3D Static Magnetic Field Analysis of Torque and Rotor Shaft Attraction Force of Narrow-Gap Stepping Motors for Driving the Hands of a Wristwatch

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In this study, a three-dimensional static magnetic field analysis was conducted on a narrow-gap stepping motor for driving the hands of a wristwatch. The purpose of this analysis was to design a stepping motor with a low power consumption, by calculating the holding and detent torques and rotor shaft attraction force in two cases, namely a rotor with no eccentricity and a rotor with 5 µm eccentricity. We analyzed why existing stepping motors are constrained to a gap width of 300 µm. We further confirmed that the rotor shaft attraction force, which is derived from the rotor eccentricity, increases rapidly with the decrease in gap width, which in turn has a negative impact on the stepping motor. In the future, we intend to study the movement of a wristwatch comprising a metal wheel bearing, to design a stepping motor with a narrow gap, and subsequently reduce the power consumption.

Keywords: holding torque, detent torque, rotor shaft attraction force

1. Introduction

The hands of a normal analog wristwatch are driven by a stepping motor. The necessary minimalization and power consumption reduction of the stepping motor, have been achieved through the manufacturing technique of the respective watchmakers. However, in the present manufacturing technique, the width of the gap between the rotor and the stator is restricted to 300µm. In this study, we aim to reduce the power consumption of the stepping motor by suppressing the detent torque, which is achieved through a narrow gap of 150µm, increasing the net holding torque, while reducing the thickness of the part that generates the detent torque of the stator, and adjusting the specified thickness (1),(2).

The magnetic field analyses of the narrow-gap stepping motor have not been reported (3)-(5). A three-dimensional static magnetic field analysis is performed on the three new stepping motors with narrower gaps between the rotor and the stator (types B, C and D) to compare them against the stepping motor A for the purpose of designing a reduced power consumption. Fig. 2 shows a three-dimensional static magnetic field analysis model for the new stepping motor, with segment (a) representing the whole model, segment (b) showing part A, and segment (c) representing the plane view of part A.

2. Analysis and Experiment

2.1 Static Magnetic Field Analysis Model

Fig.1 shows a three-dimensional static magnetic field analysis model for a stepping motor used in a wristwatch that is manufactured by Company A (herein referred to as “stepping motor A”), whereas segment (a), (b), and (c) show the whole model, part A, and the plane view of Part A, respectively. The stepping motor A is composed of a rotor hole, as well as a stator, with two notches of the radius \( r \) in the proximity of the rotor hole, a single coil with a yoke, and a rotor that is made of a dipolar permanent magnet.

A stepping motor wherein the rotor stops at the center of the stator thickness and is capable of sufficiently supplying magnet flux from the permanent magnet of the rotor (hereinafter referred to as the “new stepping motor”) to the stator, is adopted. A three-dimensional static magnetic field analysis is performed on the three new stepping motors with narrower gaps between the rotor and the stator (types B, C and D) to compare them against the stepping motor A for the purpose of designing a reduced power consumption. Fig. 2 shows a three-dimensional static magnetic field analysis model for the new stepping motor, with segment (a) representing the whole model, segment (b) showing part A, and segment (c) representing the plane view of part A.

The new stepping motor is comprised of a rotor hole, as well as a stator, with a two-step \( \varepsilon \) in the proximity of the rotor hole, a single coil with a yoke, as well as a rotor that is made of a dipolar permanent magnet. The two-step model is adopted to reduce the area of...
A noteworthy feature of the new stepping motor is the narrower gap between the rotor and the stator, which enhances the net holding torque, by increasing the magnetic bonding between the rotor that is made of a dipolar permanent magnet with the stator. Another significant feature is the thinning down of the stator from both sides in the portion where the detent torque is generated (this portion of the stator is hereinafter referred to as the “thinned portion”) and further adjusting of the thickness.

![Fig. 1. 3-Dimensional Static Magnetic Field Analysis Model for Stepping Motor A](image1.png)

![Fig. 2. 3-Dimensional Static Magnetic Field Analysis Model for New Stepping Motor B, C, and D](image2.png)
The main parameters of the stepping motor A and the new stepping motors B, C, and D are shown in Table 1.

