

Control Technology of Direct Electromagnetic Clutch Employed in SH-AWD System

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ABSTRACT

The SH-AWD system is a 4WD system providing continuously variable control of the torque transmitted to all four wheels to radically enhance vehicle dynamic performance. The core of the system is a direct electromagnetic clutch positioned in the rear drive unit. This new clutch was developed to enable more precise control than is possible in a conventional electromagnetic clutch. In the direct electromagnetic clutch, there is an air gap between the magnetic materials, that form the solenoid magnetic circuit. The solenoid force generated across this gap is converted into clutch thrust, without the need for the torque amplifier employed in conventional electromagnetic clutches. The fact that thrust acts directly on the clutch increases the precision of control. However, the size of the air gap changes when the thickness of the clutch changes, and this causes change in the solenoid force. A search coil is therefore used to detect changes in the size of the gap as changes in magnetic flux, enabling the current to be corrected in order to ensure that the appropriate solenoid force is consistently generated. In addition, measures to increase the accuracy of detection have enabled more precise control of torque transmission.

1. Introduction

The SH-AWD system performs variable control of the torque transmitted to the four wheels according to the driver's operation and the condition of the vehicle, thus enhancing the vehicle's dynamic performance, as represented by cornering performance and stability⁽¹⁾.

In order to satisfy the above performance factors, the electromagnetic clutch mounted on the rear drive unit must have high torque control accuracy including reduced hysteresis. The conventional electromagnetic clutch uses a ball ramp as the torque amplifier. However, the response delay due to play in rotation angle up to the operational position and the resulting drag load, affect

the torque control accuracy⁽²⁾. A direct electromagnetic clutch uses a planetary gear mechanism which enables the torque to be boosted without the above concerns occurring.

The conventional electromagnetic clutch employs a construction in which the clutch plate is held between the magnetic materials that constitute the magnetic circuit, hence the clutch plate forms part of the magnetic circuit through which magnetic flux passes. For this reason, it is not possible to use paper-based friction material, which is a non-magnetic material, in the clutch plate, and thus a ferrous clutch plate is used. As a result, it is necessary to specially treat the surface of the clutch plate in order to stabilize the inherent friction characteristics⁽³⁾. Also, because the clutch plate is a strength member that transmits torque, it is not possible to use pure iron which has superior magnetic characteristics⁽⁴⁾.

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In order to address the above issues, an air gap is provided at the magnetic material around the periphery of the solenoid, and the solenoid force generated in the magnetic material is used as the propulsion force for the clutch located outside the magnetic circuit. As a result, it is possible to use pure iron in the magnetic circuit, and to use paper-based friction material on the clutch plate.

However, when the air gap changes due to the wear of the clutch, the solenoid force also changes. Consequently, in order to accurately control the torque, it is necessary to detect changes in the air gap, and correct the solenoid force accordingly. This paper discusses the detection of the change in the air gap, solenoid correction control and the method of increasing control accuracy.

2. Direct Electromagnetic Clutch

Figure 1 shows the construction of the direct electromagnetic clutch. The yoke made of magnetic material has the main coil built-in and an air gap is provided between the yoke and the armature made of the magnetic material. When current flows through the main coil, the yoke functions as a solenoid, and a load that causes the yoke to attract the armature is generated inside. This solenoid force is transmitted to the clutch via a push cylinder, causing torque to be generated between the case and the hub.

With this construction, when the thickness of the clutch plate changes due to wear, the air gap also changes. In this case, the correlation between the current and the solenoid load changes (Fig. 2), and if no correction is performed, accurate control is not guaranteed.

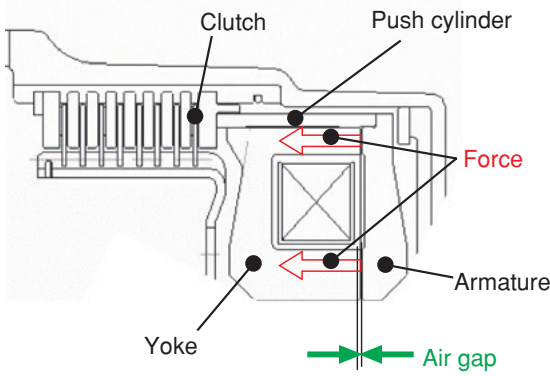


Fig. 1 Cross-section of direct electromagnetic clutch

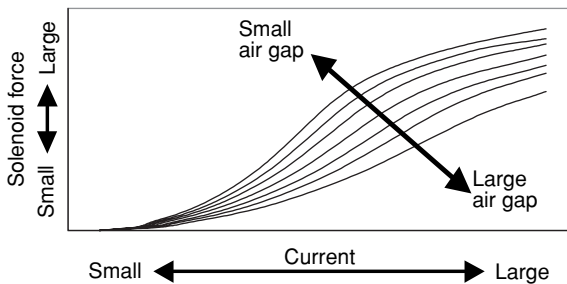


Fig. 2 Current-solenoid force characteristic

3. Air Gap Detection

The solenoid force between the armature and the yoke of the direct electromagnetic clutch is expressed by Eq. (1). As shown in Fig. 3, the solenoid force is inversely proportional to the air gap.

