

# Run-out compensation of eddy current displacement sensor for performance improvement of a bearingless motor with unequal-tooth-pitch core

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## Abstract

A bearingless motor is defined as a motor with a magnetically integrated bearing function. A displacement sensor is used to control the rotor position. Eddy-current sensors are typically located outside the motor, resulting in a large motor size. This study proposes a bearingless motor with an unequal-tooth-pitch stator to reduce system size by increasing the tooth pitch of part of the stator and placing eddy-current displacement sensors between the teeth. However, since eddy-current sensors use magnetic flux to measure distance, they are affected by the motor flux, causing an apparent vibration with components of harmonic orders of rotational frequency called run-out. This paper reports the results of a levitation test of a 10-pole, 12-slot, two-axis actively positioned bearingless motor with an unequal-tooth-pitch core employing run-out compensation. The run-out compensation was applied to the measured displacement using a function with pre-identified parameters and a notch filter. The motor successfully levitated and rotated at 4000 rpm in the actual machine test.

**Keywords** : Bearingless motor, Unequal-tooth-pitch core, Eddy current displacement sensor, Sensor run-out, Notch filter

## 1. Introduction

A bearingless motor is defined as a motor with a magnetically integrated bearing function that simultaneously generate torque and suspension force. (Chiba et al., 2005) The rotor is noncontact and thus has the advantage of being maintenance-free and oil-free. Displacement sensors are used to detect the position of the rotor. Typically, these sensors are located outside the motor, resulting in a larger system size. (He et al., 2016) (Ueno et al., 2024) To reduce the system size, a bearingless motor with an unequal pitch stator is proposed wherein the pitch of some of the stator teeth is enlarged and eddy-current gap sensors are placed between the teeth. (Kamiya and Asama, 2024) However, the eddy-current gap sensor detects the electromagnetic inhomogeneity of the target surface and apparent vibrations occur, as evidenced by the measured values (sensor run-out). (Park et al., 2004) Consequently, pulsations appear in the suspension force. This paper reports the results of a levitation drive test with run-out compensation on a 10-pole, 12-slot two-axis actively positioned bearingless motor with an unequal-tooth-pitch core. The run-out compensation was performed by combining a function with parameters identified in advance and a notch filter with the notch frequency varying with rotation speed.

## 2. Configuration of proposed motor

Figure 1 shows the cross-section of the proposed asymmetrical four-phase combined winding bearingless motor with an unequal-tooth-pitch core. This bearingless motor is a 10-pole 12-slot two-axis actively positioned motor. The suspension force in the radial direction ( $x, y$ ) is actively controlled by an eight-pole rotating magnetic field. The tilt direction ( $\theta_x, \theta_y$ ) and axial direction ( $z$ ) are passively supported by magnetic coupling. The stator core has two different

tooth pitches: 1)  $36^\circ$  at four locations every  $90^\circ$  and 2)  $27^\circ$  at other locations. The stator winding is a four-phase combined winding in which the motor winding and suspension winding are combined. The motor current and suspension current are superimposed and applied to the same coil. If the four-phase windings are arranged symmetrically, the eight-pole magnetic field becomes an alternating magnetic field, and therefore, a suspension force cannot be generated in any direction. Therefore, in this motor, the coil arrangement of each phase is asymmetrical to generate an eight-pole rotating magnetic field. Eddy-current displacement sensors (PU-05, AEC Corp.) were placed at four locations between the teeth. The target of the eddy-current displacement sensor on the inner surface of the rotor was made of a non-magnetic metal because magnetic metals interfere with the generation of suspension forces. (Liu and Chiba, 2018) The radial displacement ( $x, y$ ) of the rotor is measured differentially as expressed in Equation (1). The effects of tilt and other factors can be cancelled out.

$$\begin{cases} x = \frac{x_+ - x_-}{2} \\ y = \frac{y_+ - y_-}{2} \end{cases} \quad (1)$$

where  $x_+, x_-, y_+$  and  $y_-$  are the measured values of each displacement sensor. The stator outer diameter is 66 mm, stator stack length is 13.5 mm, rotor yoke outer diameter is 79.3 mm, and axial length of the rotor yoke and permanent magnet is 18 mm. The overhung structure improved the passive stability of the rotor in the tilt direction. The fabricated rotor and stator are shown in Figures 2 and 3, respectively.

