Step Motor Lower-Loss Technology—An Update

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Management Summary

The demand for stepping motors with high efficiency and low losses has been increasing right along with the existing focus on high torque. The selection of the most suitable grade and improvement in the fastening of the laminated cores has reduced losses significantly at their peak when compared to conventional stepping motors. Lowering the losses of the motor has enabled continuous operation previously considered impossible. An expansion of the stepping motor's usage into applications where another type motor has been used for continuous operation and other uses due to heat generation issues is now within reach. In addition, these motors are very effective for energy savings; this paper explains the technology used for lowering the iron loss in stepping motors.

Introduction

The stepping motor can control the speed and position accurately in an open loop control mode, but its disadvantage has been excessive heat generation when rotating at high speed. On the other hand, its ease of use has been a clear benefit. The stepping motor has been used mainly to utilize standstill holding brake force and torque at low speed. Another recent customer demand—the ability to operate continuously at high speed, thus shortening cycle equipment time—is yet another challenge. That challenge has been met by the use of both an enhanced lamination sheet and fastening method for the laminated iron core—greatly reducing motor loss when compared with the conventional stepping motor. The example motor shown in Table1 is selected as the conventional stepping motor described in this paper.

Losses of Stepping Motor

Classification of losses. Figure 1 shows the losses that are classified when a motor is rotating. The total losses are divided into the driver losses generated in the driver and the motor losses generated in the motor. The majority of the motor losses are copper and iron losses. The copper loss is a loss generated by the current flowing to a stator (stator winding); the iron loss is generated by the flux change in the core. The flux in the core changes by rotation of the rotor (field) or a current change of the stator (stator winding); the iron losses can therefore be classified as an iron loss by the field and the other by the stator winding. Hereafter, the former is called *field iron loss*; the latter, *stator winding iron loss*.

The iron losses can be classified into eddy current loss and hysteresis loss based on the magnetic generation principle. Other losses include mechanical loss and stray load loss. However, this discussion will disregard them—as well as those in the iron losses—because they are small enough to do so when compared with the iron and copper losses.

Field iron losses. Figure 2 shows a structure of the stepping motor. A hybrid-type stepping motor uses a permanent magnet for the rotor and equips the inductors—or teeth—on the outer diameter of the rotor core and inner diameter of the stator core. Iron loss is generated as the rotor rotates because the teeth periodically face and the flux in the stator core changes periodically. This is called field iron loss, as stated above.

Figure 3 shows a measurement system for the field iron losses. A torque meter is set between an external driving motor and a motor to be measured; the rotor is rotated from outside. The rotational speed and the torque are measured and the iron loss is calculated by Equation 1 as:

$$W_0 = (2\pi / 60) \cdot N \cdot T \qquad (1)$$

W_0	=	Field iron loss (*W*)
N	=	Rotating speed (*r/min*)
T	=	Torque (*N·m*)

As mentioned, the iron losses consist of the eddy current loss and the hysteresis loss; each loss-per-unit-mass is expressed as:

$$W_e = c_e \cdot B_m^{2} \cdot t^{2} \cdot k^{2} \cdot N^{2} \qquad (2)$$

$$W_h = c_h \cdot B_m^{1.6} \cdot k \cdot N \qquad (3)$$

W_e	=	Eddy current loss (W/kg)
W_h	=	Hysteresis loss (W/kg)
c_e, c_h	=	Iron loss constant determined by material
t	=	Thickness of lamination sheet (mm)

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Table 1—Specification of conventional stepping motor

Frame size	60 mm
Length	60 mm
Phase	2 phase
Pole pair	50
Resistance	1.6 ohm
Rated current	1.7 A
Maximum holding torque	1.2 Nm

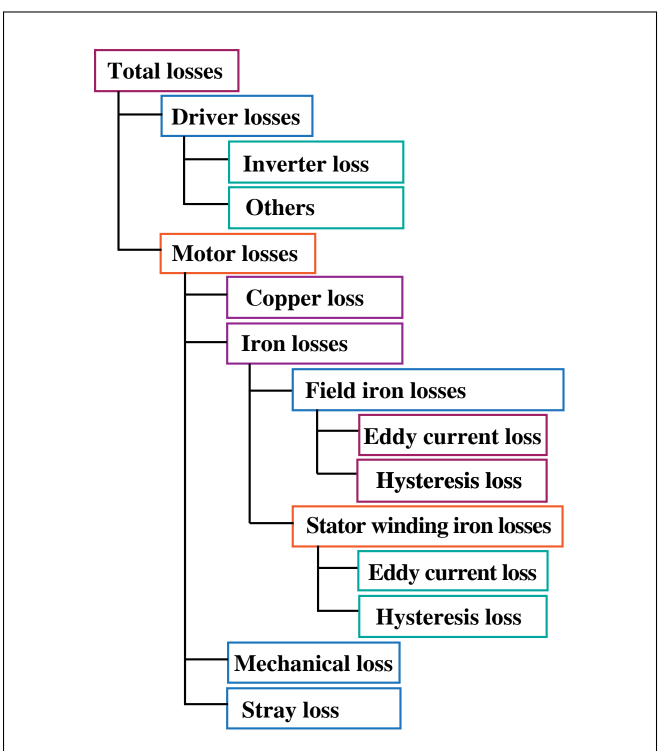

Figure 1—Classification of losses.

