Fundamental study on magnetorheological fluid brake for regional jets

Taichiro. SUMI^{*1}, Norihiro. SATO^{*1}, Makoto. SONEHARA^{*2} (Mem.),
Toshiro. SATO^{*2} (Mem.), Hiroyuki. WAKIWAKA^{*2} (Mem.) and Yoshimi. KIKUCHI^{*1} (Mem.)

Non-contact type brake is excellent in maintainability so it is optimum as an axle brake for aircraft. In this paper, basic experiments were carried out using magnetorheological fluid brake experimental equipment to study non-contact type brakes, the axle size of regional jets was investigated. The maximum brake torque of a regional jet's axle size based on the experimental equipment was 2,421 Nm. This can satisfy only about 27 % of the necessary torque. In order to increase brake torque, increase the number of discs and decrease the gap h .

Keywords : Magnetorheological fluid , brake torque, temperatrrre, aircraft

(Received: 21 July 2018, Revised: 4 February 2019)

1. Introduction

Currently, aircraft use contact type brake systems. In the past, brake discs were made of steel, and now carbon composites are used. Carbon composites are more advantageous than steel in terms of heat resistance, high heat absorption and being lightweight [1], [2]. In recent years, the trend of FBW (Fly By Wire) is causing civil aircraft using contact type brakes to have electrified drive systems. However, because it depends on contact, wear of the disc is significant and performing needed maintenance actions is frequent. If the brake is both non-contact and electrically controllable, wear of the disc can be reduced, and maintenance requirements can be improved.

Currently, the authors have been studying non-contact type hybrid brakes (a hybrid of two types of non-contact brakes, ECB (Eddy Current Brakes) [3] and MRB [4], [5] (MagnetoRheological fluid Brakes)) as axle brakes for regional jet. At low rotation, the ECB brake torque decreases, so check that the change in MRB brake torque is small when the rotation speed is low. Here we report on a preliminary investigation of current-brake torque characteristics for MRB.

The purpose of this study is as follows, (1) measure the current-brake torque characteristics of multiple fluids using a small MRB system, (2) investigate whether the brake torque required for hybrid brakes can be achieved using the characteristics obtained from the experiment.

2. Structure

Fig. 1 shows a diagram of the structure of the MRB experiment equipment used in this study, and Fig. 2 shows a photo of the same equipment. The upper flange, lower flange and disc materials used are S45C, and nonmagnetic stator used SUS303. The radius of the disc is 42 mm, and the number of coil turns is 400 in total.

The gap h between the disc and the upper and lower flanges is filled with the MRF (MagnetoRheological Fluid). By applying current to the upper and lower coils while the disc is rotated, and by changing the viscosity of the MRF receiving the generated magnetic field, it is possible to change the brake torque applied to the disc.

Brake torque was measured using a torque meter (Unipulse:TM301).

The basic formula for brake torque is shown in the following equation [6].

$$T_H = \frac{2\pi}{3} N k H_{\text{MRF}}^{\beta} (r_b^3 - r_a^3) \quad [\text{Nm}] \quad (1)$$

$$T_{\mu} = \frac{\pi}{2h} N \mu_p (r_b^4 - r_a^4) \omega \quad [\text{Nm}] \quad (2)$$

T_H is the brake torque generated by the applied magnetic field, and T_{μ} is the brake torque generated by the viscosity of the MRF.

Each parameter is as follows,

k : Fluid dependent constant parameter [Pa/A/m],

H_{MRF} : Magnetic field applied to fluid [A/m],

β : Fluid dependent constant parameter,

r_a : Inner diameter of the disc [m],

r_b : Outer diameter of disc [m],

N : Number of discs,

μ_p : Viscosity of fluid [Pa/s⁻¹],

ω : Angular velocity [rad/s].

