

Development of Axial Motor

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ABSTRACT

Research was conducted on an axial gap-type rotating machine with the aim of increasing the torque density. To expand the torque-generating surface, an interior permanent magnet (IPM) rotor was used in a double stator-type motor that enables effective use of both sides of the rotor. This IPM rotor combines main magnets with a magnetization direction in the axial direction, auxiliary magnets with a magnetization direction in the circumferential direction, and laminated electrical steel, and fixes these components in place using adhesive. The developed motor was confirmed to have a torque density per unit volume approximately 50% higher than that of a radial-type motor. In addition, to address the manufacturing issues for a rotor structure based on this bonded structure, the yoke was manufactured using the rolling laminate method, and a new structure was developed that inserts the magnets into the yoke, integrates them with the magnetic circuit, and then fixes them in place by interference fitting inner and outer rings that are nonmagnetic reinforcing components. This structure was confirmed to have sufficient strength and stiffness, and the motor efficiency was also approximately the same as that of a rotor manufactured using the adhesive method. The new structure was ultimately confirmed to achieve a volumetric torque density 1.34 times that of a radial-type motor.

1. Introduction

With increased awareness towards the global environment in recent years, demands are strengthening to reduce automobile emissions and the greenhouse gas CO₂. To meet these expectations, Honda aims to contribute to the global environment by developing and popularizing environmentally friendly vehicles such as electric vehicles, hybrid vehicles, and fuel cell electric vehicles.

To increase application of electric vehicles, the motor that is the drive source is expected to manifest the desired torque and output power within a smaller design space. This means that even higher torque density and power density are required as motor performances. Power performance can be enhanced by increasing the motor speed and boosting the voltage. However, this involves an increase in ancillary parts such as a reduction gear and boost converter. In addition, the magnetic flux level or the current level must be increased to enhance torque performance, but magnetic flux density and current density are physical property limits of materials, so enhancement must rely on material advances. This study investigated a new structure and manufacturing method for an axial-type motor with a shape that increases the torque density by using existing materials without an increase in ancillary parts.

The torque generated by a motor is determined by the area of the torque-generating surface and the magnetic flux

density at the torque-generating surface. The torque to be generated can be increased even with the same volume by using a structure that increases the torque-generating area and the magnetic flux density within the limited space. Conventional motors have a structure called a radial gap type that locates the rotor inside the stator. This limits both the rotor surface area that generates torque and the arrangement of the magnets inside the rotor, so increasing the volumetric torque density is an issue. This study aimed to increase the volumetric torque density of the motor by combining the following two technologies:

- (1) Expansion of the torque-generating surface area by using a double stator axial-type motor
- (2) Use of a Halbach-type magnet arrangement that has a magnetic lens effect

2. Features of the Double Stator Axial Gap Motor

2.1. Difference from Radial Gap Type

Figure 1 shows the torque-generating surfaces of a conventional radial gap-type rotating machine and an axial gap-type rotating machine. In the radial gap-type motor, the interlinkage magnetic flux surface that generates the torque is the surface of the cylindrical rotor and has a ring shape. In contrast, in the axial gap-type motor, the stator and rotor are axially opposed, and the interlinkage magnetic flux surface

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is shaped like a disc. In addition, the torque-generating surface area can be doubled by placing stators on both sides of a rotor or by placing opposing rotors on both sides of a stator. Further, in this case the rotor core back yoke or the stator core return pass can be eliminated. This means that the axial dimension can be shortened to less than double that of the conventional type, which enables increasing the torque density per unit volume⁽¹⁾.

2.2. Double Halbach-type IPM Motor

As mentioned above, the motor torque is determined by the area of the torque-generating surface and the magnetic flux density at that surface. This study selected a double stator axial gap-type structure that increases the torque-generating surface area. In addition, a Halbach-type magnet arrangement was used to increase the magnetic flux density at the torque-generating surface and further increase the torque density⁽²⁾⁻⁽⁴⁾.

