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DESIGN AND USE OF AN EDDY CURRENT RETARDER IN AN AUTOMOBILE

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ABSTRACT−In this study, the structure and working principles of an eddy current retarder acting as an auxiliary brake set is introduced in detail. Based on the principle of energy conservation, a mathematical model was developed to design a retarder whose nominal brake torque is 1, 900 N·m. According to the characteristics of the eddy current retarder, an exclusive test bed was developed and used for brake performance measurements. The main technical parameters, such as the brake characteristics, temperature characteristics and power consumption, were measured with the test bed. The test data show that the brake torque of the eddy current retarder obviously decreased in the continuous braking stage and that there is a certain amount of brake torque in the normal driving state because of the remnant magnetism of the rotor plate. The mathematical model could be used to design an eddy current retarder. The exclusive test bed could be used for optimization of an eddy current retarder as well as for R&D of a series of products.

KEY WORDS : Auxiliary brake, Eddy current retarder, Mathematical model, Design, Test

1. INTRODUCTION

Modern automobile design is focused on driving safety, comfort and environmental protection. With the increase in driving speeds and loads, the main brake system is no longer satisfactory for meeting the braking requirements of heavy-duty vehicles and buses. Because of space constraints, it is hard to increase the braking efficiency of the main brake system through improved design. Traffic accidents usually occur when brake plates or brake drums become overheated after the main brake system has been working for a long time. This is especially true for long downhill routes. Technology laws have been put in place in many nations requiring that auxiliary braking devices must be installed for specific vehicles. Auxiliary braking devices include exhaust brakes, eddy current retarders, engine brakes and hydraulic retarders. The eddy current retarder is the most common type of auxiliary braking device.

Because it is a non-contact, continuous type of brake set, the eddy current retarder can improve comfort, especially in the automobiles used in the urban setting that need to brake frequently in the normal course of driving. This device is not used for stopping an automobile; it is only used as a complement to the main brake system. After an eddy current retarder is installed in an automobile, the frequency of main brake system use decreases, so the life of the brakes is extended. Because most of brake load is taken on by the eddy current retarder, the temperature rise in the brake disc or drum is reduced, and the braking efficiency of the main brake system is improved. Therefore, the safety of the automobile is also enhanced. Because the main brake system gets used rarely, the brake noise and dust can also be reduced, so this system benefits the environment. Currently, in heavy automobiles and large-scale passenger cars, the eddy current retarder has a standard configuration. However, the design technology of eddy current retarders needs to be perfected and developed further.

2. ANALYSIS MODEL

2.1. Structure and Working Principle

An eddy current retarder is made up of eight cores, an air gap, coils and rotor plates, as shown in Figure 1. A coil is installed on the cylindrical surface of a core. The coil creates the windings. There is an even number of windings, and they are distributed equally around the circumference of the core. When the windings of the eddy current retarder are electrified, the kinetic or potential energy of the automobile can be transformed into thermal energy and dissipated into the atmosphere by a wind tunnel cast in the rotor plate, according to the electromagnetic principle.

When a driver turns the control handle for deceleration or braking, the windings of the eddy current retarder are electrified automatically. As a result, the magnetic line among the field stator poles, the air gap, and the front and rear rotor plate constitutes a loop, as shown in Figure 2.

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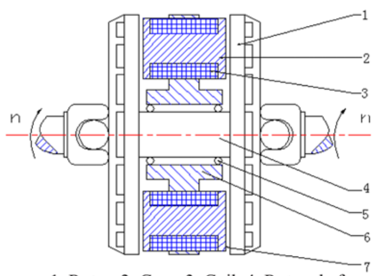
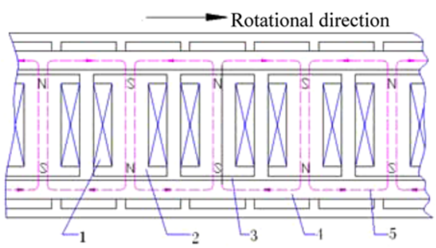


1. Rotor, 2. Core, 3. Coil, 4. Rotor shaft,
5. Bearing, 6. Fixed frame, 7. Air gap

Figure 1. Structure of the eddy current retarder.



