Experimental Characterization of the Slinky-Laminated Core and Iron Loss Analysis of Electrical Machine

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The magnetic properties of a motor core deteriorate during the manufacturing process due to mechanical stresses in the materials. It is particularly hard to predict the characteristics of the slinky-laminated electrical machines, because stresses and strains occur simultaneously in the core. To examine the *B–H* curve and the iron loss of a core affected by the manufacturing process, a slinky-laminated surface-mounted permanent magnet synchronous motor (SPMSM) was proposed as an analysis model. The magnetic properties of the slinky-laminated core and the stacked core were compared as the results of material experiments, using the proposed motor core. With the examined material data, the iron loss of the slinky-laminated SPMSM was investigated via the finite-element method (FEM). Finally, the proposed motor was subjected to a no-load test and a mechanical loss test. Based on the test results, the actual iron loss of the motor was obtained through loss segregation and was then compared with the FEM results to verify the validity of the material experiment and loss analysis methods.

Index Terms— **Compressive stress, iron loss, magnetic property, slinky lamination, strain, tensile stress, washing machine.**

I. Introduction

THE manufacturing of the magnetic parts of the electrical machines requires several industrial processes. These may have effects on the magnetic properties of the material, especially in terms of iron loss [1]–[3]. With the development of manufacturing techniques and production machines, the slinky-lamination method is now being used to significantly reduce the material waste [4]. For this process, a long iron band is rolled up spirally and bonded, as shown in Fig. 1 [1]. Thus, not only compressive stress but tensile stress and strain occur in the core. As a result, the magnetic properties deteriorate, and it becomes hard to estimate the deteriorated properties of the slinky-laminated material.

There have been several studies on the various manufacturing effects on the magnetic properties [1]–[3]. In these studies, the effects of mechanical stress caused by wire cutting, shrink fitting, pressing, and the punching process were examined through the experimental methods. Although some of them dealt with the effects of the wound or the slinky-lamination method, they did not verify the validity of the material experiment results by analyzing the actual iron loss of the motors considering the examined material data. In [5]–[7], the deteriorated magnetic properties caused by shrink fitting were investigated. Only the impact of the compressive stress was examined, however, and this was done through a test using specimens. This cannot be considered suitable for accurately analyzing the iron loss of the slinky-laminated core in the electrical machines.

In this investigation, an outer-rotor surface-mounted permanent-magnet synchronous motor (SPMSM) with a slinky-laminated stator core for a washing machine is proposed. A material test using the slinky-laminated stator was conducted to obtain the deteriorated B–H curve and iron loss data. The test was carried out over several levels of excitation field at several frequencies, and the results were compared with those of the conventionally stacked lamination method. In addition, the iron loss of the motor was analyzed through the finite-element method (FEM) using the examined material data. It was finally compared with the experimental result of the actual iron loss of the motor.

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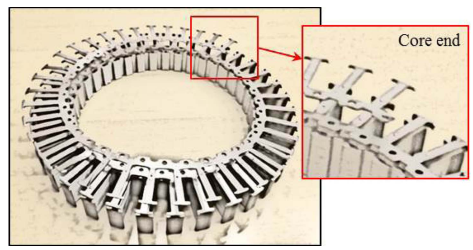

Fig. 1. Slinky-laminated stator core.

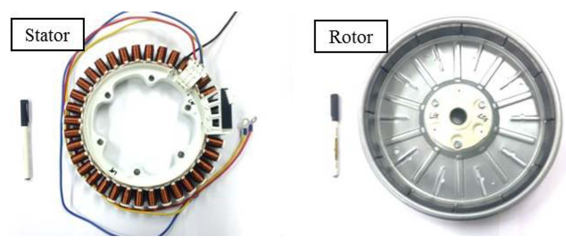

Fig. 2. Proposed SPMSM for the washing machine.

II. Proposed Model

An outer-rotor-type SPMSM, as shown in Fig. 2, consists of 48 poles-36 slots, and a ferrite magnet was used in the rotor. The diameters of the rotor and the stator are 283 and 265 mm, respectively. The stator is slinky laminated with a 1 mm cold-rolled steel sheet, and the rotor is made by stamping a galvanized cold-rolled steel sheet. The stack length of

TABLE I
SPECIFICATIONS OF THE PROPOSED MOTOR

Item	Unit	Value
Maximum voltage / current	V_{DC} / A_{peak}	310 / 10
Torque (washing / dehydrating mode)	Nm	37 / 2
Speed (washing / dehydrating mode)	rpm	46 / 1200
Rotor/Stator diameter	mm	283/265
Stack length of the stator	mm	24
Overhang (magnet / stator)	%	136.67
Pole / slot number	-	48 / 36
Magnet material	-	Ferrite

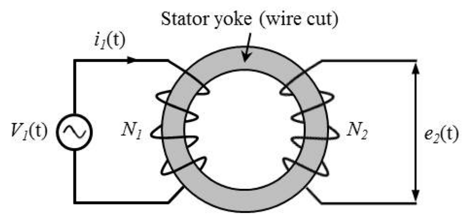

Fig. 3. Experimental set for the magnetic material properties.