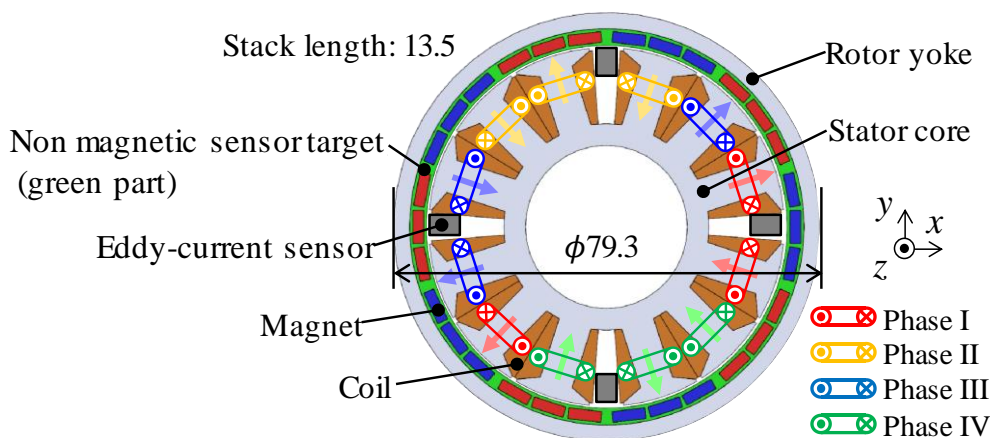


Fig. 1 Asymmetrical four-phase combined winding bearingless motor with unequal-tooth-pitch stator.



Fig. 2 Rotor of the proposed motor with smooth inner surface to be used as eddy-current sensor target. Outer diameter of the yoke is 79.3 mm, and axial length of the yoke is 18 mm.

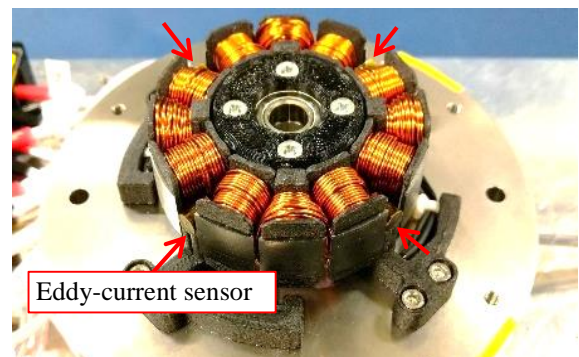


Fig. 3 Stator of the proposed motor. Eddy-current sensors are placed between teeth. Outer diameter is 66 mm, and stack length is 13.5 mm.

### 3. Identification of sensor run-out with ball bearing support

A non-levitation drive test was conducted with the rotor shaft supported by mechanical ball bearings to identify sensor run-out. Figure 4 shows the control block diagram.  $K_s$  is the suspension force coefficient matrix, and  $C$  is the decoupling matrix between the motor current and suspension current. Displacement control was not used in the non-levitation test. References of the suspension force ( $f_x^*$ ,  $f_y^*$ ) were always set to zero. Figure 5 shows the measured rotor radial displacements  $x$  and  $y$  at 10000 rpm. Although the rotor was fixed by a mechanical bearing, apparent oscillations occurred, called sensor run-out. The main components of the displacement oscillation were the 5th-, 15th-, and 25th-order harmonics of the rotational speed. Figure 6 shows the relationship between the run-out and rotational speed in the  $x$ -direction. The 5th-, 15th-, and 25th-order harmonics increased, and the phase changed with the rotational speed. These are caused by the leakage flux of the rotor permanent magnet interlinking with the displacement sensor coil, generating an induced voltage as the rotor rotates. Here, compensation functions are defined to compensate for the 5th-, 15th-, and 25th-order harmonics with respect to the rotational speed, as expressed in Equation (2).

