Lower-Loss Technology

FOR A STEPPING MOTOR

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Management Summary

The demand for stepping motors with high efficiency and low losses has been increasing, although the demand had been previously focused on high torque. Also, the selection of the most suitable grade of lamination for improvement in 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 that was previously impossible. An expansion of the stepping motor's usage into applications where another motor has been used for continuous operation and other uses—due to the heat generation problem—can now be pursued. In addition, these motors are very effective for energy saving. This paper explains the technology used for lowering the iron losses of the stepping motor.

Introduction

The stepping motor can control the speed and the position accurately in an open-loop control mode. The stepping motor had a disadvantage of intense heat generation when rotating at high speed; and an advantage in that it can be used easily. The stepping motor has been used mainly to utilize the standstill holding brake force and the torque at low speed. But recently, another customer demand for being able to operate continuously at high speed has risen, thereby shortening the cycle equipment time. The motor loss is greatly reduced compared with the conventional stepping motor by use of a suitable lamination sheet and fastening method of the laminated iron core. This paper focuses on lowering the losses of the stepping motor. The motor shown in Table 1 is selected for 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 generated by the current flowing to a stator (stator winding), and 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); therefore, the iron losses can be classified into an iron loss by the field and the other by the stator winding. Hereafter, the former is called field iron loss, and the latter is called 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, including those in the iron losses, because they are small enough 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 inductors called teeth on the outer diameter of the rotor core and inner diameter of the stator core. The iron loss is generated when the rotor rotates because the teeth periodically face and the flux in the stator core changes periodically. It 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, and the rotor is rotated from outside. The rotational speed and the torque are measured, and the iron loss is calculated by the equation:

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

W_0: Field iron loss [W]
N: Rotating speed [r/min]
T: Torque [N·m]

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

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

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

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]
k: Constant by number of pole pair
Bm: Flux density [T]
N: Rotating speed [r/min]

From these equations, it is understood that 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, and it is to be proportional to the first-to-second power of the rotational speed. Figure 4 shows a measurement result of field iron loss of the conventional motor. It is expressed by Equation 4 approximately, and is proportional to the 1.44th power of the rotational speed.

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

continued

Table 1—Specification of Conventional Stepping Motor	
Frame size	60 mm sq.
Length	60 mm
Phase	2 phase
Polo pair	50
Resistance	1.6 ohm
Rated current	1.7 A
Maximum holding torque	1.2 Nm

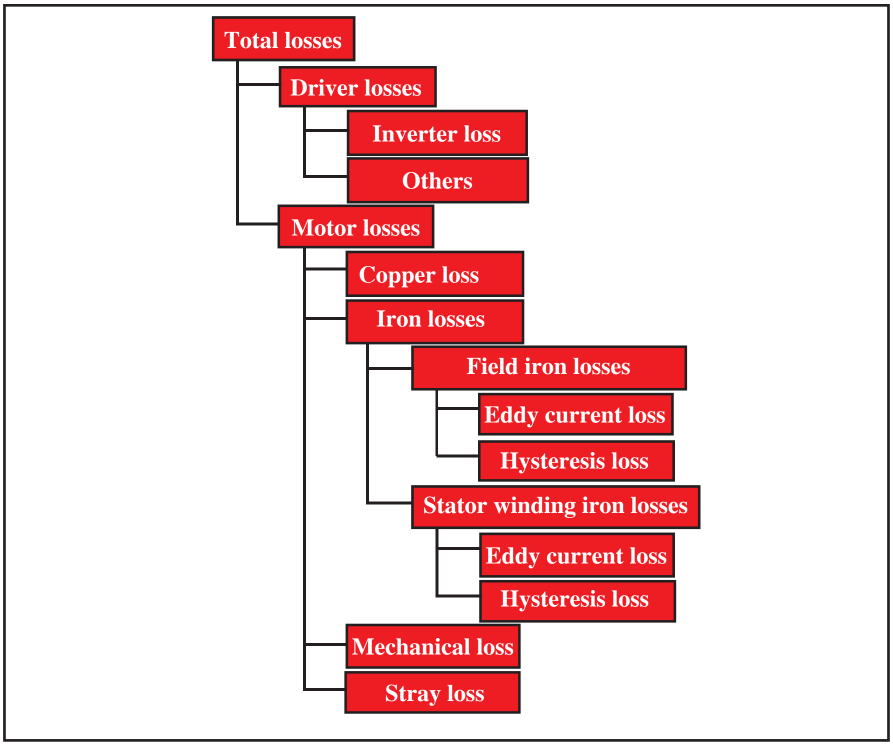

Figure 1—Classification of losses.

