Loss Separation Evaluation under Motor Installed Conditions

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Abstract

In order to achieve high efficiency and low loss of motor, it is important to accurately grasp the losses caused in motor for each factor. We manufactured a motor loss separation measuring unit. Using this unit, we then made a method to measure and separate the losses of the specimen which imitates a motor core. In the evaluation of the mechanical loss, the windage loss during high-speed rotation of the specimen can be separated by measuring the mechanical loss under reduced pressure.

In the evaluation of iron loss, it is possible to compare and evaluate the deterioration of iron loss due to shrink-fitting compressive stress using the shrink-fitting simulation mechanism of the stator core, and the deterioration of iron loss due to machining strain in the process of manufacturing the stator core.

This time, we conducted an experiment to extract windage loss from mechanical loss and obtained respectable separate measurement results. We confirmed the factors that increase windage loss through the experiment.

1 Preface

In this study, we aimed to reduce the energy loss generated in the motor and improve efficiency. Losses are roughly divided into iron loss, copper loss, mechanical loss, and stray loss. For the motor, other than main loss factor like iron loss, there are factors that cause loss of levels we could not ignore. It is well known that there are loss increasing factors stemming from the motor structure or operating conditions.

In order to attain a goal of loss reduction, we have to accurately evaluate and separate motor loss and clarify the main factors. We then must take adequate measures to reduce such losses.

In this study, we manufactured a unit for separate measurements of motor losses and we are currently working on quantitative evaluation of loss. In this paper, we introduce the separate measurements of mechanical loss.
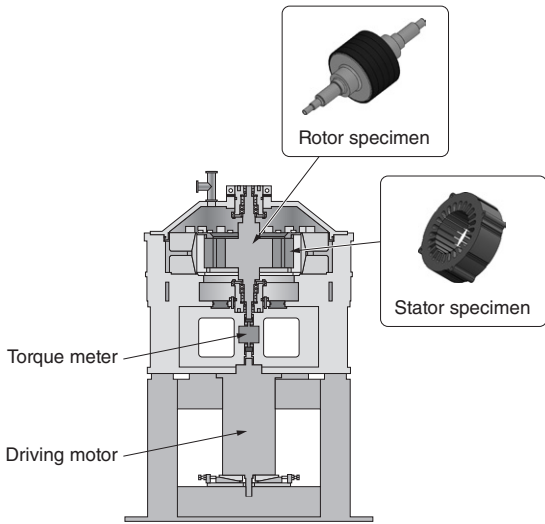
2 Outline of Motor Loss Separation Unit

Fig. 1 shows an external appearance of the motor loss separation unit and **Fig. 2** shows its con-
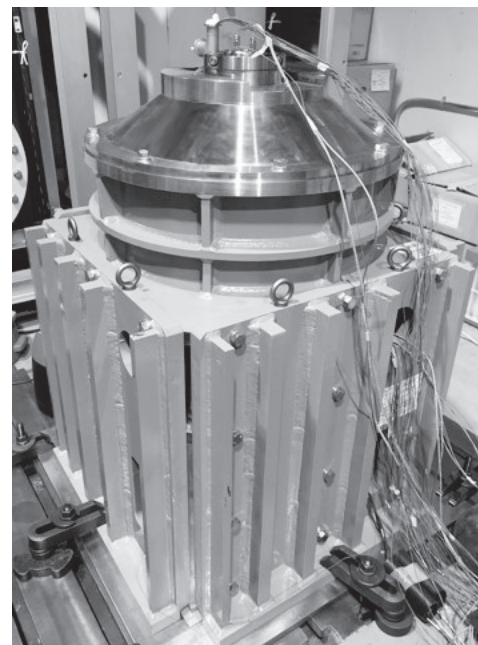
Fig. 1   **External Appearance of Motor Loss Separation Unit**

An external appearance of the manufactured unit is shown.

figuration. The rotor core and the stator core, both constituting specimens, are allocated at the top of the unit. At the bottom of the unit, the rotary shaft of

Fig. 2 Configuration of Motor Loss Separation Unit

The unit configuration is shown.

Fig. 3 Schematic Diagram of Specimen

A configuration of the specimen for mechanical loss measurements and the names of the respective parts and their locations are shown.
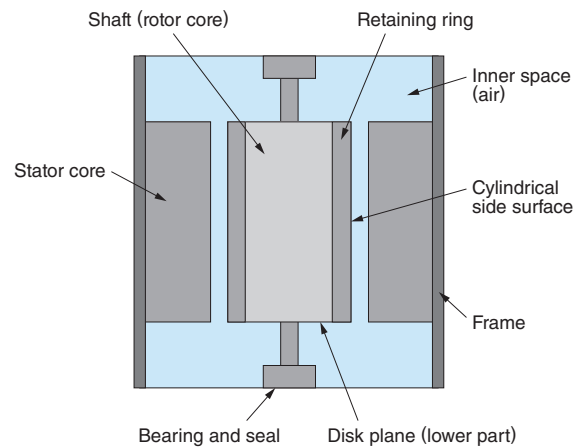
the driving motor and the specimen rotor shaft are connected through a torque meter. When the specimen rotor is rotated by the driving motor, the generated loss is detected by the torque meter as a shaft torque.