1. Coil, 2. Core, 3. Air gap, 4. Rotor plate,
5. Magnetic line of flux

Figure 2. Magnetic line of an eddy current retarder (circumference stretch).

The magnetic line is cut by the rotor plate when rolling in the magnetic field, such that innumerable eddy currents are subsequently formed in the rotor plate, and most of them appear on the inner side because of the skin effect. Joule heat is then generated by the interaction of the eddy current and the resistance. The magnetic field holds back movement of the electriferous conductors. The resistance direction can be judged by Fleming's rule.

2.2. Conservation of Energy

When the eddy current retarder (and the air drag, mechanical friction losses and tires losses) brakes an automobile, the reduced mechanical energy of the automobile is transferred into heat in the rotor plate, as described in equation (1):

$$\Delta(E+V)-Q=0 \tag{1}$$

where $\Delta(E+V)$ is the amount of mechanical energy change and Q is heat quantity generated by the rotor plate.

The energy consumed by the eddy current retarder in the braking process is equal to the amount of mechanical energy change

$$\int_0^T p\mathrm{d}t-\Delta(E+V)=0 \tag{2}$$

where p is the instantaneous power of the eddy current retarder and t is time.

The instantaneous power of the eddy current retarder is as follows:

$$p=\frac{2S^2\Delta_{\mathrm{h}}B^2\omega^2\sin^2\omega t}{\pi\rho} \tag{3}$$

where S is the air-gap area of the magnetic yoke, Δ_{h} is the equivalent skin depth, B is the magnetic induction density, and ω is the angular velocity of the magnetic field in the air gap. ρ is the resistance of the rotor plate.

2.3. Brake Torque

By equation (3), an effective braking power is given as follows:

$$P=\frac{1}{T}\int_0^T p\mathrm{d}t=\frac{S^2\Delta_{\mathrm{h}}B^2\omega^2}{\pi\rho} \tag{4}$$

According to equation (4) and $P=T\omega_{\mathrm{n}}$, the brake torque could be given as follows:

$$T=\frac{N_{\mathrm{p}}^2S^2\Delta_{\mathrm{h}}B^2\omega_n}{\pi\rho} \tag{5}$$

where T is the brake torque, N_{p} is the magnetic pole (its quantity is 4) and ω_{n} is the angular velocity of the rotor plate, The relational expression between the angular velocity of the rotor plate and the angular velocity of the magnetic field is given as follows:

$$\omega=N_{\mathrm{p}}\omega_{\mathrm{n}} \tag{6}$$

3. DESIGN EXAMPLE

3.1. Structural Design

In this paper, the design torque of the eddy current retarder is 1,900 N·m, corresponding to a rotational speed of 1000 rpm. The equivalent skin depth can be determined by the following expression:

$$\Delta_{\mathrm{h}}=\sqrt{\frac{2}{\omega\mu_{\mathrm{r}}\mu_0\sigma}} \tag{7}$$

where Δ_{h} is the equivalent skin depth, μ_{r} is the relative permeability, μ_0 is the space permeability (its quantity is $4\pi\times10^{-7}$ H/m) and ω is the angular velocity of the magnetic field in the air gap. The material physical values for the rotor plate were substituted into the above expression, and Δ_{h} was equal to 0.7958 mm.

After the magnetic circuit of the eddy current retarder has been simplified, the magnetic induction density B can be deduced as follows:

$$B=\frac{\mu_0S_pNI}{2l_g} \tag{8}$$

where S_p is the section area of the iron, N is the number of windings, I_g is the current intensity and is the air gap (1.4 mm here).

