Development of Motor-Integrated ECU

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Energy saving that shows consideration for the environment and smaller vehicle components for expansion of vehicle interior space are needed. Therefore, for motors and ECU (Electric Control Unit) used in an electric power steering, not only reduction in size and weight but higher efficiency are required. For this purpose, motors and ECU which conventionally were mounted separately have been integrated. Here development results of motor integrated ECU are introduced.

***Key Words**: electric power steering, motor, ECU, integration, high efficiency, small size, light weight*

1. Introduction

In recent years there has been a rapid increase in hybrid and electric vehicles triggered by escalating oil prices and sensitivity towards the environment. A rapid shift in steering system trends from hydraulic power steering to electric power steering (EPS) also has been occurring due to intensified efforts to improve fuel efficiency. A larger number of electrical components are now used on each vehicle and as such there is a demand for energy-saving EPS in order to alleviate the burden on the battery. Moreover, in response to the demand to expand vehicle interior space, smaller vehicle components are required.

To meet these demands, JTEKT has developed and commercialized a motor-integrated ECU which is smaller, lighter in weight and higher in efficiency.

2. Development Aims

Figure 1 shows the power efficiency of the EPS system. Power is supplied from the vehicle's battery, electric current flows from the ECU to the motor and is converted to rotational energy. That rotational energy passes through a reduction gear and becomes rack thrust which moves the tires. In regards to the vehicle itself, it is important to suppress power consumption, and for that to be achieved, motor and ECU power loss must be suppressed to as minimum an amount as possible.

Conventionally, the motors used in the EPS and ECU were individually assembled in vehicles. As such, it was electrically necessary to wire the motor and ECU separately and power was lost as a result of wiring resistance. By integrating the motor and ECU as JTEKT has done in this development, the wiring loss between the motor and ECU has been reduced, and higher efficiency could be achieved. Moreover, by reducing the ECU specialized heatsink capacity and improving the coil lamination factor, components could be made smaller and lighter.

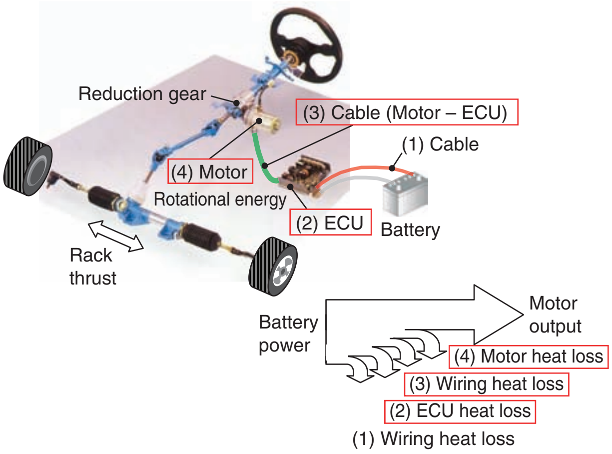


Fig. 1 Structure of EPS system and its power efficiency

3. Description of the Development

3. 1 Motor-Integrated ECU

As **Fig. 2** shows, in the motor-integrated ECU, the motor, motor rotational angle sensor and ECU are positioned along the vertical axis.

A brushless motor is used and is configured with a stator which creates a field using coils and, on the inner diameter, a rotor which uses a permanent magnet. The ECU is configured with a power circuit which drives the motor by sine-wave current using MOS FET, a microcomputer, internal power, communication interface, control circuits composed of pre-drivers, etc., a heatsink, a cover and so on.

3. 1. 1 Advantages of Integrating the Motor and ECU

As a result of directly connecting the motor and ECU, wiring loss between the motor and ECU has been reduced and the efficiency of the power supply from the battery to the motor has been improved. Moreover, conventionally the offsetting of the motor rotational angle sensor was carried out in vehicle manufacturers' assembly processes however by doing this at JTEKT within our own assembly process, we have alleviated the workload for vehicle manufacturers. Finally, in contrast to the conventional motor where the angle 0 position of the rotational angle sensor was offset at a mechanical angle level at the motor independently, in the case of the motor-integrated ECU, better positional accuracy can be obtained by offsetting it with an electric angle level accuracy.

