Magnetic Form applying a C-Shaped Magnet for Hybrid Electric Vehicles

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Currently, electrification for vehicles such as battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs), and hybrid electric vehicles (HEVs) has received considerable attention, owing to the urgent need to reduce CO2 emissions created from transportation and the energy dependency on crude oil. Honda has set a target whereby two-thirds of total global sales should come from EVs by 2030. A traction motor is an essential component of electrified vehicles. Generally, interior permanent magnet synchronous motors (IPMSMs) are used as traction motors owing to their high torque and power density, high efficiency and ease of use. The design of rotors, which consist of magnets and electrical steel sheets, is important for IPMSMs because their average torque, efficiency, quietness, as well as cost depend on it. We have developed a novel rotor, which allows for a degree of freedom in the shape of the magnets. In the proposed rotor, first, the shape and position of the magnets are determined parametrically under manufacturing constraints. Then, the shape of the electrical steel sheet is determined by the ideal flux-line using maximized Lq-Ld. This involves combining q-axis flux and flux shape optimization for a practical design of the rotor. We also reduced torque ripple by considering the magnet position and dimple design. Rotors that are used in electrified vehicles are rotated at a maximum speed without gearing; therefore, the rotor must be designed by taking into consideration not only the magnetic forces but also the centrifugal ones. Therefore, we studied a mechanical simulation by optimizing magnetic performance while limiting maximum stress and displacement. We also developed a new production process for a C-shaped sintered and hot-deformed magnet.

Keywords : Motor, Magnet, HEV, BEV, Vehicle, Stress Gradient Index, Haigh-diagram, [7],

### 1. Introduction for Magnet Trend

In conventional interior permanent magnet synchronous motors (IPMSM), it is generally common to use neodymium sintered magnets in a sheet form. (1)

With the recent development of neodymium sintered magnets and a hot deformation production process, it has become possible to make advantageous use of a degree of freedom in magnet shape. (2)

The application of the degree of freedom for magnets in the traction motors of Hybrid Electric Vehicles (HEVs) to achieve compactness was examined in the present research. The research managed to achieve both compactness and cost reduction, making it very significant.

The HEVs traction motors used in the mainstream of electrification products from Honda were taken up as the object of research. The motor specifications are shown in Table 1. In light of constraints on the motor space, interior permanent magnet synchronous motors, which are compact and efficient, were used.

| Type | IPMSM |
|------|-------|
| Phase | 3 |
| Number of poles | 12 |
| Winding pattern | Hair-pin winding, Distribution |
| Cooling system | Oil-cooled |
| System voltage [V] | 630 |
| Maximum motor power [kW] | 135 |
| Maximum rotation speed [rpm] | 14500 |
| Maximum motor torque [Nm] | 335 |
| Peak efficiency [%] | 98 |

Table 1 System specifications

For the present research, the shape selected from the degree of freedom in magnet shape was C-shape because it is a viable industrial product that also achieves favorable dimensional variation during production. The research was conducted using this shape. Another reason for this is that it allows a choice between the two magnet manufacturing methods of sintering and hot deformation processing. Adoption of the C-shape also makes it possible to reduce machining processes by the use of near net shape processing. It was found, therefore, that using a C type magnet would make it possible to reduce process costs. (Figure. 2, 3)

Moreover, the selection of hot deformation processing made it possible to achieve a coercivity (Hc) of 1500 kA/m, or higher without including heavy rare earths. If motors are designed with care regarding resistance to demagnetization, then this would contribute to the development of motors without the high cost risk and procurement risk of heavy rare earths.

The substance of this approach was reported with regard to the design method for traction motors for HEVs use. The present research also addressed the magnetic flux barrier shape by...
creating a shape with a structure resistant to demagnetization in a way that would produce a motor that satisfies the specifications even without using heavy rare earths if a hot-deformed magnet is selected.\(^{(3)}\)

| Type          | C-shape        |
|---------------|----------------|
| Production process | Sintered/ Hot deformed |
| Residual magnetic flux density \(B_r\) [T] | 1.38 |
| Coercive force \(H_c\) [kA/m] | ≥1500 |

2. Development direction for Neodymium sintered Magnet

A focus on the progress made in magnet development shows that the highest energy product has recently been approaching the theoretical upper limit.\(^{(4)}\)

Another development is that, due to price and supply risks, magnet coercivity has been rapidly enhanced since 2011 by reducing the amount of heavy rare earths added.

