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Development of a New High-efficiency, Lightweight Model of Permanent Magnetic Retarder

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Abstract

A new model has been developed for the permanent magnetic retarder (PMR), which is an auxiliary brake for trucks and buses. The new model has high braking torque with a minimum magnet weight by optimization of the magnetic circuit, such as increase in the number of poles of magnets. The structure has been thoroughly simplified by developing a new switching device. As a result, we succeeded in drastically reducing the magnet weight per unit. By reducing the amount of neodymium, which is a rare material contained in permanent magnets, both economic and environmental merits were obtained. The new model has many advantages, such as compact size, light weight, and high braking force. Furthermore, the number of models was expanded and model selection is facilitated by modular design of components. These improvements made it possible to install the PMR on various types of commercial vehicles.

1. Introduction

Retarders are used as auxiliary brakes of trucks, buses, and other medium- and large-sized commercial vehicles. There are several types of retarders: hydrodynamic retarders that use oil's viscous resistance and electromagnetic retarders and permanent magnetic retarders that use electromagnetic induction. Hydrodynamic retarders require supply of hydraulic oil and electromagnetic retarders require supply of large currents, so the entire equipment is heavy and large. To solve such a problem, Nippon Steel Corporation has been manufacturing the permanent magnetic retarders shown in **Fig. 1** since 1990 as their only manufacturer in the world. This type of retarder has many advantages, for example, they are small and lightweight and they do not require maintenance. They have been used in Japan in an overwhelming number of cases.

Permanent magnetic retarders can suppress overspeed on downhill travel and can reduce the stopping distance of vehicles. They have also contributed to traffic safety through reduction of drivers' operation load by reducing the number of application times of the foot brakes. In addition to such advantages, they reduce the abrasion loss of the brake linings and the amount of wear debris scattering, having beneficial effects (improvements) from economic and environmental perspectives.

In recent years, the weight on board has been increasing for commercial vehicles and the engines have been downsized and motorized for higher fuel economy. Therefore, the performance of exhaust brakes and engine brakes tends to be insufficient. To compensate for such lack of braking force, the need to install permanent magnetic retarders on more vehicle types is increasing. We have developed a new high-efficiency, lightweight model that is easy to install on vehicles and that satisfies such need by bringing together our overall ability and various cutting-edge technologies.

2. Working Principle of Permanent Magnetic Retarders and Characteristics of the New Model

Figure 2 illustrates the structure of the main part forming the magnetic circuit of a permanent magnetic retarder. The part consists of a rotor that is connected to the propeller shaft of a vehicle and that rotates and a stator having permanent magnets in it that is secured to the non-rotating section of the vehicle. When the rotor rotates in the magnetic field formed by the permanent magnets, eddy

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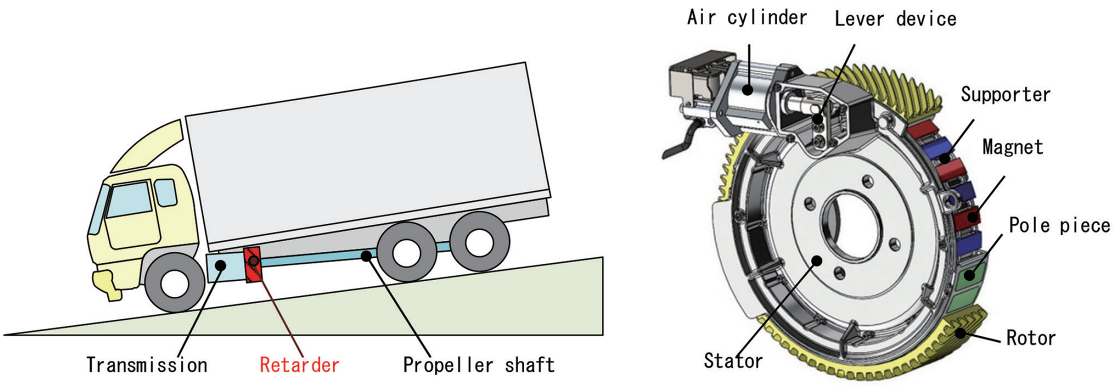


