Vector (Two-Dimensional) Magnetic Phenomena

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Abstract—In this paper, some interesting phenomena were described from the viewpoint of two-dimensional magnetic property, which is reworded with the vector magnetic property. It shows imperfection of conventional magnetic property and some interested phenomena were discovered, too. We found magnetic materials had the strong nonlinearity both magnitude and spatial phase due to the relationship between the magnetic field strength *H*-vector and the magnetic flux density *B*-vector. Therefore, magnetic properties should be defined as the vector relationship. Furthermore, the new Barukhausen signal was observed under rotating flux.

Index *terms*—two-dimensional magnetic property, magnetostriction, Rotational Barkhausen Signal, Chaos attractor

I. INTRODUCTION

In the past, the single-sheet testers (SST) and Epstein testers have been used to measure the magnetic properties of electrical steel sheets, taking only the magnitude of the alternating magnetic field into account (hereafter these are referred to as one-dimensional or scalar measurements). However, the rotating magnetic flux appearing at the T-joint of the three-phase, three limbed transformers and in the stator core of motors have the characteristics differing from those of alternating magnetic flux; the iron losses due to rotating flux are larger than ordinary alternating iron losses, and are known to be a factor acting to increase total iron losses.[1] This difference depends on the spatial phase relation between the magnetic field vector $\boldsymbol{H}$ and the magnetic flux density vector $\boldsymbol{B}$. Hence the magnetic properties obtained solely through scalar measurements are inadequate for optimal design of electrical machines, which generate rotating magnetic flux. We previously pointed out the need for *two-dimensional magnetic measurements* (*vector measurements*) in alternating and in rotating magnetic fields, in order to better understand the detailed behavior of magnetic flux within materials, and reported on the two-dimensional magnetic characteristics obtained by such methods.[1]

When performing magnetic field analyses using the finite element method or some other technique, the magnetic properties of the material must be input, and when the directions of the ***B***-vector and the ***H***-vector differ, the magnetic reluctivity to be input is the tensor quantity.

In the first half of this paper, we describe the *two-dimensional* (*vector*) *magnetic properties* by the *two-dimensional magnetic measurement method*, and the improved magnetic field analytical method considering the magnetic reluctivity tensor.

And then the typical magnetic phenomena measured by two-dimensional magnetic measurement are presented in the latter half of this paper. These are two kinds of phenomena. One is about a three-dimensional magnetstriction by two-dimensional measurement with special three-axis strain gauge. Another is about the development of chaos in *Rotational Barkhausen Signal* under rotating flux condition. A chaos attractor was introduced from this signal.

II. DEFINITIN OF VECTOR MAGNETIC PROPERTY

In our conventional magnetic field analysis, the vector magnetic properties of the arbitrary direction under the alternating flux condition were expressed as reluctivity tensor by following equation:

$$\begin{Bmatrix} H_x \\ H_y \end{Bmatrix} = \begin{bmatrix} \nu_x & 0 \\ 0 & \nu_y \end{bmatrix} \begin{Bmatrix} B_x \\ B_y \end{Bmatrix}, \tag{1}$$

$$\nu_x = f_x(B,\theta_B), \quad \nu_y = f_y(B,\theta_B). \tag{2}$$

The reluctivity ν_x and ν_y depend on magnetic flux density B and an inclination angle θ_B as shown in Eq.(2). However, this expression is unable to express the alternating hysteresis. Because even if and equal to be zero, and are not zero when the alternating hysteresis exists like Fig. 1.

Accordingly, we define the relationship between ***B***- and ***H***-vector considering the both alternating and rotating hysteresis as follows:

$$\begin{cases} H_x = \nu_{xr} B_x + \nu_{xi} \dfrac{\partial B_x}{\partial t} \\ H_y = \nu_{yr} B_y + \nu_{yi} \dfrac{\partial B_y}{\partial t} \end{cases}, \tag{3}$$

$$\nu_{xr} = f_{xr}(B,\theta_B), \quad \nu_{yr} = f_{yr}(B,\theta_B)$$
$$\nu_{xi} = f_{xi}(B,\theta_B), \quad \nu_{yi} = f_{yi}(B,\theta_B)$$

where ν_{xr}, ν_{xi}, ν_{yr} and ν_{yi} are expressed by consideration of the 3rd harmonic component as follows:

$$
\begin{cases}
\nu_{xr} = k_{xr1} + k_{xr2}B_x^2 + k_{xr3}B_x\left(\dfrac{\partial B_x}{\partial t}\right) + k_{xr4}\left(\dfrac{\partial B_x}{\partial t}\right)^2 \\
\nu_{xi} = k_{xi1} + k_{xi2}B_x^2 + k_{xi3}B_x\left(\dfrac{\partial B_x}{\partial t}\right) + k_{xi4}\left(\dfrac{\partial B_x}{\partial t}\right)^2 \\
\nu_{yr} = k_{yr1} + k_{yr2}B_y^2 + k_{yr3}B_y\left(\dfrac{\partial B_y}{\partial t}\right) + k_{yr4}\left(\dfrac{\partial B_y}{\partial t}\right)^2 \\
\nu_{yi} = k_{yi1} + k_{yi2}B_y^2 + k_{yi3}B_y\left(\dfrac{\partial B_y}{\partial t}\right) + k_{yi4}\left(\dfrac{\partial B_y}{\partial t}\right)^2
\end{cases}
\tag{4}
$$

The coefficients k_{xrn}, k_{xin}, k_{yrn} and k_{yin} (n=1, 2, 3, 4) are obtained from the measurement data.

