Product Introduction

Development of EPS with In-house Manufactured PP for Yamaha Motor

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1 Introduction

KYB's electric power steering (EPS) for off-road vehicles has a long history, dating back to 2005 when the EPS was first used in the world on all-terrain vehicles (ATVs) of Yamaha Motor Co., Ltd . ("Yamaha Motor"). Specifically, the EPS is a column EPS whose electronic control unit (ECU) is separate from the EPS body (the "conventional EPS"). This conventional EPS has been used in ATVs and recreational off-highway vehicles (ROVs) by many manufacturers. It is still being mass-produced 20 years after it was first introduced.

Meanwhile, the percentage of off-road vehicles equipped with EPS has been increasing. Especially with the recent trend of larger vehicles, EPS has been required to deliver higher power to provide the driver with comfortable steering, such as the need for less steering force and suppressed kickback. KYB also set the goal of achieving higher EPS power and developed a pinion EPS for off-road vehicles equipped with an in-house manufactured power pack (an ECU-integrated brushless motor; "PP") . This EPS is hereinafter referred to as the "Pinion EPS" . Since 2019, we have been mass-producing the Pinion EPS for other vehicle manufacturers.

However, the majority of existing off-road vehicles used the column EPS. Vehicle manufacturers were expected to undertake large-scale development if they installed a different type of EPS in their off-road vehicles. In reality, we had to develop a higher-power column EPS and expand the EPS product line.

In this project, we developed a column EPS equipped with an in-house manufactured PP (the "Product") in order to increase the performance of the conventional EPS. We started mass production in 2024 for Yamaha Motor's Wolverine RMAX 1000 (Fig. 1) and Grizzly 700 (Fig. 2). The following sections describe the mechanical specifications and control functions of the Product.

Fig. 1 Wolverine RMAX1000 (ROV)

Fig. 2 Grizzly700 (ATV)

2 Mechanical Specifications

2. 1 Adoption of Standard Module and Conventional EPS Parts

The EPS market for off-road vehicles is smaller than that for passenger cars. Therefore, it was important to develop the Product with a limited number of new parts in consideration of cost.

For the Product, we then decided to use the standard module that we had developed for the Pinion EPS. The standard module is a compact package of the in-house manufactured PP, a torque angle sensor, and a worm reduction gear (Fig. 3). The use of this module resulted in a higher reduction ratio, a larger motor assist torque, and about 2.8 times the EPS output torque of the conventional EPS. A comparison of key specifications between the conventional EPS and the Product is shown in Table 1.

In general, when EPS is installed in a vehicle, the engagement specifications must be customized to match the vehicle layout. This means that 100% standardization of EPS is impossible unless the customer chooses off-the-shelf products. The Product, which uses the standard module and parts of the conventional EPS, has a minimum of new parts to achieve a standardization rate of as high as 80%.

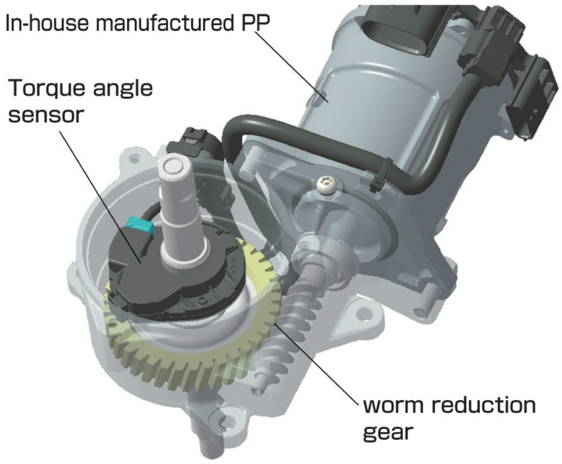

Fig. 3 Components of standard modules

Table 1 Comparison of key specifications

Item	Conventional EPS	The Product
Reduction ratio	17：1	18.5：1
Motor assist torque	1.5Nm	4.2Nm
EPS output torque	22.9Nm	65Nm

2. 2 Gear Case Main Mold Standardization

The column EPS consists of two housings, except the motor/PP. The gear case houses the worm gear reducer.

The column EPS for ROVs and ATVs comes in different specifications depending on the vehicle requirements. Here are two examples. The first is the difference in the way the torque is transmitted from the column EPS to the tires. For ROVs, the output shaft of the column EPS is connected to an intermediate shaft. The torque is typically transferred from the shaft to the tires via a rack and pinion.

For ATVs in turn, the output shaft of the column EPS is screwed to a pitman arm. In most cases, the torque is transmitted from the pitman arm to the tires via a tie rod. The connection point between the pitman arm and the tie rod is not on the same axis as the output shaft (Fig. 4). The output shaft is subjected to a bending moment during torque transmission. This is a characteristic of the column EPS for ATVs.

The output shaft of the Product for ROVs, where bending moments are small, is supported at a single point to reduce cost, while that for ATVs is supported at two points as a measure against bending moments. The first support of the output shaft has been designed to be at the same axial height for both models, making it possible to standardize the internal structure of the gear case, except for part of the structure on the side of the output shaft.

