Design of the Voltage Driver Circuit for Magneto rheological Damper

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Abstract. In order to improve the response speed of magneto rheological (MR) damper, the system is in need of a fast response driving power supply. Firstly, response characteristics of the MR damper was analyzed. Secondly, according to the basic principle of electromagnetic response, the design of the control software and the hardware circuit with a step-down BUCK circuit as the main circuit and a PID controller were proposed. The performance test of the designed power supply show that the coil current response time of the MR damper is less than 1ms driving by the power supply developed, which can meet the corresponding requirements of control system of the MR damper. The success of the driving power supply lays a foundation for further improvement of the control performance of MR damper.

Introduction

The dynamic quality of the magneto-rheological (MR) damper response was determined by the characteristics determine. During the process of the design and the performance assessment of the damper, the response is an important factor in the performance, which includes the rheological response and electromagnetic response of the MR damper[1]. The speed of the Rheological response is faster, and the electromagnetic response becomes integral part of the response of MR damper. The electromagnetic response is closely related to the form of the driver circuit.

In recent years, the application of magneto-rheological dampers was received widespread attention. The transient response performance of magneto-rheological dampers were studied by Ren Jian-ting[2], the impact of the structural parameters and the circuit parameters for the response time were analyzed. The corresponding achievements were made for the excitation driving circuit of the MR damper. The current drive of the MR damper was designed using the PWM switch mode by Yu Miao et al[3]; the intelligent controller was designed based on the DSP2812 by Shen Na et al[4]; the driving circuit of the MR shock absorber excitation coil was designed based on the PWM integrated chip TL494 by Zhu Shi-xing et al[5]; which the circuit response time was less than 1ms; there are many studies have also made appropriate progress[6-8].

In this paper, based on the principle of the MR damper, the BUCK circuit was selected as a main circuit topology and the PID controllers was introduced, which the response of the circuit could be improved and at the same time the circuit output could be linear controlled in this program.

Response analysis of MR damper

Rheological response

The time which was required during the magneto-rheological fluid changes from a steady flow to another in magnetic field was called rheological response time. The rheological response time was studied form both the theoretical and experimental aspects in the paper [2], and the results show that the rheological response time

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depends on the material properties (Viscosity, density and volume content of suspended particles) of MRF and the size of the working gap of the MRF devices. The rheological response time increases with increasing working gap, and the time which the MRF flow from the Newton transition to Bingham is greater than the time flowing in the opposite direction. Hayward's studies[9]. have shown that the bulk modulus of the fluid varies with entrained air content, therefore, the air content in the fluid is also an important factor influencing rheological response time[10]. Currently some qualitative results of the rheological response time were obtained but the specific mathematical model of rheological response time had not yet formed.

The response time which the MR fluid reaches the steady state is less than 6.5ms measured by the LORD company[11]. The response time of MR fluids is generally 1~ 2ms in the research of Jeon[12]. At present, the preparation methods were different to product the MRF, and the response time is not exactly the same, but the response time was controlled within a millisecond basically.

Electromagnetic response

The yield stress of the MRF changes with the magnitude of the electromagnetic coil current which winding on the line trap of the MR damper, and the damping torque was obtained, so the performance of the damper was directly affect by the characteristics of the coil. Since the coil is inductive load, it has a storage effect. When switching current, the coil current is not changed with the ideal step characteristic due to the transient response in the circuit. The electromagnetic response characteristics of the coil were analyzed as follows.

Ignoring effects of eddy currents in the core, the excitation coil circuit can be equivalent the circuit which inductance and resistance were in series, which is shown in fig.1. And the control equation for the current in the coil was,

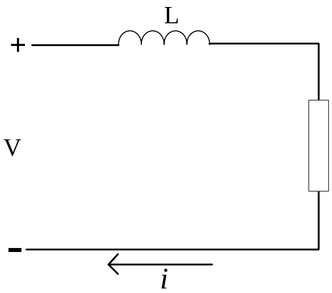

Fig.1 equivalent circuit of the excitation coil

$$L\frac{d}{dt}i(t)+Ri(t)=V(t) \quad (1)$$

Which the L and R are the inductance and resistance of the coil, and V is the input voltage.