Fig. 1 Permanent magnetic retarder (PMR)

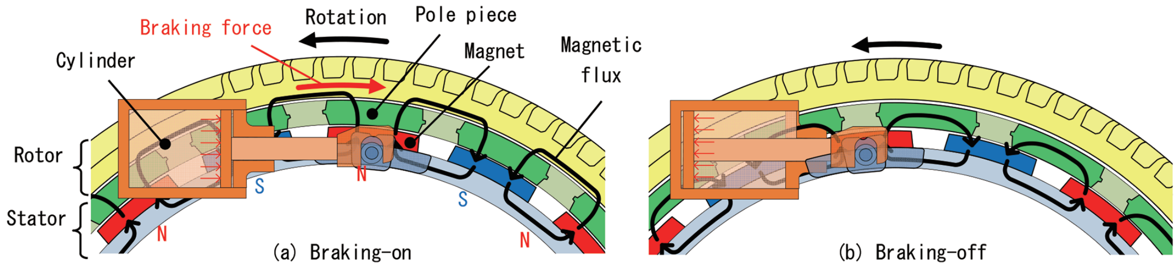


Fig. 2 Magnetic circuit of PMR

currents are generated on the rotor. The interaction between the currents and magnetic field generates Lorentz force in the direction opposite to the rotation direction. This force works as braking force that suppresses the rotation of the propeller shaft. At this time, the temperature of the rotor increases due to Joule heat from the currents.

On and off of braking is switched by making the permanent magnets reciprocate in the circumferential direction using air cylinders. When the braking is on, the magnetic flux of the permanent magnets reaches the rotor through the pole pieces that are a ferromagnetic material, which generates braking force while the rotor is not in contact with the stator. When braking is off, a pole piece and the adjacent magnets form a closed circuit to prevent the magnetic flux from reaching the rotor. In this way, the magnets are moved by half of the arrangement interval of the pole pieces arranged in the circumferential direction to switch on and off of the braking.

The higher-efficiency magnetic circuit exerts strong braking force with the minimum weight of magnets and equipment. The structure of the equipment has also been thoroughly simplified. In addition, modular design of parts has expanded the number of product types and alternatives, which has made it significantly easier to install retarders on vehicles. The following chapters describe the details of the development.

3. Optimization of the Magnetic Circuit

3.1 Improvement of the efficiency of the magnetic circuit through multipolarization

Permanent magnetic retarders use sintered neodymium magnets (Nd-Fe-B) containing rare earth elements. The amount used needs to be minimized for resource savings and stable supply of products in addition to reduction of the weight of products. Therefore, for the new model, numerical analysis was used to optimize the magnetic circuit through multipolarization.[1] In this study, nonlinear transient electromagnetic analysis where the rotor, stator, and space around them were determined as the analysis domain was performed. The rotational motion of the rotor was considered by moving the analysis mesh.[2] The commercial software JMAG® was used as the analysis tool.

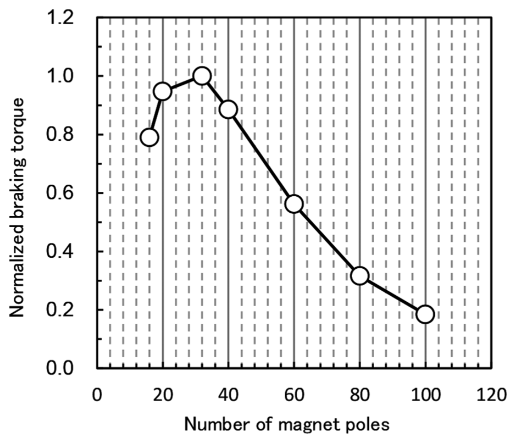


Fig. 3 Influence of number of magnet poles on braking torque (under constant magnet weight)

Figure 3 shows analysis results of the relationship between the number of magnet poles and the braking torque under constant weight of the magnets. The braking torque in the figure is dimensionless having been normalized by the maximum torque value. The results show that, when the number of poles is 32, the braking force is the maximum and thereby the braking efficiency is the highest.

