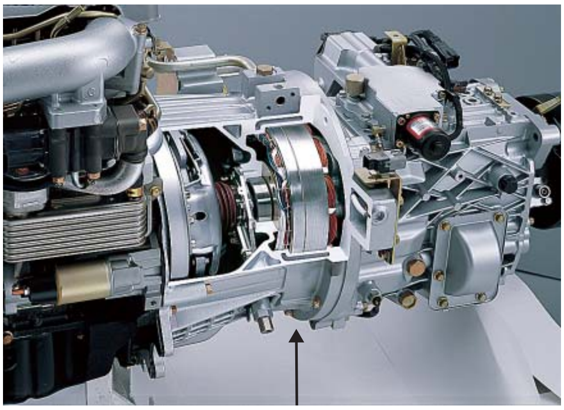

Development of Motors and Inverters for Light-Duty Hybrid Trucks

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From the perspectives of preventing global warming and maintaining resources, the issues of fuel efficiency and vehicle emission regulations have intensified in recent years, and the demand for green cars is increasing every year. Mitsubishi Heavy Industries, Ltd. (MHI) has been supplying motors and inverters for prototype hybrid vehicles to various car manufacturers and also started to supply them for light-duty hybrid trucks in May 2006. This paper gives an outline of our reliability assurance in the processes from designing to manufacturing of the motors and inverters.

1. Introduction

In recent years, there have been increasing discussions on the effects of vehicle exhaust gas on the global environment, for example the California's Low-Emission Vehicle Regulations in the U.S, the New Long-Term Emission Regulations in Japan, and emission gas controls in Europe. Meanwhile Brazil produces alternative fuels such as ethanol which is known as clean fuel. The world's nations decided on CO_2 reduction targets under the Kyoto Protocol and have launched efforts to prevent global warming. When viewed by the industrial sector, the ratio of CO_2 emissions from vehicles is considerable.

In addition to the global environmental problems, there is also a problem of reserve-production ratios (RPR) of fossil fuels, and the development of technology to reduce petroleum consumption is becoming an important mission for manufacturers. Petroleum consumption in Japan is about 300 million liters per year, 35% of which is used as vehicle fuel. Vehicle exhaust gases include CO_2, NOx and PM. Carbon dioxide causes global warming, while NOx and PM pollute the environment. Therefore, improving fuel consumption and controlling exhaust gas are strongly required worldwide. Further, responding to the hikes in gasoline prices in the U.S. over the past few years, car manufacturers are accelerating their efforts to expand the supply of hybrid vehicles and develop new products.

MHI started to develop servo motor technology as early as the 1970s and has introduced it to special vehicles and industrial machinery. The compact and lightweight features of MHI motors are highly regarded, and motors and inverters for prototype hybrid vehicles have been supplied to various car manufacturers since 2000. Long term verification tests with actual vehicles were completed in 2006 and commercial production of motors and inverters for light-duty hybrid trucks began in May of that year.

This paper describes the development of these motors and inverters in processes from design to manufacturing by focusing on reliability assurance.

2. Motors and inverters for light-duty hybrid trucks

The features of MHI's motors are compactness, light weight, and high power, and so can be mounted between the automatic clutch and the automated mechanical transmission in a compact manner. Because of this, the vehicle is started by the motor alone and energy is efficiently regenerated when the engine is detached during deceleration. Further, this compactness also allows parts sharing between the base and hybrid vehicles. **Figure 1** shows a light-duty hybrid truck equipped with an MHI motor, while **Fig. 2** shows a light-duty hybrid truck inverter developed by MHI. (The title photo shows the motor itself.)

Fig. 1 Light-duty hybrid truck (photo provided by Mitsubishi Fuso Truck & Bus Corporation)

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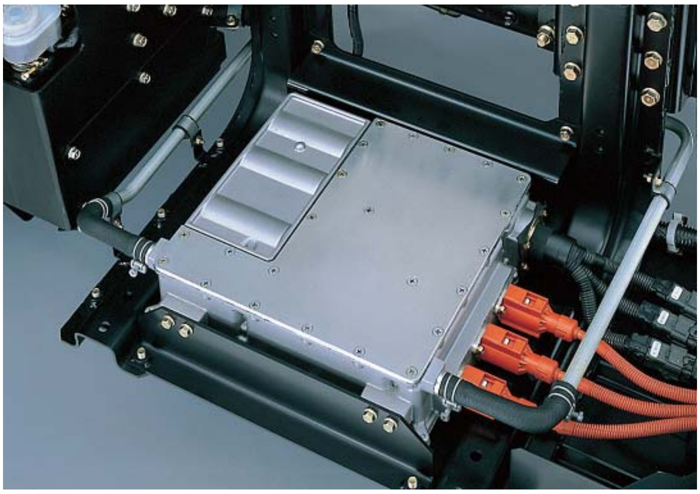