The changes to the numerical values of the main parameters caused due to the transition from stepping motor A to the new stepping motors B, C, and D, are described below.

The rotor hole diameter \( a \) is reduced from 1800 to 1525 (B) and 1375 \( \mu \)m (C and D), whereas the diameter of the thinned portion \( at \) is set to 1450(B) and 1300 \( \mu \)m (C and D). Both the rotor magnet diameter \( \rho \) and the rotor magnet thickness \( hm \) remain the same at 1150 and 400 \( \mu \)m, respectively. The step \( e \) of 25 \( \mu \)m (B, C and D) is implemented for the new stepping motor, in order to accommodate the notch (radius 160 \( \mu \)m) of the stepping motor A. Furthermore, the thickness of the stator \( hs \) remains unchanged at 500 \( \mu \)m, whereas the thicknesses of 37 (B), 25 (C), and 18 \( \mu \)m (D) are used for the corresponding thickness of the thinned portion of the new stepping motor, \( ts \). The coil of the stepping motor A is used for the new stepping motor as well.

The stepping motor is composed of a rotor hole and a stator, with two notches or two steps, and this is a commonly used design in wristwatch types (7). The rotor consists of a single coil with a yoke and is made of a permanent dipolar magnet.

The amplitudes of net holding and detent torque should be considered while designing the stepping motor.

The amplitude of the net holding torque \( Tha \) is given by the following equation (7):

\[
Tha = \frac{\pi h m \rho^2 B r}{4a} \cdot n \cdot i \; \text{Nm} \; \cdots \cdots \cdots \cdots \cdots \cdots \cdots (1)
\]

where \( h m \) is the thickness of rotor magnet, \( \rho \) is the rotor magnet diameter, \( B r \) is the residual magnetic flux density, \( a \) is the rotor hole diameter of the stator, \( n \) is the number turns, and \( i \) is the drive current.

The amplitude of detent torque \( Tda \) is given by the following equation (7):

\[
Tda = \frac{\beta S h m}{\mu_0} \cdot \frac{\rho^2}{\alpha^2} \cdot i \; \text{Nm} \; \cdots \cdots \cdots \cdots \cdots \cdots \cdots (2)
\]

where \( \beta \) is the coefficient, \( S \) is the asymmetrical area of the rotor hole of the stator (\( S \) is \( \pi \alpha^2 \) in the case with two notches of radius \( r \) and \( \pi e a / 2 \) in the case with two steps of size \( e \)), and \( \mu_0 \) is space permeability and is equal to \( 4\pi \times 10^{-7} \; \text{H/m} \).

It is seen that \( Tha \) and \( Tda \) are inversely proportional to the rotor hole diameter \( a \) and \( a^2 \), according to (1) and (2), respectively. Therefore, \( Tda \) is much larger than \( Tha \) for a smaller value of \( a \). To solve the problem, a smaller value of \( r \) or \( e \) is considered. As shown in Fig. 2 (b), \( hm \) is replaced with \( ts \), which is the thickness of thinned portion of the stator, to make the \( ts \) smaller, when the rotor hole diameter \( a \) is small.

The design process of the new stepping motor has been explained below. At first, the asymmetrical area of the rotor hole of the stator \( S \) is designed for each stepping motor in Table 2. For the new stepping motor, \( at \) is used instead of \( a \). All values of \( S \) are almost similar to each other.

Furthermore, to suppress the increase in the amplitude of detent torque \( Tda \) caused due to a smaller value of \( a \), the thickness of the new stepping motor B, C, and D is set as 37, 25, and 18, respectively, instead of 500 \( \mu \)m.

Comparisons of \( Tha \) and \( Tda \) with those calculated by the analysis are explained in 3.1 Holding Torque and 3.2 Detent Torque, respectively.