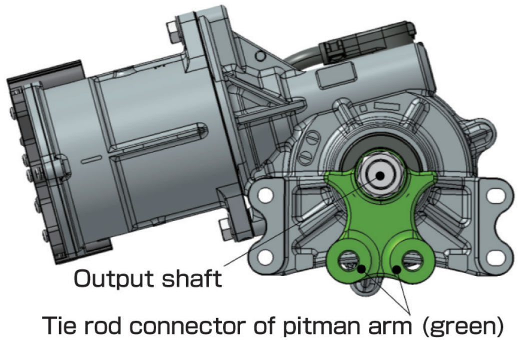

Fig. 4 Output shaft structure for ATVs (with pitman arm assembled)

The second example of different specifications depending on the vehicle requirements is the difference in the way the housing is attached to Yamaha Motor's vehicles. The column EPS for ROVs is attached to the vehicle with the female threaded housing on the input shaft side, while the column EPS for ATVs is attached to the vehicle with the housing on the output shaft side using nuts and bolts.

The conventional EPS is designed so that the vehicle attachment function and the worm reduction gear installation function are implemented in two different housings. This means that the die casting mold of the gear case is not standardized (Fig. 5)

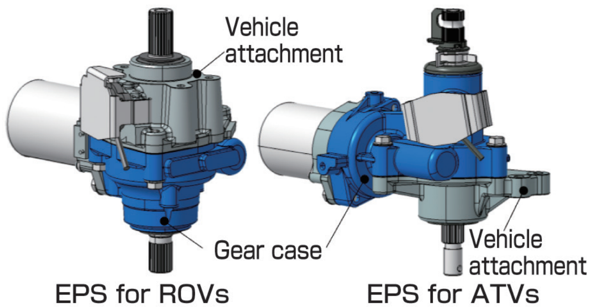

Fig. 5 Gear case of conventional EPS

In the Product, the EPS for ROVs also uses the vehicle attachment of the EPS for ATVs (Fig. 6). This addition allows the vehicle attachment for ATVs to be used as the fixture attachment point for the EPS assembly process, eliminating the dedicated assembly attachment point prepared in the conventional EPS. Now, the EPS for ROVs and ATVs have the same appearance and the main die casting mold of the gear case is shared. In addition, we have set a dedicated inner ring for this model in part of the structure on the output shaft side. It is now possible to produce the gear case with fewer set-ups.

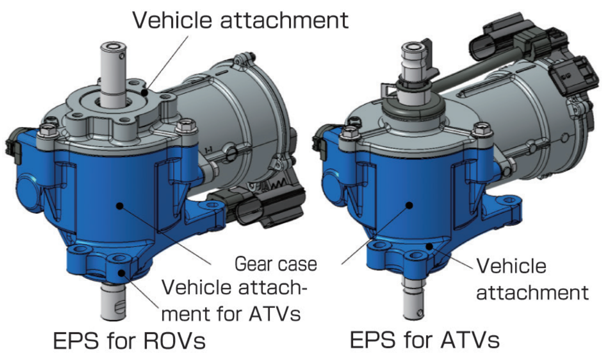

Fig. 6 Gear case of the Product

3 Control Function Development

Among the steering functions required in off-road vehicles, steering responsiveness and disturbance inhibition are particularly important. In order to meet the steering performance requirements, the Product was installed with base current control, stabilizing control, and derivative current control.

Fig. 7 shows a general block diagram of the Product's control system.

The next sections describes the implementation of each control.

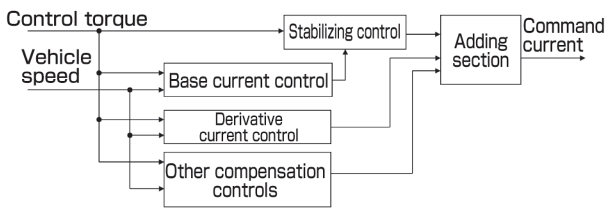

Fig. 7 General block diagram of the Product's control system

3. 1 Base Current Control

This is a control function that determines the current value for controlling the base current (the "base current value") from the control torque generated when the driver operates the steering. Compared to the conventional EPS, the Product uses a high-output motor based on which the base current value has been set. Table 2 compares the electrical equipment of the old and new products.

Table 2 Comparison of electrical equipment of old and new products

Item	Conventional EPS	The Product
Configuration	ECU-separate motor	ECU-integrated motor
Motor	Brush type	Brushless
Motor assist torque	1.5Nm	4.2Nm
Weight	1.60kg + 0.87kg	2.0kg

To enable the driver to clearly perceive the onset of steering, we tuned the steering feel range as shown in Fig. 8 (within the area enclosed by the green dashed line). As a result, the steering feels smoother than the conventional EPS.