This unit has a mechanism to simulate air flow and wind pressure within the motor, and compressive stress at the time of shrinkage fit into the stator core so that the specimens can simulate a motor installed environment. When this mechanism is used for mechanical loss evaluation to measure mechanical losses in the state of pressure reduction around the specimens, windage loss can be separated and extracted from mechanical losses. In the case of iron loss evaluation, the effect of the stresses can be evaluated by measuring the iron loss under the condition that an arbitrary compressive stress is applied to the stator core.

3 Windage Loss Calculation Formula

Fig. 3 shows a schematic diagram of the specimen. The specimen of stator and rotor cores is a dual cylinder of the radial gap type, such that the outer cylinder is stationary and the inner cylinder is rotational. Under this structural condition, windage loss is generated on the side surface areas of the rotor and the stator, and in the upper and lower disk surface areas of the rotor (an inner cylinder).

When the inner cylinder is rotated at the inner cylinder radius r_i (m), the turning angle velocity ω

(rad/s), and the peripheral speed u_i (m/s), the windage loss generated on the cylindrical side surface is calculated with the expression below, proposed in the F. Wendt thesis[1].

According to the status of the specimen and testing conditions, Reynolds number Re_r is derived from Expression (1) below.

$$Re_r \equiv u_i d/v \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

Where, d is the gap length (m) from the rotor outer diameter to the stator inner diameter and v is kinematic viscosity coefficient of fluid (m²/s). Subsequently, the relationship between the friction moment coefficient C_{Mr} and Reynolds number Re_r is given by an empirical formula that differs according to size of the Reynolds number. The relationship between the friction moment coefficient C_{Mr} and torque M_r is given by Expression (2) below.

Consequently, windage loss P_{Wr} on the side surface is given by Expression (3).

$$C_{Mr} \equiv M_r/(2\pi\rho r_m^4\omega^2 L) \cdots\cdots\cdots\cdots\cdots (2)$$
$$P_{Wr} \equiv M_r\omega \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Where, ρ is fluid density (kg/m³), L is cylinder height (core stack thickness)(m), and r_m is the center radius between inner and outer cylinders (m).

Subsequently, windage loss generated on the rotor upper and lower disk planes is derived from the expression below proposed by Schlichting[2].

Reynolds number Re_z is defined by Expression (4).

$$Re_z \equiv u_i r_i / v \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

The relationship between the friction moment coefficient C_{Mz} and Reynolds number Re_z is given by an empirical formula that differs according to size of the Reynolds number. The relationship between the friction moment coefficient C_{Mz} and torque M_z is given by Expression (5) below. Consequently, windage loss P_{Wz} on the rotor upper and lower disk surface areas is given by Expression (6).

$$C_{Mz} \equiv M_z / (1/2\rho\omega^2 r_i^5) \cdots\cdots\cdots\cdots\cdots\cdots (5)$$
$$P_{Wz} \equiv M_z\omega \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

Consequently, windage loss P_W generated on the dual cylinder surface areas, which simulate the stator and the rotor, is given by the sum of the cylinder side plane windage loss P_{Wr} of Expression (3) and upper/lower disk surface planes windage loss P_{Wz} of Expression (6), and it is given by Expression (7) below.

$$P_W = P_{Wr} + P_{Wz} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

For confirmation, expressions above assume that the rotor, and the stator are completely cylindrical, and all surfaces and planes are completely smooth. For this reason, this specimen is substantially in an ideal state, compared with an actual motor. We promote our study based on this scheme.

4　Mechanical Loss Measurement

Using this unit, the mechanical losses generated in the specimen are measured. The rotor core of the specimen simulates a structure where permanent magnets are attached to the rotor surface. In this case, the unmagnetized permanent magnets are employed. The most outer periphery of the rotor is provided with a retaining ring. Bearings and seals are provided to both ends of the shaft. Iron hollow cylinders are used as specimen stator cores to eliminate effects by surface condition or shape of stator core. These specimens come in two types; the one provided with grooves to simulate slot openings and the other one having no grooves but a plane surface.

When the aforementioned rotor core of the specimen is rotated with the aid of a driving motor, mechanical losses at any revolving speed can be measured. The measured mechanical losses are considered to involve windage loss, bearing frictional loss, and seal loss.

In this experiment, variations in mechanical losses with inner pressure of the specimen are measured for the purpose of extraction of only the windage loss from mechanical losses. Based on the experimental result, mechanical losses are then estimated in the state of absolute vacuum. Since mechanical losses under the absolute vacuum are a sum of bearing loss and seal loss, it is possible to extract windage loss by defining a differential component that can be obtained by subtracting mechanical losses under the absolute vacuum from those under atmospheric pressure.