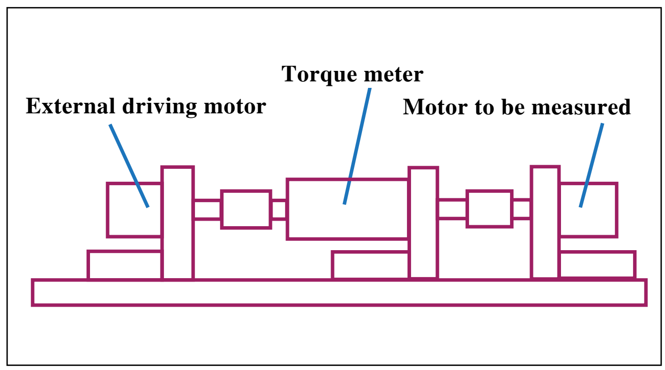

Figure 2—Measurement system of field iron losses.

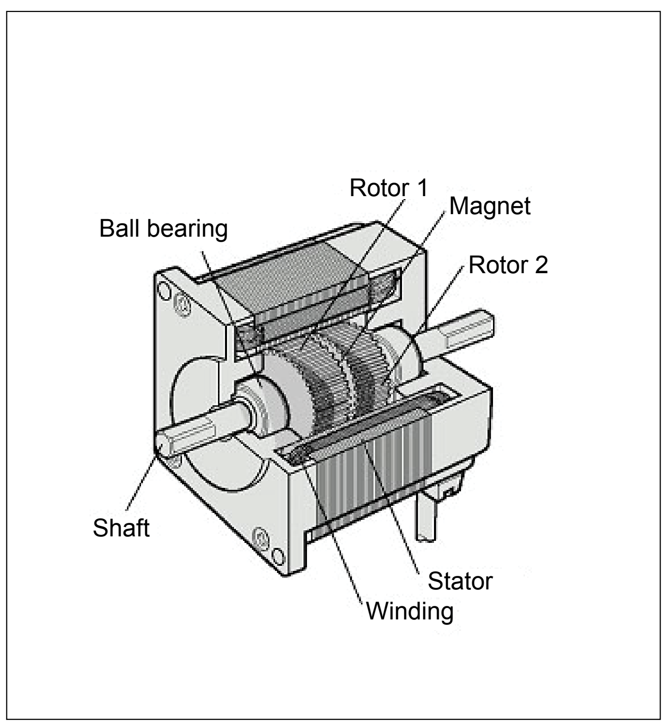

Figure 3— Structure of stepping motor.

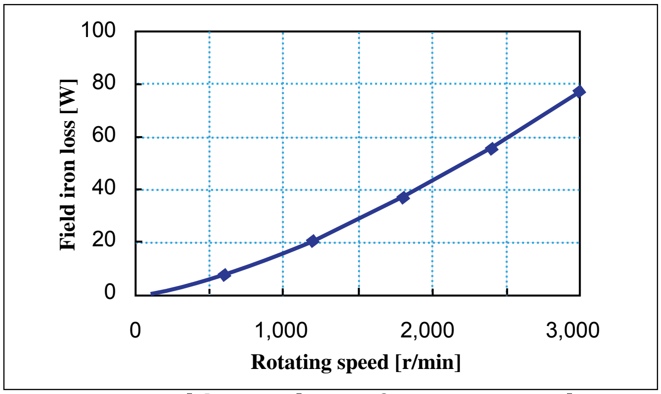

Figure 4—Field iron loss of conventional stepping motor.

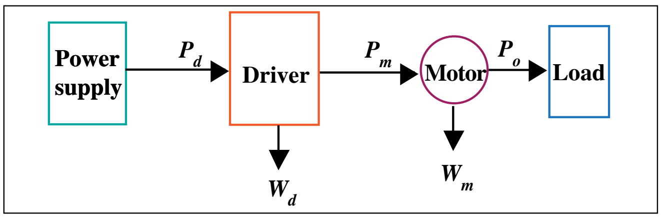

Figure 5—Configuration diagram of loss measurement.