In an axial-type motor, the magnets are normally arranged so that the magnetization direction within a single pole matches the axial direction and the directions of adjacent poles alternate by 180 degrees. This is repeated to create a rotor with continuously alternating N and S poles. In contrast, arranging the magnets so that the magnetization directions are orthogonal as shown in Fig. 2 produces a magnetic lens effect that strengthens the magnetic flux in one direction. This was used to create a double Halbach-

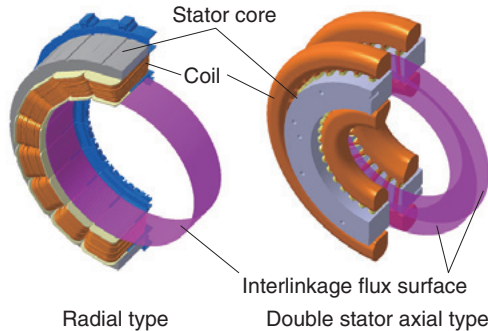


Fig. 1 Interlinkage flux surface

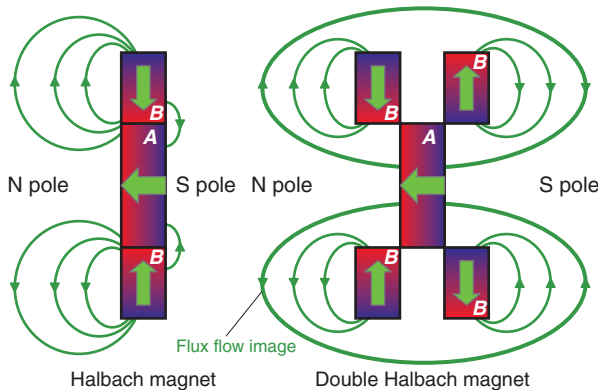


Fig. 2 Double Halbach magnet arrangement

Table 1 Specifications

	IMA motor	Axial motor
Number of poles	12	12
Magnet	Nd-Fe-B	Nd-Fe-B
Stator diameter [mm]	258	258
Rotor diameter [mm]	179	220
Motor length [mm]	80	88
Volume [L]	4.2	4.6

type magnet arrangement that manifests this magnetic lens effect on both surfaces of the rotor as shown in Fig. 3.

In addition, the structure has low magnetic resistance electrical steel in the axial direction on both sides of the main magnets that are opposed to the stator, and a rotor-holding component (frame) made of nonmagnetic materials in the spaces surrounded by the main magnets and auxiliary magnets. This strengthened the magnetic flux flow to the stator side and created an Interior Permanent Magnet (IPM) rotor with embedded magnets.

2.3. Verification of Torque Density

A prototype engine was designed and manufactured to confirm the effects of expanding the torque-acting surface area and increasing the magnetic flux density on increasing the torque density. As shown in Fig. 4, this prototype has the same six pole pairs and outer diameter size as the 2006 model year CIVIC IMA motor. Table 1 lists the detailed specifications.

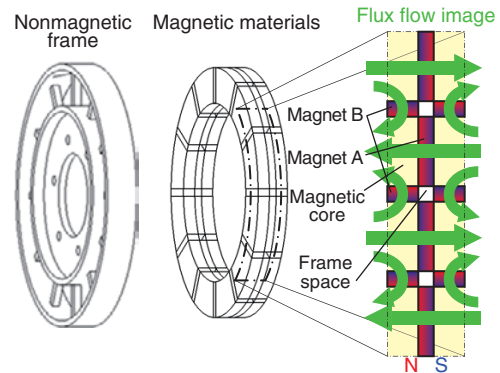


Fig. 3 Double Halbach-type rotor structure

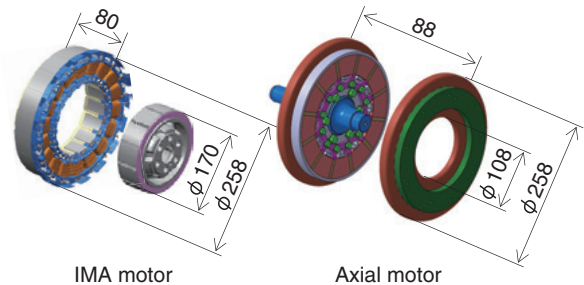


Fig. 4 Motor dimensions

Figure 5 shows the results of measuring the torque characteristics of the prototype motor. Comparing the generated torque confirmed that the prototype motor manifests 1.63 times the torque of the conventional motor. The volumetric torque density was 1.48 times that of the conventional radial gap motor, and 1.22 times even when converted to the torque per unit magnet mass for comparison. This confirmed that the double stator axial-type motor can greatly increase the torque density compared to a radial-type motor.

