# Study on Manufacturing Method to Reduce Cogging Torque of Motor with Separate Core

Hiroyuki Akita[1], Yuji Nakahara[2], Takashi Yoshioka[3], Takashi Miyoshi[4]
Mitsubishi Electric Corporation[1,2,3], Osaka University[4]

Keywords: motor, torque ripple, core precision, circularity, separate core, manufacturing method, level difference

## Abstract

This paper presents a new manufacturing and estimating method of motors to achieve low torque ripple. We have developed the manufacturing method to increase the coil fill factor of motors by using separate core. That caused high efficiency of motor, however, the core precision tends to be bad in the case of separate core and that causes large torque ripple. In this paper we declared the relationship between core precision and torque ripple. And a new evaluation method which predicts torque ripple more precisely than the evaluation method from the circularity of inner core has been established.

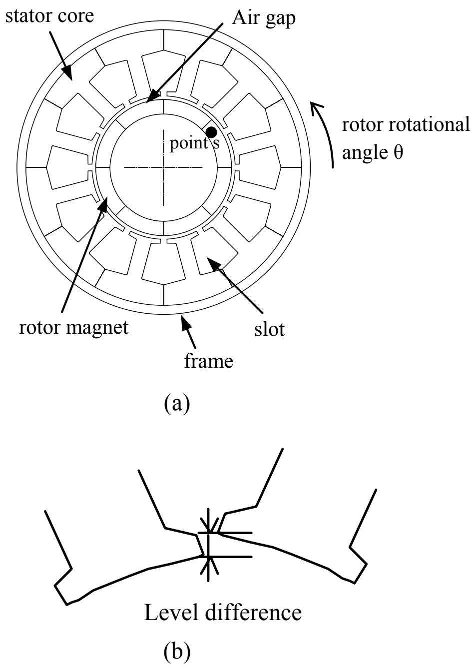
## 1 Introduction

With the brushless DC motors coming into increased use in recent years due to high efficiency requirements, the concentrated winding coil structure has become popular. The authors have studied on the manufacturing method(1) applying separate cores for a concentrated winding motor in order to reduce the coil resistance for higher efficiency. A brusshless DC motor is expected to have higher accuracy rotation, lower vibration and noise, which can be achieved by reducing cogging torque. The separate core, however, is more likely to cause machining errors than the unit core, and even a slight machining error may lead to unbalanced magnetic flux distribution at the time of motor rotation, resulting in increased cogging torque. The inner diameter shape largely influences the cogging torque, but the effect of the slight error as per region of the inner diameter shape on the cogging torque is not clear yet.

In this paper, therefore, the occurrence mechanism of cogging torque attributed to the machining error is analyzed, and an evaluation method for the inner diameter shape in order to prevent cogging torque during manufacturing process of the stator is studied.

## 2. Motor structure and cogging torque

Fig. 1 shows the structure of an 8-pole, 12-slot machine to be used in the research. The stator uses a separate core per magnetic pole tooth, and the rotor uses ring-shaped sintered neodymium magnet. The coil, which is not illustrated in the figure, is wound around each magnetic pole tooth of the stator. The torque pulsation caused by one turn of rotor rotation with no current passed through the coil is called the cogging torque. It is known that for each turn of rotor rotation the component with 8-cycle pulsation and the component with 16-cycle pulsation are caused by the stator machining error, while the component with 24-cycle pulsation is caused by combination of the number of poles and the number of slots(2). This paper especially aims at reducing the 8-cycle component which is largely affected by the inner diameter shape of the stator. The 8-cycle compornent is called 2f component, with f indicating the basic wave frequency of armature current.



(a)

(b)

**Fig. 1.** Motor structure

## 3. Relation between circularity of stator inner diameter and cogging torque

Fig. 2 shows the measurement results of circularity and cogging torque 2f component for 20 sample stators used in the experiment in terms of the ratio of the stator inner diameter and the rated torque respectively. The correlation coefficient of circularity with cogging torque 2f component is low at 0.48, so that the circularity is considered inappropriate as an evaluation index to estimate the cogging torque 2f component.