$$F = 10^7 S \mu_0^2 U^2 / 8\pi \delta^2 \quad (1)$$

Where,

F : Solenoid force S : Cross-sectional area of the magnetic circuit

μ_0 : Permeability of a vacuum ($4\pi \times 10^{-7}$)

U : Magnetic field strength

δ : Air gap

The cross-sectional area of the magnetic circuit is expressed by Eq. (2). As shown in Fig. 4, the solenoid force is proportional to the magnetic flux.

$$S = 8\pi F / 10^7 B^2 \quad (2)$$

Where,

B : Magnetic flux

Consequently, it is possible to detect the air gap by detecting the magnetic flux.

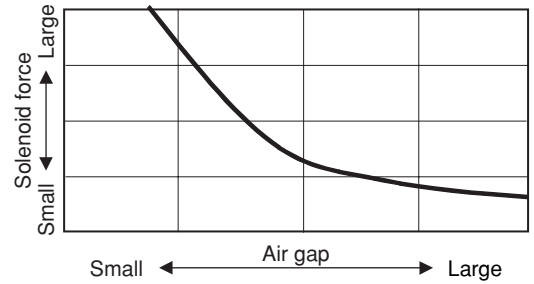


Fig. 3 Air gap-solenoid force characteristic

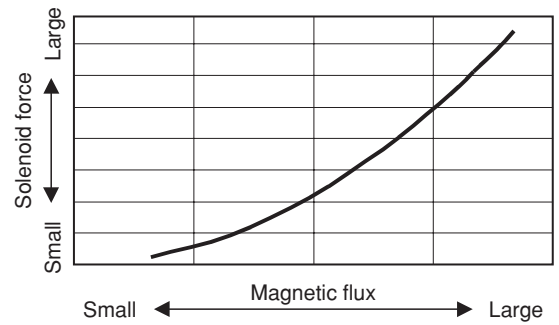


Fig. 4 Magnetic flux-solenoid force characteristic

4. Magnetic Flux Detection

A search coil is used to detect the magnetic flux (Fig. 5). The search coil is located on the inside of the yoke. This is because the search coil is integrated⁽⁵⁾ with the main coil for manufacturing ease, and it is easily affected by the magnetic flux flowing through the magnetic circuit (Fig. 6).

The detection principle uses Faraday's law, as expressed by Eq. (3).

$$e = N_s d\phi/dt \quad (3)$$

Where,

e : Search coil Voltage

N_s : Number of search coil turns

ϕ : Magnetic flux around the search coil

From this it can be seen that a voltage is generated in the search coil along with the time change of the magnetic flux.

By integrating Eq. (3) with time, Eq. (4) is obtained.

$$\phi = \int e dt / N_s \quad (4)$$

The current flowing through the main coil is fluctuated, causing the magnetic flux around the search coil to change, which results in the generation of a voltage in the search coil (Fig. 7). The integrated area in the figure indicates the right term of Eq. (4). The magnetic flux can be obtained by dividing this area by the number of turns on the search coil.

