Development of Electromagnetic Field Analysis Technology with High Frequency Band

K. INOUE

The electric motor and sensor used in electric power steering require further miniaturization and higher accuracy, and therefore it is necessary to establish technology that accurately reflects the performance characteristic of the product in order to satisfy demands. Once this had been achieved, the electromagnetic phenomenon inside the product was made visible, and electromagnetic field analysis technology was developed using the Finite Element Method to enable confirmation of the performance characteristic which takes into account the influence of the electromagnetic phenomenon. This report introduces verified examples regarding the Variable Reluctance resolver by using electromagnetic field analysis technology in a high frequency band, while taking into account the Magnetic Skin Effect, eddy current loss and hysteresis loss.

Key Words: *steering system, vr resolver, electromagnetic field analysis, eddy current loss, hysteresis loss, magnetic skin effect*

1. Introduction

The electric power steering (EPS) system, which provides an assist function using an electric motor, is expected to evolve into the advanced driving assist system with the aim of preventing accidents due to incorrect operation or lack of awareness of the driver. Although the electric and electronic parts to realize this system are being developed as quickly as possible, there remain many issues within the system that must be addressed. One of these issues is the necessity of optimizing the structure of the VR (Variable Reluctance) resolver, an angle sensor for the electric motor. This requires determination of the optimal frequency for the VR resolver from the A/D (Analog/Digital conversion) input cycle of the ECU, after which this frequency is used to maximize the VR resolver output and ensure detection accuracy. However, it is difficult to estimate the ratio of effect administered by each parameter through development based on conventional examination of an actual machine. Furthermore, as electromagnetic phenomena inside a product cannot be analyzed, it is also difficult to judge whether the parameters are optimal.

As such, after achieving the visualization of electromagnetic phenomena inside products and identifying and examining the mechanisms of these phenomena, JTEKT has developed electromagnetic field analysis technology at high frequency bands with the aim of deriving optimal parameters which satisfy the required performance of the VR resolver. This report introduces case examples of this technology.

2. VR resolver

Figure 1 shows the VR resolver on which this study has been conducted. The VR resolver has a simple structure comprised of a rotor core for the rotor, stator core for the stator, excitation coil for inputting sine wave signals, and an output coil wound around the stator core for detecting changes in the magnetic flux which flows through the stator core.

The turning angle of the VR resolver is detected by rotating the rotor core while sine waves signals flow through the excitation coil. Rotating the rotor changes the clearance between the stator core and rotor core, which causes the magnetic flux flowing within the stator core to change accordingly. The turning angle of the rotor core is then calculated from the amount of change in the signal of the output coil which has been affected by the change in magnetic flux.

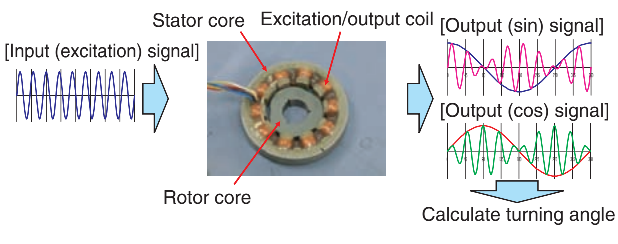

Fig. 1 Variable Reluctance resolver : VR resolver

3. Electromagnetic field analysis simulation

3. 1 VR resolver model

The VR resolver model is shown in **Fig. 2**, and the laminated structure of the VR resolver model in **Fig. 3**. The VR resolver model for electromagnetic field analysis was achieved using the finite element method to create the shapes of the rotor core, stator core, excitation coil and output coil.

The model shapes of the rotor core and stator core were created from the values of the VR resolver drawing. The magnetization characteristic, which demonstrates the performance of the electromagnetic steel plates used for the rotor core and stator core, was set as the actual measurement value on the model in light of the effect of machining and assembly. The electrical conductivity, which shows the ease of the flow of magnetic flux inside the plates, was set to the nominal value.

In consideration of the effect of magnetic flux leakage from the stator core, the model shapes of the excitation coil and output coil were created using the values of the cross-sectional area of a coil assembled in the slot and from the number of turns of each coil. The resistance values of each coil on the model were set as the actual measurement values of an actual VR resolver.