The reason why the circularity cannot be used for evaluation of cogging torque 2f component lies in the fact that the circularity is a figure that merely expresses the size of configurational error and does not reflect the shape or position of the error. Especially in the case of the separate core shown in Fig. 1(a), the neighboring magnetic pole teeth have their ends radially deviated causing level difference in the inner circumference, as shown in Fig. 1(b), so that the core tends to have larger cogging torque 2f component than the stator with lenient configurational change in general. Thus, in consideration that the sharp change in inner diameter shape inflicts a large effect on the cogging torque 2f component, study is carried out on the relationship between change in the inner diameter shape and the cogging torque 2f component.

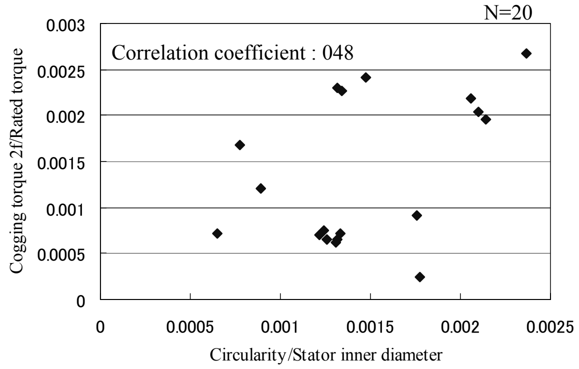


**Fig. 2.** Relation between circularity and cogging torque

## 4. Introduction of evaluation index taking account of the effect of change in inner diameter shape

If a point s is taken in the polar coordinates of rotor, and when this point s reaches the position of rotational angle q against the stator as the rotor rotates, a torque T (s, q) is generated at the point s due to the change in magnetic energy E (s, q), and can be expressed as equation (1).

If a point s is taken in the polar coordinates of rotor, and when this point s reaches the position of rotational angle q against the stator as the rotor rotates, a torque T (s, q) is generated at the point s due to the change in magnetic energy E (s, q), and can be expressed as equation (1).

$$T(s,\theta)=\frac{\partial E(s,\theta)}{\partial\theta} \tag{1}$$

The magnetic energy E (s, q) is directly proportional to the square of the product of rotor magnetomotive force F(s) and magnet permeance including magnetoresistance, and can be expressed as equation (2).

$$E(s,\theta)\propto\{F(s)\}^2\{P(s,\theta)\}^2 \tag{2}$$

Torque T0(q) can be obtained by subustituting equation (2) into equation (1), and integrating for s over one cycle of rotor. A (s, q) is defined as in equation (3) which is a component of torque T (s, q).

$$A(s,\theta)=\frac{\partial\{P(s,\theta)\}^2}{\partial\theta} \tag{3}$$

Torque T (s, q) is a function of A (s, q) and magnetomotive force F(s). Here, permeance P (s, q) is both a function of an air gap between the stator and the rotor and a function of the stator inner diameter accuracy. Hence, A (s, q) is a function of the change in stator inner diameter as point s rotates in the stator, and it is aslo a function of change in stator inner diameter in q direction. In the present model, since the magnet has 8 poles, if the rotor has ideal shape without any configurational error or any characteristic difference of the magnet, the same magnetomotive force should appear at every 45 degrees. As mentioned previously, torque T0 (q) at the rotational angle q is the T (s, q) integrated over one cycle of the rotor. Here, the integration is carried out after taking the scalar sum of A (s, q) per 45 degrees in order to visually grasp the stator inner diameter accuracy and the effect of cogging torque 2f component.

Fig. 3 shows the inner diameter shape measured as a distance from a standard circle using a sample with level difference between the magnetic pole teeth. Fig. 4 shows the result of A (s, q) calculated from measured inner diameters for each division A1 ~ A8 in Fig. 3, and expressed as a curve, which we call "A curve". Here, the inner diameter shape of the stator is supposed to be same in the direction of the stator length, with the 45 deg division expressed in 360 deg as one cycle of the magnet. Next, the scalar sum for each A curve phase is calculated and expressed as A0 curve in polar coordinates in Fig. 5, where the vector sum of the curves is one cyclic component of A0 curve and is expressed in the figure as Y vector, with the size and phase indicated by the arrow mark.