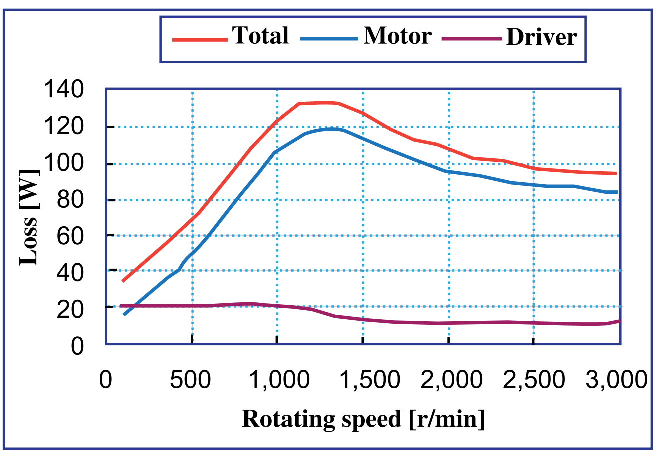

Figure 6—No-load loss of conventional stepping motor.

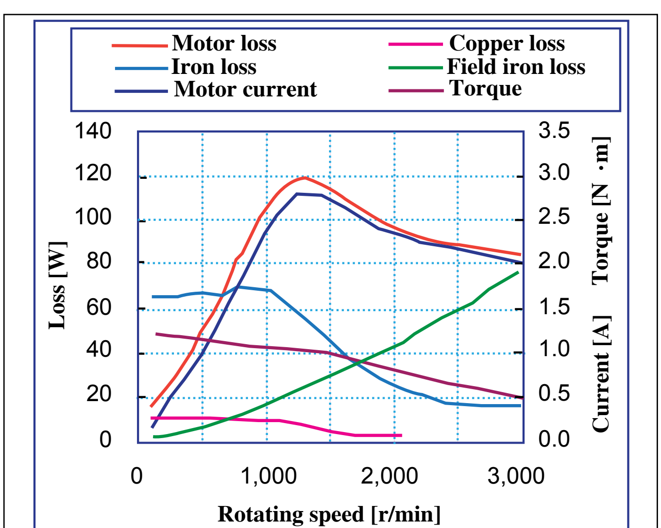

Figure 7—Motor loss of conventional stepping motor.

k	=	Constant by number of pole pair
B_m	=	Flux density (T)
N	=	Rotating speed (r/min)

These equations demonstrate why the eddy current loss is proportional to the square of the rotational speed, and the hysteresis loss is proportional to the rotating speed. The iron loss is a sum of the eddy current loss and the hysteresis loss; it is proportional to the 1st ~ 2nd power of the rotational speed. Figure 4 shows field iron loss in the conventional motor (Eq. 4; approximately), and is proportional to the 1.44th power of the rotational speed.

$$W_0 = 7.84 \cdot 10^{-4} \cdot N^{1.44} \quad (4)$$

Separation of motor losses. The configuration diagram of the loss measurement is shown in Figure 5. A power meter is set between the power supply and the driver, and the driver and the motor, respectively, for measuring power and current.

The driver input, motor input and the output are assumed to be P_d, P_m, and P_o, respectively. The difference between the driver input and the output makes a total loss W_u and the difference between the motor input and the output makes a motor loss W_m. Each value is expressed by the following:

$$W_u = P_d - P_o \quad (5)$$

$$W_m = P_m - P_o \quad (6)$$

The difference between driver input and motor input is driver loss W_d and is expressed by:

$$W_d = P_d - P_o \quad (7)$$

The stepping motor is controlled with a driver so that a constant current may flow, regardless of load; a smaller load therefore results in greater loss.

Consequently, the loss evaluation of the no-load stepping motor is the severest. When assuming $P_o = 0$ (Eqs. 5–6), the whole driver input results in a total loss; the whole motor input results in a *motor loss*. Figure 6 shows the no-load loss of the conventional stepping motor. It is understood that the motor loss is relatively significant when compared with the driver loss.

This brings us to the separation of the motor losses.

Motor copper loss is calculated by:

$$W_c = n \cdot I^2 \cdot R \quad (8)$$

Iron loss follows with:

$$W_{fe} = W_m - W_c \quad (9)$$

W_c	=	Copper loss (W)
W_{fe}	=	Iron loss (W)
n	=	Number of phases
I	=	Current in RMS value (A)
R	=	Winding resistance (ohm)

Figure 7 shows the result of separating the conventional stepping motor's loss from both copper and iron loss. The motor current, torque and field iron loss are described for reference.

Although the current of the stepping motor is controlled to be at a constant value in the fixed-current area of 1,000 r/min or less, the current decreases at higher speed. This is because the voltage to operate the constant-current control becomes insufficient due to an increase in impedance at high speed. The area where the current decreases is known as a "constant-voltage area."

Figure 7 also shows maximum motor iron loss at about 1,200 r/min. In practice, iron loss during rotation is greater than the field iron loss because the stator winding iron loss is added to the field iron loss. The difference therefore between the iron loss and the field iron loss is a stator winding iron loss. The stator winding iron loss decreases in the constant-voltage area because the current is also decreased. The conventional motor has a characteristic in which field iron loss becomes equal to iron loss at about 3,000 r/min.