Fig. 3 shows a contour diagram of the magnetic field in the direction of the axis of rotation for the experimental equipment using JMAG. The applied current is 1 A, the number of turns of the coil is 200 in both the upper and lower sections, and the direction of the magnetic field generated from the upper and lower coils is same. In addition, in order to know the distribution of the magnetic field H_{MRF} applied to the MRF in detail, an analysis was

Correspondence: T.SumI Research center for aerospace systems, Faculty of engineering, Shinshu University 3349-1 Zakoji, Iida city, Nagano pref., 395-0001, Japan
email: 18w2062j@shinshu-u.ac.jp

^{*1}Research center for Aerospace systems, Faculty of engineering, Shinshu University

^{*2}Department of electronics and information systems engineering, Faculty of engineering, Shinshu University

performed by dividing the MRF into seven parts according to the distance r from the axis of rotation. A comparison of the magnetic field H_{MRF} in the axis direction under the disc is shown in Fig. 4. It can be seen from Fig. 4 that the magnetic field is concentrated on both the inner side and the outer side of the coil but not much between the upper and lower coils. As shown in Fig. 4, the magnetic field inside the coil was almost constant irrespective of the radius. The magnetic field inside the coil is generally larger than the magnetic field outside the coil. Since the magnetorheological fluid has a relative permeability lower than that of S45C, it has a large magnetic resistance. Therefore, it is noted that the proportion of the magnetic field H_{MRF} applied to the MRF from the total field is higher.

3. Basic study

In this chapter, after describing the current-brake torque characteristics and rotational speed-off torque characteristics of the equipment for the MRB experiment, the increasing temperature dependence on varying MRF will be explained. The objective is to clarify the fundamental characteristics of increasing temperature while under continuous operation and of brake torque against of the exciting current, the rotational speed of the disc and the type of MRF.

Fig. 1 Experiment equipment structure of MRF brake (1/4 model).

Fig. 2 Photo of experimental equipment.

Fig. 3 Contour diagram of the magnetic field in the direction of the axis of rotation of the experimental equipment using JMAG.

Fig. 4 Comparison of the radial magnetic field H_{MRF} under the disc.

3.1 Brake torque characteristics

3.1.1 Current-brake torque characteristics

Fig. 5 shows the current-brake torque characteristics when rotational speed is used as a parameter. Fluid conditions were measured using an MRF-140CG (LORD) and the fluid gap h was 3 mm. Brake torque T_H is proportional to the current I , and any differences dependent on rotational speed are small. As can be seen from equation (1), since T_H is proportional to the applied magnetic field, it is also proportional to the current and does not depend on the rotational speed. The difference between the theoretical value and the measured value was very small.

Fig. 6 shows the current-brake torque characteristics when the gap h is used as a parameter. Fluid conditions were measured using an MRF-140CG and the rotational speed was 500 rpm. At a 1 A current, the brake torque T_H was at 2.2 times when the gap h was multiplied by 1/3. This is thought to be because the magnetic resistance of the fluid decreases as the gap h decreases and magnetic field increases, so that brake torque T_H increases. The reason why it is not simply tripled is that the influence of the magnetic resistance of the upper and lower flanges becomes larger because of magnetic saturation, and the constant parameter β depends on the used MRF. β is a parameter indicating that as the magnetic field applied to the fluid increases, the generated stress gradually saturates. The theoretical value is calculated assuming that yield stress acts at the boundary between the disc and the fluid, but in reality only the force less than the yield stress appears, so the measured value was small.

Fig. 7 shows current-brake torque characteristics when the type of fluid is changed. The fluid gap h was measured at 1 mm, and the rotational speed was 500 rpm. The fluids compared with characteristics are shown in Table 1.

Fluids with a particle size of 5 μm and 8 μm and fluid mixtures of 8 μm plus 3 μm were almost equal in brake torque. In addition, the brake with particles 3 μm in diameter was largest among the silicone oil-based fluids.

Fig. 8 shows the maximum permissible current density (10 A/mm²) flows in the coil cross section area of the experimental equipment measured using the MRF-140 CG, which has the highest brake torque as shown in Fig. 7. The maximum permissible current I_{MAX} obtained is 5.45 A, and the maximum brake torque T_{HMAX} obtained is 14.5 Nm. The I_{MAX} is when the coil cross-sectional area is 120 mm², 200 turns, occupancy 0.9, current density 10 A/mm² flows.