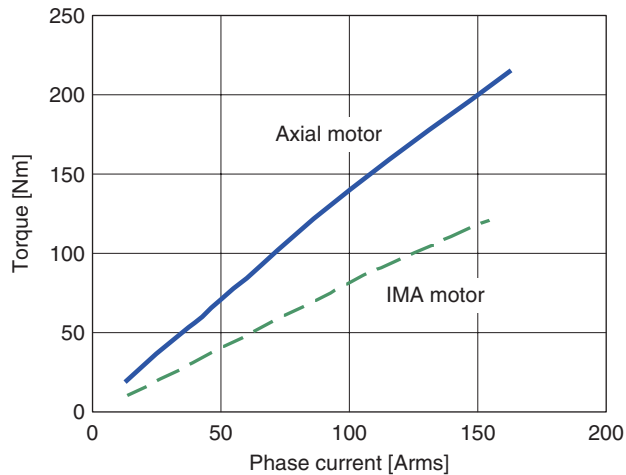


Fig. 5 Comparison of current-torque characteristics

3. Enhancement of Rotor Structure in Consideration of Manufacturing Method

3.1. Rotor Issues

In a radial-type motor with magnets embedded in an IPM rotor, the magnetic circuit does not change in the axial direction and is two-dimensional. Therefore, the rotor yoke is generally made by punching and laminating thin sheets of electrical steel, and then press-fitting or otherwise fixing these laminates to the shaft that supports rotation and transfers the torque. The parts where the magnets are inserted are also punch-molded to create spaces that hold the magnets after lamination. This means that the electrical steel can be punch-molded into a shape that simultaneously realizes both the magnetic characteristics and mechanical strength, so there are no major manufacturing method issues.

In contrast, axial-type rotors have the following three issues:

- (1) Selection and molding of three-dimensional magnetic circuit yoke materials
- (2) Machinability of nonmagnetic reinforcing components (stainless materials)
- (3) Integration of magnetic circuit components and reinforcing components

Figure 6 shows the structure of the rotor manufactured to measure the torque characteristics. There are no particular issues concerning the molding and magnetization of the magnets used in an axial-type motor. However, the rotor magnetic circuit is not identical in the radial direction and is three-dimensional, so issue (1) is how to create the yoke that comprises the circuit. Soft magnetic composites and sintered material are generally used as the yoke materials for the three-dimensional magnetic circuit. However, the iron loss is greater than that of laminated electrical steel, so this study selected electrical steel. When using thin electrical steel sheets to configure a three-dimensional magnetic circuit for an axial-type rotor, a shape with the thin electrical steel sheets laminated in concentric rings most effectively suppresses the generation of eddy current. However, to achieve a fan shape similar to the main magnets that are magnetized in the axial direction, electrical steel pieces with different lengths and radii of curvature must be laminated sheet by sheet in the circumferential direction. This requires multiple cutting dies with different length dimensions and curvature-forming press machining. Another manufacturing method is to cut yoke materials wound and bonded in a hoop (quasi-concentric shape) into fan shapes using a machining method such as wire-cutting that can secure insulation between each layer. In any case, it must be said that these manufacturing methods are not suited to large-scale mass production compared to the yoke of a radial-type rotor.

Issue (2) is the machinability of the component (frame) used to secure strength and rigidity as a rotor. When magnetic flux flows easily through the frame component, a magnetic flux short-circuit occurs inside the rotor, and the magnetic flux that does not contribute to torque increases. Therefore, nonmagnetic materials must be used. Aluminum alloy is a general nonmagnetic material that is lightweight and easy to machine, but the required stiffness cannot be secured within a limited space (dimensions), so austenite stainless⁽⁵⁾ was used. However, austenite stainless is a challenge to machine, so a machining process is required to accurately form a one-piece part with thin spokes such as

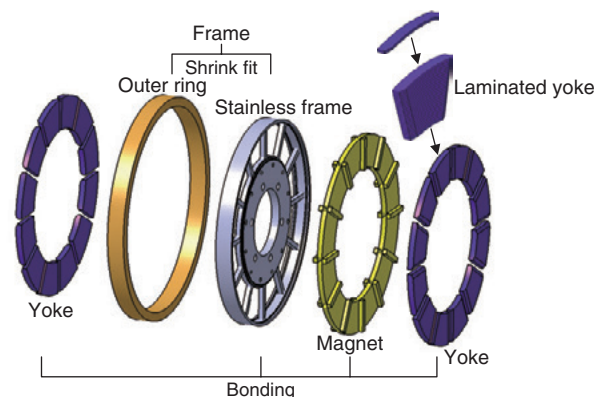


Fig. 6 Bonded fragment structure

shown in Fig. 6. Therefore, this manufacturing method is also not suited to large-scale mass production.