According to Equations (6)~(8), the main design

Figure 3. Design example of an eddy current retarder.

parameters of the eddy current retarder are given as follows: ① There were 8 cores and coils, and they were distributed equally around the circumference. The diameter of the core was 90 mm, the number of turns of the coil was 294, and the total current excitation was 105 A. ② The outer and inner diameters of the rotor plate were 475 and 350 mm, respectively, and its axial distance was 16 mm. There were 16 cooling blades in the rotor plate, and the structure of the blade was an after-curved shape (inlet blade incidence: 36.8º, outlet blade incidence: 28.3º). ③ The air gap between the magnetic yoke and the rotor plate was 1.4 mm. ④ The shape of the magnetic yoke was sectored, there were 8 sections and the area was 6746.1 mm^2.

The rotor was made up of two rotor plates and a rotor shaft. The shape of the rotor plate was a circular ring. Usually, the rotor plate is made of ferromagnetic materials with high magnetic inductivity and low remnant magnetism. Electrically pure iron, low-carbon steel and other magnetic materials are often used. The two rotor plates were connected with the rotor shaft.

In order to promptly emit the heat energy generated by the eddy current and to control the temperature rise in the rotor plates, there were many leaves and air channels. The rotor was connected with a transmission shaft by two pairs of flanges, and it rotated freely with the transmission shaft. There was a very small air gap between the rotor plate and the stator poles, and the former and latter air gap were uniform to ensure that the rotor did not scratch the stator during the rotating process. In order to reduce the reluctance, a smaller value should be selected for the air gap. However, when determining the size of the air gap, machining tolerances, the thermal expansion and other factors must also be considered. The air gap should not be too small. It is generally selected to be in the range between 0.76 m and 1.70 mm for different structural types of eddy current retarders.

3.2. Calculation of Brake Characteristics

When the design parameters of the eddy current retarder were substituted into equation (5), the values of the brake characteristics were determined, as shown in Table 1. The table shows that the brake torque increased with rotational speed, and after it achieved its maximum value, the brake torque declined with further increases in the rotational

Table 1. Calculated values of the brake characteristics for the eddy current retarder.

Characteristics	Rotational speed (r/min)					
	200	400	600	800	1 000	1 200
Brake torque (N·m)	956	1468	1515	1529	1526	1506
Brake power (kW)	20.1	61.6	95.4	128.4	160.2	193.5

speed. For the case when the magnetic saturation is not considered, the relationship between the braking power and the rotational speed was approximately linear.

4. TESTING AND ANALYSIS

4.1. Test-bed Structure and Operation

The developed test bed was made up of a frequency conversion DC motor, a raising gearbox, an adjustable inertia flywheel group, a speed regulating device, and a series of sensors, such as a temperature sensor and a current sensor. The principle diagram of the test bed is shown in Figure 4. A DC motor was used for driving the raising gearbox. The eddy current retarder was connected with the transmission shaft. When an automobile is in a normal driving state, its kinetic energy is equivalent to the kinetic energy of the raising gearbox and the adjustable inertia flywheel group, so the developed test bed could model an automobile under different loads. Three temperature sensors were used for measuring the temperature rise of the two rotor plates and the windings. The torque and speed sensor was used for measuring the brake torque generated in the braking process and the rotational speed of the main shaft. The excitation voltage and excitation current was

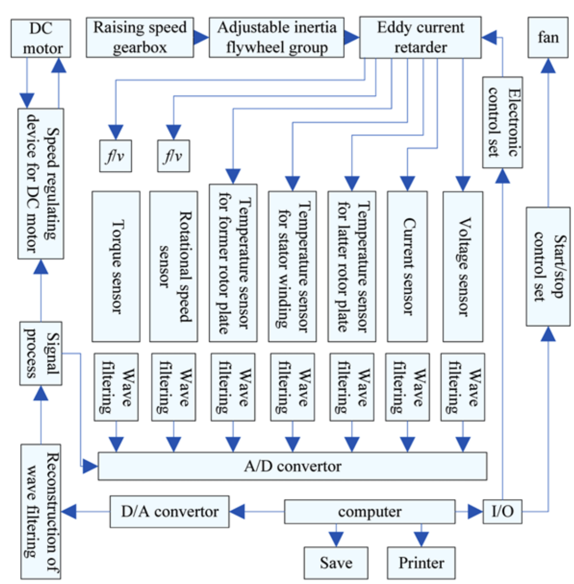


Figure 4. Principle diagram of the test bed.