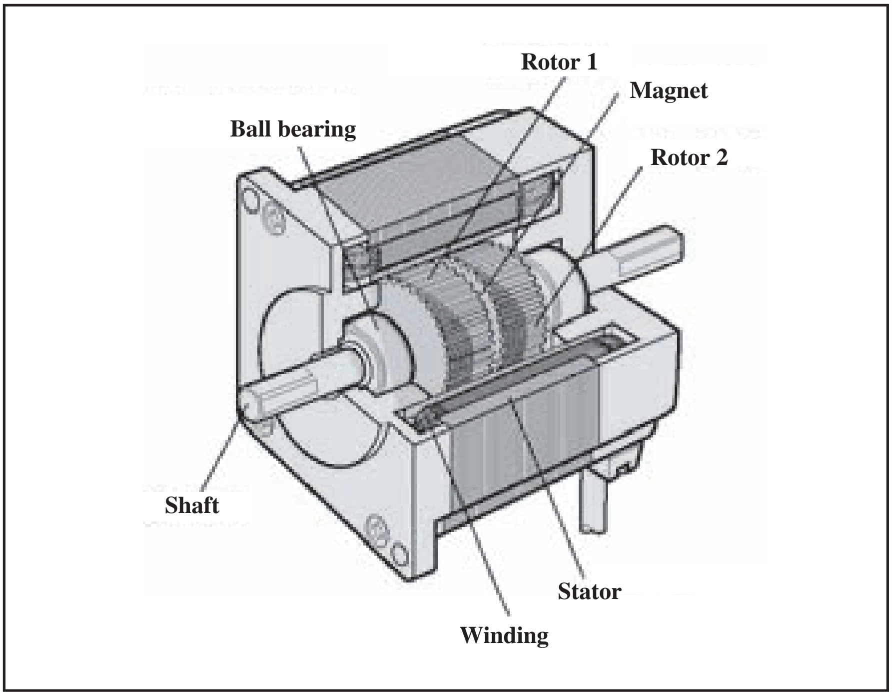

Figure 2—Structure of stepping motor.

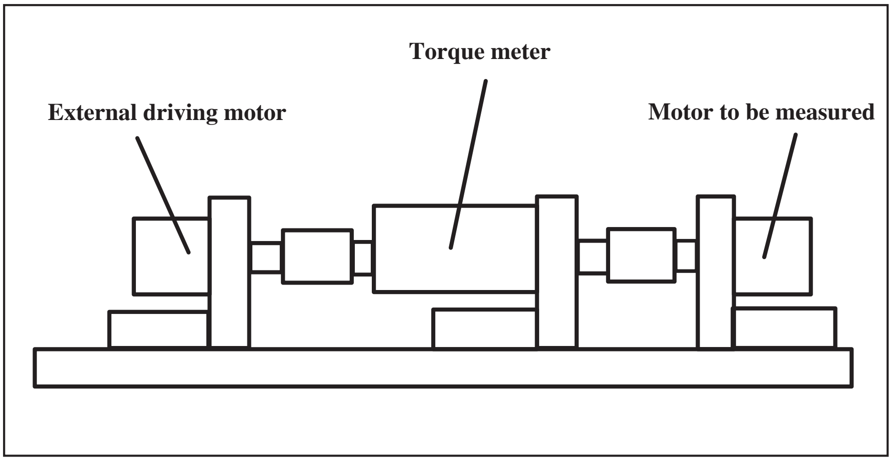

Figure 3—Measurement system of field iron losses.

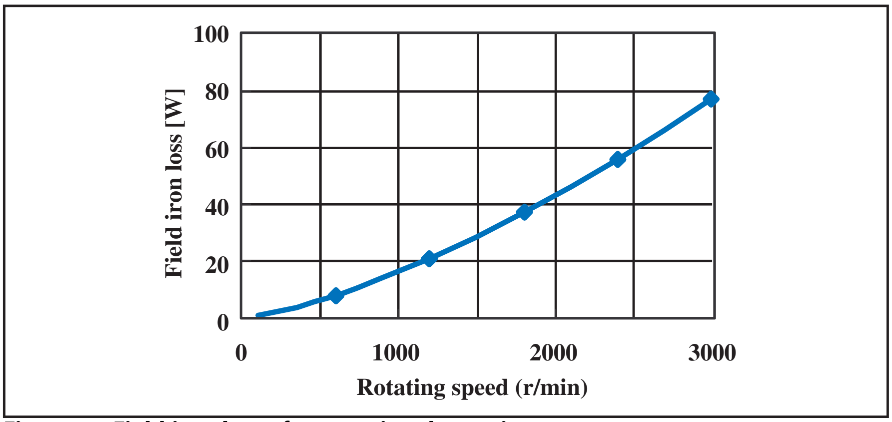

Figure 4—Field iron loss of conventional stepping motor.

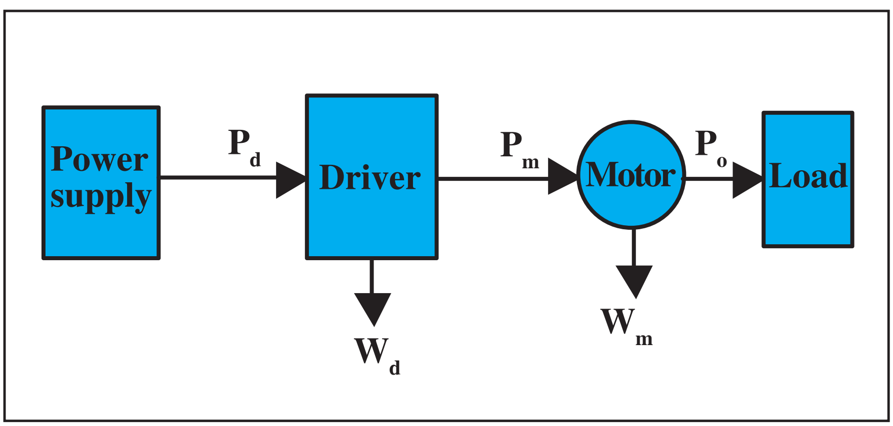

Figure 5—Configuration diagram of loss measurement.