2.2 Experiment The experimental method described by this paper is same as that described in our report (2), and the value of the drive current for the stepping motor is equal to the time expressed as a value of electrical current for the driving pulse with a narrower pulse width, until the point where the second hand begins stops and involves a drive circuit and a coil but excludes a digital circuit. The power source used to drive the stepping motor is a power supply with a constant voltage of 1.5 V, and the power consumption can be evaluated using the drive current.

Table 3 shows the drive current and its ratio, which are cited from our report (2) regarding A and B. Its ratio indicates the ratio (drive current ratio) of the difference between the one-second average drive current value (\( I_a \)) of B and the three-sample average value (\( I_a^3 \)) of the one-second average drive current value (\( I_a \)) of A with respect to value (\( I_a^3 \)), as shown by (3).

\[
\frac{I_a - I_a^3}{I_a} \times 100(\%) \; \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (3)
\]

Under no load, the weight is not suspended on the minute hand of the wristwatch and the drive pulse that is comprised of six pulses of the same pulse width, is applied to the stepping motor every second. The pulse width of the drive pulse is narrowed until the second hand starts to stop within a one-minute period. Here, the ratio of drive current of B versus A was -6 %.

Under a specific load, the weight is suspended on the minute hand of the wristwatch and the drive pulse that is comprised of 18 pulses of the same pulse width, is applied to the stepping motor every second. The pulse width of the drive pulse is narrowed until the second hand begins to stop within a one-minute period. The ratio of drive current of B versus A was -15%, -14%, and -15 %, when the torque resulting from the weight is 2.0, 2.2, and 2.4 \( x 10^{-4} \; \text{Nm} \), respectively.

Table 3. Drive Current and its Ratio

| load | 10^4 Nm | \( \mu A \) | \( \mu A \) | % |
|------|---------|----------|----------|---|
| 0    | 0.53    | 0.50     | -6       |
| 2.0  | 1.70    | 1.45     | -15      |
| 2.2  | 1.83    | 1.57     | -14      |
| 2.4  | 2.04    | 1.73     | -15      |

2.3 Static Magnetic field Analysis Results The origin of the coordinate \( O \) which is the center of the rotor, X-axis, and Y-axis are shown in Fig. 1 (c) and 2 (c). The mechanical-angular
dependency of the holding torque in the counterclockwise direction from the X-axis, when the magnetomotive force is -5.8 AT (sign of AT is minus), is shown in Fig. 3. The eccentricity verification of the rotor is set to ±5 µm, based on the designing of the stators whose tolerance of the distance between two positioning holes with the tolerance of the diameter ±5 µm, shown in Fig.1 (a) and Fig.2 (a), is ±5 µm. In this case, no rotor eccentricity exists, while an eccentricity of ±5 µm occurs in the X-axis direction and when an eccentricity of ±5 µm is in the Y-axis direction, illustrating five different values.

The mechanical-angular dependency of the detent torque is shown in Fig.4, when no rotor eccentricity exists, while an eccentricity of ±5 µm occurs in the X-axis direction and when an eccentricity of ±5 µm is in the Y-axis direction, illustrating different cases. When the gap in the new stepping motor D becomes narrower than that in the new stepping motor C, the detent torque drifts away from the sinusoidal wave form and the absolute values become unequal. This is attributable to the magnetic saturation that occurs with the thinned portion of the stator.
The mechanical-angular dependency of the net holding torque, with no rotor eccentricity, is shown in Fig. 5. Net holding torque is defined as the torque after subtracting the detent torque from the holding torque. In the case of the magnetomotive force of 5.8 AT (sign of AT is plus) for counterclockwise rotation of the rotor, it is noticed that the sign of net holding torque shown in Fig. 5, should be inversed.

The mechanical-angle dependency of the rotor shaft attraction force ($F_x$, $F_y$) in the X-axis and Y-axis directions and their absolute values ($F = \sqrt{F_x^2 + F_y^2}$) for the five cases, consisting of the instances with no rotor eccentricity, as well as +5 and -5 μm eccentricity to the X-axis direction, along with +5 and -5 μm to the Y-axis direction are shown in Fig. 6, 7, 8, 9, and 10, respectively. As shown in Fig. 9(a) as well as a few other instances, in the case that sign $F_y$ is plus, $F_x$ is in the vicinity of 0 and $F_y^2$ is considerably larger than $F_x^2$, the absolute value $F$ seems to be overlapped with $F_y$.