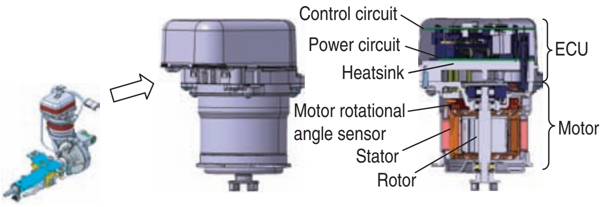


Fig. 2 Structure of motor-integrated ECU

3. 1. 2 Directly Connecting the Motor and ECU

The electrical connection wiring (motor three-phase wiring and motor rotational angle sensor wiring) must not interfere with the efficient use of the space inside the ECU. Taking this into consideration, for the motor three-phase wiring, the three-phase line pullout inside the motor was routed around the outer edge of the motor and joined to the power terminal strip on the ECU side by bolts. Regarding the motor rotational angle sensor wiring, the terminal from the rotational angle sensor was positioned on the motor outer edge, and after passing through the terminal guide section on the ECU side, the wiring could be soldered to the control substrate.

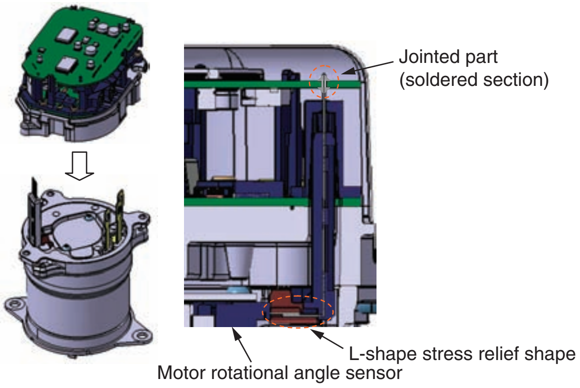


Fig. 3 Stress relief at jointed part

Here, depending on the heatshock of the mounting environment, the difference in the linear coefficients of expansion of each material causes stress to occur at the soldered joint of the motor and ECU, however by making the rotational angle sensor terminal an L-shape, stress was alleviated (**Fig. 3**).

As these results, the strength safety factor of jointed parts (soldered parts) becomes approximately double of the target value, In fact, 5 times or longer heat cycles are predicted for the joint part (soldered section) compared to the estimated ones from the crack occurrence to joint part breakage(**Fig. 4**).

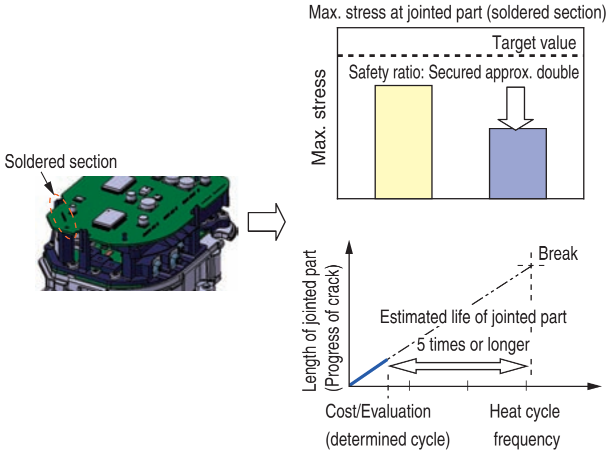


Fig. 4 Effect of stress reduction at jointed part and life estimation

3. 2 ECU

3. 2. 1 Reduced Capacity of the ECU Specialized Heatsink

The motor-integrated ECU heats up due to switching loss at actuation, pattern wiring loss, motor copper and iron loss, etc.

In order to prevent malfunctions caused by the heat of electronic components, the heatsink plays an important role in suppressing temperature increase and allowing heat release. In this development, by directly connecting the motor and ECU, a configuration has been formed whereby the heat masses of the motor and ECU are shared through their mutual heat transfer. As such, in order to optimize the heatsink capacity set specifically for the ECU in the conventional structure, a heat simulation and verification test were carried out (**Fig. 5**).