For the voltage source, the input voltage is a constant, then the solution of (1) is

$$i(t)=i_d[1-\exp(-\frac{t}{\varepsilon})] \quad (2)$$

Which $\varepsilon=\frac{L}{R}$ is the coil time constant. And it is indicated in formula (2) that the current reaches 95% of the stable value i_d when the electromagnetic response time is 3ε at least.

With a current source instead of a voltage source, the feedback is

$$\frac{d}{dt}V(t)=\gamma[i_d-i(t)] \quad (3)$$

The coil current control equation of the current source is obtained using equation (3) into (1).

$$L\frac{d^2i}{d^2t}+R\frac{di}{dt}+\gamma i=\gamma i_d \quad (4)$$

Which γ is proportional gain, by adjusting the gain γ the power system work can be worked in underdamped ($\xi = R/2\sqrt{\gamma L} < 1$), which the current response time can be speed up. When the circuit reaches steady the state current transient response is

$$i(t) = i_d \left[1 - \frac{\exp(-t/2\varepsilon)}{\sqrt{1-\xi^2}} \cos(t\sqrt{(1-\xi^2)\frac{\gamma}{L_0}} - \varphi) \right] \quad (5)$$

Which $\varphi = atg(\frac{\zeta}{\sqrt{1-\zeta^2}})$ is phase angle.

Assuming the voltage is not saturated, the time which the coil current achieves the desired current i_d is

$$t = 2\varepsilon \frac{(\pi - \arctan\alpha)}{\alpha} \quad (6)$$

which, $\alpha = \sqrt{(4\gamma L)/R^2 - 1}$ 。

According to the equation (5) and (6), it is shown that the response time of the coil current could be significantly reduced if properly adjusting the proportional gain γ . The schematic of the current response characteristics driven by a voltage source and current source is shown in fig. 2

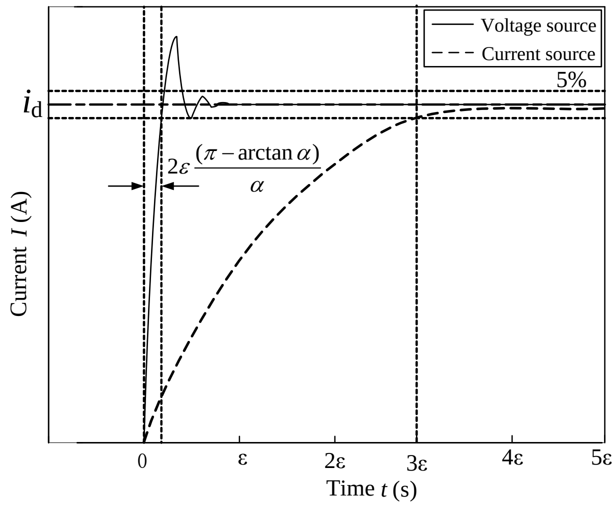

Fig.2 The schematic of the current response characteristics driven by a voltage source and current source

Based on the above analysis, the electromagnetic circuit response time is relevant to the coil parameters and the hardware design of the power control circuit. In the different power-driven, the response time of the coil step current is different. It is no sense to research the damper response regardless of the driven power.

High-speed drive power supply design

Due to the high-speed characteristics of pneumatic actuators, the coil current of the MR damper embedded in the rotary servo cylinder was required to adjusting quickly in the practical application, and was easy to connect with the outside control algorithm. According to the measured parameters and the actual control needs based on the prototype coil, the design requirements of the high-speed response driven power were proposed as follows:

(1)In step signal with the control voltage, the response time of coil current is less than 1ms.

(2)The coil current within 0 ~ 2.5A was controlled linearly by the control voltage within 0 ~ 5V.