To consider the mechanism in which the braking force changes

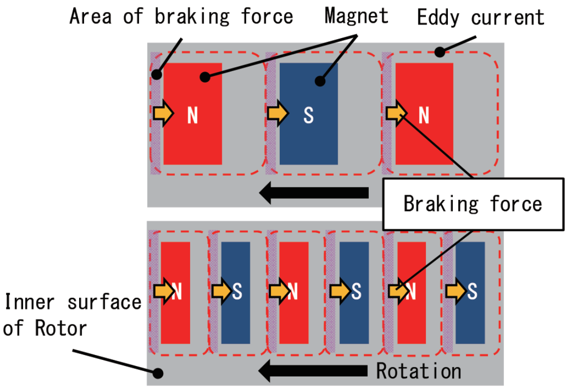


Fig. 4 Mechanism to enhance braking force by increase of number of poles

depending on the number of magnet poles, **Fig. 4** that schematically illustrates areas on the inner surface of a rotor where eddy currents and braking force are generated is used. As the number of poles increases, the number of closed loops on the inner surface of the rotor where eddy currents flow increases. In line with such increase, the number of areas where braking force is generated increases. At the same time, the magnetic flux output from one magnet decreases, so the braking force in individual generation areas decreases due to the demagnetizing field generated by the eddy current. Considering these two effects, it is considered that, when the number of poles is 32 or less, the effect of the increase in the number of generation areas is large, so, as the number of poles increases, the braking force also increases. Meanwhile, when the number is more than 32, the latter effect by the demagnetizing field that reduces the braking force may be larger.

Based on this knowledge, the number of magnet poles was increased to 32 from the conventional 16 for the new model (multipolarization). In addition, a new magnet fixation method to be mentioned later was introduced and other improvements were made to further improve the braking efficiency, which enhanced the braking force per unit magnet weight to 1.5 times that of the conventional model at maximum.

3.2 Reduction of operating force to simplify the braking switching mechanism

Operating force is required to move the magnets when braking is switched between on and off. In a permanent magnetic retarder, air cylinders are used for such switching, so, if the operating force can be reduced, the number of air cylinders can be minimized and thereby the accompanying parts for the air pressure system can be eliminated, which can further reduce the weight and size.

Operating force is affected by the number and shape of magnets and those of pole pieces. The previous section showed that the braking efficiency was the highest when the number of poles was 32. Therefore, electromagnetic field analysis was performed for study based on the 32-pole configuration. Processing magnets reduces the braking force and requires processing cost. To avoid this, magnets of simple shape were used to develop a shape of a pole piece effective in reducing the operating force.[3)]

Figure 5 illustrates the cross section of the developed pole piece in the axial direction. **Figure 6** shows the analysis results of the operating force. CASE-1 uses a pole piece of a simple shape for comparison. CASE-2 uses the developed pole piece in which a notch is provided at the edge of the surface facing a magnet. Figure 6 shows the operating force when the braking is switched from off to on. These results show that the developed type (CASE-2) can reduce the maximum operating force by approximately 50%. This is because the notches provided suppress the sudden increase in the magnetic flux density when the corner sections on the outer circumference side of the magnets approach the corner sections on the inner circumference side of the pole pieces and thereby they can reduce leakage of magnetic flux at the corner sections of the pole pieces due to magnetic saturation.

