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Electromagnetic Steel Solution in Electromagnetic Field Technique

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Abstract

Electromagnetic steel with fine magnetic characteristic is not easy for practical use because of problems such as anisotropy and magnetic saturation. Electromagnetic calculation technology, which considers magnetic material characteristics, is useful for solving these problems. New electromagnetic calculating, tools named "TESSon-1 and 2" have been developed. These consider magnetic anisotropy, the effects of mechanical stress and rotating magnetic flux. Results calculated by the tools correspond well to the experimental results.

1. Introduction

Since steel material is not only a structural material but also a ferromagnetic substance, it is widely used in electric devices such as motors and transformers, to take advantage of its magnetic characteristics.

The magnetic characteristics of a ferromagnetic substance are complicated as seen in anisotropy and hysteresis. Both are based on factors such as magnetic domain, magnetic wall and texture[1, 2)]. It is very difficult to elucidate the magnetic characteristics directly by solving the principle equations, such as the first principle and molecular dynamics[3,4)], using numerical analysis, even using the latest and highly advanced computer technology. The result is that only measurement is available to obtain the actual magnetic characteristics.

On the other hand, the methods used to design electric devices such as motors and transformers, for which the above-mentioned magnetic material is used, have changed only slightly in recent years. Most of the methods to design such devices are based on the concepts of linearity and anisotropy[5,6)].

However, the recent progress of a production of magnetic material is so striking that magnetic properties such as iron loss and permeability became much better than before[7)]. Generally, the latest materials with excellent magnetic properties, beginning with grain-oriented electromagnetic steel, have characteristics such as magnetic saturability; material getting magnetized easily, and anisotropy. The magnetic properties are not isotropic and depend on the direction. It is therefore essential to apply the technique of designing the electric devices by taking account of the magnetic properties not found in conventional materials, such as magnetic saturation or anisotropy, to make the most of the magnetic properties of those new materials.

The recent environmental issue and the top-runner mode have greatly aroused the needs of more efficient electric devices. Since it is recognized that the optimal designing method using conventional materials with concepts of linearity and isotropy has already achieved a certain level, to make the electric devices with higher efficiency than the conventional ones, the establishment of the technique to use new magnetic materials is necessary.

The method of designing electric devices, using the numerical analysis of the magnetic field by the finite element method, has advanced to a level of practical application thanks to the progresses of computer technology and analytical method[8)]. However, solving the Maxwell equations is not sufficient to analyze the properties of new magnetic materials in electric devices, because influences of the rotating magnetic field and stress exist in the electric devices. It is therefore necessary to express the influences with a mathematical model and solve simultaneous equations of the model and the Maxwell equations.

The technology of electromagnetic analysis has been under study at Nippon Steel for the past 20 years, when the finite element method was first applied to the Maxwell equations[9,10)]. As a result, software named "FLEDY®(FIELD OF EDDY)" was produced by Nippon Steel and is ready for sale outside the company. It was applied later to the design of equipment that is used in the steelmaking process, making a multi-physical model with the physical phenomena such as fluid, heat transfer, solidification, and quality as a ferromagnetic substance[11, 12)].

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This paper describes the technique to use a material with high-level magnetic characteristics, in which Nippon Steel takes pride. Mainly described is the technique of solution using magnetic field analysis.

2. Electromagnetic Steel Solution

Nippon Steel manufactures electromagnetic steel sheets, and sells them to users, who are generally manufacturers of electric devices. The electromagnetic steel sheets that have been manufactured recently have fine but complicated magnetic properties such as nonlinearity and anisotropy. Whether the fine properties are exhibited or not depends often on how to use the high-grade sheets in the electric devices. This tendency is remarkable in the highest-grade sheets because of its being highly anisotropic. The development of solutions must be offered to users to solve the problem of applying the magnetic properties of electromagnetic steel sheets, so that the users can draw out full of those fine properties.

The sort of materials, forms, and how to excite are different by the users' purpose. The technique of electromagnetic field analysis that can draw out full of the fine properties is a very effective tool. Moreover, the technique has the versatility of above-mentioned specifications, and it is easy to use according to respective purposes. The authors, et al. believe that the solutions for the users, whose concept is shown in **Fig. 1**, should be developed by reflecting the magnetic properties of the high-grade sheets on the techniques of electromagnetic field analysis and measurement.

The figure shows that through this business, we offer to the users the technique of application to make the most of the magnetic properties of electromagnetic steel sheets, by using the techniques of electromagnetic field analysis and high-degree measurement. On the other hand, the users' demands can be reflected on the development of material.