Issue (3) is integration of the magnets and the yoke with the stainless frame-reinforcing component in order to configure the rotor. To realize an assembly structure with dimensional tolerance, a layout that resembles parquetry with gaps must be used, so bonding is performed by filling the gaps with adhesive. However, there are currently no known adhesive materials suited to the conditions of elastic deformation of the frame when rotating at high speed and rotor temperature rise during operation. This might result in a motor that is unsuitable for automotive applications.

3.2. Method of Addressing Rotor Issues

To address these three issues, the rotor yoke was formed by rolling laminate using a notching press, and then the magnets were inserted and integrated with the magnetic circuit. In addition, a multi-ring press-fit structure was developed that secures the outer circumference by compression using aluminum die-casting, and then interference-fits the outer ring that provides the centrifugal force strength.

3.2.1. Laminated steel roll yoke

The rotor yoke was changed from the prototype shape used to confirm the increase in torque density to a shape with chamfered corners that contact the auxiliary magnets so that the back EMF voltage waveform more closely approximated a sine wave. The notching press rolling-laminate manufacturing method was then used to create a shape based on this yoke shape that has the minimum necessary bonding locations and hooks to hold the auxiliary magnets (Fig. 7 right side).

As shown in Fig. 8, the yoke on both sides is formed in a single process by rolling up hoop-shaped materials of the rotor yoke width that have had the magnet and nonmagnetic pin insertion spaces cut out by a punch. The inner circumference is short and the outer circumference is long, and punching and rolling are performed continuously while precisely controlling the feed rate (pitch) for each punch so that the main magnet insertion spaces and the yoke have a fan shape. Figure 9 shows a photograph of the yoke formed by rolling laminate.

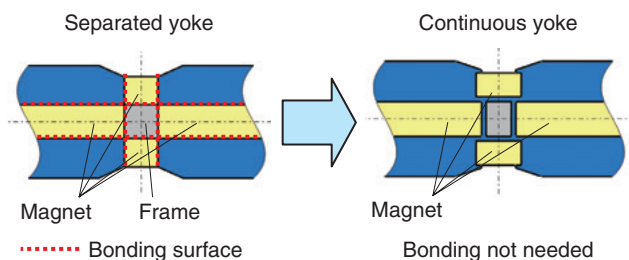


Fig. 7 Change in yoke structure

3.2.2. Multi-ring press-fit structure

A multi-ring press-fit structure was designed that broadly comprises the three layers of the abovementioned yoke formed by the rolling laminate, and inner and outer rings made of nonmagnetic materials. This secured rotational strength and stiffness.

Figure 10 shows the assembly process. An aluminum layer is applied to the surface of the outer circumference of the laminated yoke by aluminum die-casting before the final process to press fit (shrink fit) the outer ring. This provides the following effects:

- (1) Fixing of the laminate by compression
- (2) Fixing of the magnets by deformation of the outermost layer (anchor effect)
- (3) Easy control of the outer diameter dimension by machining the aluminum layer

These effects enabled securing of rotational strength, thrust stiffness, and the surface pressure of each layer required for torque transmission. This enabled manufacture of a rotor that does not need to rely on adhesive material strength.