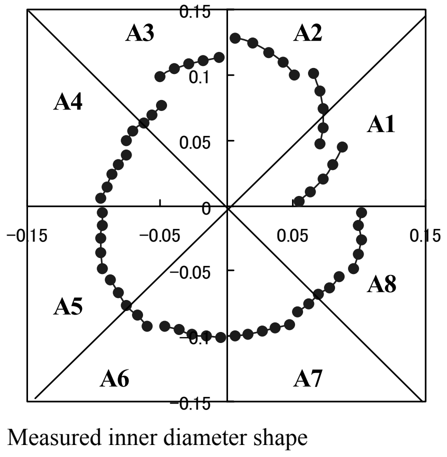


**Fig. 3.**. Measured inner diameter shape

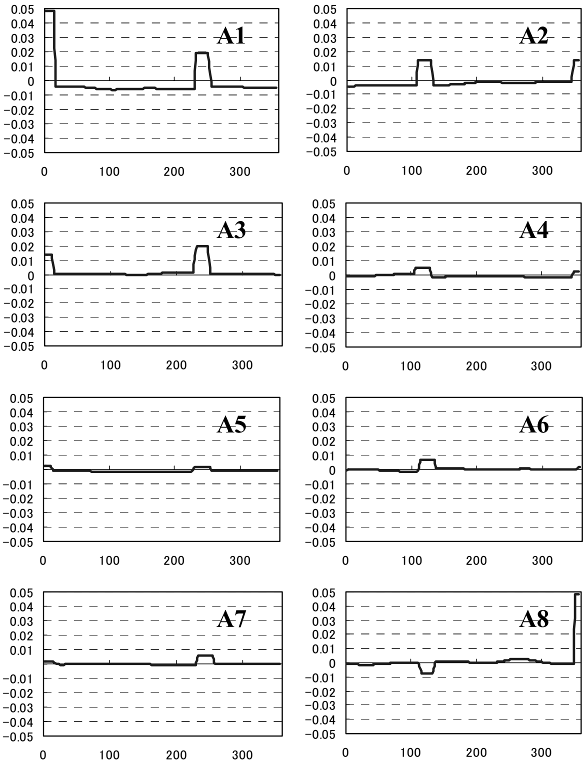


**Fig. 4.** A curve occurring between each magnet and stator

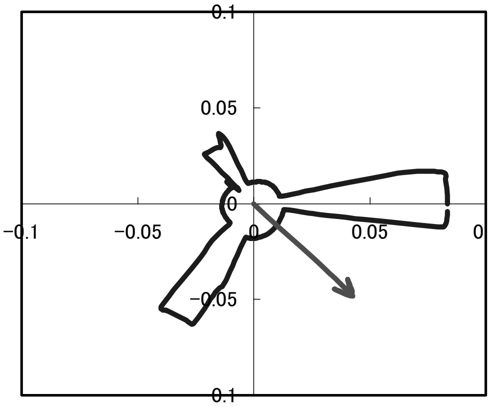


**Fig. 5.** A0 curve and Y vector

The sample shown in Fig. 2 is arranged by using the size of Y vector, whichi we call “Y value”, and shown in Fig. 6, indicating a high correlation coefficient 0.96 between the Y value and the cogging torque 2f component. Thus, it can be deduced that the Y value can be used as a indicator to estimate the cogging torque 2f component.