Accordingly the technique of electromagnetic field analysis, taking account of material properties, becomes a key factor. The technique of electromagnetic analysis itself was established more than 10 years ago, including the edge element, ICCG method, and Newton-Raphson's convergence method. However, only a few examples of analysis exist using the analytical technique with material properties taken into consideration.

The conventional technique of analysis using the Maxwell equations alone is not sufficient for the above analytical technique, because to express the relation between the magnetic field and magnetic flux density, it is necessary to trace back to modern physics and the theory of magnetic domain and magnetic wall. In other words, it is necessary to solve the simultaneous equations of electromagnetic field and magnetic material. Only those who are studying the world's foremost electromagnetic steel material and at the same time the world's foremost technique of electromagnetic field analysis can achieve this fusion technique. Nippon Steel is one of the few companies in the world that meet the above-mentioned requirements.

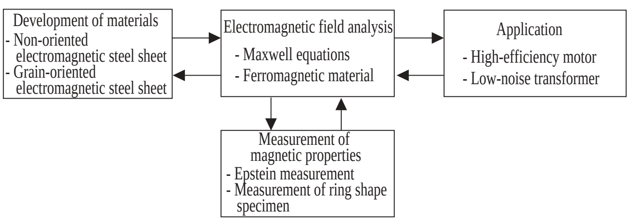


Fig.1 Position of the technique of electromagnetic field analysis in electromagnetic material solution

To use the magnetic material for electric devices, it is necessary to calculate magnetic flux density distribution and iron loss distribution, depending on nonlinearity, anisotropy, rotating magnetic field, hysteresis and stress. Order-made electromagnetic field analysis tool have to be made for each purposes, and this time "TESSon-1" (Theoretical Evaluation Simulation System for Iron Loss) and "TESSon-2" to use in FLEDY® are developed.

3. Technique of electromagnetic field analysis taking stress and anisotropy into consideration: TESSon-1[13)]

First, as an example of the electromagnetic field analysis, the difference of iron loss distribution caused by the difference of material is shown. **Fig. 2** shows the magnetic properties of the non-oriented electromagnetic steel sheets, NO material 50H230 and 50H1300. The former has higher permeability and lower iron loss. **Figs. 3, 4** and **5** show the difference of calculation result of iron loss distribution of a motor core. At Fig. 3, sort of material differs. 50H230 is used in Fig. a and 50H1300 in Fig. b. Fig. 3 shows that 50H230 has lower iron loss distribution.

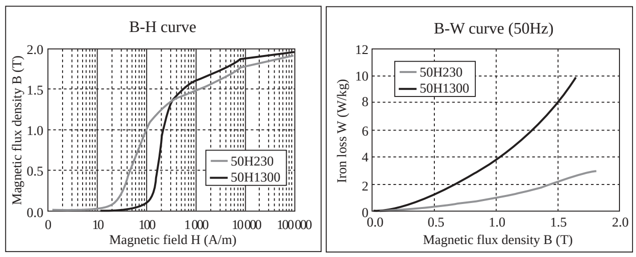
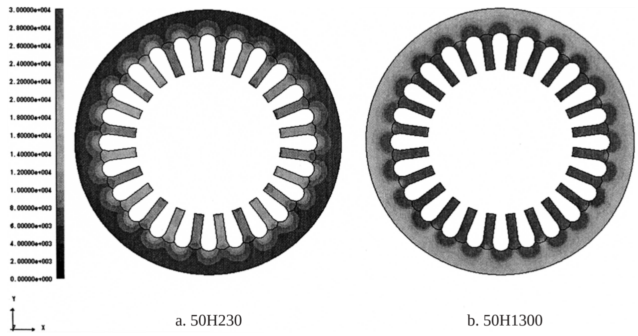
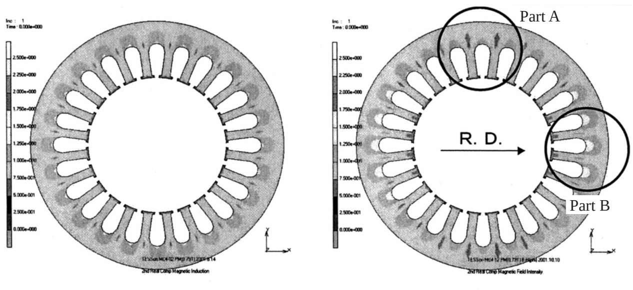