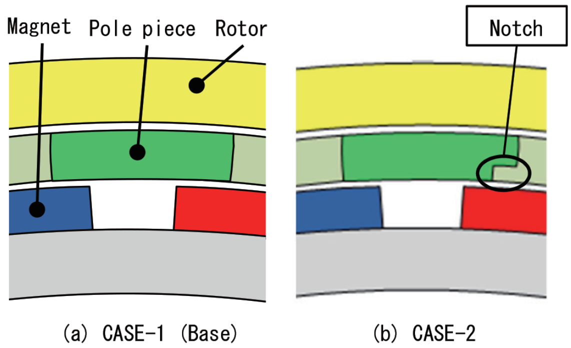


Fig. 5 Cross-section of pole piece

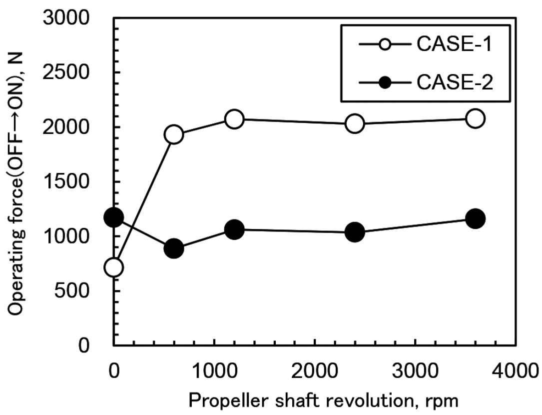


Fig. 6 Operating force for switching

Based on the study results above, the new model has pole pieces in the developed shape. The operating force was significantly reduced and the number of air cylinders was minimized as described later.

4. Development of a New Magnet Fixation Method to Realize Multipolar Magnetic Circuits

The previous chapter showed that, when the number of magnet poles was increased to 32 from 16, the braking force per unit magnet weight became maximum. In the conventional model, a supporter was pressed to the step of a magnet and secured to the yoke (bearing member) with a bolt as shown in **Fig. 7**(a). However, when the number of magnets was doubled, the intervals between the magnets became small, which made it difficult to secure a space for a bolt. The authors have developed a new magnet fixation method to achieve the multipolar magnetic circuits shown in Fig. 7(b) and **Photo 1**.

To reduce the weight while enhancing the constraint of the magnets, a supporter is spot welded to the yoke and the support secures

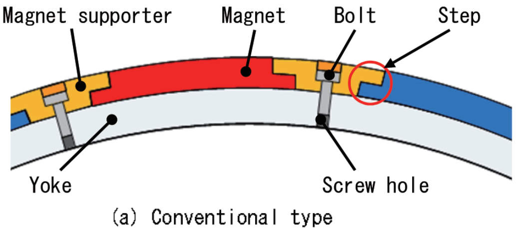


Fig. 7 Structure to fix magnets

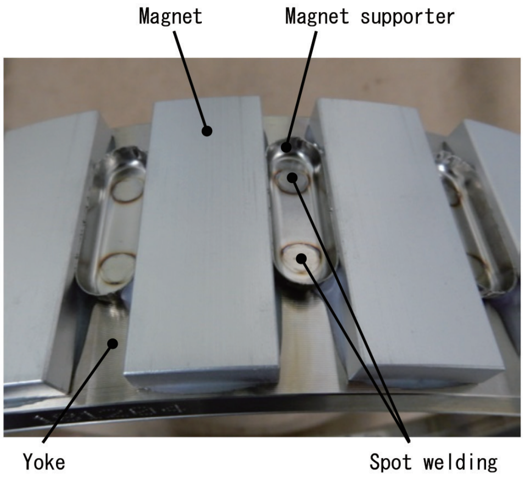


Photo 1 Magnet supporter

a magnet. An adhesive is also used to bond the magnet to the yoke. This method can eliminate processing of steps on magnets, and can thus avoid decrease in the braking efficiency due to local increase in the distance between the magnets and rotor at the steps, which can further increase the braking force. In addition, the elimination of steps can reduce the processing cost of magnets.

The adhesive needs to have stable bonding strength in temperature environments where it changes from −30 to 120°C for an extended period of time. Therefore, a thermal cycle test for an extended period of time was carried out to select a two-liquid-mixing acrylic adhesive that can maintain the necessary bonding strength while degradation is the minimum.

Meanwhile, magnets expand and contract as the temperature changes, so supporters should have a function to follow such behavior of the magnets through elastic deformation and retain the pressing force in the circumferential direction. Therefore, the deformation and stress state when magnets and supporters were assembled and when the temperature was changed were evaluated by nonlinear thermal stress FE-analysis.[4, 5] For the analysis, the commercial software ABAQUS®, which has been used to evaluate the strength of rotors, was used. The supporter shown in Photo 1 was developed.[6] The supporter is manufactured by press forming an austenite stainless steel sheet into the shape of a bathtub. Its elastic deformation range is wide and it has sufficient stiffness to retain a magnet.