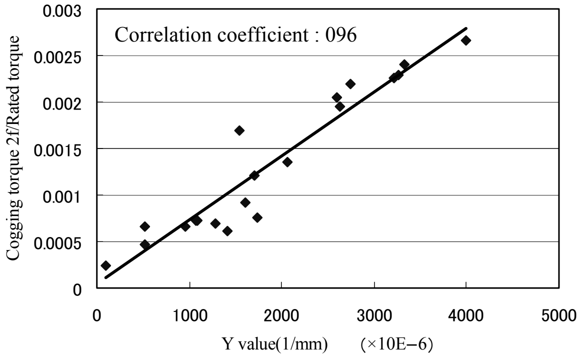


**Fig. 6.** Relation between Y value and cogging torque 2f component

Further, since Fig. 5 is a visual expression of the cause of the Y vector occurrence, it can be learned that the value of A (s, θ) near 0 degrees and 240 degrees, which we call “A value”, inflicts effect on the size of Y vector. Fig. 4 indicates that the A value near 0 degrees largely depends on A1 curve, and the A value near 240 degrees depends on A1 and A3 curves. Further, Fig. 3 indicates that the aforesaid values are influenced by the level difference in the separate sections No. 1, No. 2 and No. 5, and thus the region inflicting effect on cogging torque 2f component can be identified.

Although the level difference is attributed to the configurational error due to the mold accuracy and the assembly error due to the tool accuracy, the cogging torque 2f component can obviously be restrained by reflecting the cause clearly indicated by A curve in manufacturing process. On the other hand, it is possible to reduce the cogging torque 2f component by changing the level difference shape after assembling.

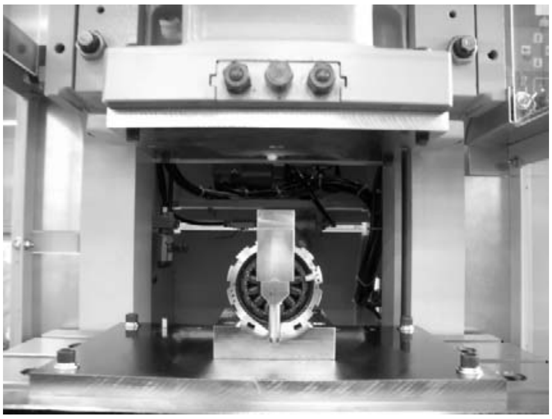


Fig. **7.** Experimental equipment

## 5. Experimental verification 1

Here, in order to verify the supposition in previous chapter, the change in the cogging torque 2f component caused by the change in level difference between magnetic pole teeth will be examined. Fig. 7 shows the photograph of the experimental equipment, where the stator has its outer periphery fixed by the frame before being pressed. The stator composed by core press-fitted into motor frame is located on the pedestal with its outer circumference supported by cylindrical tool, and is subjected to deformation through pressing by a punch installed to the sub-press. The punch touches the inner periphery of the magnetic pole tooth before causing plastic deformation of the magnetic pole tooth end as shown in Fig. 8. As the stator is supported by cylindrical tool, the deformations at places other than motor frame and core end are of ignorable levels. Once the magnetic pole tooth undergoes plastic deformation, a change is seen in the level difference with the neighboring magnetic pole tooth. The plastic deformation is controlled by the push-in rate of the sub-press from the position the punch touches the core. Fig. 9 shows a graph indicating the measured push-in rate of the sub-press and deformation of magnetic pole tooth. The linear relation between the two suggests that the level difference can be controlled by the push-in rate.

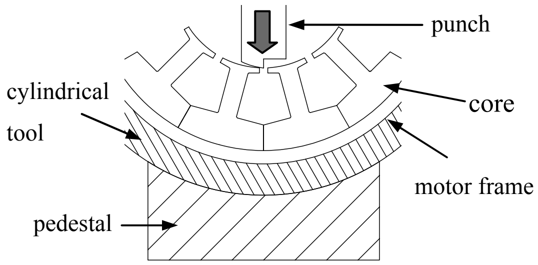


**Fig. 8.** Punch shape

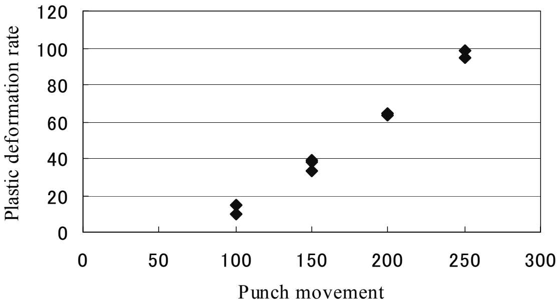


**Fig. 9.** Relation between push-in rate of sub-press and deformation of magnetic pole tooth

We describe the result of the change in level difference of the 2 samples with large level difference between magnetic pole teeth at 0 degrees, which is similar to the sample shown in Fig. 3.

