Accuracy Improvement of a Magnetic Sensor Signal of an Excavator Using 3-D FEM

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High-class excavators have magnetic position sensors on a bucket, arm, and boom in order to inform the position of the bucket to the operator. The sensor signal is influenced by the eddy current. Therefore, the relationship between the stroke speed and sensor signal must be informed in order to compensate the bucket position. This paper describes an accuracy improvement of the magnetic sensor signal of the excavator using 3-D FEM and a compensation method of the bucket position. Finally, the compensation method is verified by carrying out measurements through a bench test.

***Index Terms*—Eddy current, 3-D FEM, skin effect, linear sensor.**

I. Introduction

HIGH-CLASS EXCAVATORS have magnetic sensors on a bucket, arm, and boom in order to inform the position of the bucket to the operator. Commonly, an encoder is used to detect the position. However, it is difficult to install the encoder in a cylinder tube due to its large size and the encoder disturbs the excavating operation. Therefore, we have been developing a small sensor which consists of the stroke sensor and reset sensor as shown in Fig. 1. The stroke sensor is a mechanical sensor which is contacted with the piston and the reset sensor is a magnetic sensor. The position detected by the stroke sensor has some errors due to the slip. The purpose of the reset sensor is to cancel the errors of the stroke sensor. However, it was observed that the reset signal also has the errors due to the eddy current in the cylinder tube.

This paper describes an accuracy improvement of the reset sensor signal of the excavator using 3-D FEM. A compensation method focusing on the relationship between the stroke speed and sensor signal is proposed. Finally, the compensation method is verified through a bench test.

II. Operational Principle

The piston which moves in the cylinder tube has the permanent magnet which is magnetized in a moving direction as shown in Fig. 1. The Hall sensor which is installed on the cylinder tube detects the magnetic flux from the permanent magnet. When the magnetic flux which the hall sensor detects changes from N pole to S pole, the position information from the stroke sensor is updated. Therefore, if the magnetic flux waveform is deformed due to the eddy current, the reset sensor transmits a wrong position information to the stroke sensor. The magnetic flux waveform is computed using 3-D FEM in this paper.

III. Sensor Signal Analysis and Experiment

A. Analysis Method

An electromagnetic analysis using 3-D FEM was conducted using the magnetic vector potential $\boldsymbol{A}$ and the electric scalar potential ϕ. The analysis model is shown in Fig. 2. The number of tetrahedral meshes and nodes are 189,177 and 51,222, respectively. The cylinder assembly shown in Fig. 1 is not a symmetric structure in a circumferential direction of the cylinder tube. However, the 1/4 model shown in Fig. 2 is used because the effective angle of the permanent magnet is only 40 deg and the magnetic flux of the permanent magnet flows locally.

The stroke speed of the piston is 40, 187, 303, 411, 517, and 608 mm/s and the magnetic flux which passes perpendicularly through the Hall sensor is computed. In order to consider a skin effect, the static analysis ignoring the eddy current was firstly conducted. The magnetic flux detected by the Hall sensor is shown in Fig. 3. The distance between the N- and S-pole peaks is 60 mm, and this is equal to a half period of the magnetic flux variation. When the piston moves at 608 mm/s, the skin depth is 4.84 mm. Therefore, the mesh model shown in Fig. 2 considers the skin effect and 1-mm layer meshes are created in the cylinder tube [1]-[2].

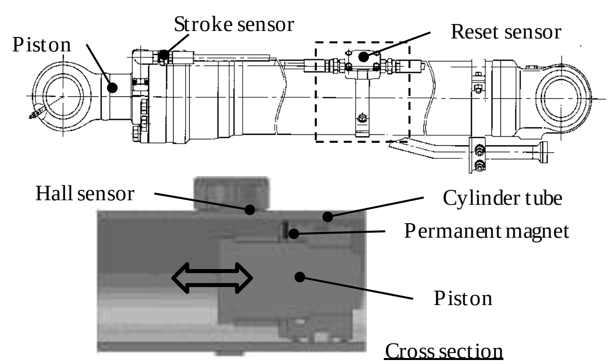

Fig. 1. Cylinder assembly.

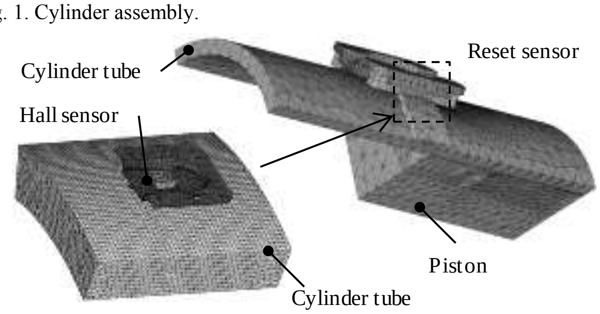

Fig. 2. Analysis model (1/4 model).