Though the motor loss is the sum of both iron and copper loss, the copper loss is relatively small and the motor loss is almost equal to the iron loss at high speed. The maximum loss of the conventional motor is 119 W—of which iron loss is 112 W—or 94% of the motor loss. Reduction of iron loss is thought to be an effective development for mitigating the loss of a stepping motor.

Lower-Loss Technology for a Stepping Motor

Lower iron loss using suitable lamination sheet. Two methods are derived from Equations 2–3 for lowering iron loss:

1. Material with a small iron loss constant (c_e, c_h) is used.
2. A thin lamination sheet is used.

The above become possible by changing the grade and thickness of the lamination sheet.

Iron-loss-per-unit mass:
Lamination Sheet 1 > Lamination Sheet 2 >
Lamination Sheet 3 > Lamination Sheet 4

Stator cores were made for trial purposes with the above lamination sheets; a comparison of their maximum loss is shown in Figure 8. The vertical axis shows the ratio based on the motor loss of Lamination Sheet 1; the comparison of loss by material was conducted under the same conditions of holding torque.

In general, reduced iron loss is achieved with use of a higher-grade lamination sheet. However, the saturation flux density will then also tend to decrease when the specified value in iron loss becomes small. When used for the motor, the torque becomes smaller; the current was adjusted to create a uniform torque. Therefore the smaller the specified value in iron loss from the lamination sheet, the greater the copper loss.

And yet—saying the smaller the specified value in iron loss of the lamination sheet, the smaller the field iron loss—doesn't necessarily mean that the specified value in iron loss of the lamination sheet in the condition of a constant torque applies. That's because the stator winding iron loss depends on the current; it reverses the iron loss value in Lamination Sheets 3 and 4. The best lamination sheet was selected, considering not only the specified value in iron loss of the lamination sheet but also the torque characteristic.

Lower iron loss using suitable fastening method. Figure 9

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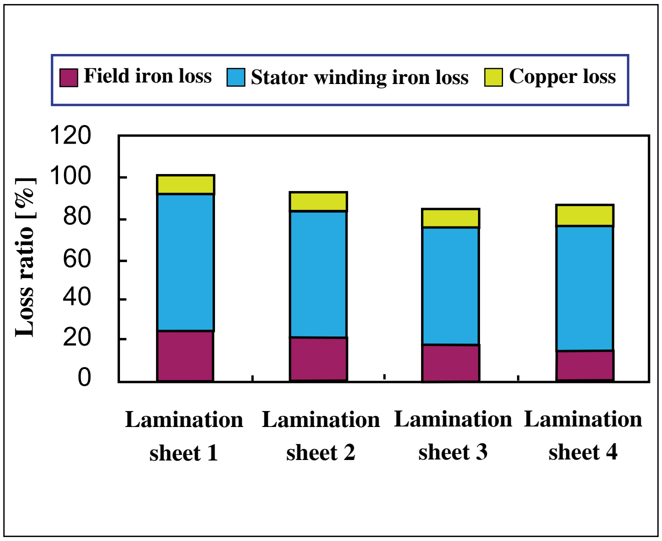

Figure 8—Relationship of lamination sheet material and loss.

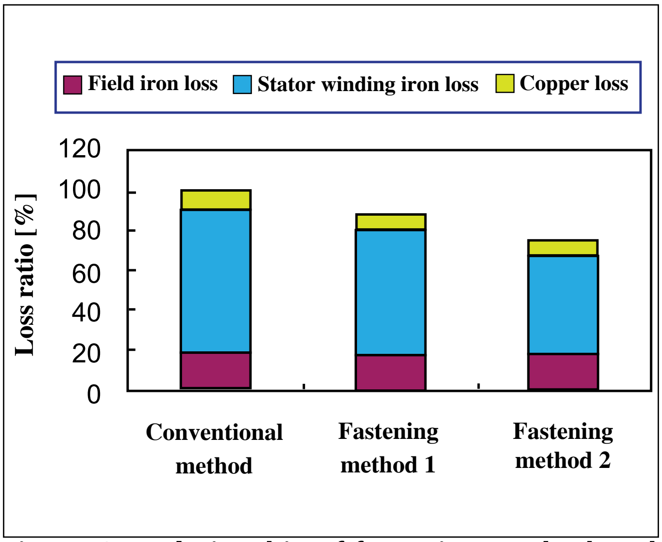

Figure 9—Relationship of fastening method and loss of (laminated) stator core.