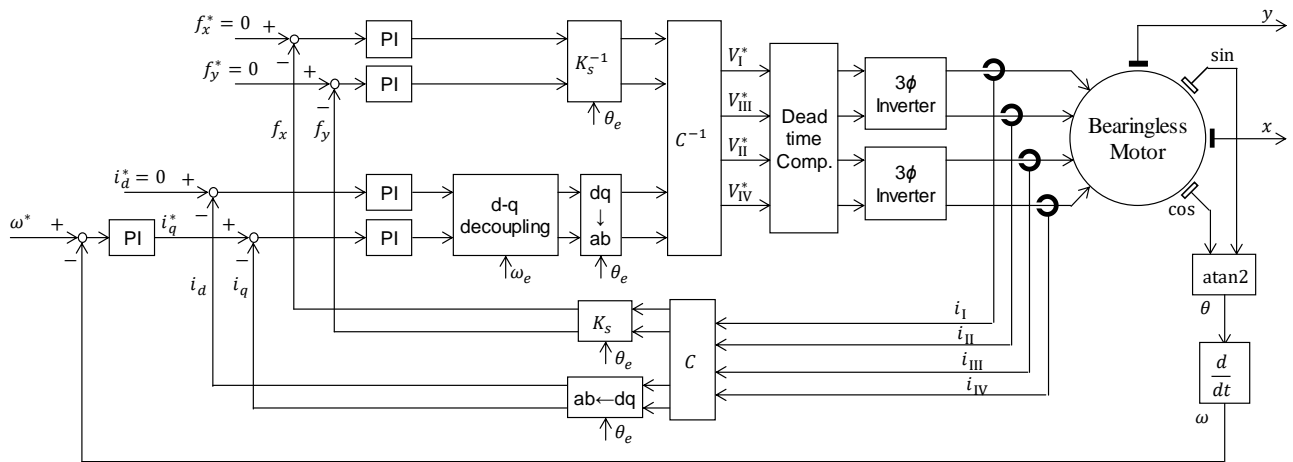
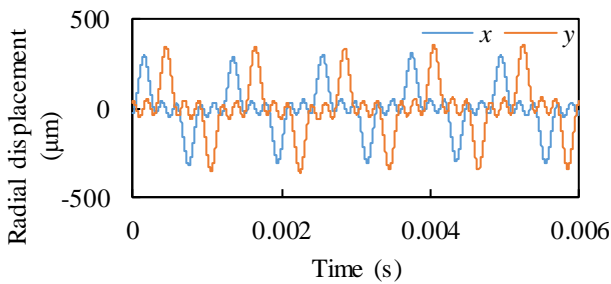
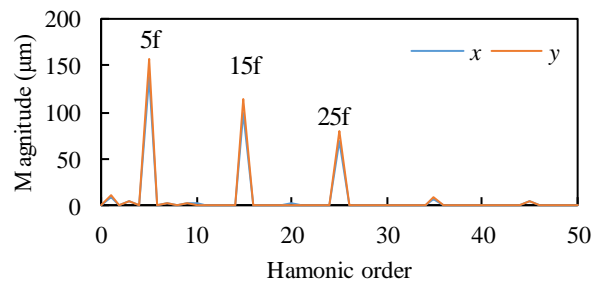


Fig. 4 Control block diagram for non-levitation drive test with ball bearing support.

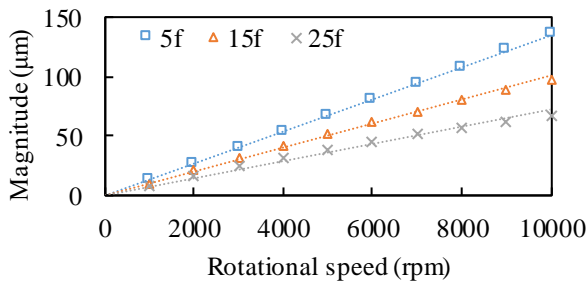


(a) Wave form.

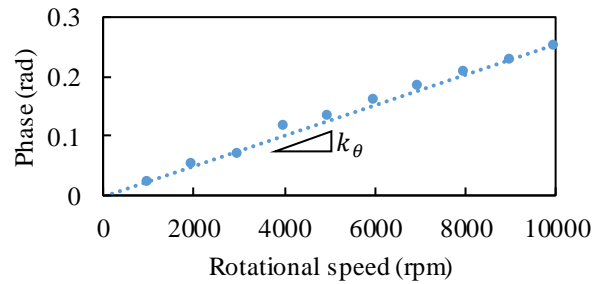


(b) Harmonic components.

Fig. 5 Measured run-out in radial displacement of the rotor with ball bearing support at 10000 rpm.



(a) Magnitude.



(b) Phase.

Fig. 6 Relationship between the run-out of measured  $x$  displacements and rotational speed



compensation at 4000 rpm. Before compensation, the displacement had run-out oscillations, after compensation, the oscillations decreased. Table 1 lists the magnitudes of the run-out compensation before and after compensation. The compensation using Equation (2) reduced the 5th-, 15th-, and 25th-order magnitudes by more than 80%. When notch filters were added, the magnitudes were reduced by up to 99.9%.