Fig. 2 Inverter for light-duty hybrid truck

Table 1 Required specifications input to design tools

Item	Symbol	Unit	Input value
(1) Max. Torque	Tmax	Nm	* * *
(2) Max. Speed	Nmax	rpm	* * *
(3) Max. Voltage	VBr	VDC	* * *
(4) Max. Current	Imax	Arms	* * *
(5) Outer diameter of stator	Do	mm	* * *
(6) Max. Power	Pout	kW	* * *

Example of data list outputs of design tools

- Motor specifications ----- Armature resistance, inductance, torque constant
- Performance characteristics ----- N-T characteristics, output characteristics, temperature characteristics, efficiency map
- Losses ------- Copper loss, iron loss, wind loss
- Driving characteristics ----- Temperature trend during continuous driving, temperature trend during 10-15 mode drive, temperature trend during any given drive pattern

3. Design of motors and inverters

As hybrid vehicle motors require increased compactness and light weight, a wider driving range, and higher efficiency compared with motors for industrial machinery, they are designed using the procedures below.

3.1 Requirements for hybrid vehicle motors

Figure 3 shows the motor performance of various travel modes. Hybrid vehicle motors are expected to have enough performance to meet the specific objectives of each travel type. Through optimizing the number of poles and slots of the motor, MHI has realized (1) increased torque stability (reduction of the high harmonic components of magnetic flux), (2) maximum utilization of magnets and magnet wires, and (3) reduced magnetic resistance. As a result, downsizing and weight saving of about 60% in comparison with MHI's conventional model has been achieved.

3.2 Automatic design by use of tools

When the requirements specified in **Table 1** are input to the design tools, they output a data list (mentioned below) to complete the basic design of the motor and inverter. The design tools have been improved based on prototype vehicle test data to ensure higher accuracy (+/−5% or below). The design tools can quickly provide the motor design specifications needed to attain the target performance and have contributed to a sharp reduction of design man-hours. As output examples, **Fig. 4** shows the N-T characteristics and efficiency map, while **Fig. 5** shows the temperature trend during continuous driving.

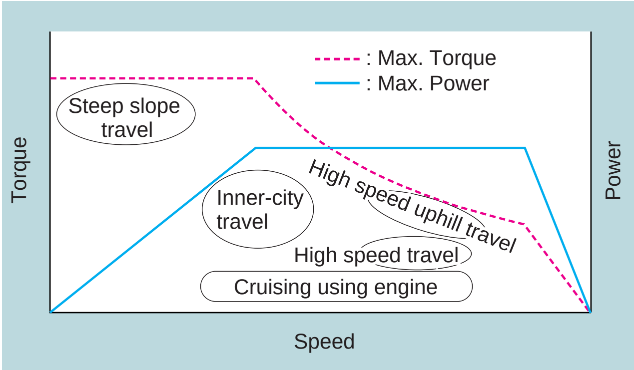

Fig. 3 Performance curve of hybrid vehicle motor

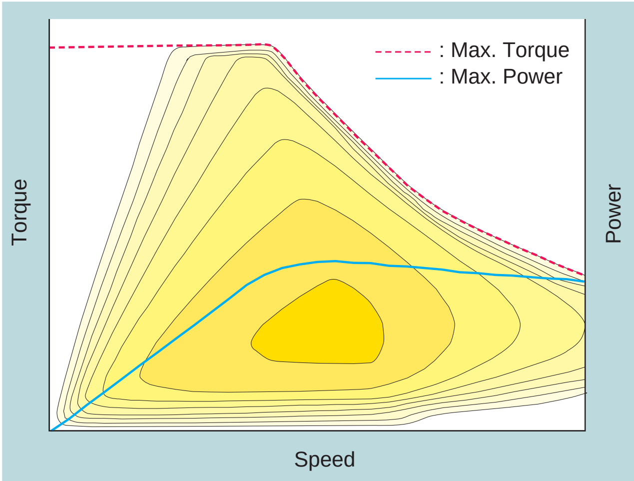

Fig. 4 N-T characteristics and efficiency map (example of output)
The contour line map shows the efficiency distribution, where efficiency increases toward the center.

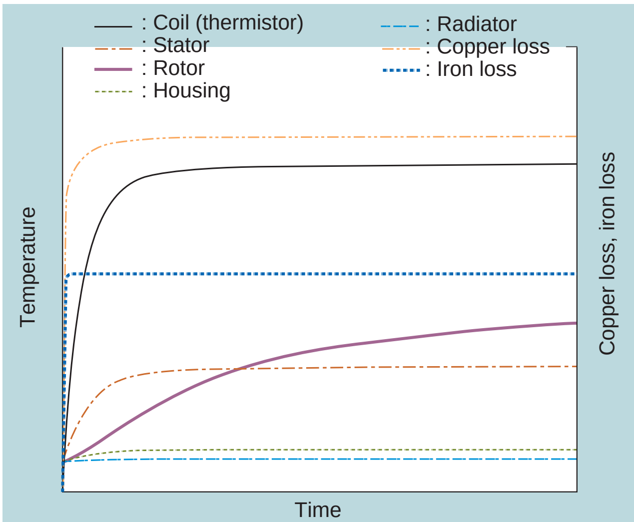

Fig. 5 Temperature trend during continuous driving (example of output)