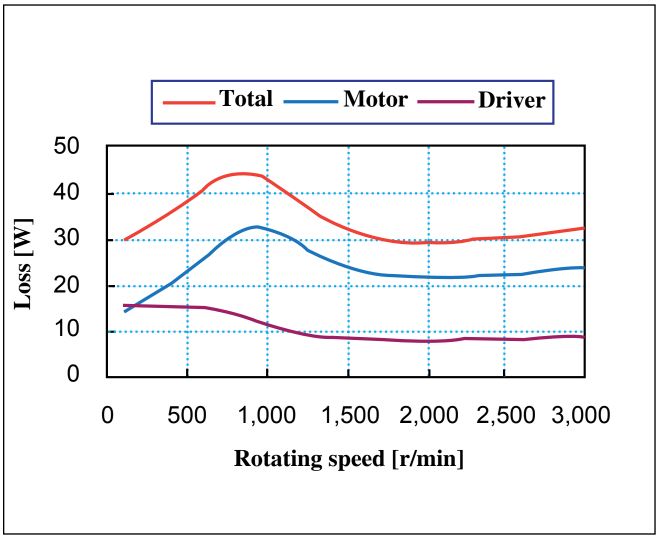

Figure 10—No-load loss of low-loss stepping motor.

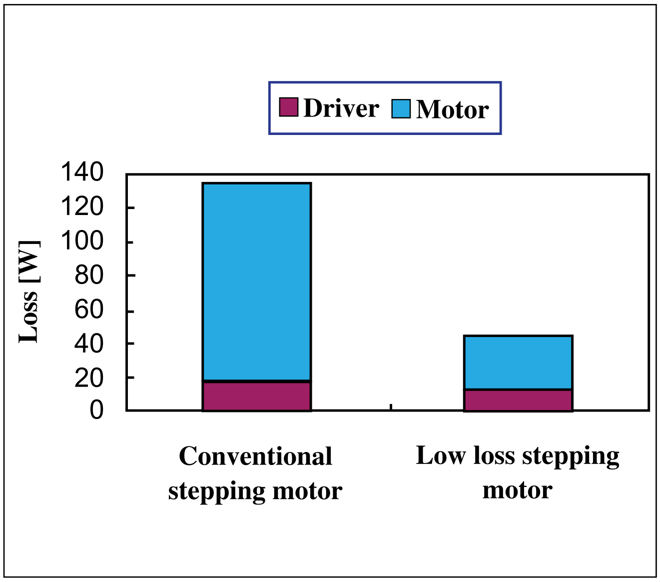

Figure 11—Loss comparison.

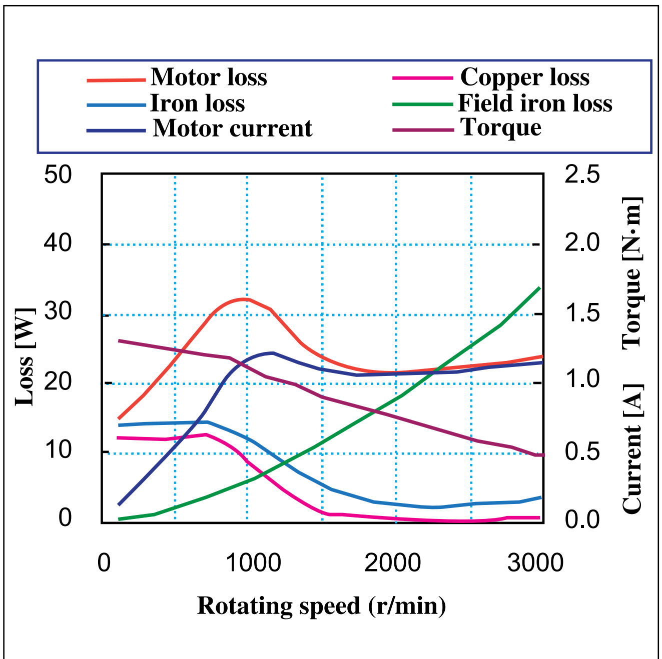

Figure 12—Motor loss of low-loss stepping motor.

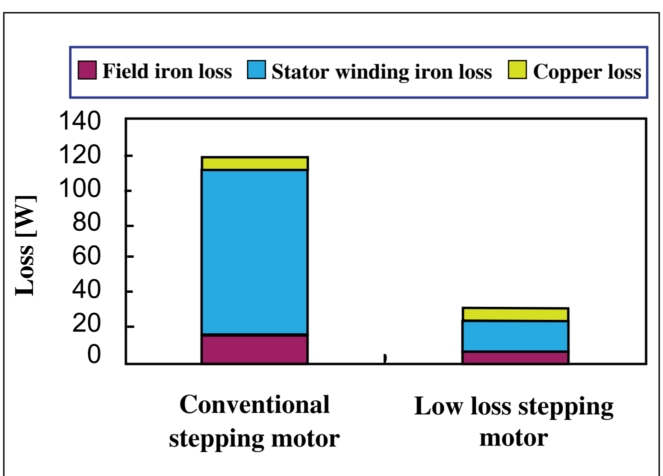

Figure 13—Comparison with conventional stepping motor.

shows the relationship of the fastening method and the loss of the (laminated) stator core; note the stator core is made of the lamination sheets to which insulation coating is given. Presently, fastening by dimples is the most common method.