Fig.2 Magnetic properties of 50H230 and 50H1300



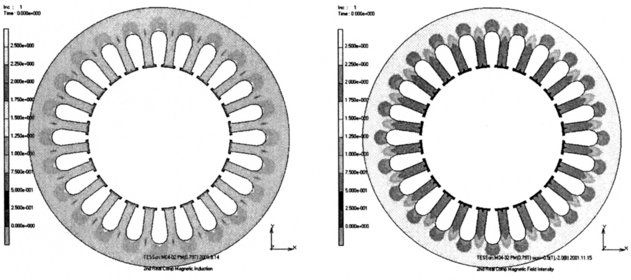
a. 50H230 b. 50H1300

Fig.3 Distribution of iron loss of 50H230 and 50H1300



a. Anisotropy ignored b. Anisotropy considered

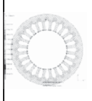
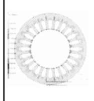
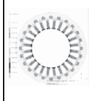
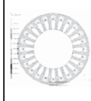
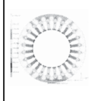
Fig.4 Distribution of iron loss when anisotropy is considered



a: Stress ignored　　b: Stress considered

Fig.5 Distribution of iron loss when stress is considered

Table 2 Factors to fill up the gap of iron loss between the calculated value by the conventional method and measured value

Analytical conditions	Anisotropy	Ignored	Considered	Ignored	Ignored	Considered
	Stress	Ignored	Ignored	Considered	Ignored	Considered
	Time harmonic distortion	Ignored	Ignored	Ignored	Considered	Considered
Iron loss distribution						
Contribution rate*			10 %	50 %	40 %	100 %

* Rates of factors to fill up the gap of iron loss (gap between measured value and conventional calculated value is set at 100%).

Next, at Fig. 4, anisotropy is not considered in Fig. a and it is considered in Fig. b. Fig. 4 shows that consideration of anisotropy makes the anisotropy of iron loss distribution. At the teeth of part A, iron loss becomes large because the magnetic flux flows toward the direction of difficult axis, whereas at the teeth of part B, iron loss is small because the magnetic flux flows toward the direction of easy axis. Similarly, at the yoke of part A, iron loss is small because the magnetic flux flows toward the direction of easy axis, whereas at the yoke of part B, iron loss is large because the magnetic flux flows toward the direction of difficult axis.

Lastly, at Fig. 5, stress is not considered in Fig. a and it is considered in Fig. b. Fig. 5 shows that consideration of stress makes the difference of iron loss distribution. This is because the dampening of fine magnetic properties occurs by compression stress.

Fig. 6 and **Table 1** show the comparison between the result of this electromagnetic field analysis and the experimental result by rotating iron loss simulator[14]. These show the fine accuracy of this electromagnetic analysis.

Table 2 summarizes the influences of anisotropy, stress and time harmonic distortion, to iron loss. At a rough estimate, the rate of contribution of these factors to the increase of iron loss is anisotropy: 10%, stress: 50% and time harmonic distortion: 40%.

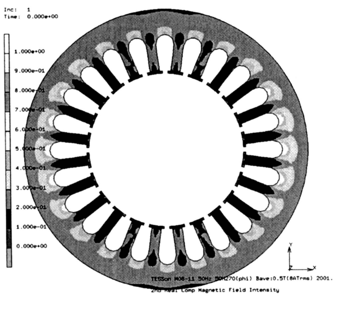


Fig.6 Calculated result of iron loss distribution

Table 1 Example of comparison of iron loss, between measured value and calculated value

	Measured	Calculated
Motor core iron loss (W/kg)	0.24	0.25

4. Electromagnetic field analysis taking hysteresis and rotating magnetic field into consideration: TESSon-2[15-17)]

Fig. 7 shows the experimental result measured with the concept of two-dimensional vector magnetic measurement method. The figures clarify the importance of two-dimensional vector magnetic property measurement method, which expresses the magnetic properties of steel sheets precisely. The upper part shows the loci of magnetic flux density vector (circular fine line) and magnetic field vector (distorted heavy line). The left one shows the loci of vectors in case of non-oriented (NO) electromagnetic steel sheet and the right one shows them in case of grain-oriented (GO) electromagnetic steel sheet. The electromagnetic steel sheet is thin enough to regard that the sheet is magnetized two-dimensionally, not three-dimensionally. Both sheets are magnetized to make the loci of magnetic flux density vector circular on the plane with radius of 1T.