Fig. 5 Brake torque-current characteristics with rotation speeds as a parameter (MRF-140CG, $h = 3$ mm).

Fig. 6 Brake torque-current characteristics with gap h as the parameter (MRF-140CG, Rotation speed = 500 rpm).

Fig. 7 Brake torque-current dependence on varying MRF ($h = 1$ mm, Rotation speed = 500 rpm).

3.1.2 Rotational speed-off torque characteristic

Fig. 9 shows the rotational speed-off torque characteristic with the gap h as a parameter. Speed-off torque is the relationship between the brake torque and the rotational speed when the current is 0, which is the brake torque due to the viscosity of the fluid. The higher the rotational speed the larger the off torque. Also, when the rotation speed is high, the off torque is found to be saturated. From equation (2), the off torque should increase in proportion to rotational speed. However, equation (2) is an expression that does not consider the velocity distribution of the fluid during disc rotation. So the actual value is saturated due to the influence of the fluid velocity distribution.

3.2 Characteristics of increasing temperature

Fig. 10 shows the characteristics of increasing temperature as a function of time. The excitation current I was set at 1 A, the rotation speed was 500 rpm, and the gap h was 1 mm for 30 minutes. In fig. 7, MRF-140 CG and fluid having a particle size of 3 μm had large values of brake torque, and the temperature rise was large in fig. 10.

In addition, since the volume of the fluid are smaller than the volume of the experimental apparatus main body, even if the fluid changes, the influence on the increasing temperature is considered to be small from the viewpoint of specific heat.

Fig. 11 shows the torque versus temperature characteristics during the temperature rise experiment. The change in torque was severe except for MRF-140 and fluid with particle size of 3 μm .

4. Consideration of MRB

4.1 Comparison of maximum brake torque

Converting the MRB experimental equipment used in this section to the scale of a regional jet must consider whether it meets the brake torque required for an axle brake. The required brake torque of a regional jet immediately after landing is about 9,000 Nm [7]. The ECB is responsible for essentially half of this value. Table 2 shows a comparison of experimental equipment and regional jet size. The maximum brake torque T_{HMAX} calculated from the disc outer diameter r_b , inner diameter r_a and height z is 2,421 Nm. Therefore, only about 27 % of the required torque can be obtained. As a method of increasing the brake torque, the following can be considered.

Fig. 8 Estimation of brake torque in maximum permissible current (MRF-140CG, $h = 1$ mm, Rotation speed = 500 rpm).

Fig. 9 Rotational speed-off torque characteristic with gap h as parameter (MRF-140 CG).

Table 1 Fluid compared with characteristics.

Company	Particle size [μm]	wt %	Base liquid	Components
LORD	3~10	85	Hydrocarbon synthetic oil	Fe-50Co-2V
Sigma High Chemical	5	85	Silicone	Fe
Sigma High Chemical	8	83	Silicone	Fe-50Co-2V
Sigma High Chemical	3	83	Silicone	Fe-50Co-2V

(1) Increase the number of discs making a multi disc structure. Considering that the brake torque increases proportionally with the number of discs, it is necessary to increase the number of rotating discs to 4 in order to achieve 9,000 Nm. It is necessary in this case to increase the number of discs N when the magnetic field H_{MRF} applied to the MRF is not reduced.

(2) Increasing the magnetic field applied to the fluid by decreasing the gap h to increase the brake torque.

4.2 Increasing temperature in regional jet size

Fig. 12 shows an extrapolated view of increasing the temperature of the MRF-140CG. The energy that must be consumed when the airplane lands is 23 MJ [7]. Increasing temperature calculated 17.8 deg. C. when supposition that the landing average rotation speed is 800 rpm and it is 15 s, at regional jet size experimental equipment. As shown in Fig. 5, since the influence on the brake torque due to the change in the rotation speed is very small, the difference from the experimental data at 800 rpm is assumed to be an error.