The difference in the results of the simulation and verification test was approximately 10℃, which was practically as per design. Based on these fundamental data, the necessary margin in relation to the allowable temperature of parts was found, and by optimizing the ECU specialized heatsink capacity set, mass was reduced by approximately 20% of the conventional heatsink (**Fig. 6**).

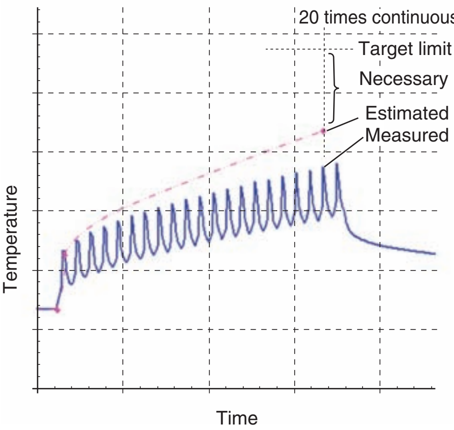


Fig. 5 Result of temperature verification

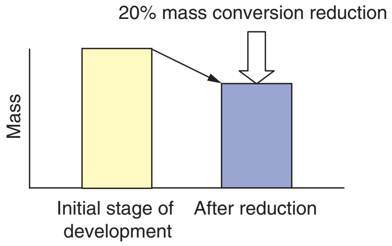


Fig. 6 Weight reduction of specialized heatsink

3. 2. 2 ECU Bus Bar Configuration

Conventionally, the circuit and the substrate of the power and control circuits were separated and their respective substrates were electrically connected by bus bars. Furthermore, these bus bars had multiple pins and narrow pitches and were connected on the substrates (**Fig. 7**).

However, there was concern that this configuration would be difficult to assemble.

As such, by adding a substrate insertion guide pin to the power circuit and a bus bar guide to maintain the bus bar tip position, it became easier to assemble the control circuit.

Moreover, the area where clearance from the soldering iron is necessary in the bus bar soldering was moved to the substrate edge and by concentrating the bus bars on the substrate edge, space for the efficient implementation of components was secured. Finally, the production efficiency in the manufacturing process where the bus bars are soldered on the substrate was improved.

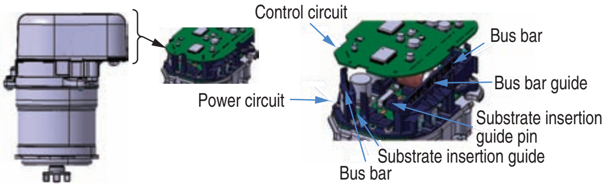


Fig. 7 Configuration of bus bar

3. 3 Motor

3. 3. 1 Magnet

As an alternative to conventional rare-earth ring magnets, segment magnets were adopted (**Fig. 8**). By adopting segment magnets, it is no longer necessary to use magnets between poles therefore reducing magnet usage by approximately 45% compared with the conventional product and contributing to weight reduction became feasible. By reducing the amount of rare-earth used, in order to correspond to an issue receiving much attention recently with the concern regarding resource depletion, this move also contributes to global environment protection.

Reduction of magnetic force variation becomes an issue when segment magnet is adopted. One ring magnet has multiple magnetic poles, however in the case of segment magnets, the same number as the one of poles is required. Variation of each pole's magnetic force when the magnets are assembled into the motor does not only affect the magnetism of the magnets but also leads to variation in dimensions. As such, segment magnets more often cause magnetic force variation than ring magnets. This variation must be reduced as it creates cogging torque of an order in response to the number of slots. On the developed product, the higher positional accuracy of the magnets makes it possible to obtain a cogging torque equivalent to that created in the case of ring magnets, achieving the target value (**Fig. 9**).

Even if there is no variation in magnetic force, torque fluctuation occurs depending on the combination of poles and slots. **Section 3. 3. 3** discusses the optimization of the magnet shape in order to reduce this torque fluctuation.