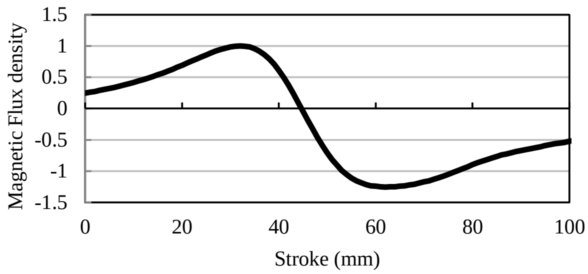

Fig. 3. Normalized magnetic flux of the static analysis.

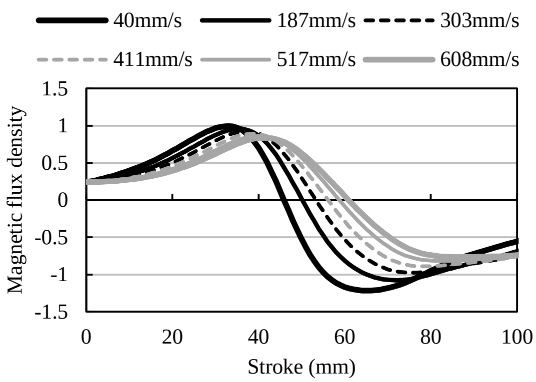

Fig. 4. Normalized dynamic magnetic flux.

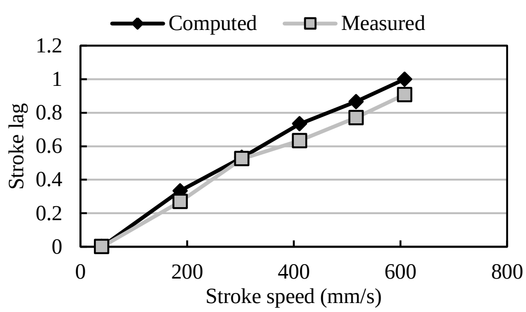

Fig. 5. Normalized computed and measured stroke lags.

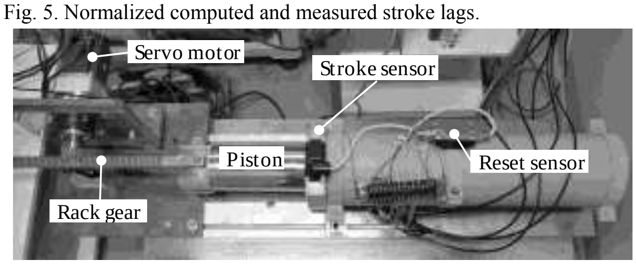

Fig. 6. Experiment setup.

B. *Electromagnetic Analysis*

The magnetic flux waveforms of the Hall sensor when the piston moves at a speed of 40, 187, 303, 411, 517, and 608 mm/s were computed and are shown in Fig. 4. It is observed that the magnetic flux variation is delayed and the peak values are lower due to the eddy current as the stroke speed of the piston increases. In other words, the stroke position when the magnetic flux changes from a positive value to a negative value is delayed and wrong stroke position information is transmitted.

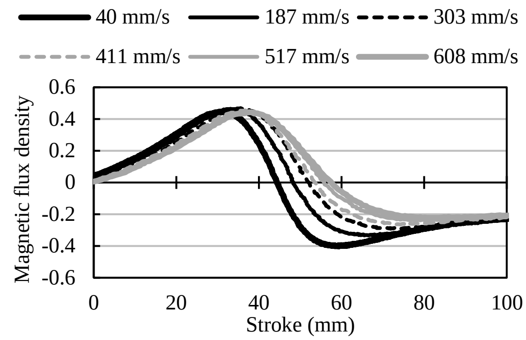

Fig. 7. Normalized measured magnetic flux.

In order to compensate the stroke position, the stroke which the magnetic flux becomes zero between the positive and negative peaks is firstly calculated at each stroke speed. Next, the stroke lag compared with the stroke of 40 mm/s is calculated and the relationship between the stroke speed and normalized stroke lag is shown in Fig. 5. From Fig. 5, it is observed that the stroke lag can be obtained by a linear function of the stroke speed. Therefore, we can compensate the stroke position using a stroke speed from the stroke sensor.

C. *Experiment*

The test bench is shown in Fig. 6. The piston is moved using the servo motor and the rack gear. The measured magnetic flux is normalized by the computed magnetic flux and is shown in Fig. 7. From Fig. 7, the measured magnetic flux qualitatively shows a good agreement with the computed magnetic flux. The measured peak values of the magnetic flux are half of the computed magnetic flux. This is thought to be due to the difference of the air-gap length between the cylinder tube and Hall sensor. The measured relationship between the stroke speed and normalized stroke lag is shown in Fig. 6 with the computed relationship. The computed stroke lags show a good agreement with the measured stroke lags although the measured magnetic flux is about half of the computed magnetic flux. Therefore, we can conclude that the difference of the absolute values of the magnetic flux does not influence on the stroke lags and the compensation method using a linear function is effective.

IV. Conclusion

In this paper, sensor signals of an excavator were computed using 3-D FEM. The stroke lags due to the eddy current were calculated and were compared with the measured stroke lags. It was verified that a compensation method using a linear function of the stroke speed was effective.

V. References

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