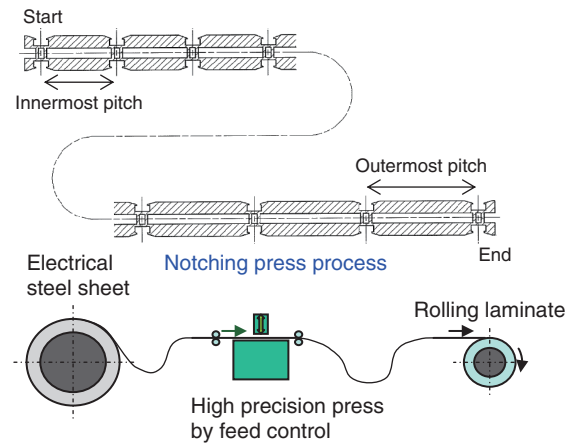


Fig. 8 Yoke manufacturing process using notching press

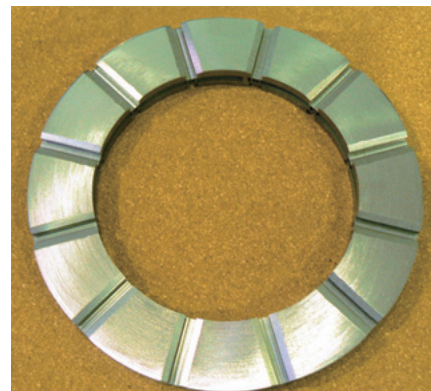


Fig. 9 Laminated roll yoke

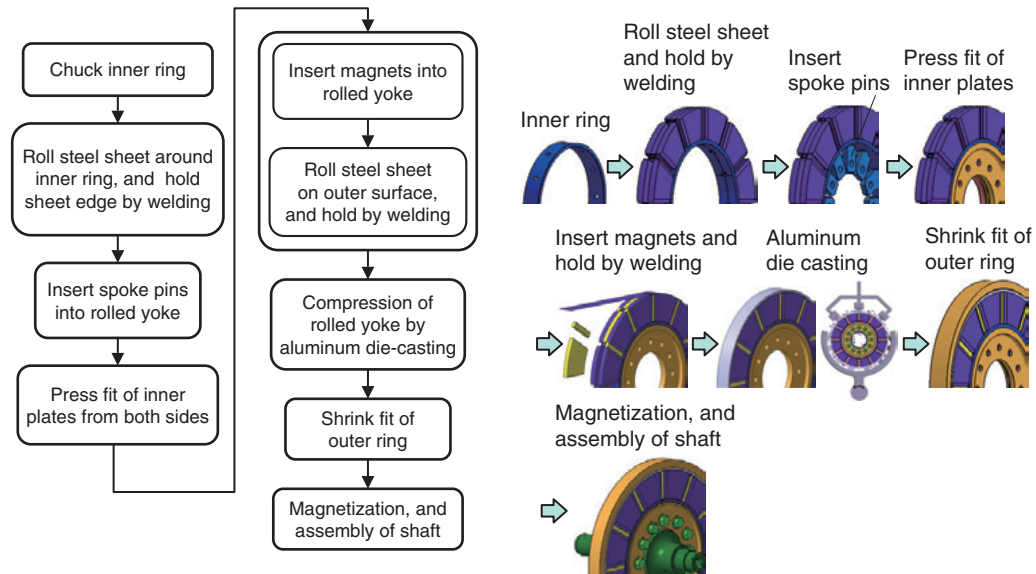


Fig. 10 Rotor assembly process

3.3. Confirmation of Strength and Stiffness

Figure 11 shows the rotational strength, Fig. 12 shows the thrust stiffness, and Fig. 13 shows the torsional stiffness, measured using the prototype multi-ring press-fit rotor.

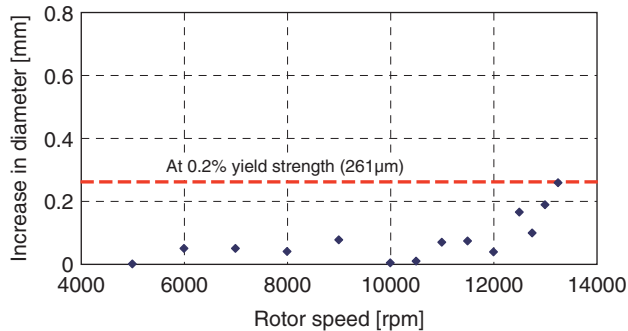


Fig. 11 Rotational strength

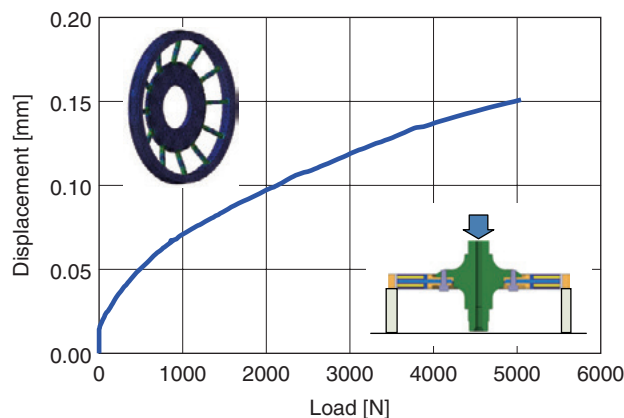


Fig. 12 Thrust stiffness

First, regarding the rotational strength, the amount of outer diameter deformation of the stainless outer ring was measured to confirm the rotor speed at which the elastic deformation range is not exceeded. The results showed that elastic deformation was within the allowable range even at 12000 rpm, which is 1.85 times the hypothesized maximum rotor speed of 6500 rpm. This confirmed that sufficient strength can be secured.