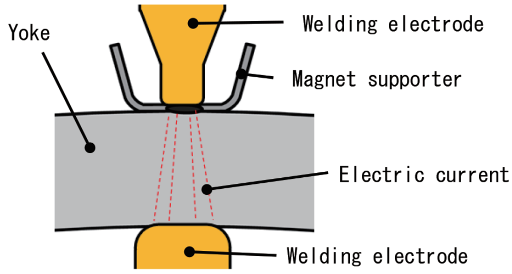


Fig. 8 Spot welding for magnet supporter

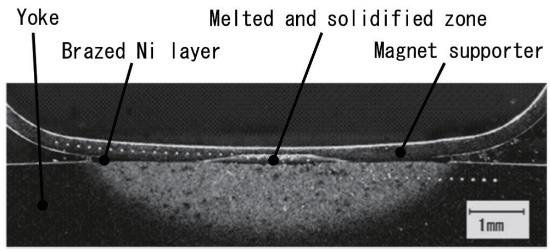


Photo 2 Cross-section of the spot welding for magnet supporter

The supporter is joined to the yoke by spot welding. A yoke is manufactured by plating carbon steel with a thickness of approximately 10 mm with Ni for rustproofing. The supporter is made from stainless steel with a thickness of approximately 0.3 mm. That is to say, Nippon Steel has developed its unique new technology to spot weld three layers made from different materials whose thickness ratio is as large as approximately 30 times.

Special electrodes that encourage electric current concentration on the supporter side was designed. In the design, the diameter at the tip of the electrode on the supporter side is small and that on the yoke side is large as shown in **Fig. 8**. In addition, a welding technique for this fixation structure was established by optimizing welding conditions such as welding pressure, currents, and energization time. **Photo 2** shows an example cross section at the joint. A normal melted and solidified zone has been formed at the center. A brazed zone at which only the Ni plating layer is melted and solidified is seen around the melted and solidified zone and the brazed zone enhances the bond strength. Regarding the strength of the welds, a static fracture test and fatigue test (loading in the separation direction and in the shearing direction) performed using welded supporters as test samples showed that the welds had sufficient durability.

In addition, establishment of this spot welding technique completely automated the process for securing magnets, which used to be manually performed, improving productivity.

5. Development of a New Braking Switching Mechanism and Simplification of the Structure

In the conventional model, two air cylinders were used to move the magnets to switch on and off the braking as shown in **Fig. 9**(a). Air tubes and a solenoid valve were used for connection between the cylinders. The air cylinders were arranged such that they protruded from the main retarder body, so it hindered reduction of the installation space.

In the new model, as shown in Chapter 3, the force required to move the magnets was significantly reduced by improving the shape of the pole pieces. In addition, because the travel distance of the magnets at the time of baking switching was halved thanks to multi-polarization, a lever mechanism was adopted to move the magnets as shown in Fig. 9(b), which doubled the driving force of the cylinders, which reduced the number of cylinders to one.

The new model uses a new type of cylinder integrated with a solenoid valve. This new cylinder eliminates tubes between the cylinders and between the cylinders and solenoid valve, allowing the structure to be simple and reducing the number of parts as shown in Fig. 9(b). The weight of the equipment including magnets was reduced by 29% at maximum compared to the conventional model. In addition, such reduction in the number of tubes and cylinders reduced the amount of air supply, which significantly reduced the braking response time (time from transmission to when braking force is exerted) and improved controllability.

In addition, for the new type of cylinder, the functions listed below are selectable. When retarders with large braking force are used for continuous braking for an extended period of time, measures to prevent the rotors from overheating may be required. The authors have developed the three-positional cylinder[7)] to control the heat generated in a rotor during braking. The cylinder can hold the magnets midway (LOW) in addition to braking on (HIGH) and off (OFF).