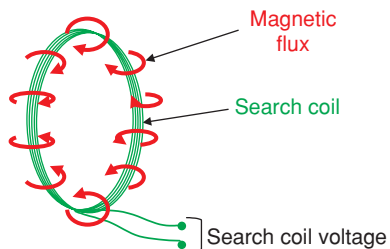


Fig. 5 Search coil concept

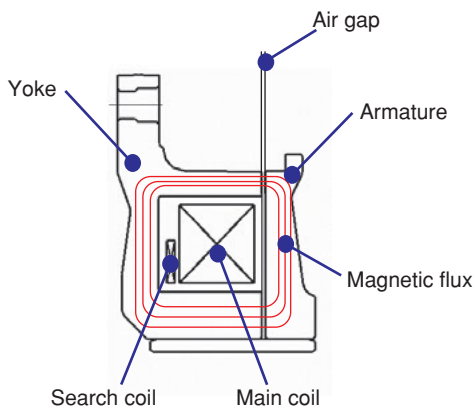


Fig. 6 Layout of magnetic circuit and search coil

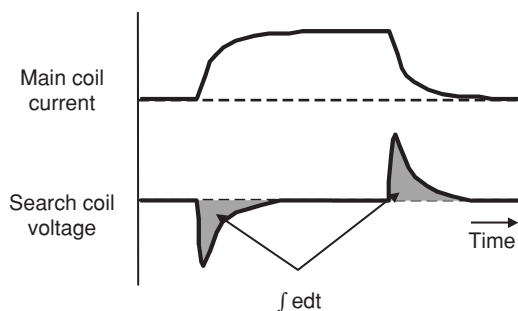


Fig.7 Voltage during DC current control

5. Solenoid force Correction Control

Next, the correction control method of the solenoid force is described. First, a 3-dimensional table representing Magnetic flux – Current – Torque (Fig. 8) is incorporated in the ECU.

Based on the detected magnetic flux, the Target torque – Current value table is selected from the 3-dimensional table. Based on this table, the current value corresponding to the target torque is obtained, and control implemented (Fig. 9).

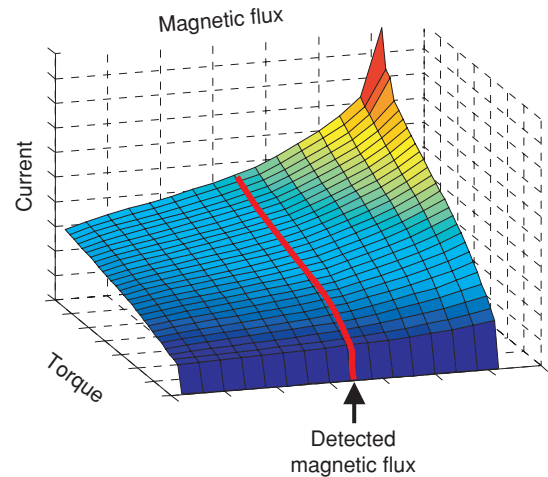


Fig. 8 Current-torque-magnetic flux table

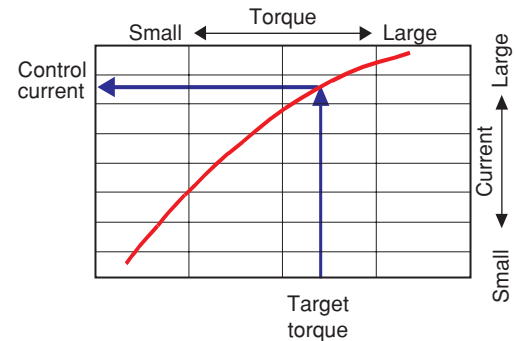


Fig. 9 Current-torque table

6. Control Accuracy Increase Technology

6.1 Effect of PWM Control

Figure 7 shows the results of measurement using direct current. The actual current control method is PWM (Pulse Width Modulation) control. While PWM control of the current is taking place, the search coil voltage oscillates due to variations in the magnetic flux, reducing its accuracy.

Therefore, the current was switched off after a PMW control of constant current, and the region in which the current falls gradually, along with the magnetic inductance, was sampled (Fig. 10). The search coil voltage changes slowly without oscillating. This enables the integrated area to be obtained stably, thus permitting increased magnetic detection accuracy.

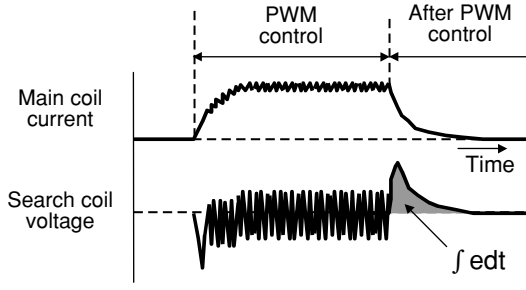


Fig. 10 Voltage during PWM current control

6.2. Effect of ECU Reference Voltage

If the sampling period when the ECU converts a search coil voltage to A/D is defined as θ , it is possible to express Eq. (4) by means of Eq. (5), and as shown in Fig. 11 the voltage is integrated.

$$\phi = \int e dt / Ns \div \theta \Sigma e / Ns \quad (5)$$

Where,

θ : Sampling period

The reference voltage is different for each individual ECU, and even for the same ECU it varies with changes in the environmental temperature. Consequently, when detecting the search coil voltage, the offset voltage between the ECU reference voltage and the search coil zero voltage is included as an error (Fig. 12). Therefore, it was decided to integrate the search coil voltage over the same period as the detection period (Fig. 13) immediately after the search coil voltage is detected, and then using Eq. (6) to subtract the resulting value from the integrated value obtained when the voltage was detected. This enables the effect of variations in the ECU reference voltage to be eliminated, and realizes increased magnetic flux