Next, the thrust stiffness was confirmed by measuring the displacement when the outer ring is fixed and thrust force is applied to the shaft (equivalent to a concentrated load). The displacement at the maximum thrust force of 5000 N was 0.15 mm, which is sufficiently small relative to the minimum air gap of 0.6 mm. In addition, the thrust load acting on the rotor due to the magnetic attraction

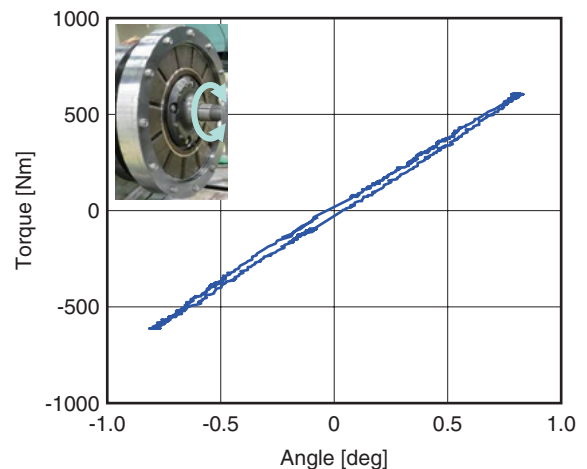


Fig. 13 Torsional stiffness

Table 2 Comparison of losses

	Bonded rotor	Rolled rotor
Iron loss [W]	692	630
Copper loss [W]	483	518
Motor loss [W]	1175	1148

force acts as a distributed load on the yoke surface. Therefore, CAE calculations show that displacement can be suppressed to 62% of that when thrust force is applied to the shaft. This confirmed that sufficient stiffness is secured.

Regarding stiffness relative to torsional torque, discontinuous behavior did not occur even at alternating torque of 600 Nm, which is three times the maximum torque of 200 Nm. This confirmed that the new rotor also has sufficient stiffness and strength with respect to torque transmission.

3.4. Confirmation of Torque and Efficiency

Figure 14 compares the torque characteristics per unit volume of developed multi-ring press-fit rotor with enhanced rotor structure reliability and the parquetry structure rotor. The back EMF voltage is 11% lower due to the magnetic flux short-circuit from the couplings used to create a rolling-laminate yoke and the reduced magnet surface area due to the smaller auxiliary magnet size. The torque characteristics vary approximately in proportion to this degree of voltage drop. Figure 14 shows that the double stator axial gap-type motor has a torque density 1.34 times that of the 2006 model year CIVIC IMA motor. In addition, Table 2 compares the various motor losses under typical operating conditions. The increase in the copper loss and the decrease in the iron loss due to the lower torque constant cancel each other out, confirming that the motor loss is approximately the same.

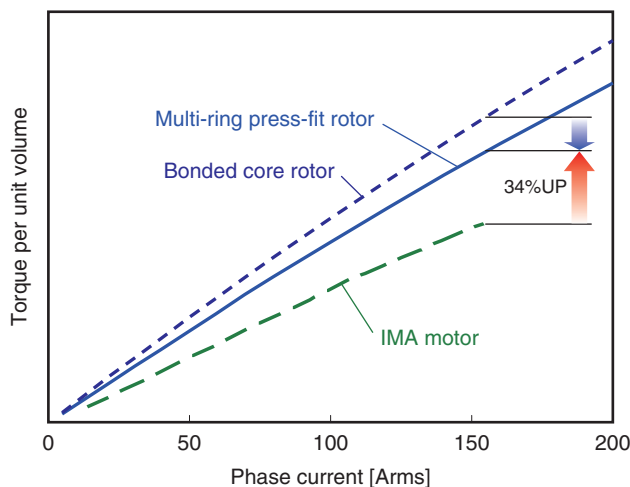


Fig. 14 Comparison of current-torque characteristics per unit volume

4. Conclusion

Research was conducted on a double stator axial gap-type motor that has two torque-generating surfaces with the aim of increasing the motor torque density. The rotor used an IPM-type structure like conventional radial gap-type motors, and an actual prototype motor was manufactured and performance was evaluated. The results confirmed that the torque density per unit volume increased compared to that of a radial gap-type motor.

In addition, axial gap-type motors have issues with rotor strength and stiffness. Therefore, a highly reliable rotor structure was designed by combining an electrical steel rolling-laminate yoke, aluminum die-casting, and nonmagnetic rings, and the effects were confirmed in an actual motor.

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