Figure 10 illustrates the structure of the developed cylinder. In the cylinder, two floating pistons A and B, and a LOW positioning plate and separator that determine the stroke position at LOW were added to the usual double-acting cylinder mechanism (in which a stopper is provided at the center of the rod). When the state is switched to LOW, compressed air is supplied to all the air chambers as shown in Fig. 10(b). At that time, pistons A and B sandwich the LOW positioning plate due to the difference in the pressurized areas between the pistons, which stops the cylinder rod at the LOW position. The air of the section that is sandwiched by pistons A and B when the state is switched to LOW is discharged from the breather hose on the side of the body. The structure of the new model above makes it possible to dynamically control the braking force in two stages at maximum power (HIGH) and lower force (LOW). For example, during braking at HIGH, switching to LOW temporarily based on the temperature of the rotor can prevent overheating of the rotor, which makes continuous braking for a longer period of time possible.

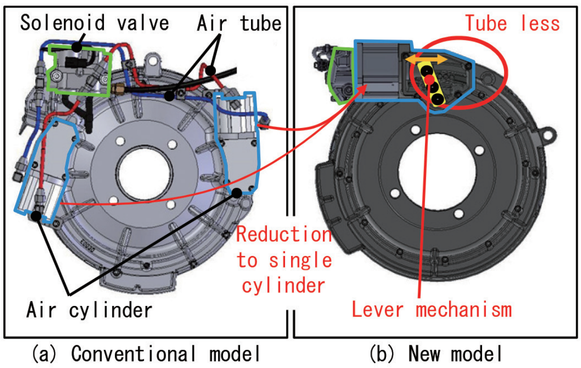


Fig. 9 Air cylinder and air tube of PMR

6. Increase in the Number of Product Types by Modular Design

Conventionally, a retarder model was designed based on the specifications of vehicles on which the model is to be installed. On the other hand, a modular design was adopted for the new model. As shown in **Fig. 11**, the same type of stator having magnets in it is used. In addition to the stator, two types of air cylinders (one with braking force control in one step and the other in two steps), two types of rotors (standard type and high-heat capacity type), and three types of copper plating (no plating, thin layer, and thick layer) were provided. As a result, a total of 12 types of retarders with different performance and functions are available. A model suitable for the target vehicle can be selected from these. The percentage of common use of parts significantly increased. This chapter describes the rotor with copper plating and the high-heat-capacity-type rotor developed for this modularization.

Applying copper plating with high electric conductivity to the inner surface of a rotor increases the density of eddy currents generated at the time of braking, which increases the braking force. However, the rotor becomes hot during braking, so, on normal copper plating, the plated layer is oxidized or separated and thereby durability cannot be secured. To solve such a problem, Nippon Steel has developed its unique multilayered copper alloy plating (technique) that can withstand use at high temperatures and repeated braking. We also have special plating equipment for the technique.

Figure 12 shows the relationship between the rotation speed of rotors and braking torque calculated through electromagnetic field analysis. The figure shows that the copper plating can significantly enhance the braking force. In addition, the relationship between the