However, the higher temperature does not satisfy to the required brake torque requirements. If satisfied the temperature is calculated to be about 66.2 deg. C. The ignition point of MRF-140CG is no more than 150 deg. C. In addition, by using a silicone oil-based MRF, brake can be achieved under higher temperature conditions.

5. Conclusions

In this study, as a preliminary research step for non-contact hybrid eddy current brakes and MRB, a basic study of MRB was performed. The results obtained are summarized as follows.

(1) The brake torque T_H is proportional to the current I , and differences dependent on rotational speed are small while a greater brake torque is obtained at a smaller gap h . The brake torque T_H was 2.2 times when the gap h was multiplied by 1/3. The reason why it is not simply tripled is that the influence of the magnetic resistance of the upper and lower flanges becomes larger because for magnetic saturation, and the constant parameter β depends on the fluid used. The brake with particles 3 μm in diameter was largest among the silicone oil-based fluids. It is demonstrated that off torque is saturated when the rotation speed is high. This is because equation (2) is an expression that does not consider the velocity distribution of the fluid during disc rotation.

Fig. 10 Increasing temperature dependence on varying MRF.

Fig. 11 Torque versus time characteristics during increasing temperature experiment.

Table 2 Comparison of experimental equipment and regional jet size.

Item	This study	Regional jet actual size	Unit
Disc outer diameter, b	42	151	[mm]
Disc inner diameter, a	10	36	[mm]
Height, z	59	212	[mm]
Maximum brake torque, $T_{H\text{MAX}}$	14.5	2,421	[Nm]

(2) The maximum brake torque T_{HMAX} calculated from the disc outer diameter r_b , inner diameter r_a and height z is 2,421 Nm. Therefore, only about 27 % of the required brake torque. A method of increasing the brake torque could be to increase the number of discs to make

a multi disc structure, increasing the magnetic field applied to the fluid by decreasing the gap h for increased brake torque

(3) Temperature increases faster as the brake torque becomes larger. This means that heat generated depends on the magnitude of the brake torque. Also, since the specific heat of the fluid is much smaller than the specific heat of the body of the experiment equipment, the influence is considered to be small.

(4) For a regional jet immediately after landing, the increasing value of temperature increase will be 17.8 deg. C for experimental equipment of regional jet size. To achieve the required brake torque of 9,000 Nm, the higher temperature is calculated to be about 66.2 deg. C. The ignition point of MRF-140CG is no more than 150 deg. C. In addition, by using a silicone oil-based MRF, the required brake torque can be achieved under higher temperature conditions.

Acknowledgment

This research clearly states that we received support from the Nagano Prefecture Aircraft System Research and Development Grant, and we are deeply grateful here.

Fig. 12 Increasing temperature dependence on actual time (MRF-140CG, Enlarged view).

References

- [1] T. Okamoto, "CNT/Carbon composite brake for aircraft", *The Ceramic Society of Japan*, Vol. 42, No. 12, pp. 958-960, 2007, (in Japanese).
- [2] Japan Aircraft Public Relations Department, Latest Aviation Practical Hand book, Aeronautical Technology /Dictionary of business terms pp. 105-139, 2007, (in Japanese).
- [3] T. Sato, T. Sumi, Y. Kikuchi, et al., *The 30th Symposium on Electromagnetics and Dynamics*, pp. 602-605, 2018, (in Japanese).
- [4] S Kumbhar, A. Patil, et al., *International Journal of Engineering Research*, Vol. 5, No. 6, pp. 462-466, 2016.
- [5] Y. Shiao, Q. Nguyen, *Procedia Engineering*, Vol. 76, pp. 12-23, 2014.
- [6] K. Karakoc, E. J. Park, A. Suleman, *Mechatronics*, Vol. 18, No. 8, pp. 434-447, Oct, 2008.
- [7] Interim Evaluation Report (draft) Outline, "Advanced system practical application project for aircraft," <http://www.nedo.go.jp/content/100876078.pdf>, 2018, (in Japanese).