Meanwhile, attention has focused on the degree of freedom in magnet shape and the degree of freedom in the orientation of magnetization, which were directions with further development potential.

First, a description will be given of the state of rapid development of manufacturing technology providing a degree of freedom in shape and orientation of sintered neodymium magnets.

Figure 2 shows the neodymium sintering processes.

The core technology in the sintered magnet method is press in magnetic field.

This process differs from the conventional one, which involves block molding of the sheet form. Here instead a multi-cavity mold was developed that produces a C-shaped magnet. This produces a near net shape and molds many magnets simultaneously so that mass production has become possible.

The next matter to consider is the hot-deformed magnet.

Figure 3 shows a scheme view of this manufacturing method.

The key process in the hot deformation production process is the hot extrusion process. Development for enhanced moldability was carried out by performing simulation of the hot extrusion die set, and it was found from this that net shape production of a C-shaped magnet is possible. In this process, the direction in which pressure is applied determines the orientation, and this process therefore handles the two elements of dimensional accuracy and orientation.

Advances in the hot extrusion process make it possible to omit the grinding process, allowing for a reduction in process costs.

In their present state, it was found that the above two methods could be applied to mass production of C-shaped neodymium magnets with radial orientation.
3. Designing use C-shaped type of magnet

The next matter for attention is the state of development of interior permanent magnet synchronous motors. A review of changes in the technology over the past 20 years shows that the evolution of interior permanent magnet synchronous motors has taken place by development occurring simultaneously within the larger framework of design, manufacturing, control technology, and material development carried out for the purpose of applying reluctance torque (5). A major part of this was the development trend toward use of ferrite magnets for the further use of reluctance torque, and this took the same direction in design as the substance of the present research. However, the highest energy product with ferrite, which has ferrimagnetism as the mechanism of its expression, was not able to satisfy the requirements for an automobile traction motor. Moreover, this approach has issues with cost and manufacturability, and so it was not placed on the market.

Figure. 4 shows the shapes of the rotors in products that have been released by Honda Motor Co., Ltd. The requirements for electric motors used in automobiles are compactness, high power, high torque, low cost, and low supply risk. Interior permanent magnet synchronous motors have evolved to meet these objectives, and every year these motors appear to have less and less room to evolve further.

What was done, therefore, was to adopt the degree of freedom in shape and orientation that had begun to emerge as the direction of magnet evolution, and to aim for a reduction in the amount of high-priced, scarce magnets and greater compactness of the motor.

Accomplishing this requires utilization of reluctance torque to the greatest extent. The output torque of permanent magnet synchronous motors with a salient pole structure can be expressed by the following Eq. (1), as is well known:

\[ T = p\phi i_q - p(L_q - L_d)i_d \ldots (1) \]

Here \( T \) is torque, \( p \) is the number of pole pairs, \( i_q \) is the \( q \)-axis current, \( L_q \) is the \( q \)-axis inductance, and \( L_d \) is the \( d \)-axis inductance.

It is well-known that, in general, when magnetic flux flows ideally on the \( q \)-axis, the result is as shown in the figure. It is important to place a magnetic flux barrier so that it traces that flow. In order to trace an ideal shape, it is necessary to change the curvature and orientation of the magnet. (Figure. 5).

By tracing this line of magnetic flux, the highest value of \( L_q \) can be achieved. In order to reduce \( L_d \) to the lowest value, it is also necessary to arrange the magnetic flux barrier so that it faces toward the center of the rotating magnetic field. Based on this conceptual approach, a model that uses a C-shaped type magnet to achieve the highest values of \( L_d \) was examined.