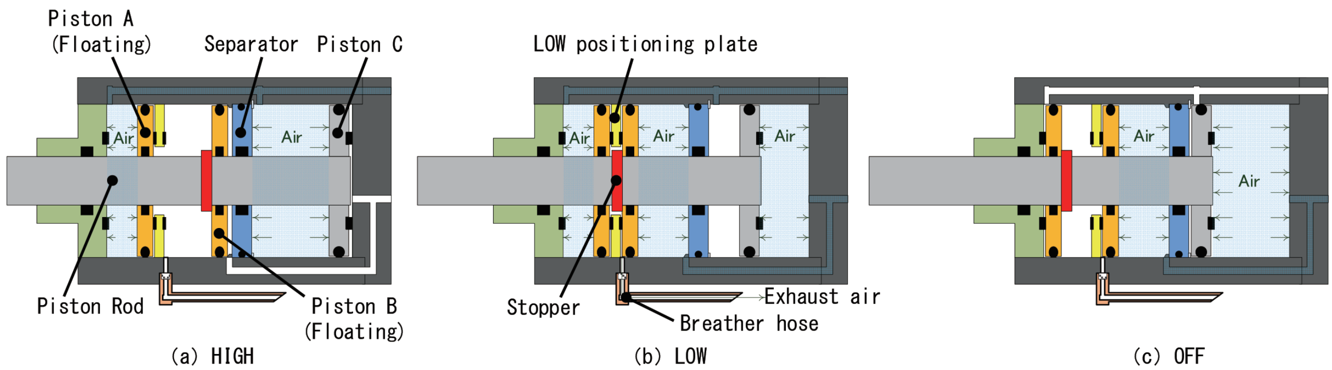


Fig. 10 Mechanism of three-positional cylinder for new high-torque retarder

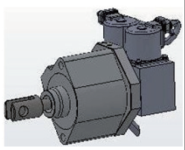
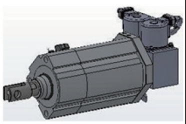
Model		Module: Stator, Main part	Module: Stator, Cylinder	Module: Rotor, Ring	Module: Rotor, Cu plate	Feature: Braking torque [Nm]	Feature: Torque control	Feature: Continuous braking time	Feature: Weight [kg]
NT60F			 Normal (1step)	 Normal	 No plating	MAX. 650	1step	Short	38
	- Ⅰ							↓	43
	- Ⅱ						2step	↓	40
	- Ⅲ							Long	45
NT75G					 Thin Cu layer	MAX. 730	1step	Short	38
	- Ⅰ							↓	43
	- Ⅱ		 3-positional model (2step)	 High-heat capacity			2step	↓	40
	- Ⅲ							Long	45
NT90G					 Thick Cu layer	MAX. 850	1step	Short	38
	- Ⅰ							↓	43
	- Ⅱ						2step	↓	40
	- Ⅲ							Long	45

Fig. 11 Line-up of new models using modular design

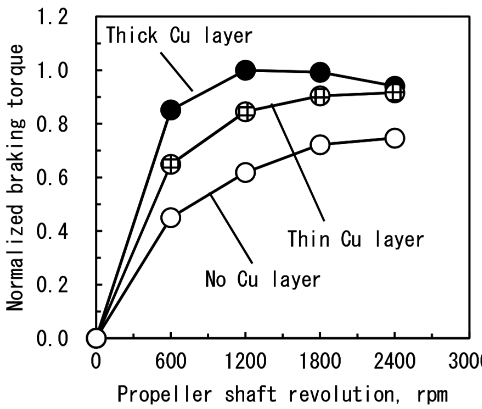


Fig. 12 Influence of Cu layer thickness on braking torque

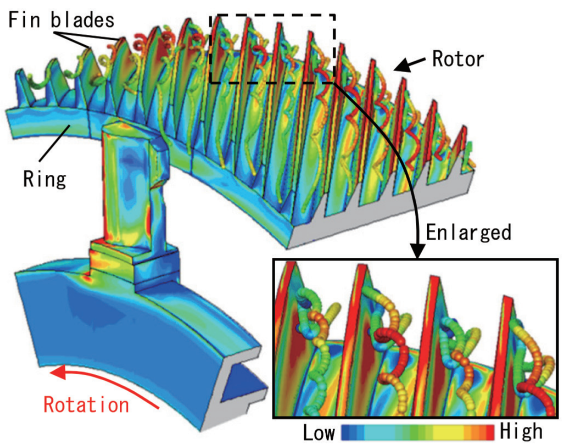


Fig. 13 Stream line of air flow and heat transfer coefficients of rotor surface

braking force and rotation speed and the maximum braking force greatly change when the thickness of copper plating is changed. Therefore, in the modularization of rotors, three types of plating are provided: no copper plating, thin copper plating, and thick copper plating. A type can be selected from these types based on the necessary braking force. The dimensions of the retarder are the same when any type of rotor is selected and its weight is also almost equal.