TABLE II
MATERIAL TEST CONDITION

Winding (turns)	Dimensions (mm)		Properties	
Primary / Secondary	Outer / Inner diameter	Height	Mass (g)	Density (g/dm³)
200 / 40	200.3 / 194.6	13.4	230.68	7.85

the stator is 24 mm, and the axial length of the magnets is 32.8 mm. The mechanical air gap between the rotor and the stator is 1 mm. The dc supply voltage is 310 V_{dc}, and the maximum current is 10 A_{peak}. The torques in the washing and dehydrating modes are 37 and 2 Nm, respectively, and the speeds are 46 and 1200 r/min. The specifications are shown in Table I.

III. MAGNETIC PROPERTIES OF SLINKY-LAMINATED CORE AND STACKED CORE

A. Experiment on the Deteriorated Material Properties

To measure the B–H curve and the iron loss under the stress and strain conditions that occur due to the slinky-lamination process, a ring core from a stator yoke of the proposed motor was prepared by a wire cut. The test conditions of the core are shown in Fig. 3 and Table II. The test was carried out over several levels of excitation field and at several frequencies.

Insulation tape was wound around the ring core for insulation purposes. For both the primary coil N_1 and the secondary coil N_2, 200 and 40 turns were used to guarantee the exciting of a high field (over 5 kA/m). The B–H curve and the iron loss test were conducted as per IEC 60404-6. In this test, the H field is measured at the primary coil, and the B field is measured at the secondary coil. Consequently, the B–H hysteresis loop can be measured to obtain the iron loss.

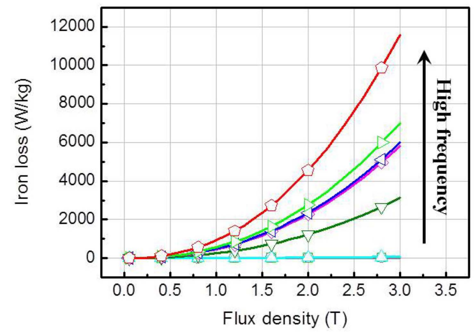

Fig. 4. Iron loss of the slinky-laminated core.

B. Iron Loss Separation

To interpolate and extrapolate the iron losses according to the frequencies and flux densities, the phenomenological principle proposed by Bertotti was adopted [1]. Based on the principle, the average power loss per unit volume of a machine W_{Core} can be decomposed into three components as

$$W_{\text{Core}} = W_{\text{Hysteresis}} + W_{\text{Eddy}} + W_{\text{Anomalous}} \ (W/\text{kg}) \quad (1)$$

where $W_{\text{Hysteresis}}$ is the quasi-static hysteresis loss, W_{Eddy} is the eddy current loss, and $W_{\text{Anomalous}}$ is the excess loss; dynamic behavior of the magnetic domains [8], [9]. However, these are dependent on the chemical and physical characteristics of the considered material [9]. Thus, for a sinusoidal supply, the static losses can be approximated by the following well known equations (2)–(4) proposed by Steinmetz, where B is the peak value of the magnetic flux density, f is the frequency, and α and β are the Steinmetz coefficients:

$$W_{\text{Hysteresis}} = k_h f B^{\alpha} \ (W/\text{kg}) \quad (2)$$
$$W_{\text{Eddy}} = k_e f^2 B^2 \ (W/\text{kg}) \quad (3)$$
$$W_{\text{Anomalous}} = k_a f^{1.5} B^{\beta} \ (W/\text{kg}). \quad (4)$$

To identify the coefficients, the iron loss data obtained from the material experiment and the least-square method were used. The interpolation result is shown in Fig. 4. Based on the magnetic properties of the stacked and slinky-laminated cores, as shown in Fig. 5, it was verified that the properties were generally deteriorated by the slinky-lamination method because of the stresses and strain in the core. The iron loss of the slinky-laminated core was 18.14% larger than the stacked core at 50 Hz.