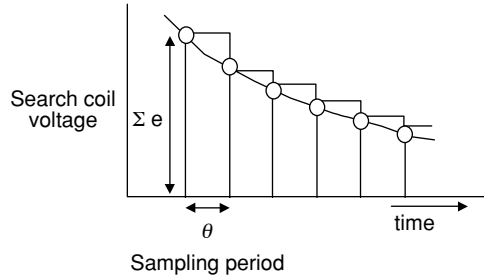


Fig. 11 Sampling period of search coil voltage

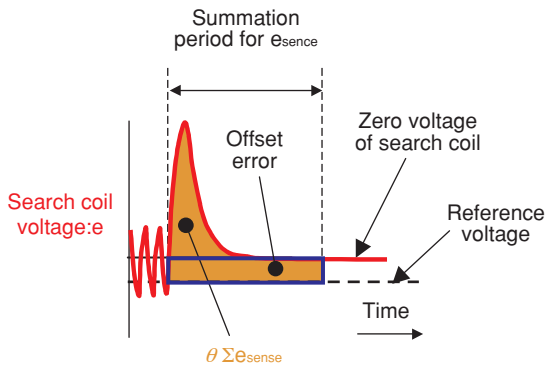


Fig. 12 Offset voltage error of search coil

detection accuracy.

$$\phi \div \theta (\Sigma e_{\text{sense}} - \Sigma e_{\text{zero}}) / Ns \quad (6)$$

Where,

e_{sense} : Integrated value of calculated voltage

e_{zero} : Integrated value of correction voltage

6.3. Effect of the Profile of the Magnetic Circuit Gap

The solenoid force characteristics versus the air gap for different magnetic circuit profiles were confirmed. For the magnetic circuit profile, three types of gaps, 30° taper type, 45° taper type, and flat were studied (Fig. 14).

It can be seen from the measured results of the solenoid force in Fig. 15 that flat types show abrupt changes in the solenoid force versus the change in the air gap, compared to the taper type. In other words, the smaller the air gap, the smaller the current determined needed for the target solenoid force. For this reason, the current resolution of the solenoid force declines, and the error in the solenoid force resulting from the current error tends to

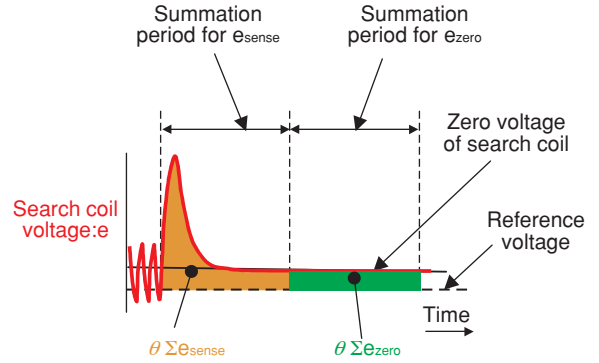


Fig. 13 Zero correction of search coil voltage

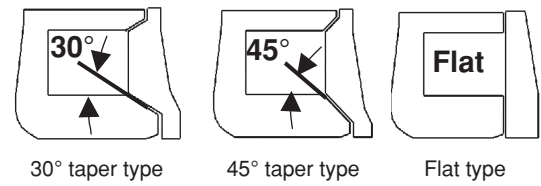


Fig. 14 Gap profile of magnetic circuit

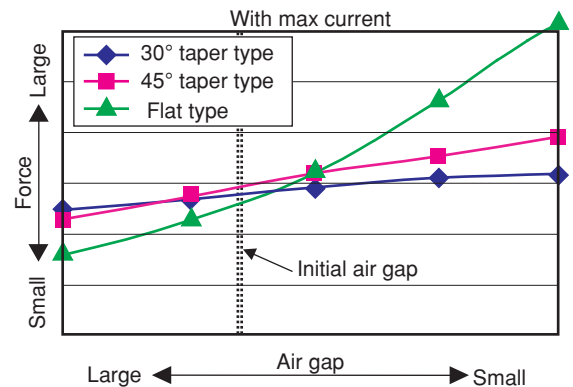


Fig. 15 Air gap-solenoid force characteristic

increase. Also, the search coil voltage when measuring the magnetic flux should be set to as high a value as possible, within the allowable range of the ECU, from the perspective of voltage resolution. However, in consideration of increases in the magnetic flux and the search coil voltage with respect to the current after the air gap is changed, it is unavoidably necessary to measure the magnetic flux using a small current from the outset. Consequently, the current resolution declines, and the magnetic flux detection error is possible to increase. This means that it is possible to increase the magnetic flux detection accuracy and the solenoid force control accuracy by selecting a suitable taper type magnetic circuit gap. Here, a taper angle of 45° which results in a large solenoid force at the initial gap was selected.