First of all, Fig. 10 shows the changes in inner diameter shape, A0 curve and Y vector when one of the samples was pressed to plastic deformation gradually in 3 steps in the direction of reducing the level difference at 0 degrees position. The cogging torque 2f component was measured at each step of deformation. The measurement result of inner diameter shape in Fig. 10 indicates that the level difference gradually decreases as the plastic deformation is applied. Further, this also leads the A0 curve near 0 degrees to decrease and Y vector to become smaller. Fig. 11 shows the change in the level difference and Y vector, and Fig. 12 the change in the Y value and the cogging torque 2f component. As the level difference decreases, the Y value becomes smaller, leading to the reduction in the cogging torque 2f component. In other words, the cogging torque 2 f component can be reduced by making the Y value smaller by slight deformation of the level difference through pressing. Thus, the supposition was verified through active application of deformation.

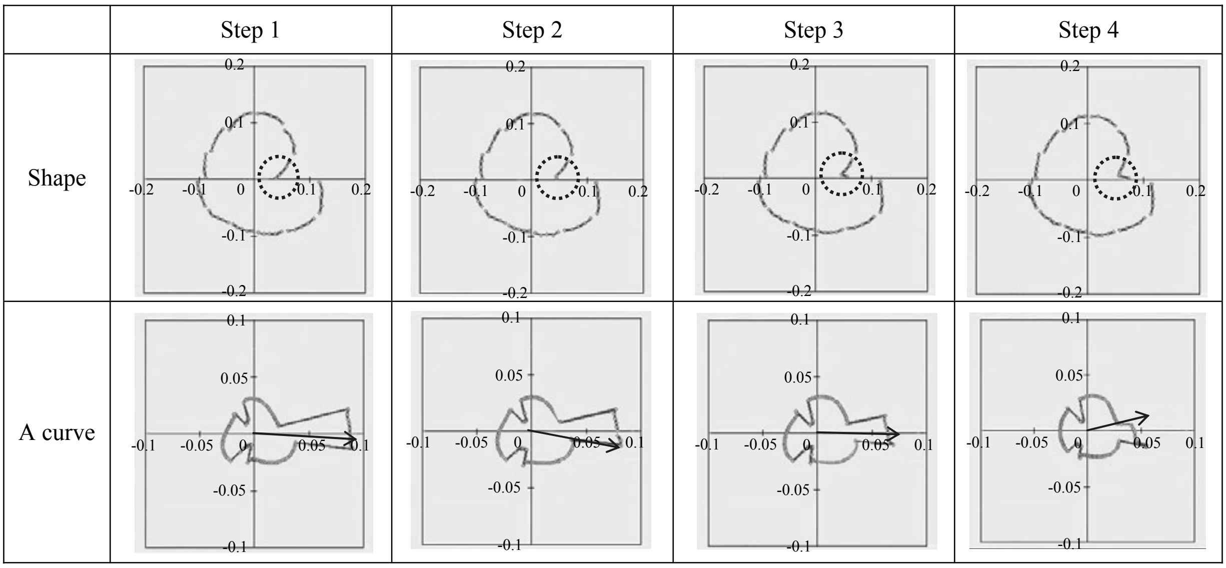


**Fig. 10.** Changes in inner diameter (top), A curve and Y vector (bottom) through pressing

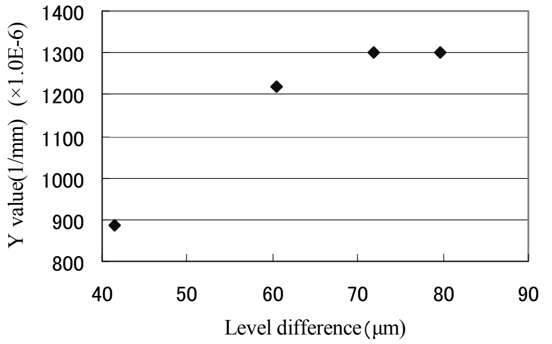


**Fig. 11.** Changes in level difference and Y value through pressing

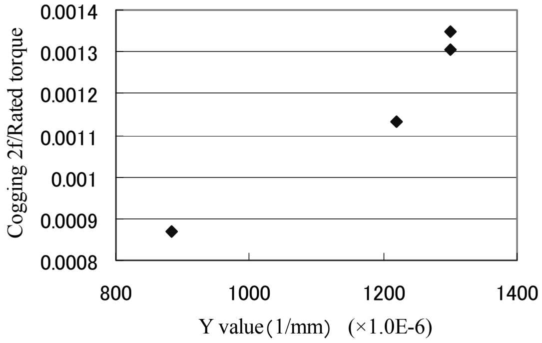


**Fig. 12.** Changes in Y value and cogging torque 2f component through pressing

## 6. Experimental verification 2

By applying the supposition the experiment was conducted for eliminating the level difference by creating a new level difference. Fig. 13 shows the changes in the inner diameter shape, A0 curve and Y vector when another sample, with level difference at 0 degrees position, is pressed to plastic deformation gradually near 90 degrees to form a level difference, indicating clearly that the level difference near 90 degrees increases as the plastic deformation proceeds. The level difference at 0 degrees was made to opposite direction to the level difference at 90 degrees, with the level difference at 0 degrees showing clockwise inward change while the one at 90 degrees showing clockwise outward change. The value of A0 curve near 0 degrees was found to decrease as the level difference increases by machining, and so was the case with Y vector. Fig. 14 shows the changes in the level difference and Y vector while Fig. 15 the changes in the Y value and the cogging torque 2f component, indicating the Y value getting smaller as the level difference increases and subsequently the cogging torque 2f component getting reduced. In other words, by creating a level difference against an existing level difference at a different position using a press, the A value can be nullified and the Y value decreased, leading to the reduction in the cogging torque 2f component. According to the experimental result in previous chapter, the circularity can be improved by reducing the level difference through machining. According to the experimental result in this chapter, however, the cogging torque 2f component decreases in spite of the circularity getting deteriorated because of the newly made the level difference. This suggests that the cogging torque 2f component depends not on the circularity but on the inner diameter shape, and that its size is determined by the combined effect of the respective regions. And this can be regarded as one of the grounds to verify the supposition of this paper. According to the supposition, therefore, the