In this initial research, a concentrically layered model was designed. This model adopts C-shape type neodymium magnets with a motor that is well-known as a “double-layer type of IPMSM” (5). (Sec. Table 3 Model 1).

| Configuration | Model 1 | Model 2 | Conventional |
|---------------|---------|---------|--------------|
| Max Torque [Nm] | 317.5  | 343.5  | 333.5        |
| Magnet Torque [Nm] | 137.4  | 147.3  | 153.0        |
| Torque Reluctance Torque [Nm] | 180.1  | 196.2  | 180.5        |
| \( L_d \) [mH] | 0.160  | 0.167  | 0.164        |
| \( L_q \) [mH] | 0.338  | 0.354  | 0.341        |
| M-point | 384.5 | 401    | 420.5        |
| Max Current [Arms] | 335    | 335    | 335          |
| Magnet Volume [g] | 1060   | 1060   | 1205         |

This model shows the possibilities for reluctance torque. At the same time, it suggests some shortcomings in the C-shaped layout.

The first model successfully demonstrated that the benefits realized by reluctance torque are greater than those realized by magnet torque.

With the first model, however, a large torque ripple occurred. The reason for this was that the magnet orientation was centered in the \( d \)-axis so that magnetic flux originating in the rotor was concentrated in a single point.

It can be inferred that the concentrically layered layout sharpens the magnetic flux waveform. Even when the concentrically layered layout was optimized, it did not conform to the torque ripple specifications of a HEV’s traction motor.

For the next model, therefore, the polar center of the magnet was offset, and a search was made for a model in which the center of
orientation was not concentrated. The result was Model 2, which has a shape known as the "inverted-delta type of IPMSM." Since the center of orientation was offset, however, the high-frequency components in the waveform of the interlinkage flux have changed. (Figure 6)

The FFT results for interlinkage flux were then obtained. Figure 7 gives the FFT results and this shows that the 11th and 13th components are completely different in Model 1 and Model 2.

The greater magnitude of the 11th and 13th components indicates that they are causing torque ripple in the 12th high harmonic component. (Figure 8)

For the above reasons, it was found that a C-shaped layered magnet layout with a non-concentric magnet orientation having an offset center should be selected.

Optimization was carried out repeatedly to further increase reluctance torque while simultaneously positioning small holes in order at locations on the ribs that are not subject to stress in order to reduce leakage magnetic flux while increasing magnet torque so that it would be possible to trace the magnetic flux barrier along the $q$-axis magnetic path. Redesign was also carried out while searching for shapes that would be able to mitigate centrifugal stress and cooling stress.

The result yielded success in raising the reluctance ratio. The effect was to achieve a 12.2% enhancement of $L_q$.

The execution of this procedure resulted in the creation of a model that was able to increase total torque by 3% while also reducing the amount of magnets by 12%.

4. Mechanical property designing use C-shaped type of magnet

In general, IPM rotors are configured with thick supporting ribs for retention of magnets under centrifugal force. As the ribs become thinner and longer, short-circuiting of magnetic flux is prevented, the amount of interlinkage flux increases, and magnet torque becomes larger. However, this in turn causes an increase in stress on the ribs. Centrifugal force stress comprises tensile and bending stress, which makes it a challenge to design the rotor and predict its fatigue life.

The gradient of the stress applied to the rotor ribs was therefore taken into consideration. Doing this made it possible to increase the accuracy of rotor fatigue life prediction. As a result, it became possible to increase torque to its highest value and reduce fatigue stress to its lowest level.

It is known that the stress gradient of the stress that occurs, the number of weakest parts, the failure probability, the residual stress from press punching, and the roughness of the punched-out edge surfaces are important considerations for methods of accurately predicting rotor fatigue life.\(^{(5,6)}\)

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**Figure 6** Simulation Result of Rotor Flux

**Figure 7** FFT Result of Rotor Flux

**Figure 8** 12th Order of Torque Ripple

**Figure 9** Contour map of principal stress

**Figure 10** Stress Gradient Controlled Test
Figure 10 shows how fatigue tests were carried out at average stress levels for a variety of different shapes in order to confirm the influence of average stress on the fatigue strength of electrical steel sheet. To clarify the influence of the stress gradient, fatigue tests were carried out to estimate the stress gradient index. Then, the stress gradient index for electrical steel sheet was obtained from the relationship between the relative stress gradient and the fatigue strength.