Calculation time was reduced by confining the laminated structure of the VR resolver model to one half of its original size due to its symmetry, and by using only five electromagnetic steel plates for the rotor core and stator core. In addition, the film coating the surface of the plates, which prevents the flow of magnetic flux between the plates, has been simulated on the model by leaving a thin layer of air between each plate.

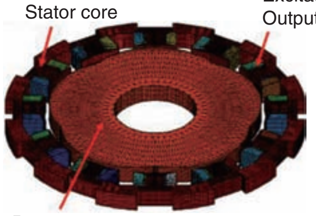

Fig. 2 VR resolver model

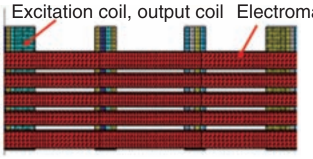

Fig. 3 Laminated structure of VR resolver model

3. 2 Eddy current loss and hysteresis loss

The VR resolver uses a high frequency range over 1 kHz. It is generally known that the effects of eddy current loss and hysteresis loss must be considered when conducting electromagnetic field analysis on products of high frequency. Consequently, we have developed a VR resolver model which takes into account the effects of eddy current loss and hysteresis loss during electromagnetic field analysis of the VR resolver. **Figure 4** shows the theoretical formula of the VR resolver model. The **first term** represents VR resolver output, the **second term** represents eddy current loss, and the **third term** represents hysteresis loss. Eddy current loss and hysteresis loss increase with higher frequencies, while output decreases.

Actual measurements of these values have been taken in order to confirm the degree of effect eddy current loss and hysteresis loss have on the VR resolver. **Figure 5** shows the VR resolver used for the measurements of eddy current loss and hysteresis loss, and **Fig. 6** indicates the results of these measurements. Loss in total output is approximately 20% when the excitation frequency is around 12.5 kHz, and approximately 60% around 20 kHz. This demonstrates the necessity of considering eddy current loss and hysteresis loss during electromagnetic field analysis of the VR resolver.

$$W_{out} = \underbrace{VI\cos\theta}_{\text{Output}} - [\underbrace{K_e f^2 B^2}_{\text{Eddy current loss}} + \underbrace{K_h f B^2}_{\text{Hysteresis loss}}]$$

Wout: Electrical energy, V: Excitation voltage, I: Excitation current, θ: Phase difference of excitation voltage and excitation current, Ke: Eddy current coefficient, Kh: Hysteresis coefficient, f: frequency, B: magnetic flux density

Fig. 4 Theoretical formula of VR resolver model

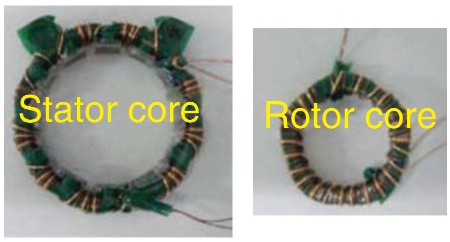

Fig. 5 VR resolver used for real machine examination

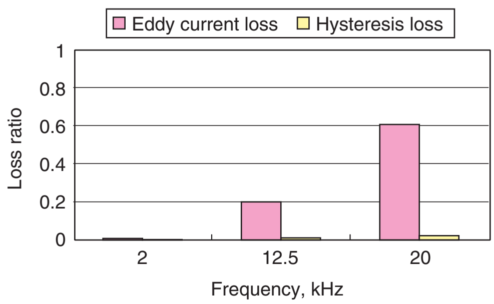

Fig. 6 Result of a measurement of eddy current loss and hysteresis loss

3. 3 Skin effect of magnetic flux

Figure 7 shows an image of magnetic flux flowing inside the electromagnetic steel plates. When the frequency is low, the magnetic flux inside a plate flows uniformly. However, higher frequencies increase the effect of eddy currents, which cause the magnetic flux to concentrate on the surface of the plate and stop flowing at its center. This electromagnetic phenomenon is known as the skin effect of magnetic flux. As previously stated, the VR resolver is of high frequency, and thus it can be assumed that the skin effect is visible in the results of its electromagnetic field analysis. Therefore, it was necessary to create a model of the laminated structure on which the skin effect can be simulated. From this model, we calculated the depth of penetration of the magnetic flux on the VR resolver using a formula shown in **Fig. 7** for calculating the depth to which magnetic flux has penetrated (depth of penetration of magnetic flux) inside the plates. From this value, were able to integrate into electromagnetic field analysis a method of calculating the optimum number of low-thickness divisions into which the plates could be divided in the layering direction.