IV. LOSS ANALYSIS

A. Finite-Element Method

With the deteriorated material data examined in Section III, the iron loss of the motor was analyzed via FEM. Fig. 6 shows the process of determining the iron losses, which is described in detail as follows [10], [11].

1) *Step 1:* Using nonlinear FEM, the flux density at each mesh for one electrical angle period was calculated, as the rotor was rotated. Here, the flux density was calculated as the radial and tangential components.
2) *Step 2:* Using the flux density from Step 1, Fourier transform was performed to find the magnitude of the fundamental and harmonic components.

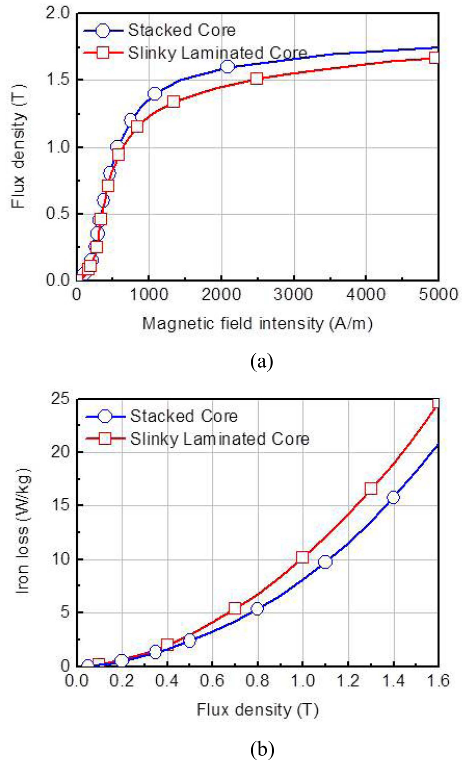

Fig. 5. Comparison of the material data. (a) B–H curve. (b) Iron loss at 50 Hz.

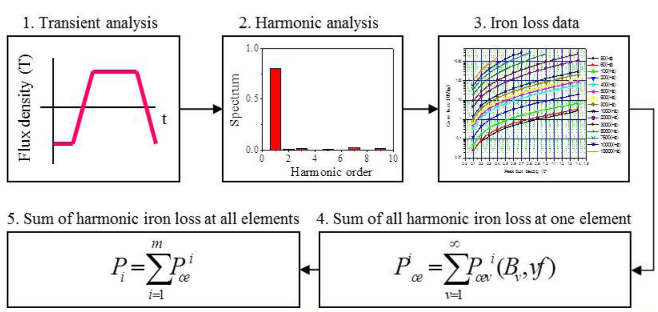

Fig. 6. Calculation process of the iron loss of the motors.

3) *Step 3:* From the iron loss data for the material, the iron loss corresponding to the frequency and the flux density of each harmonic was calculated. The material information was based on the empirical data.
4) *Step 4:* The sum of the iron loss due to the harmonic components at each mesh was calculated.
5) *Step 5:* The iron losses of all the meshes were added to determine the total iron loss of the machine.

The flux density, the harmonic analysis result, and the sum of all harmonic iron loss at one mesh at 1000 r/min using the deteriorated iron loss data are shown in Fig. 7. The selected mesh is the one located in the middle of the stator teeth, and the iron loss data used at Step 3 was shown in Fig. 4. The total iron losses at 0–1000 r/min as the result of Step 5 will be presented and compared with the experimental result in Section IV-B.

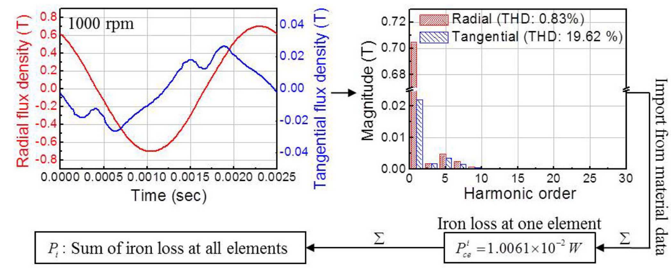

Fig. 7. Results of Steps 1–4 at one mesh at 1000 r/min.

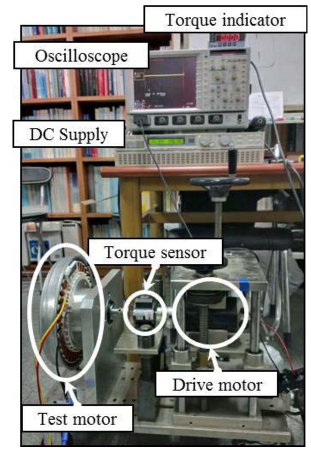

Fig. 8. Experiment set for the no-load test.