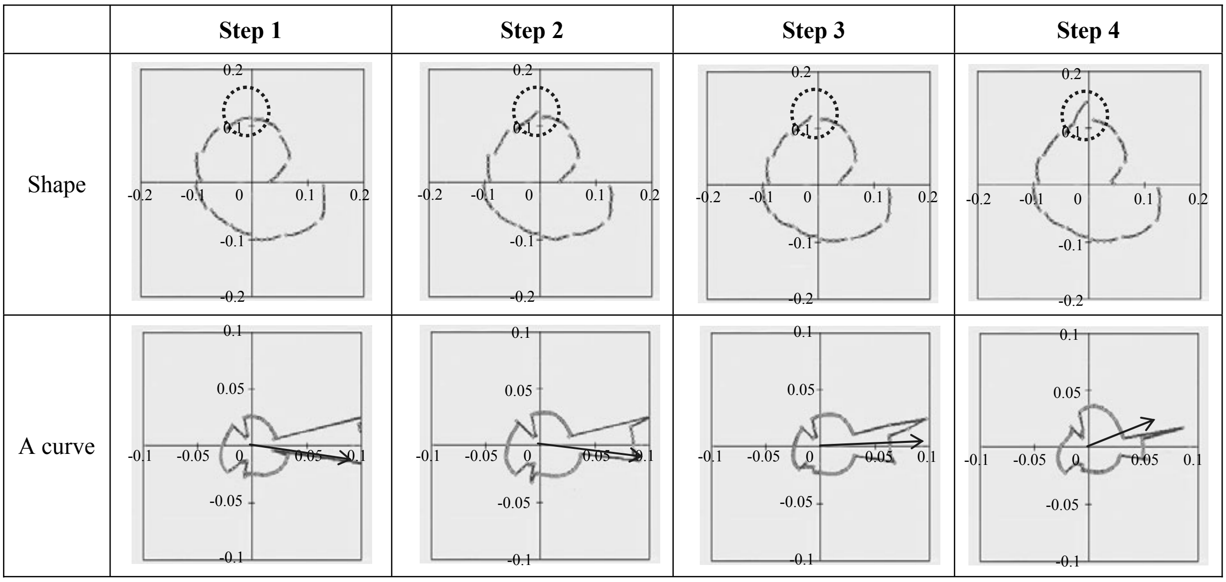


**Fig. 13**. Changes in inner diameter (top), A curve and Y vector (bottom) through pressing

minute control of the inner diameter shape as well as the due attention to the circularity of the inner diameter is required to reduce the cogging torque 2f component. The fact that the superposition leads to the reduction of the cogging torque 2f component further suggests that the cogging torque 2f component caused by items other than configurational errors such as stress distribution, distribution of machining deterioration, etc. could be nullified by adding new level difference.

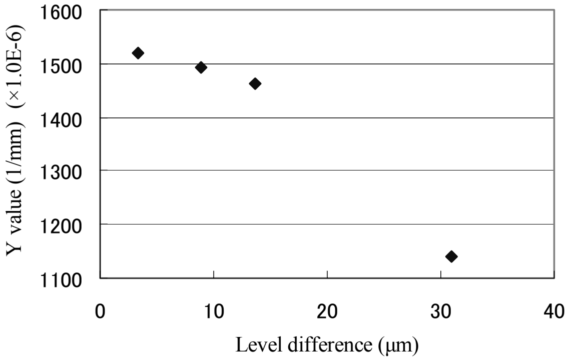


**Fig. 14.** Changes in level difference and Y value through pressing

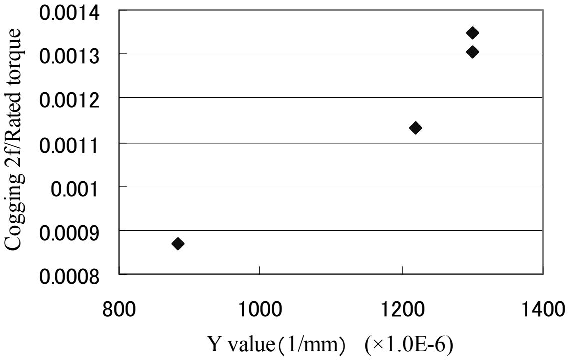


**Fig. 15**. Changes in Y value and cogging torque 2f component through pressing

## 7. Conclusions

The following points can be deduced from the study of the effect of the stator inner diameter shape on the cogging torque 2f component.

1. If Y vector is defined as an index of the magnetic effect of the stator inner diameter, a high correlation is found to exist between Y value and cogging torque 2f component.
2. The analysis of A curve can lead to identification of the region causing Y vector occurrence.
3. From the experiment showing the level difference reduced through post-machining, it is learned that the cogging torque 2f component can be reduce by reducing Y vector.
4. From the experiment showing addition of new level difference through post-machining, it is learned that the cogging torque 2f component can be reduced by reducing Y vector in spite of the deterioration of circularity.
5. In order to reduce the cogging torque 2f component, fine control of the inner diameter shape as well as the circularity is required.
6. From the two experiments showing creation of level difference, it is learned that the Y vector is an index to evaluate the cogging torque 2f component, and that the A curve can be used for cause analysis and measures for reducing the cogging torque 2f component.

## References

[1] Akita, et al.: A New Core; IEEE Industry APPLICATIONS Magazine,Nov.|Dec. 2005 vol.11, No.6 p38-43 (2005)
[2] Goto, et al.: Elucidation of DC motor cogging torque and new method at reducing the cogging torque; IEE Journal B, Vol. 103-B, p711 (1983)