5　Result of Mechanical Loss Measurement

Table 1 shows the conditions of an experiment under decompressed pressure. This experiment is named Experiment 1. Based on the result of Experiment 1, **Fig. 4** shows mechanical loss variations in compliance with the inner pressure. In this

Table 1	Conditions of Experiment under Decompressed Pressure

Conditions of the core specimen at the time of decompressed experiment, inner air environment, and operating conditions are shown.

Rotor core	Non-polarized rotor
Stator core	Mimic stator cylinder
Inner fluid in the specimen	Air
Range of decompression	0～−0.08 MPa (5 points at the intervals of 0.02 MPa)
Rotor speed	20,000 min⁻¹
Specimen losses	Windage loss, bearing loss, seal loss
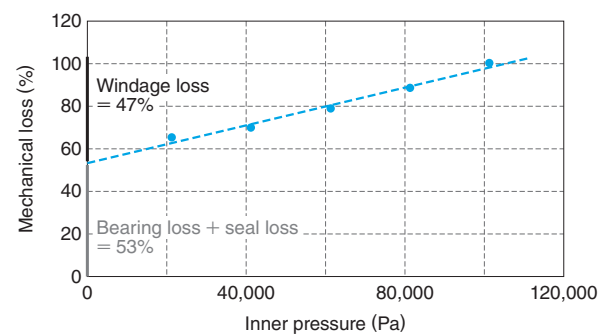
Fig. 4	Mechanical Loss Variations in Compliance with Inner Pressure

During decompression of inner pressure in the specimen, the relationship between the inner pressure and mechanical losses maintains a linear property. The loss changing with a linearity falls under the windage loss attributable to air friction.
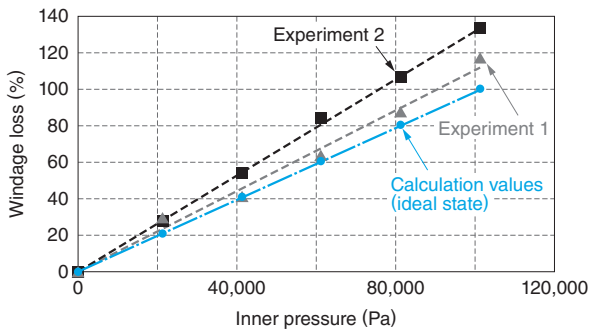
Fig. 5 Windage Loss Variations in Compliance with Inner Pressure

For calculation values, side surfaces of the rotor and stator are assumed to be smooth. For Experiment 1, the rotor surface is assumed to be rough and the stator has a smooth surface. For Experiment 2, the rotor surface is assumed to be rough and the stator have slot openings. These graphs suggest that windage loss is greatly influenced by difference in the surface conditions.

case, mechanical losses measured before decompression are assumed to be 100%. According to the graph, it can be recognized that there is a proportional relationship between the inner pressure and mechanical losses.

According to the approximation curve of the measured result, mechanical losses under the absolute vacuum are identical with an intercept of the graph and its value is 53% of mechanical losses before decompression. This value falls under mechanical losses attributable to mechanical contact and is equal to a total of bearing loss and seal loss. Accordingly, windage loss before decompression is equal to 47% that is a remaining part. By virtue of this experimental approach, it has been made clear that windage loss can be extracted from mechanical losses.

Another experiment was carried out under the same conditions as specified in **Table 1**. In this case, the stator core provided with slot openings was used. This experiment is named Experiment 2. **Fig. 5** shows a result of obtaining a graph that shows the windage loss varying with inner pressure of the stator core. Windage loss before decompression is assumed to be 100%, obtained from Expression (7) in **Section 3** for calculation of windage loss.

For Experiment 1, a combination of the rotor with a retaining ring and the stator with a plane surface without slot openings is employed. Compared

with the calculation result of Experiment 1, windage loss for this time shows an increase of 17%. Regarding one of the possible causes, the surface roughness on the rotor can be considered to increase friction.

Experiment 2 was carried out on a combination of the rotor with a retaining ring and the stator with slot openings. Compared with the calculation values, there is an increase of 33% in Experiment 2. This is a 16% increase from Experiment 1. Judging from conditional difference between Experiments 1 and 2, such a result has been derived from stator surface roughness attributable to the effect of slot openings.

Since use of an actual motor corresponds to a case of Experiment 2, these experimental results suggest that designing of the reduced windage loss is possible by taking an emphasized consideration into fluid contact conditions.

6 Postscript

For our study, we manufactured a motor loss separation unit, measured mechanical losses to extract windage loss, and obtained sufficient separation measurement results. Furthermore, for windage loss, we confirmed that the conditions of the rotor surface and stator surface affect the loss and that these factors increase losses.

For future issues, we are planning to carry out measurements and evaluation of iron loss increasing factors in the stator so that reduction of losses can be further intensified.

《**References**》

（1） Von F. Wendt: "Turbulente Stromungen zwischen zwei rotierenden konaxialen Zylindern," Arch. Appl. Mech. 4 (6), pp.577-595, 1933
（2） Schlichting, Boundary Layer Theory, McGraw-Hill Press, New York, 1979