(3)The coil current does not fluctuate under the stable control voltage.

design scheme

Based on the measured parameters of the coil, the coils can be modeled as the RL Circuit in series with the 17Ω resistance and 16mH inductance. And the coil current is:

$$i_L = \frac{U_S}{R} + (I_0 - \frac{U_S}{R})e^{-\frac{t}{\varepsilon}} \qquad (7)$$

Where the time parameter $\varepsilon = L / R$.

Depending on requirements (1), in the initial non-current conditions ($I_0 = 0$), the Voltage U_s as a step signal is applied in load, the current at $t = 1ms$ is obtained from the above equation.

$$I_{1ms} = 0.6544\frac{U_s}{R} \qquad (8)$$

According to the design requirements (2), the power supply should be at least able to meet $I_{1ms} = 2.5$ A, then U_s should be greater than 65V. Taking into account that there's no special requirements with the efficiency and power factor, To simplified the design, the alternating current (AC) was rectifier filter directly to supply power, and the voltage is about 300V. When the current reaches the set value, the U_s need to reduce, and to be stable at the value which is the product of set current and resistance $U_s = I_{set}R$. If necessary, the BUCK circuit would be selected as the main topology.

Circuit Design

The BUCK circuit is a step-down chopper, the typical BUCK circuit is shown in Figure 3. The main circuit is composed by the switch S, freewheeling diode D, the output filter inductor L and output filter capacitor C.

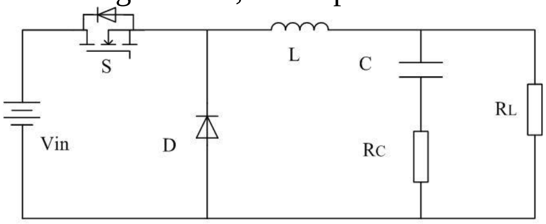

Fig.3 BUCK circuit

In order to improve the stability of BUCK circuit, PID controller is added to the circuit in order to achieve closed-loop control. Output current is obtained by sampling, the duty cycle of the PWM modulation signal can be calculated by the main control chip according to the error amount between the output current and setting current. The switch S is controlled by the PWM signal, then the output current can be reach and stabilize at the set value quickly. Consider computing speed and reliability, the Freescale DSP56F8013 was chosen as the control chip.

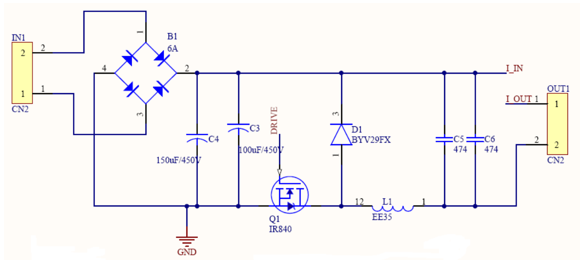

Fig. 4 Main circuit

The main circuit is shown in figure 4. The alternating current was rectifier using the full bridge non-controlled rectifier circuit (B1), and was smoothing by two electrolytic capacitors (C3、C4), so it can be as a DC input voltage to BUCK circuit. In the design the Hall sensors were used to sampling coil current, and in the fig.4., I_IN and I_OUT1 were the Hall sensor inputs and outputs respectively.

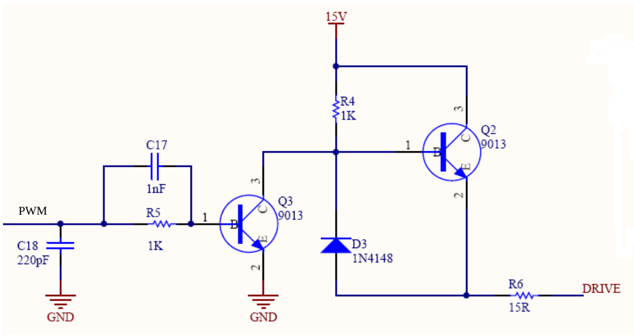

Fig.5 Drive circuit

The MOS tube was placed in the bottom circuit, which does not affect the circuit characteristics and would be for the convenience of driving MOS tube. It is shown as fig.5 where the "PWM" is a driving signal of the DSP chip outputs, and the "+15V" is the external auxiliary power supply. The amplitude of the PWM drive signal is 3.3V, and it can be driven MOS tubes after enlarged to 15V through driving circuit

Control Software Design

The software is primarily used for controlling two channel AD collection. One channel is to obtain the output current which is set by the user, the other is to sample the actual size of output current and to control the PWM output to regulate the current output. The specific procedures is shown in Figure 6.