The electrical insulation between the lamination sheets is broken down at the dimples. An eddy current becomes easy to flow—due to this dielectric breakdown—and the eddy current loss grows more than the value calculated by Equation 2. Figure 9 also shows the relationship of the fastening method and the maximum loss; the loss is different depending on the fastening method. The low-loss stepping motor has adopted a fastening method with a small loss.

Practical example. Figure 10 illustrates the no-load loss of a low-loss stepping motor and driver; Figure 11 shows the loss comparison with the conventional stepping motor at the rotational speed where total loss reaches its maximum value. The motor loss has decreased by 73% and the driver loss by 26% when compared with the conventional stepping motor.

Figure 12 shows the effects of separating the motor loss of the low-loss stepping motor into a copper loss and iron loss. Field iron loss exceeds iron loss at high speeds of more than 2,400 r/min, meaning that the current weakens the magnetic field—known as "field weakening."

Figure 13 shows the result of comparing loss with the conventional stepping motor at the rotating speed that maximizes motor loss. Though copper loss has increased—compared to the conventional stepping motor, because the current adjusts to enable uniform torque—stator loss is reduced by 81%, field iron loss by 73% and motor loss by 72%—when compared with a conventional stepping motor.

Figure 14 shows the temperature rise of a motor casing at maximum speed loss. At this measurement, a heat-sink equivalent to an aluminum plate in 250 mm x 250 mm x 6 mm is attached. With that, the temperature of the conventional stepping motor rose to over 60° C in about five minutes. If rotation had continued, the stator coils would burn out. Instead, the temperature of the low-loss stepping motor is less than 60 ° C and the coils will not burn out.

Loss in Positioning Operation

When a heat-sink equivalent to an aluminum plate of 250 mm x 250 mm x 6 mm is attached, the permissible dissipation of the low-loss stepping motor is about 40 W at ambient temperature. With a maximum dissipation of the low-loss stepping motor at 32 W, it is possible to drive it continuously in the above-mentioned condition.

Next up is a discussion of loss in positioning operation when a stepping motor is used mainly for positioning operation.

Loss characteristic. Figure 15 shows the relationship of the load and rotating speed. For the stepping motor, the peak value of the motor loss decreases when load increases; but the change by the load is small, while the change by rotating speed is larger.

The loss is expressed by a function of rotating speed and load torque. As such, the loss is calculated from the torque and rotating speed.

Loss calculation. Figure 16 shows the speed pattern in a typical positioning operation. This operation pattern accelerates up to rotational speed N_m in acceleration time t_1; rotates at a constant speed over time t_2; decelerates in deceleration time t_3, and stops. This operation pattern is called a "trapezoidal drive" and the area of trapezoid shows the rotation amount. Usually, applications such as inspection, assembly, etc., are done in the stop time t_4—after completion of positioning—and the following operation is begun. Time, or t_c, is from start-up to the following start-up; i.e., cycle time. When heat generation is excessive, a longer stop time for cooling is required.

Figure 17 shows the torque pattern when driven by the speed pattern in Figure 16. Torque T_L for the load torque component is necessary during a constant speed time, and acceleration torque T_a and deceleration torque T_d are necessary during an acceleration/deceleration time.

As described, stepping motor losses are impacted by rotation speed (Fig. 18).

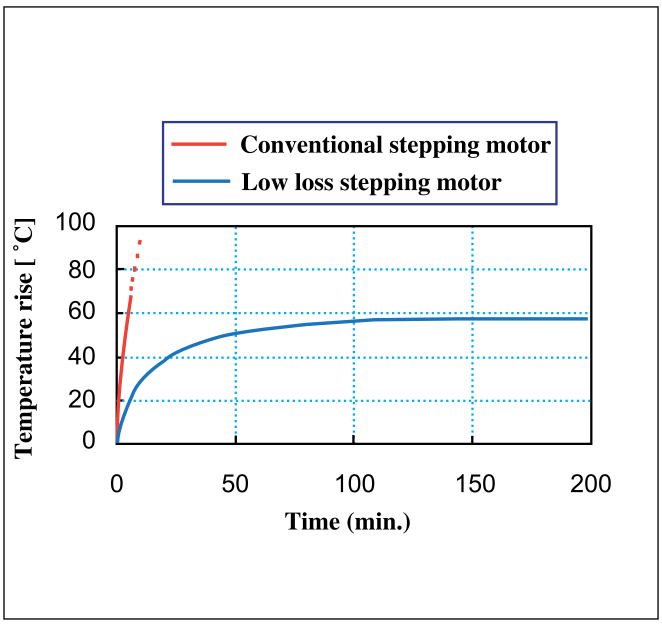

Figure 14—Temperature rise.