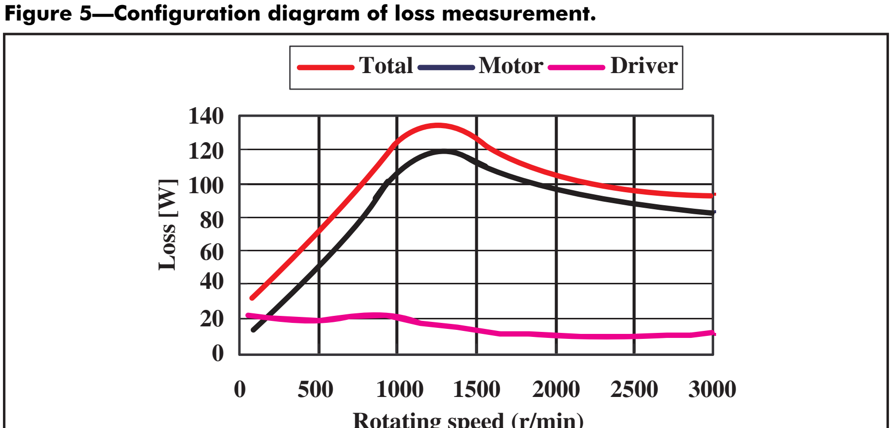

Figure 6—No-load loss of conventional stepping motor.

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 the power and the 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 Wu, and the difference between the motor input and the output makes a motor loss W_m. Each value is expressed by the following equations:

$$W_u = P_d - P_o \tag{5}$$

$$W_m = P_m - P_o \tag{6}$$

The difference between the driver input and the motor input makes a driver loss W_d, and it is expressed by the following:

$$W_d = P_d - P_m \tag{7}$$

The stepping motor is controlled with a driver so that a constant current may flow, regardless of load. Therefore, a smaller load causes a bigger loss.

Consequently, the loss evaluation of the stepping motor with no load is the severest. When assuming $P_o = 0$ (Eqs. 5 and 6), the whole driver input results in a total loss, and 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 large when compared with the driver loss.

Next explained is the separation of the motor losses. As copper loss of the motor is calculated by Equation 8,

$$W_c = n \cdot I^2 \cdot R \tag{8}$$

the iron loss follows Equation 9:

$$W_{fe} = W_m - W_c \tag{9}$$

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 copper loss and iron loss. The motor current, torque and field iron loss are described for reference.

Although the current of 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 when 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 called constant voltage area.

Figure 7 shows the maximum motor iron loss at about 1,200 r/min. When rotating, the iron loss is usually larger than the field iron loss because the stator winding iron loss is added to the field iron loss. Therefore, the difference 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 decreased. The conventional motor has a characteristic where the field iron loss becomes equal to the iron loss at about 3,000 r/min.

Though the motor loss is the sum of iron loss 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 119W, of which iron loss is 112W—or 94% of the motor loss. Reduction of the iron loss is thought of as an effective development for lowering the loss of a stepping motor

Lower-Loss Inducements for Stepping Motors

Lower iron loss by suitable lamination sheet. The following methods can be expected from Equations 2 and 3 for lowering the iron loss.:

- Material with a small iron loss constant (c_e, c_h) is used.
- Thin lamination sheet is used.

The above are 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 four kinds of lamination sheets, and the result of

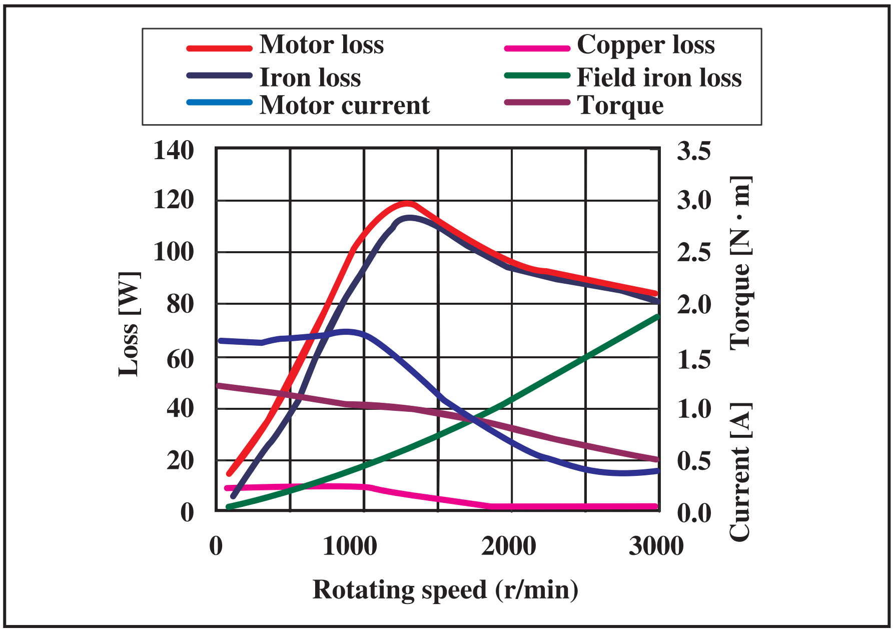

Figure 7—Motor loss of conventional stepping motor.