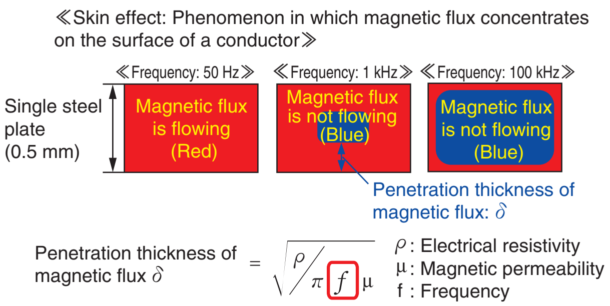

Fig. 7 Flow of magnetic flux inside electromagnetic steel

4. Model verification

To verify the validity of the model, the stator core of the VR resolver was affixed using a fixture, and the rotor was rotated while sine waves signals flowed through the excitation coil. A comparison (transformation ratio) of the output signal and excitation signal was measured for each wave when the amplitude of the output signal was at its maximum, and these measurements were compared with the results of the simulation.

Figure 8 shows the frequency characteristic, with the excitation frequency on the x-axis and transformation ratio on the y-axis. The black line indicates actual machine data, the red line indicates simulation data which takes into account eddy current loss and hysteresis loss, and the blue line indicates simulation data which does not consider eddy current loss and hysteresis loss. The frequency characteristic of the simulation taking into account eddy current loss and hysteresis loss has the same peak as the frequency characteristic of the actual machine, confirming that the model is valid. Furthermore, the results of the comparison of both simulations clearly demonstrate that effects of eddy current loss and hysteresis loss are factors in the decrease of the output signal at higher frequencies.

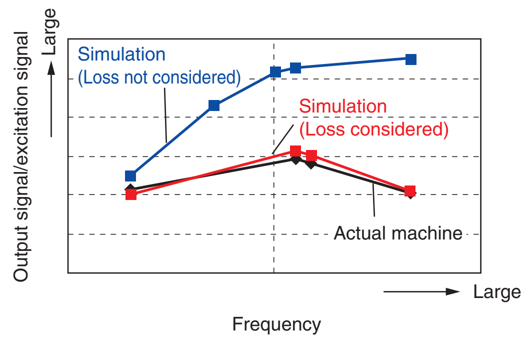

Fig. 8 Frequency characteristic of VR resolver

Furthermore, as shown in **Fig. 9**, we created a colored contour to visualize the size of magnetic flux density flowing inside the electromagnetic steel plates, in order to confirm the effect of the skin effect on the VR resolver. Areas with high magnetic flux density are red, and those with low magnetic flux density are blue. These results enabled the visualization of the range inside the plates in which magnetic flux does not flow, and confirmed that the size of this range is dependent on the frequency.

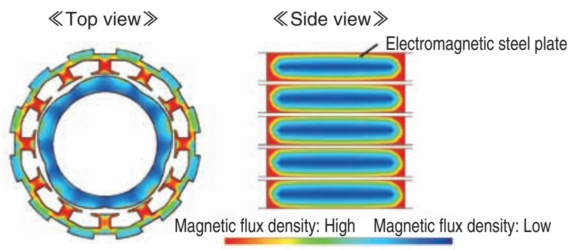

Fig. 9 Contour chart of magnetic induction in VR resolver

5. Design study on robustness

5. 1 Effect of rotor eccentricity

The rotor core and stator core are separated inside the structure of the VR resolver, which may cause the rotation centers of both to deviate (rotor eccentricity) due to incorrect assembly. This causes variation in the output signal, which leads to errors in the detection of the turning angle. **Figure 10** shows the results of the measurement of the detection error margin of the turning angle caused by rotor eccentricity.