**Fig. 5.** Mechanical-Angular Dependence of Net Holding Torque with no Eccentricity of Rotor.

**Fig. 6.** Mechanical-Angular Dependency of Rotor Shaft Attraction Force with no Eccentricity of Rotor.
Fig. 7. Mechanical-Angular Dependency of Rotor Shaft Attraction Force with 5 µm X-Axis Eccentricity of Rotor

Fig. 8. Mechanical-Angular Dependency of Rotor Shaft Attraction Force with -5 µm X-Axis Eccentricity of Rotor
Fig. 9. Mechanical-Angular Dependency of Rotor Shaft Attraction Force with 5 µm Y-Axis Eccentricity of Rotor

Fig. 10. Mechanical-Angular Dependency of Rotor Shaft Attraction Force with -5 µm Y-Axis Eccentricity of Rotor
3. COMPARISON

3.1 Holding Torque There are no changes in the X and Y-axis directions of the rotor due to \( \pm 5 \mu m \) eccentricity, with regards to the holding torque of the respective stepping motors. The gap width \( gwc \) changes from 0 to 5 \( \mu m \) and from 0 to -5 \( \mu m \). It is assumed that the net holding torques derived from the portions of the \( gwc \) and \( -gwc \) negate each other. From (1),

\[
\Delta Tha = -\frac{\pi h_m \cdot \rho^2 B_r}{a_2^4} \cdot ni \cdot 2gwc \quad \cdots \cdots (4)
\]

where \( \Delta Tha \) is defined as a variation of \( Tha \).

For every \( gwc \), there is no change with regards to the net holding torque, as \( p \Delta Tha (gwc) \) added to \( p \Delta Tha (-gwc) \) makes zero. Here, \( p \) is the proportion of the portion. In 3.2 Detent Torque, there is no change in detent torque, due to \( \pm 5 \mu m \) eccentricity, in the X and Y-axis directions. Similarly, there are no changes in the holding torque as well.

The ratio of average-peak values for the net holding torque of the respective new stepping motors with respect to the stepping motor A is shown in Fig. 11. The net holding torques of the new stepping motors B, C and D are 0.8 times, 1.0 times and 0.5 times that of the stepping motor A, respectively. This implies that the drive current of the new stepping motor A, 400 \( \mu m \) of \( hm \) is chosen, however, for B, C, and D, as we are not able to apply \( hm \), and thus we propose to introduce the effective thickness \( hms \) of the rotor, which is the \( m \) times the thickness of the thinned portion of the rotor. For B, C, and D, the \( m \) becomes 4.71, 7.20, and 5.10, respectively. We consider that the difference between the \( m \) of C and D, is related to the difference of the shape of detent torque curve. Thus, it is assumed that the value of the coefficient \( hms \) of \( Tda \) depends strongly on the gap width and the thickness of the thinned portion of the rotor. When the diameter of the rotor hole \( a \) is changed to 1450 \( \mu m \) (the gap width becomes 150 \( \mu m \)), and the detent torque is maintained for a (1800 \( \mu m \)) and the thickness of \( hm \) is retained, the notch \( r \) should 104 \( \mu m \), which may be difficult to manufacturing, because the watchmakers are only able to manufacture the stepping motors with the gap width until 300 \( \mu m \).

The ratio of average-peak values for the detent torque of the respective new stepping motors with respect to the stepping motor A, are shown in Fig. 12.

The average-peak values for the detent torque of the new stepping motors B, C and D are 0.8 times, 1.0 times and 0.5 times that of the stepping motor A, respectively.