When copper plating is used to enhance the braking force, overheating of the rotor can be suppressed thanks to the dynamic control of the braking force (adoption of a cylinder with a two-step braking force control function) mentioned in Chapter 5. However, depending on the vehicle type and use conditions, an additional measure may be required to further extend the continuous braking time. To suppress the temperature increase of a rotor, it is effective to increase the thickness of the ring section to increase the heat capacity. However, if the thickness is excessively increased, the weight increases and the cooling rate after completion of braking decreases, so if braking is repeated in a short time, the rotor may become excessively hot.

In the development of high-heat-capacity-type rotors that can be installed on vehicles for which braking with large braking force for an extended period of time is required, the relationship between braking conditions and the temperature of the rotor was calculated through numerical analysis and the thickness of the ring was optimized. The temperature of a rotor greatly changes due to the flow of air around the fin blades provided on the outer surface of the ring. Therefore, as the analysis procedures in our study, the surface heat transfer coefficient of the rotor was estimated through stationary heat and flow analysis of the air around a rotating rotor. The results were used to estimate the temperature through transient heat analysis in a solid.[8)] As the analysis tool, the commercial software FLUENT® was used. **Figure 13** shows the streamline of air flow obtained in the analysis (the colors indicate the flow velocity magnitude) and the surface heat transfer coefficient of the rotor. **Figure 14** shows the temperature history on braking of the developed rotor.

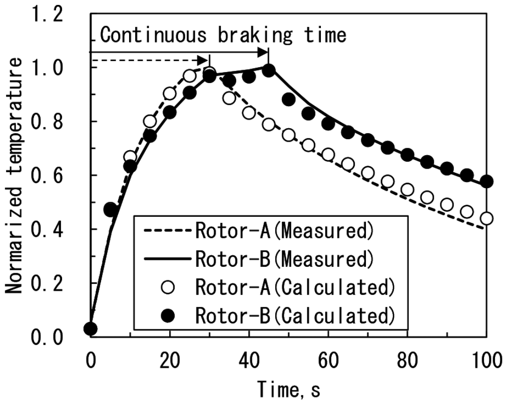


Fig. 14 Temperature history on braking of developed rotor (Rotor-A: Normal type, Rotor-B: High-heat capacity type)

The temperature in Fig. 14 is dimensionless having been normalized by the limit operating temperature. These results show that, for high-heat-capacity-type rotor B, the reduction in cooling rate after completion of braking is avoided while the continuous braking time can be extended compared to standard-type rotor A.

By combining a cylinder with the two-step control function described in the previous chapter, in addition to the high-heat-capacity-type rotor and copper plating mentioned above, an appropriate type can be selected from the perspectives of braking force and continuous braking time.

7. Conclusions

Nippon Steel has developed a new model of high-efficiency, lightweight permanent magnetic retarders by combining its various technologies for analysis (e.g., electromagnetic field analysis, thermal fluid analysis, and stress analysis), strength evaluation, welding, surface treatment, and machine design. The new model's performance and ease of installation on vehicles have been significantly improved compared to the conventional model. The main characteristics of the new model are listed below.

(1) Adopting a high-efficiency multipolar magnetic circuit has increased the braking force per unit magnet weight to 1.5 times that of the conventional model at maximum. As a result, the use of neodymium magnets per retarder can be significantly reduced, reducing environmental load by resource savings.

(2) A new mechanism for switching braking force was adopted. This mechanism has minimized the number of air cylinders required to move the magnets and permitted omission of air tubes, significantly simplifying the structure of the equipment. As a result, the number of parts has been reduced, the equipment has been downsized, and the weight of the equipment has been reduced. The weight of the equipment was reduced by 29% at maximum comparing to the conventional model.

(3) A new type of cylinder having a function for switching the braking force in two steps (maximum braking force and middling braking force) has been developed. In addition, the braking response time has been reduced to improve the equipment's controllability.

(4) A modular design was applied. One can use the 12 types with different braking force and continuous braking time by combining the common type of stator with the selectable parts such as the rotor and cylinder.

As described above, the new model of smaller and lighter permanent magnetic retarders has large braking force. The number of available product types has been increased, which has significantly improved ease of installation on vehicles and can flexibly satisfy various user needs. We will spread this equipment to further contribute to society through improved traffic safety and reduction in operational load on drivers.

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