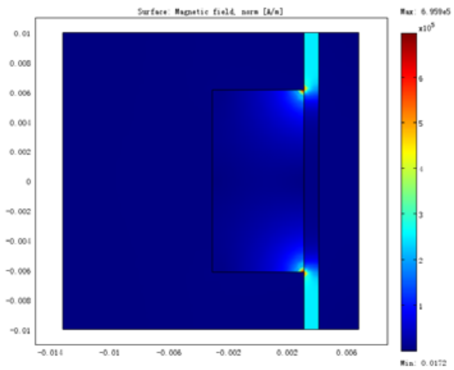
Figure 2. MR valve geometric dimensions

The geometric dimensions shown in figure 2 are: radius R is 20mm, height L is 20mm. The structural parameters, such as bobbin core radius t_a, bobbin flange height t_b, gap width d, coil width w_c, and coil height h_c, will be get by computation. Small changes in the valve gap d, would drastically affect the performance of different valves, so a fixed gap(d=1mm) was also used to ensure an unbiased evaluation in literature[2]. In practice, the width and height of the wire coils could not be varied continuously; they are integer multiples of the diameters of the individual wire strands. 24-gauge (copper diameter is 0.516mm, the dielectric diameter is 0.57mm, resistance-per-unit-length is 0.0842Ω/m at 20℃ , resistivity is 1.72e-8Ωm) wires were also chosen[7]. For convenience, the width of the coil was expressed as the number of the circumferential wire layers, or wraps. For the constraint that critical areas which the magnetic field passes in magnetic circuit were the same size, the geometric dimensions can be got for 8~22 wraps[2].

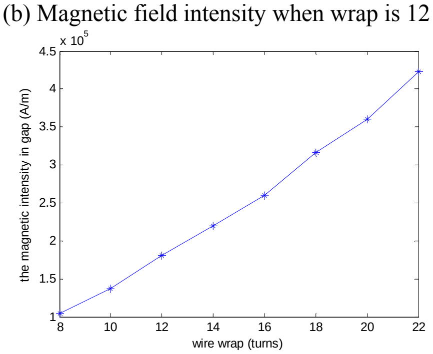
The magnetic flux density and magnetic field intensity in the MR valve gap was calculated using finite element method (COMSOL multiphysics). The results are shown in Figure 3 (a) (b) (c). Figure 3 (d) shows the damping force at different dimension for diverse warps.



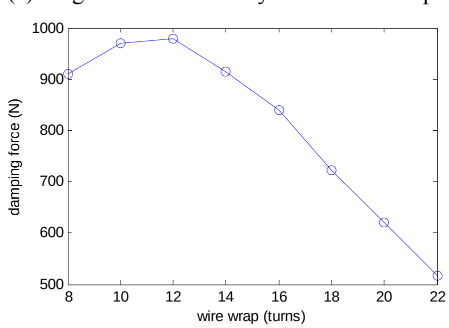
(a) The magnetic flux density when wrap is 12



(b) Magnetic field intensity when wrap is 12



(c) Magnetic field intensity at different wraps



(d) Damping force at different wraps

Figure 3. The properties of damping force and magnetic field intensity

Figure 3 (c) describes the magnetic field intensity in gap is almost proportional to the turns of coils. Though the magnetic field intensity increase, by contraries, the damping force in Figure 3 (d) drops down when the wraps exceed 12. The reason is partly that the magnetic field intensity approaches magnetic saturation of MR fluid (MRF-132AD) as it reaches 250 kA/m, and the active volume decrease at the same time[2]. This indicates there two factors need to be considered designing the better performance for MR devices. They are not only geometric dimensions but also the MR fluid properties. Especially for volume-constrained MR devices, if the maximum damping forces can't obtain the aimed value, or the controllable region is two narrow, it's necessary to consider change the MR fluid properties, such as it's volume fraction of iron particles in the fluid. The possibility was analyzed in next section.

The time constant of different dimensions is shown according to its wraps respectively in figure 4.

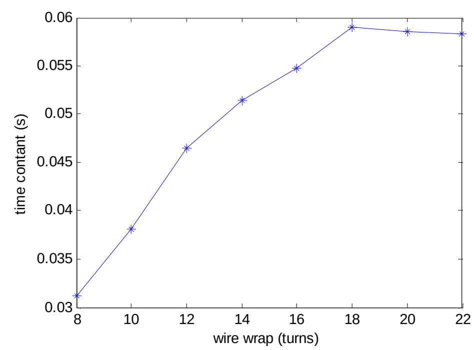


Figure 4. Time constant of the electromagnet coils

It shows that time constant generally get longer as more wraps were applied, and the increasing rate get slower. This is because the coils flux approaches saturation as the wraps increase, and don't store more energy. This indicates to make the response time shorter the designed MR devices should be far from its saturation. This complies with the requirement to widen controllable region of MR devices, but opposite to the stronger magnetic field intensity demand. In practical design, it needs the tradeoff of these two situations.