Figure 5. Exclusive test bed for the eddy current retarder.

measured in order to study the excitation power and the power consumption characteristics of the eddy current retarder. Fans were used to simulate the wind speed in the process of running, and they also made it possible to simulate the actual thermal conditions of the eddy current retarder and could be used to cool the eddy current retarder rapidly. Test data were collected by the computer-centralized control.

The test bed is shown in Figure 5. The test-bed operation process was as follows: First, the DC motor was started to drag the main shaft up to the intended rotational speed. The moment of inertia of the flywheel group was used to simulate the equivalent kinetic energy of running an automobile as an energy input of the eddy current retarder. Second, the windings were electrified in different shifts for field excitation, then the parameters, including the brake torque performance, the temperature performance and others, were measured.

4.2. Testing Capabilities and Test Items

The inertia of a 3~20 T full-load automobile could be simulated in the test bed. The rotational speed range of the main shaft was 0-3000 r/min. The following test items were performed on the test-bed. ① The brake torque-rotational speed performance test: the brake torque generated by the eddy current retarder varied with the rotor speed. ② The brake torque–time characteristic, namely, the continuous brake performance test: the brake torque of the eddy current retarder varied with time at a constant rotational speed. ③ The temperature rise-time performance test: the temperature in the rotor plates and the stator changed with time as the eddy current retarder worked. ④ The brake torque-temperature performance test: the brake torque changed with temperature in the rotor plate. ⑤ The power consumption performance test: the working current and voltage in the windings varied with time as the eddy current retarder worked.

4.3. Analysis of the Test Results

The test ambient temperature was 20ºC, and the air pressure was 0.1 MPa. The fourth brake shift of the retarder was used. From Figures 6 and 7, as the brake time increased, the temperature in the rotor plate went up rapidly and then rose slowly. Joule heat generated by the eddy current in the rotor plate reached its steady state with the heat dissipating capacity of the blades. The maximum

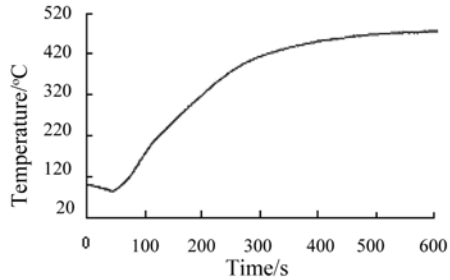


Figure 6. Temperature in the rotor plate-time curve.

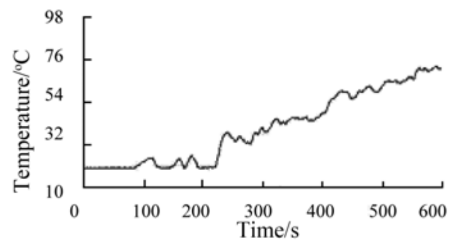


Figure 7. Temperature in the stator-time curve.

temperature on the latter rotor plate surface was approximately 505.6ºC, and the temperature on the stator went up slowly compared with that on the rotor plate. When the wire was selected, a certain level of temperature tolerance must be considered.

Figures 8 and 9 show that the winding voltage remained unchanged during the test, while the current value declines slowly. The cause of this behavior was that as the temperature rose, the resistance of the winding increased remarkably. As a result, the winding current declined.