### Table 5. \( Tda \) of Equation and Analysis

| \( Tda \) | A  | B  | C  | D  |
|---------|----|----|----|----|
| equation| 23.5 | 17.2 | 24.7 | 12.6 |
| analysis| 23.3 | 17.3 | 24.6 | 12.7 |

\( \times 10^2 \mu Nm \)
The difference between the new stepping motors C and D, is its only, and each ts is 25 or 18 \( \mu \text{m} \). Further, the ratio of the ts of D with respect to that of C, becomes 0.72, however, the ratio of the average peak value of D versus C, is 0.5. This is due to the fact that the thinned portion of D is more magnetically saturated than that of C, as shown in Fig. 4 (c) and (d). Moreover, the detent torque of D drifts away from the sinusoidal waveform at a larger distance than that of C, and adopts a triangular shape.

The detent torque \( T_d \) is approximated using the following equation:

\[
T_d = -\sin(2(\theta - \theta_0)) \quad \cdots \cdots \quad (7)
\]

where the amplitude of \( T_d \) is 1, \( \theta \) is the mechanical angle, and \( \theta_0 \) is the stable-equilibrium mechanical angle of 45\(^\circ\). In Fig. 13 showing the approximate-sinusoidal curve for the detent torque, the stable-equilibrium mechanical angle becomes \( \theta_0 \) (45\(^{\circ}\)) and \( \theta_0 + 180 \) (225\(^{\circ}\)). For each stable equilibrium mechanical angle when the rotor rotates and settles into the direction of larger mechanical angle, the rotor is pulled back and stopped to that by plus or minus detent torque of \( T_d \), respectively.

The stable-equilibrium mechanical angle for the detent torque of respective stepping motors, at one of two locations for the respective stepping motors, is shown in Fig. 14.

In Fig. 14, the stable-equilibrium mechanical angle of the new stepping motors B, C, and D are 3, 3, and 5\(^{\circ}\) greater than that of stepping motor A respectively, in the rotor rotating direction. This is attributable to the fact that the magnetic flux derived from the N-pole of the magnet returns into S-pole directly rather than through the yoke of the coil.

An increase in the stable-equilibrium mechanical angle makes it easier to observe the rotor rotation.

3.3 Average Absolute-Peak Value of Rotor Shaft Attraction Force

A comparison of average absolute-peak values for the rotor shaft attraction force of the respective stepping motors with 0 and 5\( \mu \text{m} \) of rotor eccentricity is shown in Fig. 15. In the event that there is no eccentricity, the average value for the rotor shaft attraction force of the respective stepping motors will be approximately less than or equal to one-quarter the value in the case for the stepping motor A with an eccentricity of 5 \( \mu \text{m} \). However, in the event the eccentricity is 5 \( \mu \text{m} \), the average values for the rotor shaft attraction force of the new stepping motors B, C, and D would be 3, 6, and 6 times that of the stepping motor A, respectively. This indicates that if the rotor eccentricity of the new stepping motors C and D is set to half that of the new stepping motor B, then the average value for the rotor shaft attraction forces will nearly be the same as each other.

The maximum coefficient of the static friction of the rotor shaft was approximately 0.2. Using this figure, the friction torque, caused due to the rotor attraction force of the stepping motor A, as well as the new stepping motors B, C and D, will be 0.4, 1.2, 2.4, and 2.4 \( \times 10^{-2} \) \( \mu \text{Nm} \), and will then be 1.7, 6, 8.3 and 16 \% for 23, 20, 29, and 15 \( \times 10^{-2} \) \( \mu \text{Nm} \) of the maximum values of the respective detent torque, respectively.