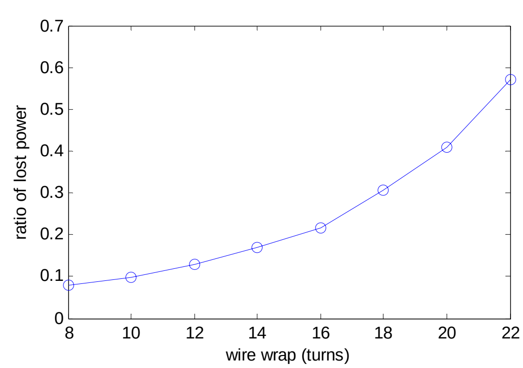


Figure 5. The ratio of lost power

The results of power lost analysis was plotted in Figure 5, where the curve represented the lost power performance of the different dimensions pertain to the wire wrap. The ratio of lost power increase continuously as the geometric dimensions increase according to the wire turns. The rate of increasing also gets larger when the wire turns increase in figure 5, and this indicates it can't just improve the magnetic field intensity just by adding wire turns, though the lost power lower than useful power at most cases. And on the other hand, this indicates that the increasing rate of MR devices' damping force power is less than its resistance power. The ratio of lost power shifts from 7.84% to 60% according to the geometric dimensions calculated at 8 to 22 wraps. In practical design, the ratio of lost power must be considered.

The resistance is included in both the time constant and power computation. The lower time constant demands higher resistance which may lead to higher power consumption and lower useful power ration. These two factors can be compromised during design.

For candidate dimensions of 8~22 wraps, the dimensionless time constant and ratio of useful power can be obtained by dividing its maximum value respectively. The results are shown in figure 6. The two curves intersected at the point 'A' in figure 6. The Candidate results, which are in close vicinity of the point 'A' or in the left section of the point 'A', are the near-optimal results having lower time constant and higher useful power ration. So the result is near-optimal when wrap is 10 or 12 obeying to this rule.

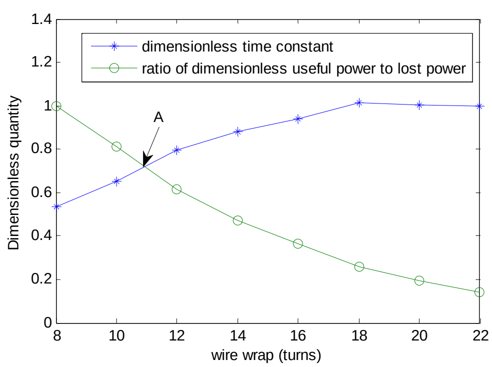


Figure 6. The tradeoff between useful power ration and time constant

7 Conclusion

Considering response time, magnetic circuit design and efficient power, the design method was analyzed. Using the magnetic field computation by finite element analysis method (COMSOL multiphysics), based on the results of magnetic design, a MR valve's properties were illustrated too. All these can supply propose for the effective design of MR devices.

The key factors need to be considered during MR devices development. By contrast with usual product, response time is another factor for Adaptive structure for its vital controllable virtue. So the time constant of electromagnetic coils' inside the MR devices is analyzed in this study, and it express the method which incorporate this parameter in structure design.

At the same time, the fundamental tradeoff between the useful power and time constant is pointed out in this analysis can limit the excessively bad situation.

All these provide recommendations for the effective design and fabrication of MR dampers or relevant devices. In other words, the MR devices design need to synthetize the key factors that influence their properties, such as magnetic circuit, response time and so on.

Acknowledgements

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Reference:

[1] Yang L K, *The theoretical and experimental investigation on semi-active vehicle suspension employing magnetorheological technology*, Ph.D Dissertation, Zhejiang University, 2003

[2] Zhang H H, Liao C R, Chen W M and Huang S L, A magnetic design method of MR fluid dampers and FEM analysis on magnetic saturation, *Journal of Intelligent Material Systems and Structure*, Vol.17, No.8, 2006, pp.813-818

[3] Kaneda T, Shizawa K and Tanahashi T, Theoretical consideration on the fundamental behavior of conducting magnetic fluids, *JSME International Journal*, Vol.30, No.268, 1987, pp.1567-1576

[4] Zhu C, The response time of a magnetorheological fluid squeeze film damper rotor system, *Key Engineering Materials*, Vol.334-335, No.II, 2007, pp.1085-1088

[5] Jeong H K, Fernando D G and Mehdi A, A comprehensive analysis of the response time of MR dampers, *Smart Materials and Structures*, Vol.15, 2006, pp.351-358

[6] Sander K, *Electric circuit analysis: principles and applications*, Addison-Wesley, 1992

[7] Guru B S and Hiziroglu H, *Electromagnetic field theory fundamentals*, Cambridge university press, 2004

[8] Walid H E, *Finite element analysis based modeling of magneto rheological dampers*, Master thesis, Virginia, 2002

[9] Li W H, Du H and Guo N Q, Finite element analysis and simulation evaluation of a magnetorheological valve, *International Journal of Advanced Manufacturing Technology*, Vol.21, 2003, pp.438-445

[10] Lee D Y and Wereley N M, Quasi-steady Herschel-Bulkey analysis of electro- and magnetro-rheologcal flow mode dampers, *Journal of Intelligent Material Systems and Structures*, Vol.10, No.10, 1999, pp.761-769

[11] Wang X and Gordaninejad F, Flow analysis of field-controllable electro- and magneto-rheological fluids using Herschel-Bulkley model, *Journal of Intelligent Material Systems and Structures*, Vol.10, No.10 1999, pp.601- 608

[12] Lindler J and Wereley N M, Quasi-steady Bingham plastic analysis of an electrorheological flow mode bypass damper with piston bleed, *Smart Materials and Structures*, Vol.12, 2003, pp.305-317

[13] Wereley N M and Pang Li, Nondimensional analysis of semi-active electrorheological and magnetorheological dampers using approximate parallel plate models, *Smart Materials and Structure*, Vol.7, 1998, pp.732-743