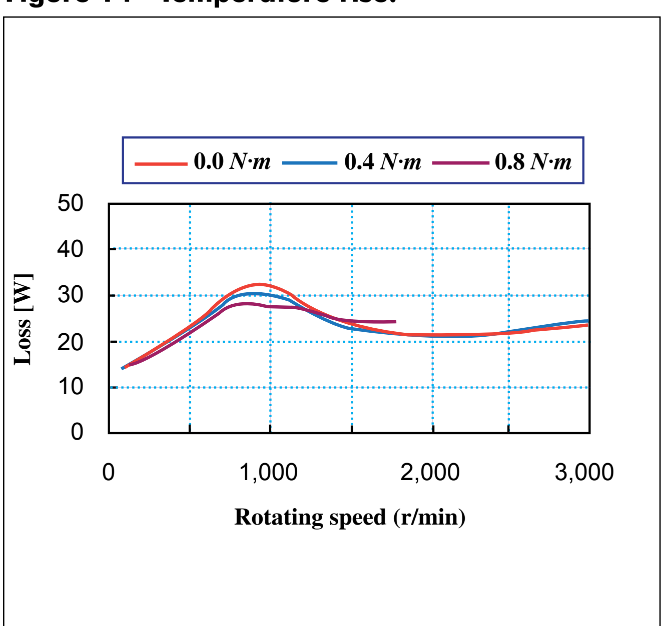

Figure 15—Loss characteristic of low-loss stepping motor.

When the instantaneous, maximum value of the loss is assumed to be $w(t)$, the average value of the loss-per-cycle is calculated by:

$$W_a = \frac{1}{t_c} \cdot \int_0^{tc} w(t)dt \qquad (10)$$

Calculation result. Motor loss is calculated when the shortest positioning operation is done with an inertial load of $J = 2.5 \times 10^{-4}$ kg• m^2 attached (i.e., 90 mm outside diameter, 5

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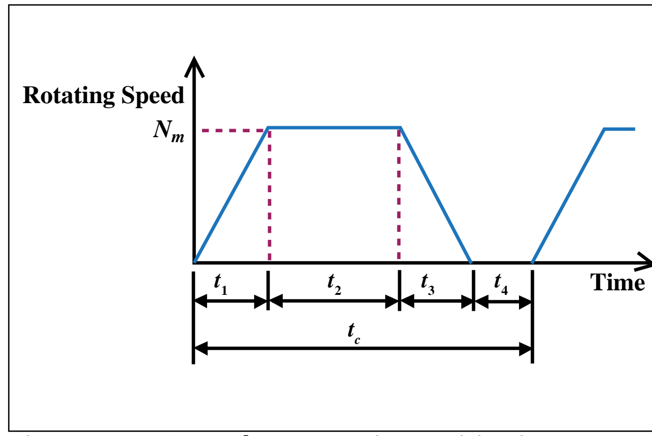

Figure 16—Speed pattern in positioning operation.

Table 2-Operation pattern			
Rotation ammount (Rotation)	Acceleration/ deceleration times (ms)	Rotating speed (r/min)	Positioning times (ms)
0.1	14	400	29
0.5	30	800	68
1	40	1,000	100
2	59	1,300	152
5	100	1,800	267
10	146	2,200	419

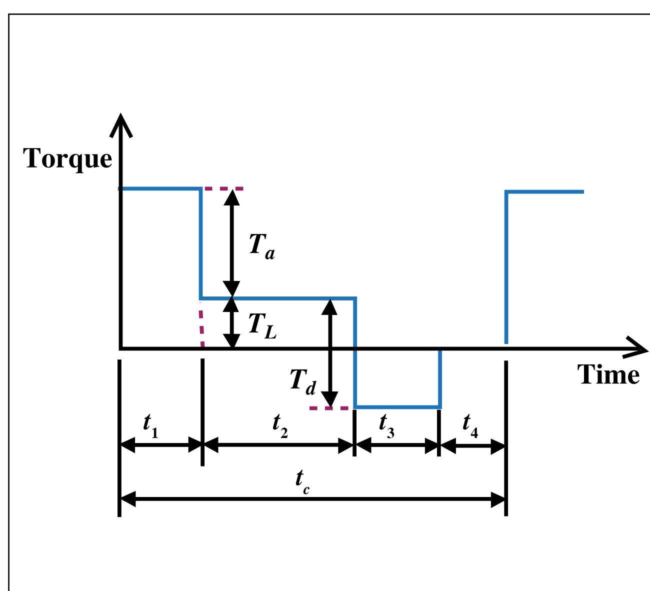

Figure 17—Torque pattern in positioning operation.