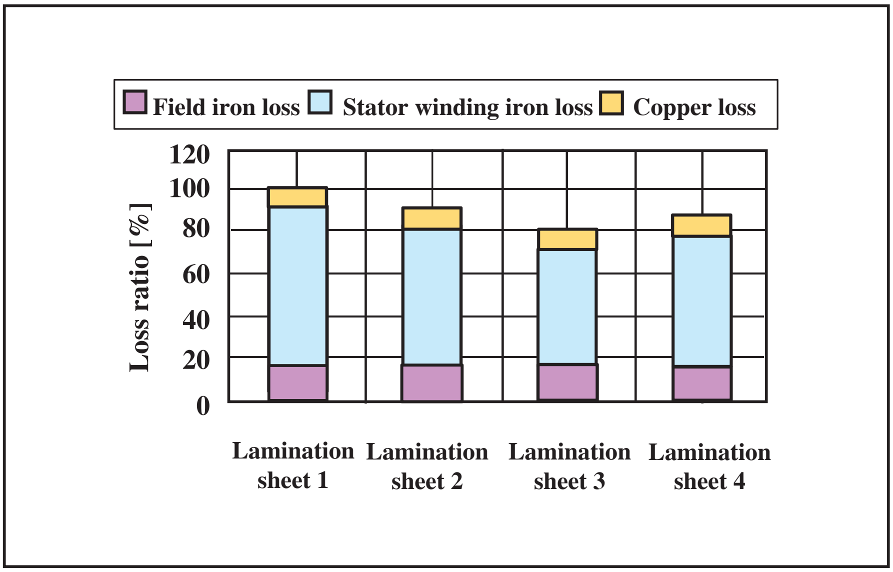

Figure 8—Relation of lamination sheet material and loss.

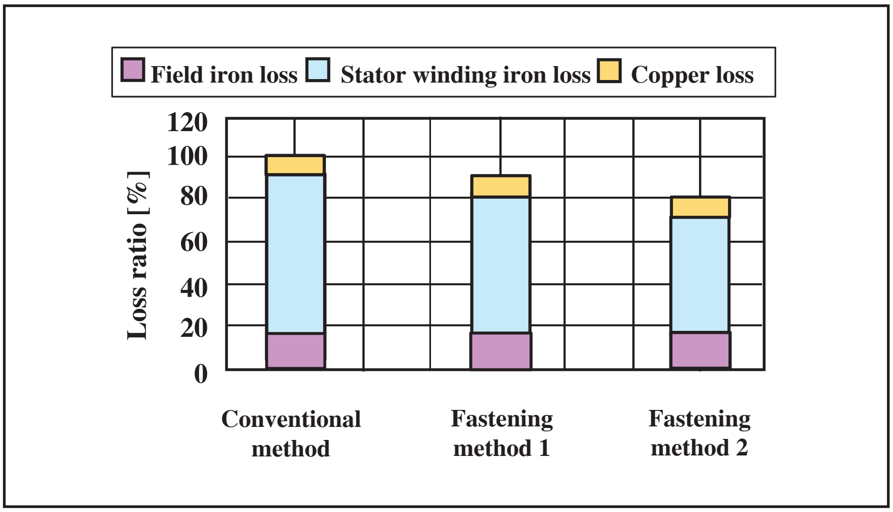

Figure 9—Relation of lamination fastening method and loss.

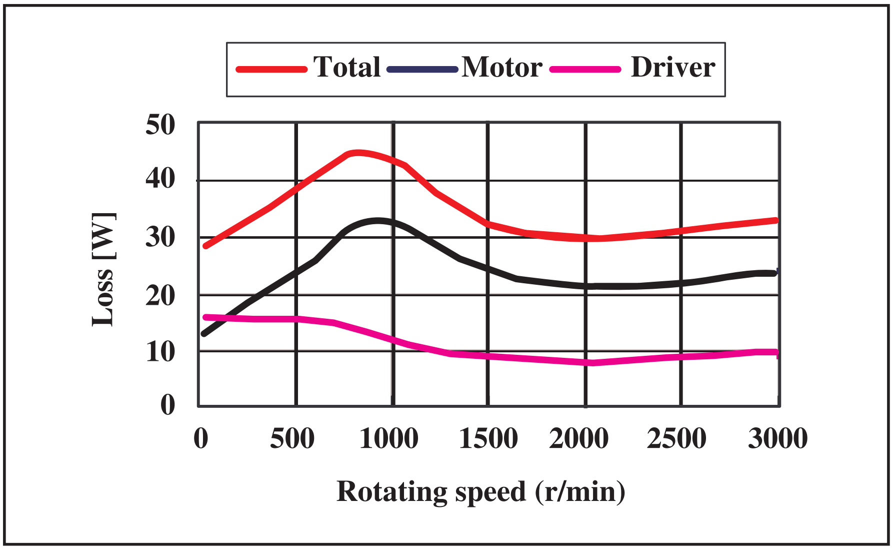

Figure 10—No-load loss of low-loss stepping motor.