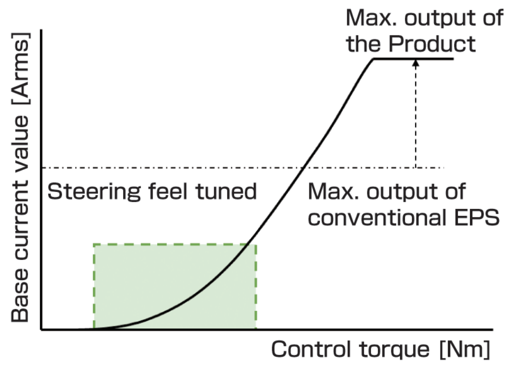

Fig. 8 Conceptual drawing of base current control

3. 2 Stabilizing Control

The Product's control system mainly consists of a torque feedback control that feeds back the EPS output torque. The input and feedback torques are used to calculate the control torque. This torque is then used to determine the motor current command via the stabilizing, base current, and compensation controls. The motor current command generates the motor torque necessary to operate the Product. Fig. 9 shows the basic configuration of the torque feedback control system.

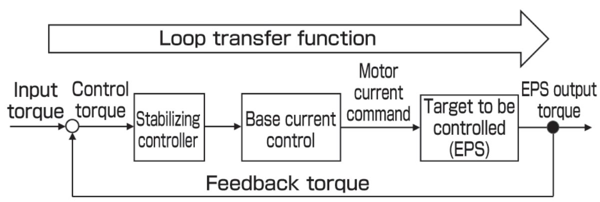

Fig. 9 Basic configuration of torque feedback control system

In the base current control described in the previous section, increasing only the current value results in an increase in the gain of the loop transfer function of the torque control system over all frequency ranges. This results in an unstable condition (causing self-excited vibration).

To ensure stability of the torque control system, the phase of the loop transfer function must be advanced in the high frequency range. The Pinion EPS uses phase compensation control to advance the loop transfer function of the torque control system. Fig. 10 shows a block diagram of the phase compensation control.

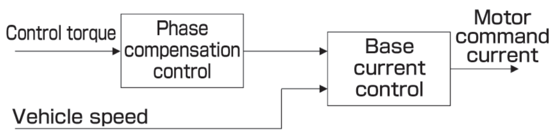

Fig. 10 Block diagram of phase compensation control

However, we found it difficult to achieve both high responsiveness and stability at the same time by increasing the base current value through vehicle tuning. This was because tuning was done in terms of frequency response (gain, phase) or based on evaluation using an actual EPS unit.

Then, in order to achieve high responsiveness and stability by increasing the base current value, we added a stabilizing control. A block diagram of the stabilizing control is shown in Fig. 11.

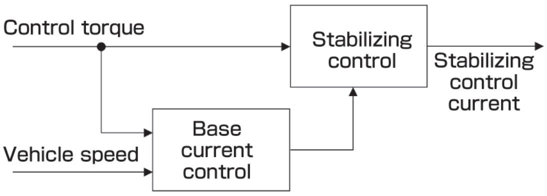

Fig. 11 Block diagram of stabilizing control

This stabilizing control provides the gain or phase margin of the torque control system regardless of the magnitude of the current slope of the base current value. Table 3 compares the specifications of the phase compensation and stabilizing controls.

Table 3 Comparison of control specifications

Comparison	Phase compensation controller	Stabilizing controller
Controller configuration	Phase advance x 2 Phase delay x 1	Feedback of status and disturbance estimation based on general stabilizing controllers
Tuning method	Based on frequency response Based on behavior evaluated using an actual EPS unit	Model-based tuning using a control target model
Tuning parameter	Gain cut-off frequency of phase compensator	Specific frequency, attenuation factor

In this project, we used a model-based development approach with a control target model to investigate parameters. We specified the natural frequency and attenuation factor to perform desktop tuning, which dramatically improved the operating efficiency.

3. 3 Differential Current Control

This differential current control processes the control torque with a high-pass filter (HPF) and a low-pass filter (LPF) to obtain a torque differential value and adds it to the base current value.

Using this control in the low control torque range allows the steering torque to increase gradually, improving the responsiveness. Fig. 12 shows a block diagram of the differential current control.

HPF is used to perform differential calculations, while LPF is used to reduce the high-frequency noise associated with differential calculations.

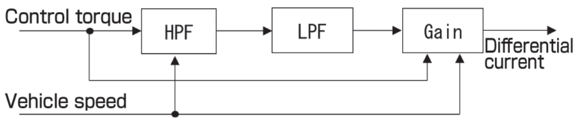

Fig. 12 Block diagram of differential current control

4 In Closing

With the adoption of the Product by Yamaha Motor as a springboard, we will also encourage other manufacturers to use the Product in vehicles that currently use the conventional EPS. In addition, we have expanded our product line of high-output EPS for off-road vehicles. From now on, we will propose appropriate specifications to meet market demands, using the Product and the Pinion EPS.

Finally, we would like to take this opportunity to express our gratitude to Yamaha Motor and those involved in KYB for their cooperation in this development project.

References

1) MIYAKE, TOMITA: "Development of EPS for Non-Passenger Vehicles", KYB Technical Review No.60 (April 2020).
2) MATSUMOTO, ENOMOTO, KENJO, FUKUSHI: "Control Technologies for In-Vehicle Electric Actuators", KYB Technical Review No.65 (October 2022).

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