We adapt the average absolute-peak value of rotor shaft attraction force to the neighborhood of the stable-equilibrium mechanical angle of 45\(^{\circ}\). Then, once the rotor stops at a mechanical angle at which the friction torque and the detent torque are balanced, such a static mechanical angle drifts in the reverse rotating direction from the stable-equilibrium mechanical angle by 1, 3.4, 4.8 and 9.2\(^{\circ}\), respectively. \( \theta_0 \) of the stepping motors B and C is greater than that of the stepping motor A by 3\(^{\circ}\) to the rotating direction and as such, rotations are predicted to be possible, however rotation is considered difficult with the stepping motor D, since the figure is only 5\(^{\circ}\) greater in the rotating direction.
4. Trial Production

A prototype of the new stepping motor is designed by changing the \( t_s \) of the new stepping motor D from 18 to 20 µm. The detent torque for the prototype can be approximated to that for B which achieved the power consumption reduction shown in Table 3. Fig. 16 shows a photograph of prototype, with segment (a) showing the whole view, segment (b) representing the stator, and segment (c) showing the rotor hole part of the stator.

The measurements of the current consumption are considered as unloaded and loaded (2.0, 2.2, and 2.4 ×10\(^{-4}\) Nm) under the same operating conditions as those in our report (2). Based on the results shown in Fig. 11, the prototype stepping motors are expected to achieve a current consumption of 67 % for the stepping motor A, however, that is not the case. Although the rotor is assembled in the rotor hole of the stator with careful attention towards rotor eccentricity, one cannot rotate under load, even when the current consumption (0.46 µA) is reduced to -13 % for stepping motor A, whereas the other can rotate under load, the current consumption (1.51, 1.62, and 1.68 µA, with 2.0, 2.2, and 2.4 ×10\(^{-4}\) Nm, respectively ) is reduced to -11, -11, and -18 %, respectively, for the stepping motor A, but there is no reduction (19 %) in the current consumption without load. Table 6 shows the drive current and its ratio. The evaluation cannot be achieved systematically with A. The reason behind this is the increased rotor shaft attraction force, due to the eccentricity of the rotor, caused by an increase in the friction torque beyond the tolerance range. The wheel bearing of the movement in the wristwatch manufactured by Company A, used in this experiment, is made of plastic and does not possess sufficient rigidity. This results in a rotor eccentricity value that exceeds the one required for reducing the power consumption. We propose that an experiment needs to be conducted to study the movement of a wristwatch with a metallic wheel bearing with sufficient rigidity in order to obtain reduced power consumption in the new stepping motors.

Table 6. Drive Current and its Ratio

| load (10\(^{-4}\)Nm) | A (µA) | Prototype (µA) | % |
|-------------------|-------|----------------|---|
| 0                 | 0.53  | 0.46           | -13/19 |
| 2                 | 1.7   | –              | -11   |
| 2.2               | 1.83  | –              | -11   |
| 2.4               | 2.04  | –              | -18   |

– cannot rotate

Fig. 15. Average Absolute-peak Value for Rotor Shaft Attraction Force of respective Stepping Motors with 0 and 5 µm of Rotor Eccentricity

Fig. 16. Photograph of Prototype

5. Conclusion

We confirm that the amplitude of net holding torque can be evaluated by (1), and, the coefficient of the detent torque \( \beta \) in (2) is 0.053. We further obtain the effective thickness \( h_{ms} \) of the rotor magnet of the new stepping motor, and this value is multiplied with the thickness of the thinned portion of the stator to obtain an amplitude which is equivalent to that of (2).

We verify that the value of the holding torque and detent torque do not change due to the rotor shaft eccentricity ±5 µm, and the stable-equilibrium mechanical angle of the detent torque shifts effectively in the direction of the rotation when the gap is smaller, which subsequently has a positive impact on the new stepping motor.

Furthermore, we inferred that the existing wristwatches are limited to a stepping motor with a gap width of 300 µm due to the following reasons.

When the gap is reduced to 150 µm, the notch radius \( r \) should be 104 µm, which may be difficult to manufacture, and the rotor shaft attraction force derived by the rotor eccentricity 5 µm is doubled, which has a negative impact on the stepping motor.

This analysis provides a supportive evidence for the power consumption reduction in the new stepping motor B, as described in the report (2).
We propose that the rotor eccentricity needs to be reduced to approximately half the value of the new stepping motor B, in order to achieve a reduced power consumption with the new stepping motor C or D. We plan to conduct an experiment of a wristwatch with a movement comprising a metal wheel bearing, as a future work.

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