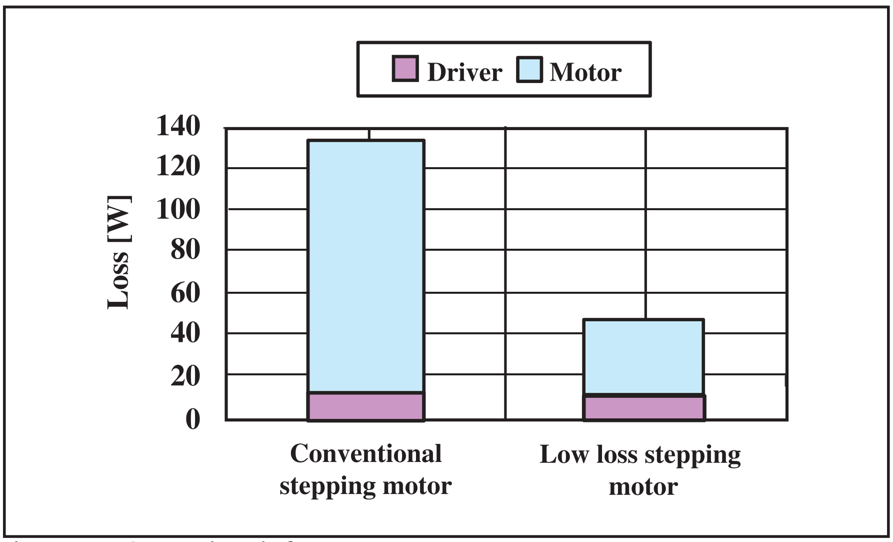

Figure 11—Comparison in loss.

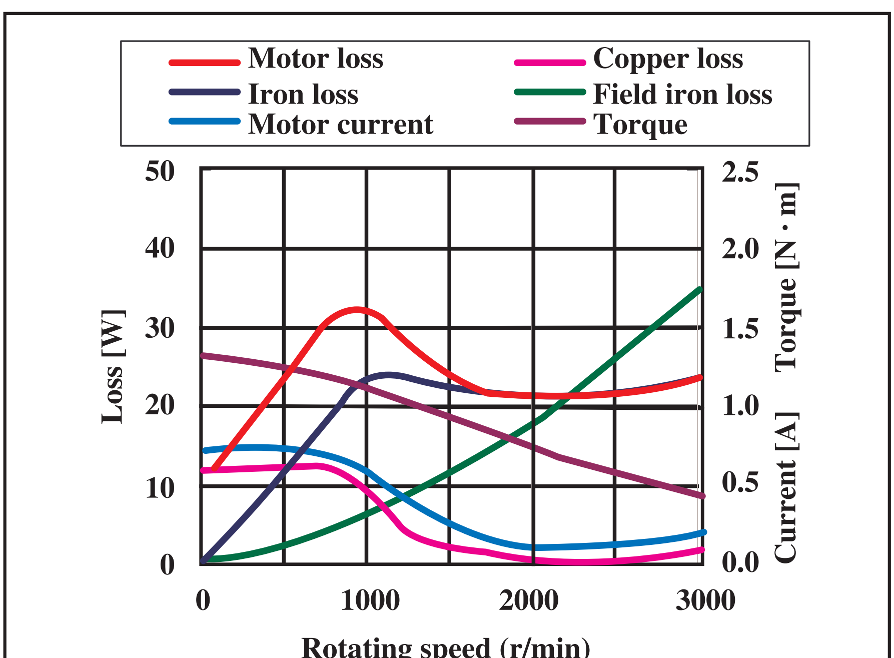

Figure 12—Motor loss of low-loss stepping motor.

their compared maximum loss is shown in Figure 8. The vertical axis shows the ratio based on the motor loss of Lamination Sheet 1. For comparing the loss by material, it was compared under the same condition of holding torque.

In general, the smaller the specified value in iron loss, the higher the grade of the lamination sheet. However, the saturation flux density tends to decrease as well when the specified value in iron loss becomes small. When it is 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 larger the copper loss.

Also, the smaller the specified value in iron loss of the lamination sheet, the smaller the field iron loss. And yet, it doesn't necessarily follow that the specified value in iron loss of the lamination sheet is a condition of constant torque, 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 by suitable fastening method. Figure 9 shows the relationship of the fastening method and loss of the stator core (laminated core), though the stator core is made of the lamination sheets to which insulation coating is given. For now, 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 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 shows 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 the 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 result in separating the motor loss of the low-loss stepping motor into a copper loss and an iron loss. Field iron loss becomes bigger than iron loss at high speeds of more than 2,400 r/min. This means that the current weakens the magnetic field, and this condition is called field weakening.