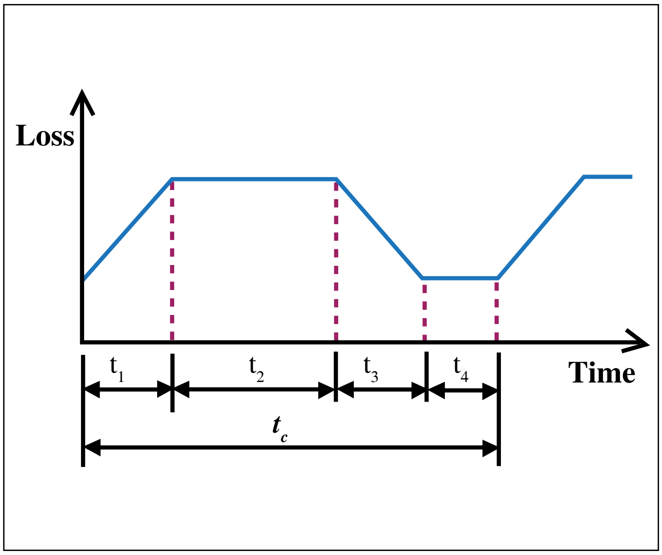

Figure 18—Loss pattern in positioning operation.

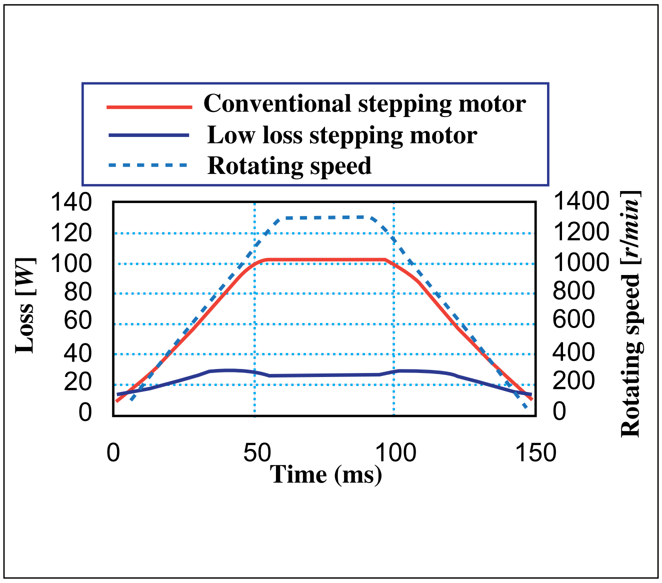

Figure 19—Calculation example.

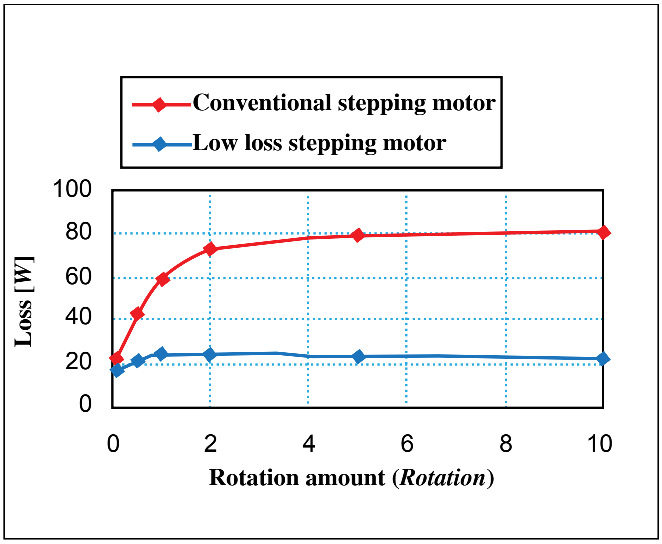

Figure 20—Relation of rotation amount and motor loss.

mm thickness and iron material). Table 2 results are derived by calculating which operation pattern/positioning time is briefest in consideration of the safety rate.

In Equation 10, the loss in each operation pattern is calculated; Figure 19 shows a calculation result of the speed pattern and loss when, for example, the rotation amount is two rotations.

Figure 20 shows the relationship between rotation amount and motor loss. When the rotation amount is 0.1, the loss difference is not significant; but when rotation amount is increased, the difference is significant.

For the conventional stepping motor, intermittent operation or fan-cooling is needed—even when a positioning operation is conducted—because the loss increases to about 80 W when the rotation amount is increased. But for the low-loss motor, a stop-time for cooling is unnecessary since the losses are only about 24 W—even when rotation amount is increased. Therefore, a continuous-positioning operation is achieved for any rotation amount.

Summary

Though the conventional stepping motor is compromised by heat-generation issues, new lower-loss-technology advances have changed the equation. It is now possible to use a stepping motor in applications requiring continuous motion at a constant speed—something unheard of until now. It then follows that applications for a stepping motor will certainly increase, as these motors are very effective for energy savings.

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