In the case of the non-oriented electromagnetic steel sheet, the locus of its magnetic flux density is circular, whereas that of its magnetic field intensity is not circular. This shows that even the non-oriented electromagnetic steel sheet is anisotropic in magnetic property.

The grain-oriented electromagnetic steel sheet is highly anisotropic in magnetic property. In the direction of rolling, its magnetic field intensity is small for obtaining a magnetic flux density of 1.0T. It is easily magnetized in the direction of rolling. The lower part shows the phase difference between the magnetic flux density vector and the magnetic field intensity vector when an angle between the directions of rolling and the magnetic flux density vector is rotated from 0 to 360 degrees. The fact that the phase difference is not equal to 0 degree reveals that the magnetic field intensity vector is not parallel with the magnetic flux density vector.

In the non-oriented electromagnetic steel sheet, the phase difference is varied from 0 to 45 degrees. This shows that the magnetic field intensity vector rotates ahead of the magnetic flux density vector. This indicates that the non-oriented electromagnetic steel sheet usually has a hysteresis property.

In the case of the grain-oriented electromagnetic steel sheet, the phase difference changes from −66 to +78 degrees. The change is particularly drastic when the magnetic flux density vector exceeds the difficult axis, and at the same time the magnetic field intensity vector changes almost by 180 degrees.

Moreover, for some time in a period, the phase difference becomes negative. This means that for some time the magnetic flux