Non-stochastic and stochastic factors were defined as follows (Table 4).

| Non-stochastic factor | Conventional | Developed |
|-----------------------|--------------|-----------|
| Ave. stress           | Typical      | Typical   |
| Stress gradient       | Modified     | High      |
| Laminar ratio         | No consideration | Actual value |
| Temp.                 | RT           | Highest Min |
| Form                  | Dumbbell test stress shape | Typical |

These data relating to materials were incorporated into the strength design.

Fatigue evaluation was carried out for the portions under greatest stress in the designed model. It can be determined from Figure 11 that fatigue life can be extended by implementing a new strength design method that takes the stress gradient more into consideration than conventional design does. And weakest point was shifted by use of new method.

![Fatigue Limit Diagram](image)

Figure 11 Fatigue life of Stress Gradient Controlled

It also became possible to calculate the cumulative damage rate accurately. With the conventional strength design method, the second layer outer rib is the weakest part, and a bending mode occurs there due to centrifugal force. (Figure 12)

Table 5 shows the differences between the conventional and the developed methods, and the differences were confirmed. Such differences occur because the strength design of the rotor uses an appropriate fatigue strength line.

Incorporating the above methods and using up the stress limits of electrical steel sheet contributes to significant enhancement of the degree of freedom of rotor shape.

| Conventional Method | New Method |
|---------------------|------------|
| 2nd Layer Outer Rib | High damage |
| Cumulative damage x/16 |
| Low damage |

![Contour Map of Damage Stress](image)

Fig. 12 Contour Map of Damage Stress

Damage rate is enable to calculate by use of modified minor rule, which have each material S-N curve.

\[
\text{Damage} = \sum \left( \frac{n_i}{N_i} \right)
\]

Here, \(N_i\) : Fatigue life under certain stress and \(n_i\) : number of cycles under certain stress.

New method use fatigue limit diagram according to the actual condition of the material. (Table 4). We could improve the accuracy of calculation for the damage rate.

For the next step, which was to confirm the actual effectiveness of this approach, verification of a variety of rotor shapes was carried out in actual motors. Figure 13 shows the fatigue failure cycle prediction accuracy for each model. The vertical axis shows the fatigue failure cycle prediction accuracy. This is the value obtained when the failure cycle as predicted by this method is divided by the failure cycle in testing. With the previous design approach, there was significant design latitude regarding strength, and its values differed greatly from model to model. With the new method, however, it became clear that fatigue life can be predicted with high accuracy.

![Fatigue Failure Cycle Prediction Accuracy](image)

Fig. 13 Fatigue Failure Cycle Prediction Accuracy

| Model | Conventional | Developed |
|-------|--------------|-----------|
| Model A | 2.01 | 1.00 |
| Model B | 16.4 | 0.93 |
| Model C | 2nd Layer Outer Rib |
| Model D | |

Table 5 Cumulative Damage Rate
5. Optimization for Torque Harmonics

Next, the high harmonic orders of torque from the rotation of the rotor, and particularly the 12th and 24th harmonic components, were optimized in the model that achieves the highest $L_q - L_d$. The 12th and 24th harmonic components of torque have an influence on the dynamics of cabin noise, so it was necessary to lower the level of vibration.

Since the motor noise from higher-order harmonics is transmitted more readily than in conventional engines, there was demand from the market to reduce the torque ripple. The spatial magnetic flux variation of the air gap was adjusted in order to reduce inductance variation and heighten the degree to which market needs are satisfied.

Specifically, a toothed tip shape was adopted for the stator and dimple shapes around the periphery of the rotor as shown in Figure 14. Together with the positioning of small holes, this had the effect of reducing higher harmonics and motor vibration.