B. Experiment of the Proposed Motor

In this paper, two kinds of experiments and the loss segregation process were conducted to find the iron loss of the slinky-laminated motor. Configuration of the experiment set is shown in Fig. 8. The experiment was conducted until 1000 r/min having taken into consideration the specifications of the power supplier and the drive motor. Rotational speed was measured using a LeCroy LT364L oscilloscope.

First, using the drive motor, the test motor assembled the stator, and the rotor was controlled to evaluate the total loss of the test motor under the no-load condition. This loss consisted of iron loss and mechanical loss. It was calculated using

$$W_{\text{Total no-load Loss}} = T_{\text{SR}} \cdot \omega_{\text{SR}}\ (W). \tag{5}$$

In (5), T_{SR} and ω_{SR} are the torque and rotation speed under the steady-state condition, respectively. The subscript SR refers to the test motor assembled the stator and the rotor.

The second test was conducted only with the rotor of the test motor. The rotor and bearings of the test motor were installed in the experiment set to measure only the mechanical loss. In other words, the stator was eliminated from the motor for the second test, and the torque and rotational speed under this condition were subscripted as R. Thus, the mechanical loss was obtained using

$$W_{\text{Mechanical Loss}} = T_R \cdot \omega_R\ (W). \tag{6}$$

In (6), T_R and ω_R are the torque and rotation speed under the steady-state condition, respectively. The mechanical loss

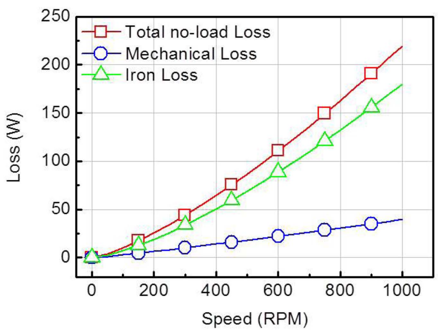

Fig. 9. No-load test results.

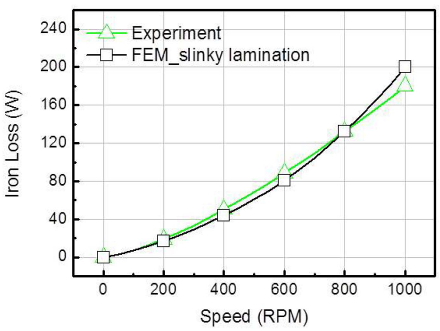

Fig. 10. Comparison of the FEM and the experiment results.

mainly consisted of the windage and bearing loss. The copper loss is negligible, because the input current is extremely small.

The iron loss of the motor according to the speed was calculated by subtracting the mechanical loss from total no-load loss as (7). Given the calculation result as shown in Fig. 9, the iron loss can be said to account for ~82% of the total no-load loss

$$W_{\text{Iron}} = W_{\text{Total no-load Loss}} - W_{\text{Mechanical Loss}}\ (W). \quad (7)$$

Finally, Fig. 10 shows the iron losses of the proposed SPMSM obtained from the experiment and the FEM considering the slinky-laminated material data. It is expected that the cause of the error is the use of the examined material data at the teeth and the yoke for the FEM. In this paper, the yoke and the teeth were applied with the same deteriorated data. Teeth, however, are rarely stressed by the slinky-lamination method, except for the edges between the teeth and the yoke. In addition, it is hard to apply the stress at the edges to FEM even though it is very high. The error also occurs in the interpolation and extrapolation of the material data using the Steinmetz equations. Nevertheless, the loss magnitude of the simulation is similar to that of the experiment.

V. Conclusion

This paper investigated the influence of the slinky-lamination method as a manufacturing process on the magnetic properties. The slinky-laminated stator core of the proposed SPMSM was fabricated by a wire cut to examine the properties. The result shows that B–H characteristics deteriorated. In addition, it was verified that the iron loss of the slinky-laminated core is larger than that of the stacked core due to the stress and strain. With the examined material data, the iron loss of the slinky-laminated motor was analyzed via the proposed FEM process. Finally, the motor was subjected to both a no-load test and a mechanical loss test. Based on the test results, the iron loss was obtained through the loss segregation. It was compared with the FEM result to verify the validity of the examined material data, loss analysis method, and loss segregation process presented in this paper.

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