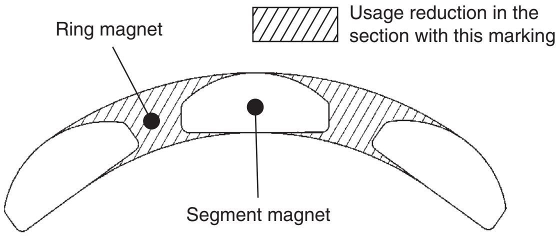


Fig. 8 Cross section of magnet

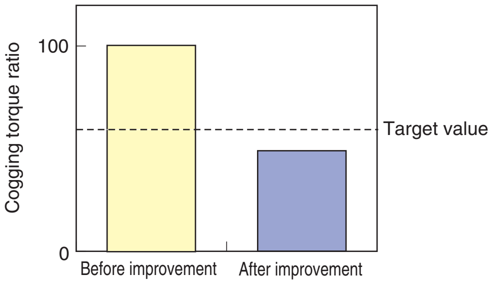


Fig. 9 Reduction of cogging torque by improvement in positional accuracy of magnet

3. 3. 2 Coil Lamination Factor

In order to utilize coil space efficiently, a 2-parallel double delta connection method was used (**Table 1**). Using this double delta connection method allowed the coil to be made thinner, and improved the lamination factor by 5% compared to the conventional product, as well as improved torque volume density (**Fig. 10**). However, because the double delta connection is a closed circuit, circulation current caused by the induced voltage 3n (n=1, 3, 5……) order harmonics occurs. Circulation current leads to heat loss therefore it is important that it is kept to a minimum as much as possible. **Section 3. 3. 3** describes the method for reducing circulation current.

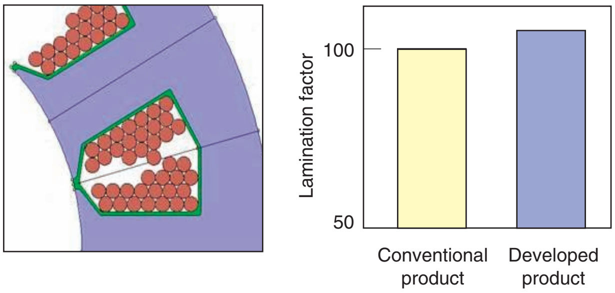


Fig. 10 Coil slot and space factor

3. 3. 3 Optimization of the Magnetic Circuit

As well as improving torque volume density, it is also important to have smooth steering. To achieve this it is necessary to reduce the cogging torque and torque ripple which lead to torque fluctuation. Torque ripple is caused by the induced voltage 3n + 2 order, 3n + 4 order (n=1, 3, 5……) order harmonics and flux leakage at the stator core tip. Widening the slot opening is effective in reducing flux leakage and torque ripple. However, because magnetic resistance changes where the slot opening and stator core tip meet, widening the slot opening will have the paradoxical effect of increasing cogging torque.

In order to solve these issues, the authors implemented an optimum design of the magnetic circuit using magnetic field analysis. The results of this are shown in **Fig. 11**. The slot opening was made a size where a good balance between cogging torque and torque ripple is achieved (**Fig. 12**). Furthermore, the magnet was made an uneven thickness with the center thick and the edges thin. Thin edges reduce permeance and Demagnetization Resistance. Taking into Demagnetization Resistance consideration, the authors decided upon an optimal unevenness while securing a set thickness. This resulted in the reduction of induced voltage 3^{rd} order harmonics which is the cause of torque ripple and circulation current (**Fig. 13**). This is the advantage of the segment magnet which can be shaped arbitrarily. By optimizing the slot opening and magnet shape, it was possible to simultaneously achieve low cogging torque, low torque ripple and low circulation current as well as improve torque volume density.