In Figures 10 and 11, the brake torque reached its maximum value at a speed of approximately 500-700 rpm. As the brake time increased, the brake torque of the eddy

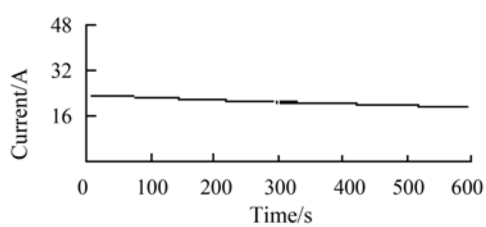


Figure 8. Winding current-time curve.

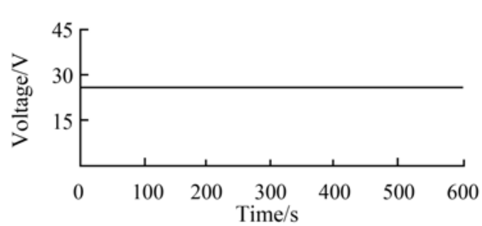


Figure 9. Winding voltage-time curve.

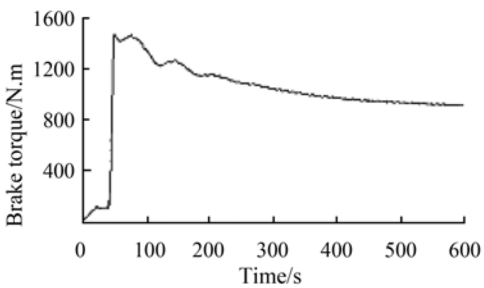


Figure 10. Brake torque-time curve.

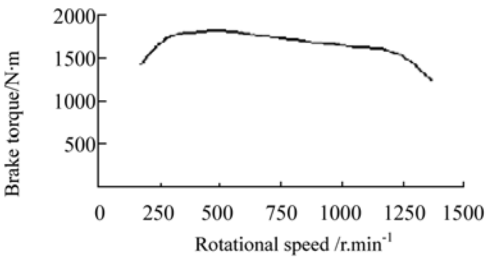


Figure 11. Brake torque-rotational speed of the rotor curve.

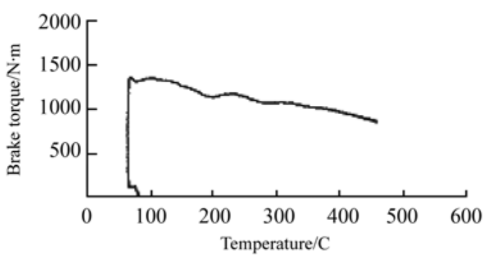


Figure 12. Brake torque-temperature of the rotor curve.

current retarder decreased rapidly by approximately 40%. It can be seen in the figure that at the initial stage, the brake torque still remained at approximately 30.5 N·m. This means that even without an excitation current (no brake status), the eddy current retarder consumed a certain amount of energy, which was a waste of energy. The cause of this behavior was that the core remanence had a certain magnetic field strength after excitation of the core. High-permeability and low-remanence materials should be selected for the core material for this reason.

Figure 12 shows that the brake torque can be divided into two stages: the initial brake stage and the continuous brake stage. The former brake torque increased rapidly, while the temperature increased slowly. For the continuous brake stage, the rotor plate brake torque declined rapidly as the temperature increased.

5. CONCLUSION

A mathematical model of the eddy current retarder was developed. Based on this model, a brake torque retarder was designed. Many performance parameters were measured in an exclusive test bed. The major conclusions obtained are given below:

(1) The eddy current retarder that was designed met the requirements, which indicates that the mathematical model of brake torque developed in this study could be helpful for designing the product.

(2) Many performance parameters of the eddy current retarder could be measured in the test bed, and the test bed that was developed was based on design optimization of an eddy current retarder and R&D on a series of products.

(3) The brake torque dropped by approximately 40% after the temperature in the rotor plate reached its maximum value on the continuous stage. On the one hand, an excessive decline in the brake torque had a serious effect on the braking stability. On the other hand, the temperature rise in the rotor plate affected the life of the eddy current retarder. Meanwhile, it was adverse to safe driving. Certain actions must be taken to limit the temperature rise, such as implementing temperature protection or time protection.

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