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

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

Loss in Positioning Operation

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

However, let's look now at a loss in a positioning operation because the stepping motor is used mainly for positioning operation.

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

The loss is expressed as a func-

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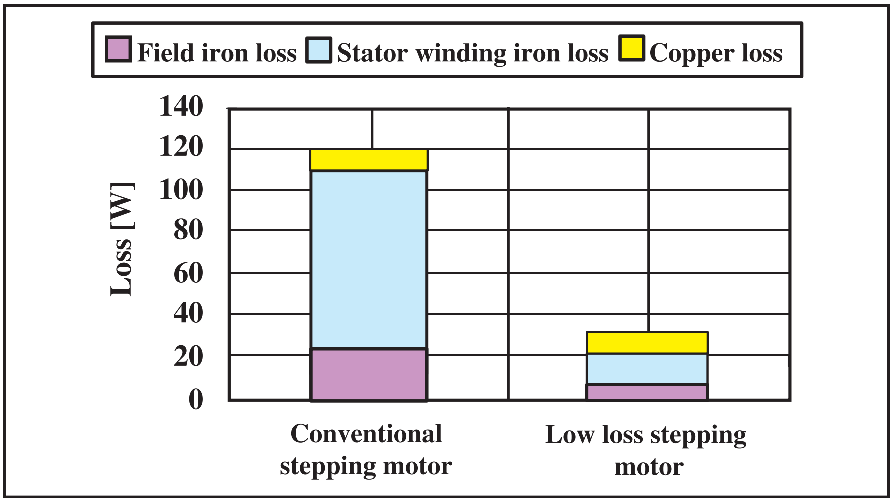

Figure 13—Comparison with conventional stepping motor.

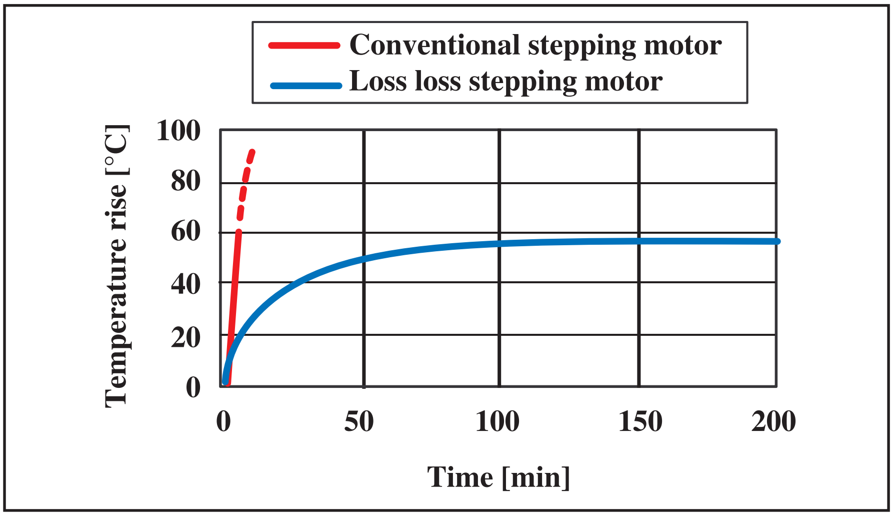

Figure 14—Temperature rise.

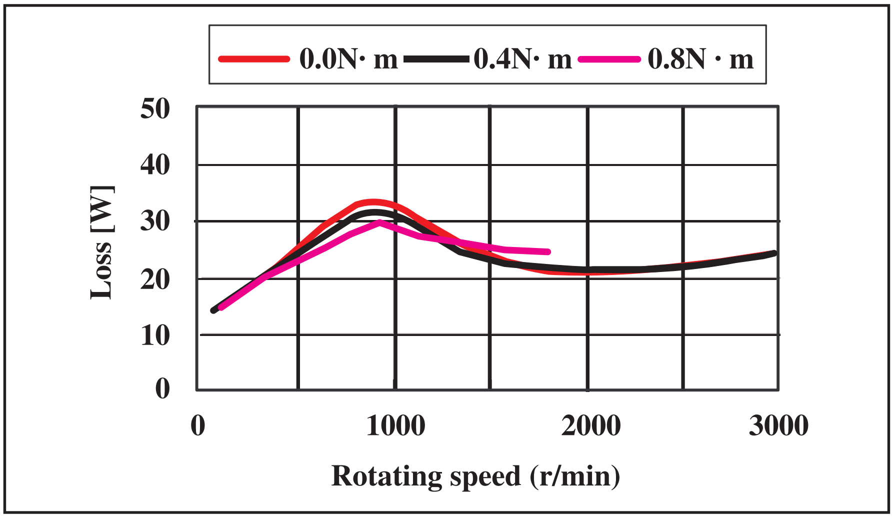

Figure 15—Loss characteristic of low-loss stepping motor.