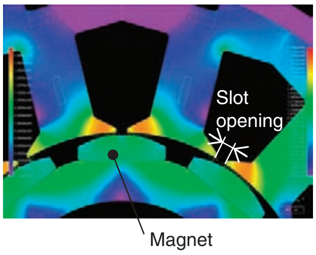
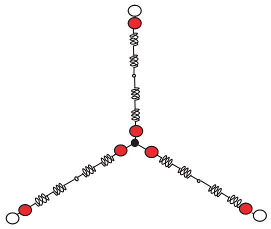
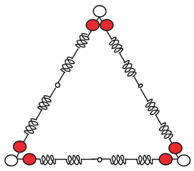
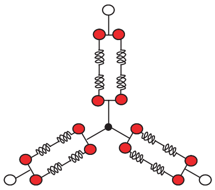
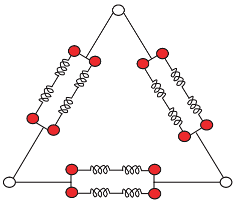


Fig. 11 Simulation of magnetic field analysis

Table 1 Relationship between wire connection and coil wire diameter

High lamination factor →

Connection method	Single (series) star [base]	Single (series) delta	Double (parallel) star	Double (parallel) delta
Connection diagram				
Coil wire dia. ratio	1	0.76	0.70	0.54
Coil roll no. ratio	1	1.70	2.00	3.50

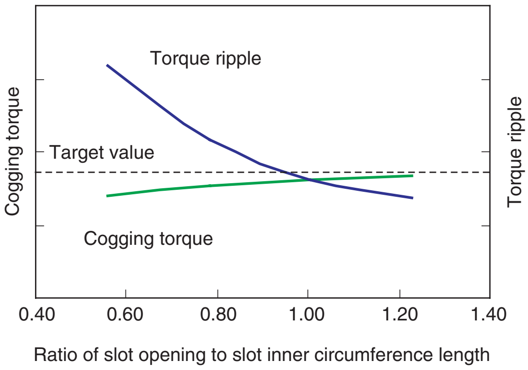


Fig. 12 Relationship between slot opening and torque fluctuation

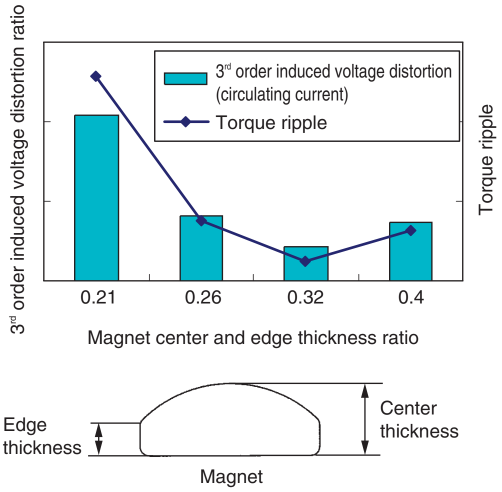


Fig. 13 Relationship between magnet shape and induced voltage distortion

4. Effects

A performance equivalent to the conventional product was secured on the developed product. In addition to the benefits of integration such as elimination of the harness, etc., the integrated-motor ECU had the effects shown in **Fig. 14** of being smaller, lighter in weight and higher in efficiency. Compared with the conventional separate configuration of the motor and ECU, the developed product has a reduced volume, mass and power consumption of approximately 30%, 35% and 10% respectively.

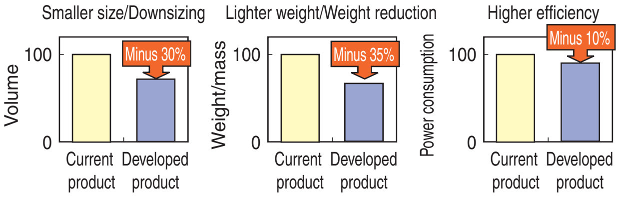


Fig. 14 Effect of smaller size, lighter weight and higher efficiency

5. Conclusion

As a swift response to the energy and space saving demands in electric power steering, JTEKT has developed and is mass producing its first in-house integrated-motor ECU. By utilizing heat, configuration and magnetic analysis simulation, effective countermeasures were investigated for each issue and the developed product was made smaller and lighter. JTEKT intends to expand this technology further in the future to develop products which are even higher in efficiency and smaller in size.

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