## 5. Conclusion

In this study, sensor run-out was identified by actual measurements and a compensation function was developed for the bearingless motor with an unequal-tooth-pitch core in which displacement sensors were placed between the teeth. Run-out compensation was performed using the compensation function and a notch filter. The motor was successfully driven at 4000 rpm in a levitation test. The magnitude of the compensated component was reduced by up to 99.9%.

## 6. Acknowledgment

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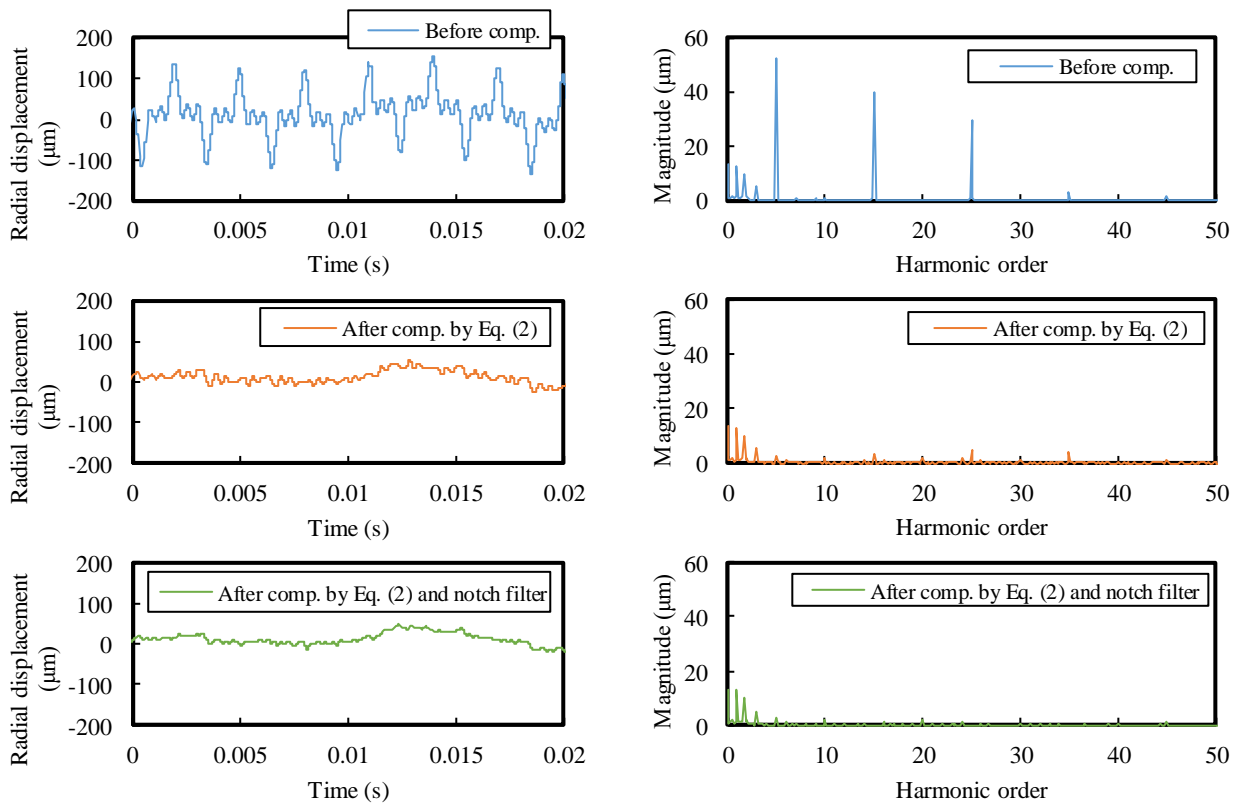


Fig. 9 Measured displacement of the rotor in the  $x$ -direction in the levitation drive test with run-out compensation at 4000 rpm.

Table 1 Comparison of the magnitude of the run-out compensation before and after compensation.

	5th		15th		25th		35th	
Before compensation	52.18	-	40.21	-	29.47	-	3.40	-
After comp. by Eq. (2)	2.98	-94.3%	3.55	-91.2%	5.05	-82.9%	-	-
After comp. by Eq. (2) and notch filter	-	-	0.15	-99.6%	0.04	-99.9%	0.13	-96.3%

( $\mu\text{m}$ )

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