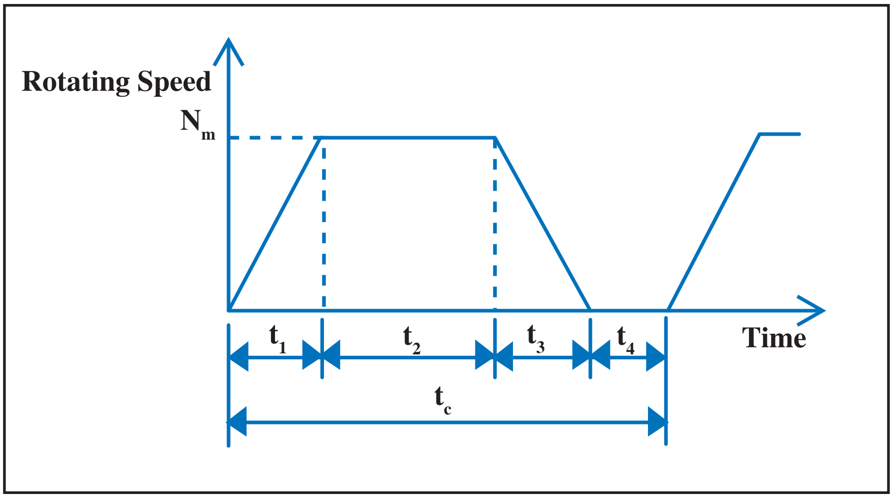

Figure 16—Speed pattern in positioning operation.

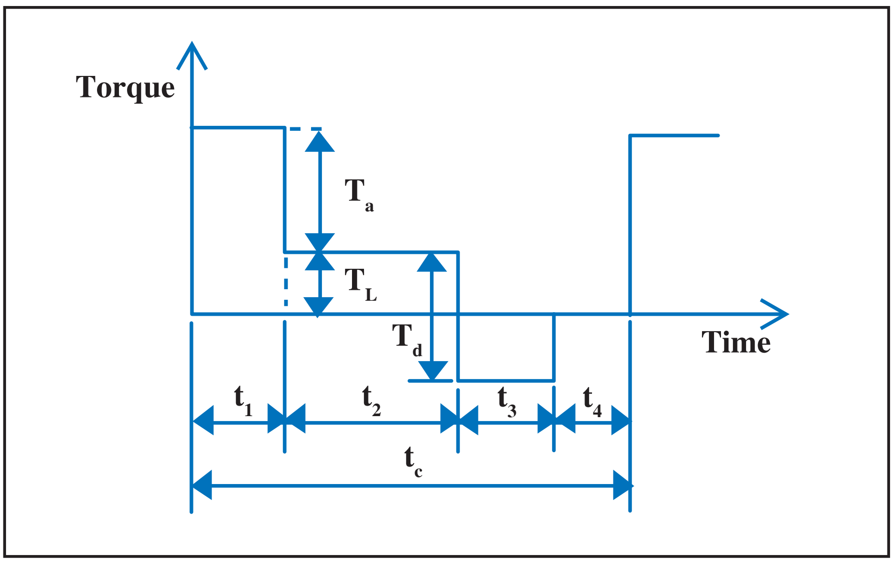

Figure 17—Torque pattern in positioning operation.

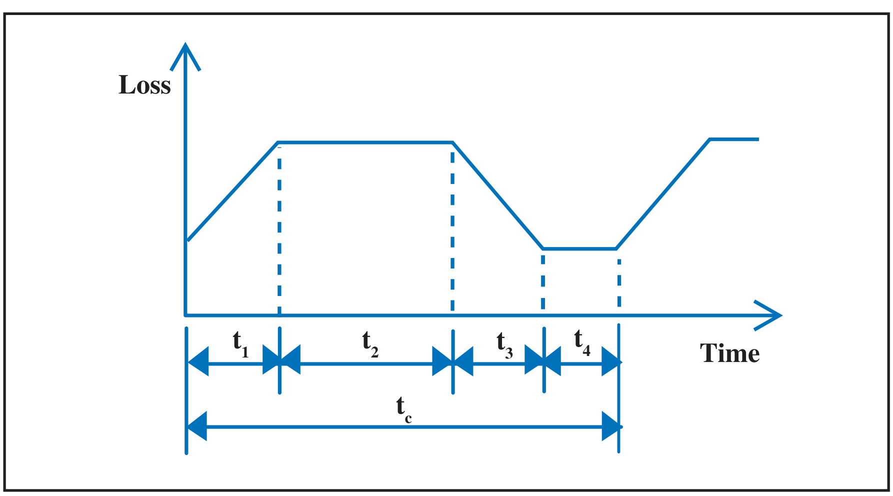

Figure 18—Loss pattern in positioning operation.

tion of the rotating speed and the load torque. Therefore, the loss can be calculated from the torque and the rotating speed.