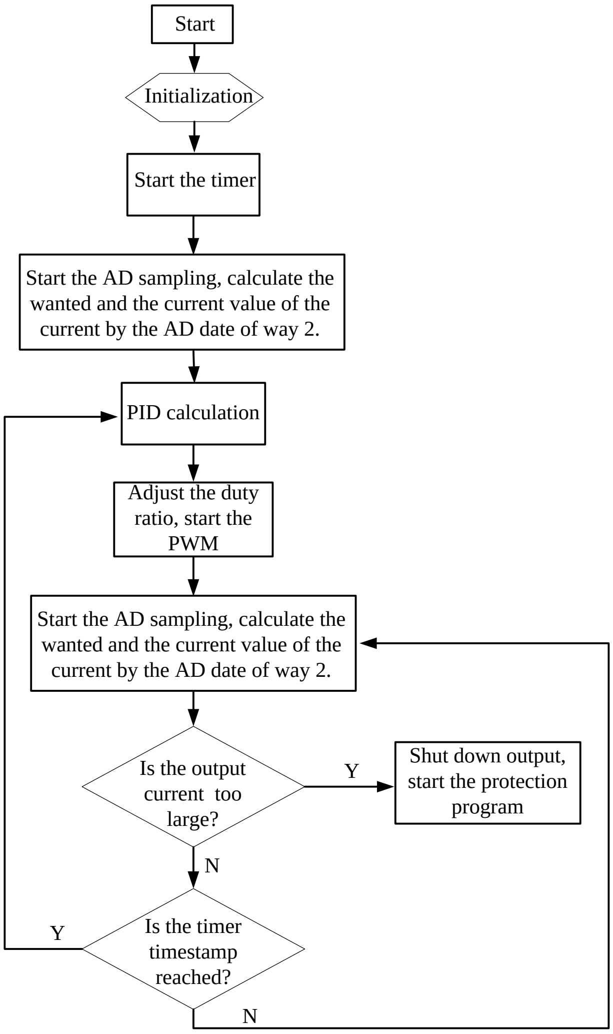

Fig.6 program flowchart of damper drive voltage

After the initialization operation, the program is to start to record the actual output current and the set value circularly. The duty cycle of the PWM signal is timing controlled according the PID operation. The exception handler would be entered and the output would be closed if the current is too large in the collection process.

Performance Test drive power

In order to examine whether the design of drive power performance to meet the design requirements, its performance would be needed to test. The response characteristics of the damper excitation coil would be measured under the different control voltage with the power supply driven. The photograph of damper drive power is shown in Figure 7.

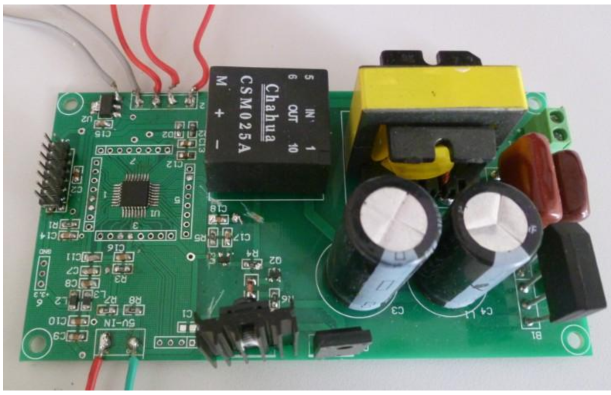

Fig.7 The photograph of damper drive power

The current response waveform of the damper excitation coil under the step control voltage of 1V, 2V, 3V, and 4V respectively were shown in figure 8. As can be seen from the test waveforms, the current had less overshoot. The current reached the set value within 1ms, and was stable at the set value within 3ms without fluctuation.