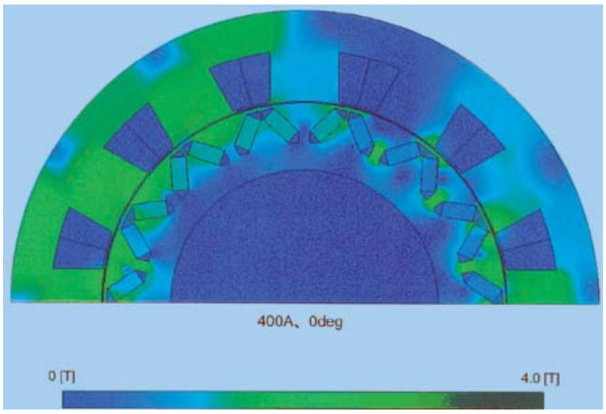

Fig. 6 Results of magnetic field analysis (example of output)

Table 2 Core tools

APQP	Advanced product quality planning
PPAP	Production part approval process
FMEA	Failure mode and effects analysis
MSA	Measurement system analysis
SPC	Statistical process control

3.3 Design verification by analysis

When there is a large change in the motor structure or motor mounting conditions, we carry out two dimensional and three dimensional analyses of the magnetic field, heat and vibration in the initial stage of the design process, verifying the feasibility of the targeted performance. As an example, the results of the magnetic field analysis of a hybrid vehicle motor are shown in **Fig. 6**, and an example of a digital mock-up for the vibration and heat strength analysis is shown in **Fig. 7**.

3.4 Selection of component parts

Unlike the motor, as the inverter is equipped with a number of electronic devices, we consider that not only thermal analysis by the design tools but also reducing the failure rate of electronic parts based on Expression (1) is an important issue.

$$\text{Failure rate } \lambda(t) = \frac{\text{Total number of failures during specified period}}{\text{(Population parameter x Operation hours)}} \text{(Fit)} \quad (1)$$

Note: Fit (Failure In Time) = 10^{-9}/hour

As the power device generates the largest loss of the inverter component parts, it is a particularly important component which influences both the performance and the cost. MHI has achieved the target power by raising the motor power factor and by using a highly reliable power device with a small capacity. Further, in the design of inverters, especially in the design of electronic circuits, the aim is to reduce the initial failure rate by means of screening and aging, and to reduce the failure rate through selecting parts with a proven long service life. As MHI is also working on improving the reliability of electronic parts supplied to the aviation, space and atomic industries, we will address this important issue by integrating these technologies.

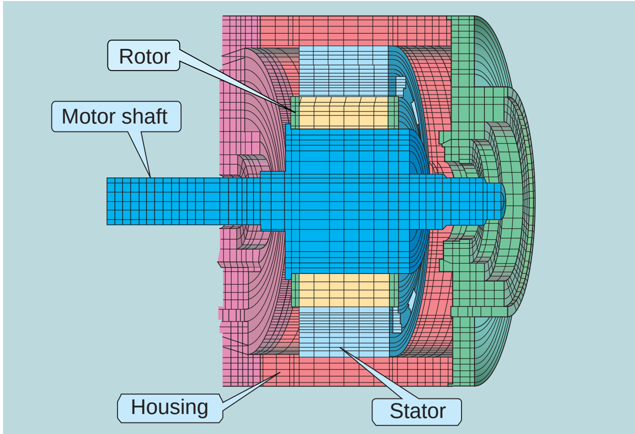

Fig. 7 Example of digital mock-up for vibration and heat stress analysis

4. Manufacture of Motors and Inverters

By using the quality system for automobile parts (**Table 2** shows the core tools of the quality system) MHI has established a production line and developed an automatic winding machine suitable for the new motors. The quality of the products currently being manufactured shows less disparity and the process capability is good. We plan to keep working on pursuing the fundamentals of the quality system to improve and maintain our quality level, thus responding to customers' needs.

5. Conclusion

Regarding the motors and inverters whose commercial production for light-duty hybrid trucks has already been started, we have outlined our efforts in improving reliability through the design to manufacturing processes.

Various kinds of system such as hybrid cars and natural gas vehicles are under development as earth- conscious cars all over the world. Energy regeneration is the characteristic which is inherent in a vehicle using a motor, where the degree of regenerated energy effect of the motor is always an important issue. Further, when low-cost fuel cells are developed in future, the motor will become their core driving power source. We will continue to reinforce our technological development and promote the development of low-cost, high-performance motors.


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