6.4. Effect of the Set Position of the Search Coil

The magnetic flux density distribution of a 45° taper type was magnetically simulated (Fig. 16). The magnetic analysis software used was ELF/MAGIC produced by ELF Co.

As a result, it can be seen that the change in the magnetic flux distribution is large in the vicinity of the air gap. It is considered that this is due to the effect of magnetic flux leaking from the air gap. Consequently, it is possible to detect the magnetic flux in a stable magnetic field created by setting the search coil at a position remote from the air gap, increasing the magnetic flux detection accuracy (Fig. 17).

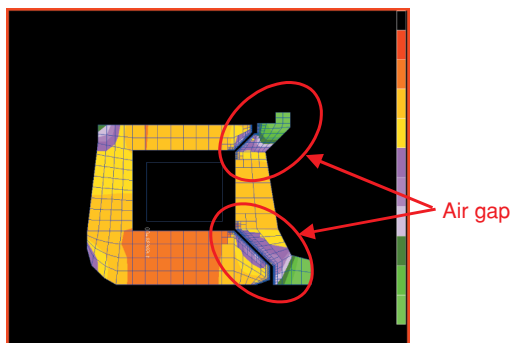


Fig. 16 Magnetic flux simulation result

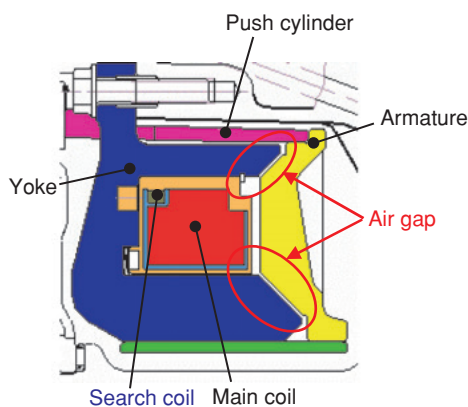


Fig. 17 Layout of search coil

7. Results

The correlation between the target torque and the actual torque was measured both with and without current correction based on magnetic flux detection. Figures 17 and 18 show the results obtained from measurements both with and without current correction. By adding correction control, more accurate correlation between the target torque and the actual torque was obtained regardless of the size of the air gap.

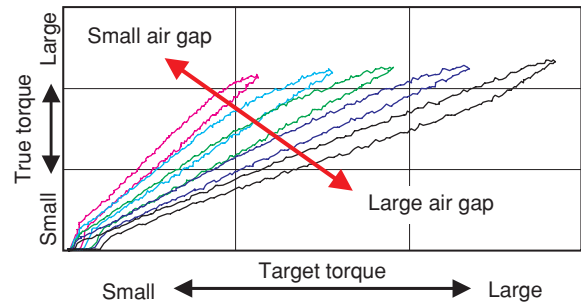


Fig. 18 Torque control result without correction

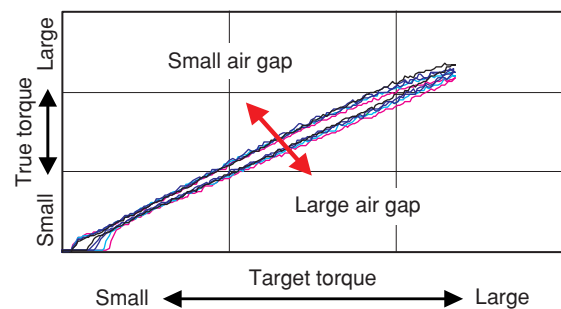


Fig. 19 Torque control result with correction

8. Conclusion

It was found that correction of the solenoid force with respect to changes in the air gap could be made by performing magnetic flux detection using a search coil and current correction control, based on the detected magnetic flux. In addition, it was verified that more accurate torque control could be realized by taking steps to increase the control accuracy. As a result, it was possible to establish direct electromagnetic clutch technology as the main technology of SH-AWD.

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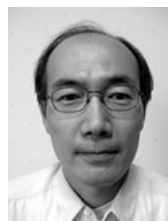
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