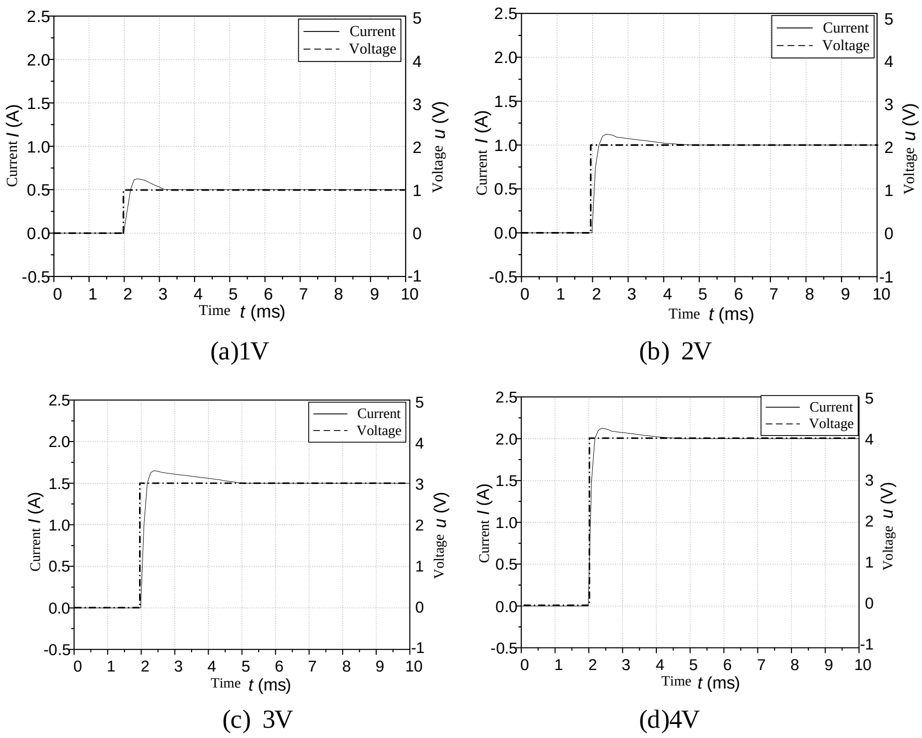

Fig.8 The current response waveform

The experimental data and the fitted curve of the damper drive power control voltage and the coil current were shown in fig.9. As can be seen from the fig.9, the curve fitting was linear basically and the error is small. And the control voltage u and the coil current I can meet the function (9):

$$I = 0.5u \quad (9)$$

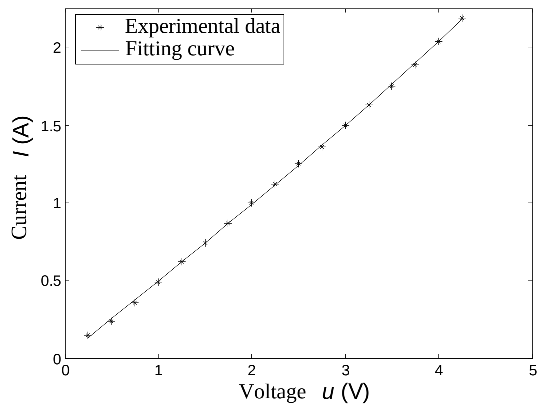

Fig.9 relationship between control voltage and output current

Measurement of the excitation coil current driven by the power show that the proposed three design requirements of the damper drive power were reached.

Conclusion

1）The MR damper response was analyzed. The response time of MRF is in milliseconds. The MR damper response time is mainly affected by the response time of the solenoid. And the response characteristics of the electromagnetic coil was analyzed.

2）The hardware circuit design and software design of the MR damper drive power were proposed in this paper, which the BUCK circuit was selected as a main circuit topology and the PID controllers was introduced. The performance testing of the driving power indicates that the current response time of MR damper coil can be less than 1ms with the power supply.

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