The main reason for this, as can be seen from the interlinkage flux change in the magnetic flux density shown in Figure 15, is stator slot air gap modulation over a single rotor cycle and the influence of modulation from switching magnetic poles.

Considering the above discussion, the angles and depths of Dimple 1 and Dimple 2 from the polar center were taken as parameters and every effort was made to reduce torque from optimization of parameters by optimizing the parameters for the 12th and 24th components of torque ripple at 60 Nm and 120 Nm, which have an influence during acceleration and moderate acceleration. Finally, a Pareto solution set was obtained (Figure. 18 and 19). Redness indicate large torque model. We could set as an elite model, which can achieve low 12th and 24th components of torque ripple at 60Nm and 120Nm minimized point.
6. Measurement Results

6.1 EMF property
We measured this motor using a motor bench system. Low levels of 5th and 7th harmonics were measured. (Figure.20)

6.2 T-I property
Target Torque-Current properties were measured for the aforementioned rotor design shapes, and the required vehicle maximum of 335 Nm was achieved. (Figure.21)

6.3 Torque ripple property
Target torque ripple of 12th and 24th properties were measured for the aforementioned rotor design dimple and teeth tips shapes. The required ripple under maximum of 2 Nm@150Nm was achieved. (Figure.22, 23)

6.4 Power property
Target power properties were measured for the aforementioned rotor design shapes, and the required vehicle maximum of 135kW was achieved by use of 630V. (Figure.24)

Figure. 19 Dimple and Stator Teeth Tips Parametric Optimization for 24th Torque Ripple

Figure. 20 EMF Result

Figure. 21 T-I Result

Figure. 22 Torque Ripple Result

Figure. 23 Torque Ripple Result

Figure. 24 N-T Curve Result
7. Summary/Conclusions

By means of the present research, the degrees of freedom of the magnet and its orientation were put to effective use to create a motor that has performance equal to or better than the conventional IPMSM even with the magnet volume reduced by 12%.

In addition, where NVH tends to become an issue in reluctance motors, the present research was able to identify a magnet orientation and rotor shape that would be fully able to satisfy quietness requirements.

In addition, the research resulted in the expectation of adequate production technology to deal with dimensional variation and mass producibility so that C-shaped type magnets could be an industrial product. It successfully showed the viability of IPMSMs with neodymium magnets having an orientation and shape like those in the present research.

The research further showed the possibility of design either using sintered magnets or by means of the hot deformation process, which has made it possible to choose rare-earth-free products that have been on the market since 2017. (5)

The application of this technology to electrification mobility can be expected to enable the realization of a reduction in magnet use and a reduction of supply and price risk. Beyond that, it may also lead to enhanced sustainability of rare earth resources.

References

(1) M. Sagawa, S. Fujimura, N. Togawa, H. Yamamoto and Y. Matsuura, "New Material for Permanent Magnets on a Base of Nd and Fe", 1984, J. Appl. Phys. 55, pp.2083-2087, 1
(2) Jacimovic J. (2019), Net Shape 3D Printed NdFeB Permanent Magnet. In F. Kongoli, M. Calin, J.M. Dubois, K. Zurek-Rozman (Eds.), Sustainable Industrial Processing Summit SIPS2019 Volume 3: Kobe Inl. Symp.
(3) S. Soma, H. Shimizu, S. Fujishiro, E. Shirado : Magnetic Form of Heavy Rare-Earth Free Motor for Hybrid Electric Vehicle, 2017, SAE, 2017-01-1221.
(4) IEEJ, "Research and development trends in high-performance permanent magnets", 2020, No. 1494 p.1-77
(5) IEEJ, "Historical Progress and Future Prospect of Technology being Related to Application-specific Electric Motors", 2021, No. 1507 p.1-64
(6) K. Inoue, "Fatigue evaluation technology for rotor, which use for electric vehicle", 2019, No.VT-19-003 p.11-13 Technical Meeting on automobile
(7) K. Inoue, "Fatigue life prediction of motor rotor considering the effect of press punching of electrical steel sheet" Technical paper of JSAE, 2020, Vol51, No.3, p422-427

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