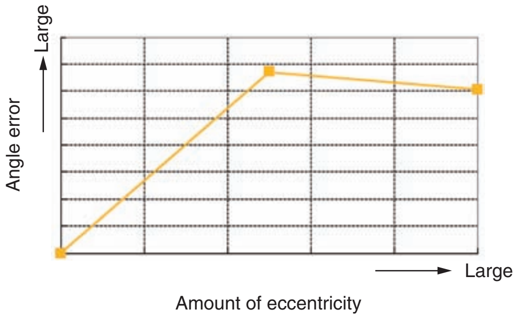

Fig. 10 Measurement result of detection error margin of turning angle by rotor eccentric

5. 2 VR resolver design with high robustness

The effect of rotor eccentricity was confirmed by simulation during the study of robustness when rotor eccentricity exists. These results are shown in **Fig. 11**. As visible in the results, rotor eccentricity causes variation in the amplitude of the output signal.

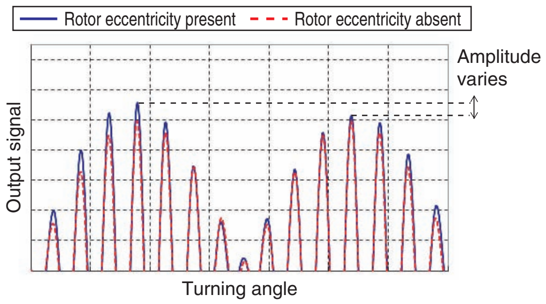

Fig. 11 Signal pulse type of output coil by rotor eccentric

Using the analysis technology developed at JTEKT, we have created prototype countermeasure parts by deriving design parameters for a VR resolver which incorporates measures to suppress amplitude variation of the VR resolver output signal due to rotor eccentricity, without reducing the amplitude of the output signal. The actual measured results using the countermeasure parts are shown in **Fig. 12**. With the countermeasure parts, the margin of error in turning angle detection due to rotor eccentricity is small, which confirms that the JTEKT analysis technology is useful in robustness design.

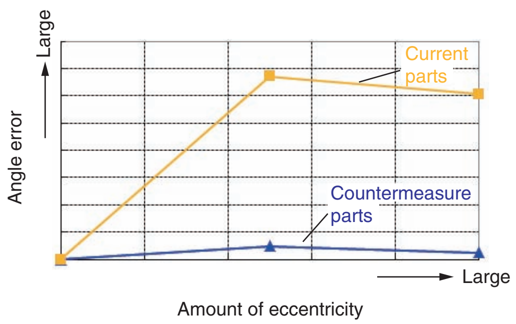

Fig. 12 Measurement result of measures goods

6. Conclusion

The development of electromagnetic field analysis technology for high frequency band has accomplished the following results.

- Established a method for electromagnetic field analysis at high frequency bands using a model which takes into account eddy current loss and hysteresis loss from high frequencies, and by setting the optimal number of divisions in the layering direction in consideration to the skin effect of magnetic flux.
- Clearly demonstrated that at high frequency bands, the output signal of the VR resolver is reduced by eddy current loss, hysteresis loss, and the skin effect, all of which are due to frequency.
- The newly developed analysis technology can be used sufficiently in robustness design.

Although this report covers electromagnetic field analysis technology at high frequency bands, it is also necessary to conduct electromagnetic field analysis with consideration to the effects of temperature fluctuation and stress strain on the electromagnetic steel plates as well. Moreover, in order to be able to utilize this technology in the development of advanced driving assist systems, it is necessary to develop analysis technology that enables design study of not only the individual components, but the entire system, including peripheral devices and controls, as well.

Acknowledgements

Special thanks to Professor Yoshihiro Kawase and Adjunct Professor Tadashi Yamaguchi of Gifu University for their collaboration and guidance, and to everyone at the research laboratory.

References

1) Y. kawase, S. Ito,: ”New Practical Analysis of Electrical and Electronic Apparatus using 3-D Finite Element Method”, Morikita Publishing Co. (1997) 199.
2) S. Ito, Y. kawase,: ”Computer Aided Engineering of Electric and Electronic Apparatus Using Finite Element Method”, Morikita Publishing Co. (2000) 162.
3) K. Nakata, S. Ito, Y. kawase,: ” Design and application of AC-DC Electromagnet Using Finite Element Method”, Morikita Publishing Co. (2000) 170.
4) Y. kawase, T. Yamaguchi, K. Tanaka, S, Ota,: ”3-D Eddy Current Analysis in Electrical Steel sheet of IPM Motor Driven by Voltage Source Inverter”, IEE Japan, 21-22 (2012) 2.

K. INOUE*

* *System Development Dept., Steering Systems Operations Headquarters*