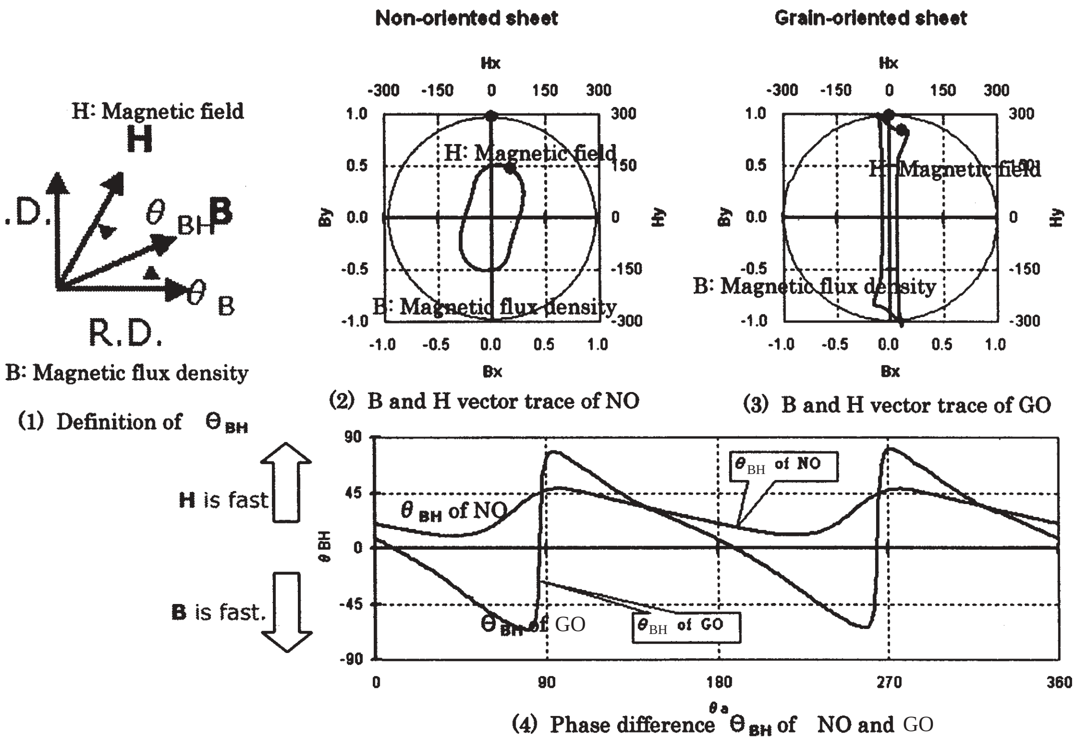


Fig.7 Basic measured results by 2-dimensional vector magnetic measurement method

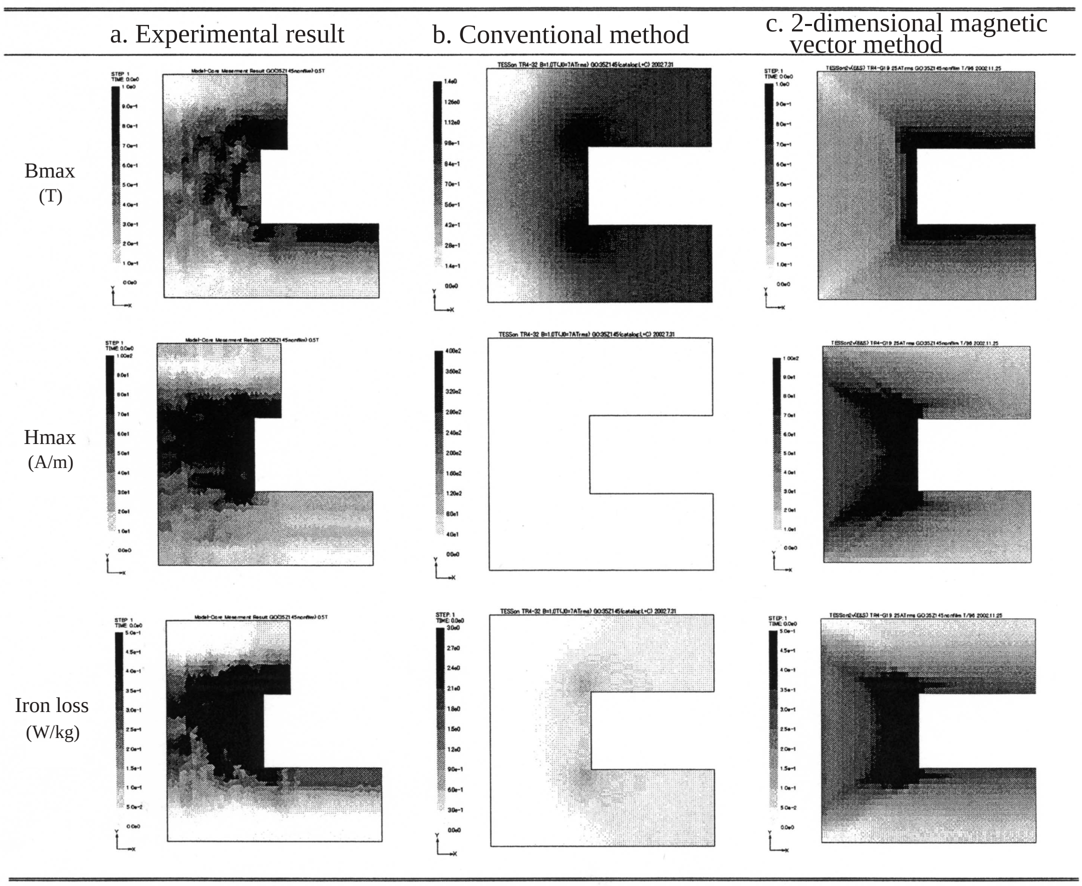


Fig.8 Comparison of magnetic properties, among the measured result, calculated result by the conventional method and calculated result by 2-dimensional magnetic vector method

density vector comes ahead of the magnetic field intensity vector. The normal B-H curve model like the Preisach model cannot express these phenomena. Consequently, the new model of magnetic properties, i.e. the two-dimensional vector magnetic property model, different from the conventional hysteresis curve model, is necessary to understand them.

Fig. 8 shows the distribution of iron loss in the 1/2 part of a transformer core. The iron loss can be calculated by equation (1).

$$W = \frac{1}{T}\int_{0}^{T} \vec{H}\frac{\partial \vec{B}}{\partial t}\, dt \qquad (1)$$

Here, *H*: Magnetic field vector, *B*: Magnetic flux density vector, *T*: Time period of *B* and *H* waves.

Fig. 8(a) shows the experimental result. It is measured by using the special sensor developed by J. Sievert (PTB), which has an H coil to meas-ure magnetic field intensity, and needles to measure magnetic flux density. The right upper part is the area where the iron loss is not measurable because the exciting coil exists. Figs. 8(b) and (c) show the calculated results, according to the conventional technique and the 2-dimensional magnetic vector method respectively. The distribution of the maximum of B, maximum of H and iron loss calculated by the 2-dimensional magnetic vector method is more accurate, i.e. closer to the measured result, than those by the conventional method.

5. Conclusion

A magnetic material that has fine magnetic properties is not easy for practical use because of the problems of anisotropy and saturability. It is necessary to establish the technique of application using the technique of electromagnetic field analysis taken account of these material properties. The authors developed the electromagnetic field analyzing tool named TESSon-1 and 2, and became able to describe the actual phenomena more precisely than the conventional analysis.

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