Loss calculation. Figure 16 shows the speed pattern in a typical positioning operation. This operation pattern accelerates up to a rotational speed N_m in acceleration time t_1, then rotates at a constant speed over time t_2, and 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 and assembly, etc., are done in the stop time t_4 after the completion of positioning, and the following operation is begun. Time t_c is from a start-up to the following start-up and is called cycle time. When heat generation is large, it is necessary to set a longer stop time for cooling down.

Figure 17 shows the torque pattern when it is 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 above, the stepping motor losses depend on the rotating speed, and the loss pattern is shown in Figure 18.

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 the following:

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

Calculation result. The motor loss is calculated when the shortest positioning operation is done with an inertial load of $J=2.5\times10^{-4}$kg · m^2 (90 mm in outside diameter, 5 mm in thickness and material of iron) attached. Table 2 results were gained by calculating the operation pattern of which positioning time is the shortest in consideration of the safety rate.

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

Figure 20 shows the relationship

between the rotation amount and the motor loss. When the rotation amount is 0.1, the difference of the loss is not so much. But when rotation amount is increased, the difference becomes large.

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 80W when the rotation amount is increased. For the low-loss motor, a stop time for cooling is unnecessary because the losses are only about 24W, even when the rotation amount is increased. Therefore, a continuous positioning operation is achieved for any rotation amount.

Conclusion

Though the conventional stepping motor had a problem with extensive heat generation, the loss of the stepping motor will be reduced greatly by the lower-loss technology. It has become possible to use a stepping motor in applications that require continuous motion at a constant speed, something not possible until now. The number of applications that a stepping motor may be suitable for will certainly increase. In application, these motors are very effective for energy savings.

Yasuo Sato received his Master's in electrical engineering from Akita University in Japan. He joined Oriental Motor in 1993 as motor design engineer to develop stepping motors. In 1996, he was transferred to the Boston Technology Group of Oriental Motor USA to research the basic factors of a stepping motor. Since returning to Japan in 2000, he has focused on developing closed-loop stepping motors and brushless DC motors.

Table 2—Operation Pattern

Rotation amount [Rotation]	Acceleration/ deceleration time [ms]	Rotating speed [r/min]	Positioning time[ms]
0.1	14	400	29
0.5	30	800	68
1	40	1000	100
2	59	1300	152
5	100	1800	267
10	146	2200	419

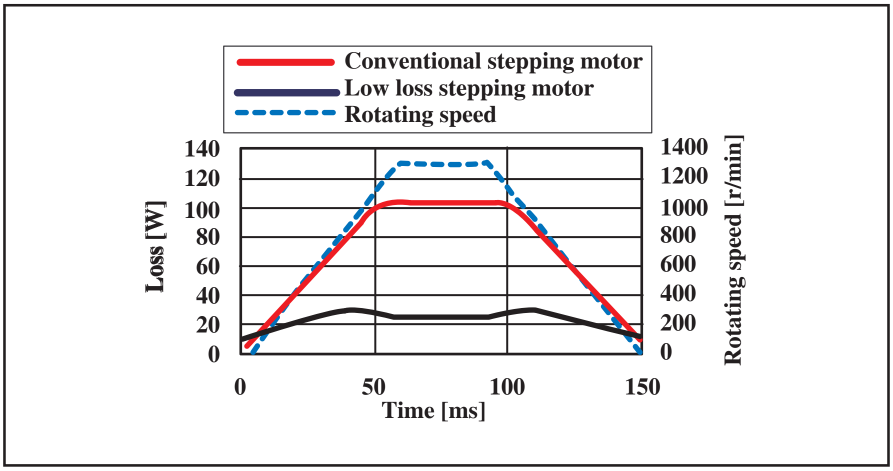

Figure 19—Calculation example.

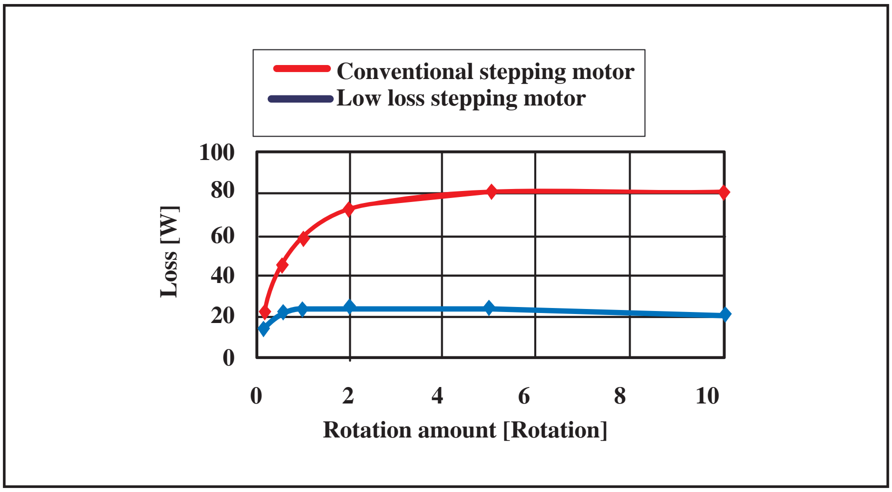

Figure 20—Relation of rotation amount and motor loss.