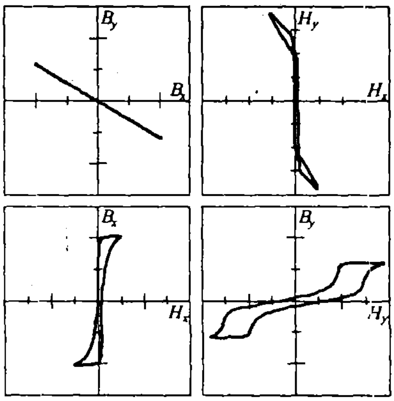


Fig. 1 Measured data under the alternating flux condition.

The specimen used in this study is a grain-oriented steel sheet (23ZDKH90 produced by NSC, 0.23 mm thickness). Because we have not enough space, we omit the detailed description of the vector magnetic measurement apparatus.[2] Substituting (3) into Maxwell's equations in a two-dimensional quasi-static magnetic field, we can obtain the following equation with the vector potential A (= A_z):

$$
\frac{\partial}{\partial x}\left(\nu_{yr}\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{xr}\frac{\partial A}{\partial y}\right) + \frac{\partial}{\partial t}\left\{\frac{\partial}{\partial x}\left(\nu_{yi}\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{xi}\frac{\partial A}{\partial y}\right)\right\} = -J_0 \tag{5}
$$

where J_0 is the exciting current density.

Next, we calculate the distribution of iron loss in the cores. The iron loss can be calculated directly from analyzed results by the following equation:

$$
P_t = \frac{1}{\rho T}\int_0^T \left(H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt \quad [\mathrm{W/kg}] \tag{6}
$$

where T is the period of the exciting waveform, ρ is the material density. First, we applied the expression presented here to a single-phase transformer core model. This core model was made by cutting off the unnecessary part from rectangular sheets, as shown in Fig. 2. The core was constructed by the grain-oriented steel sheet, and its number of lamination was equal to 40. Since the core has symmetry, a quarter of the region was analyzed.

Fig. 3 shows the distribution of loci of **B**- and **H**-vector calculated with our original method. As shown in Fig. 3(b), **H**-vector was especially large at the corner region of the core. Furthermore, it can be seen that an alternating hysteresis occurs. Fig. 4 shows the distribution of iron loss given by Eq. (6). (see appendix as measured results for comparison.)

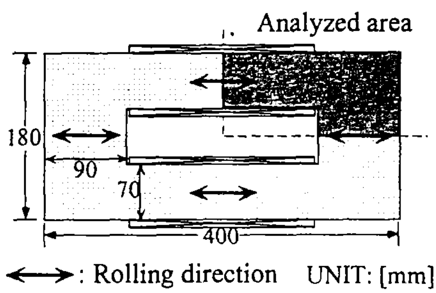
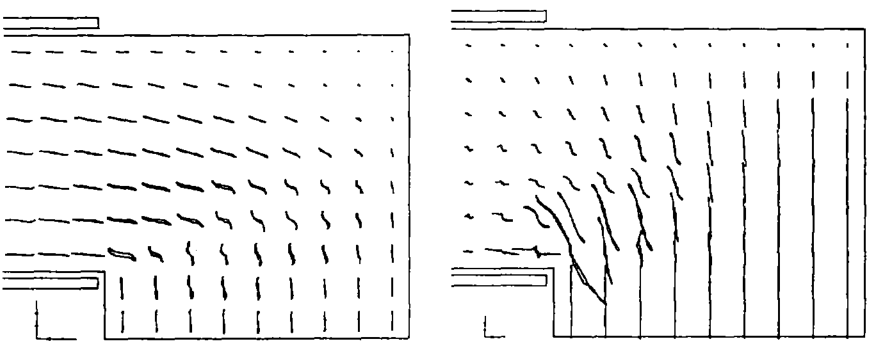


Fig. 2 The single-phase transformer core model.



(a) Loci of **B**-vector

(b) Loci of **H**-vector

Fig. 3 Loci of calculated B- and H-vector.

Fig. 4 Distribution of calculated iron loss.

IV. LOCALIZED DISTRIBUTION OF VECTOR MAGNETIC PROPERTIES OF GRAIN-ORIENTED SILICON STEEL SHEET.

Fig. 6 shows the loci of the ***B***- and ***H***-vector at each measuring position as shown in Fig. 5, respectively. Most loci of the ***B***-vectors were alternating, but some of the loci became a slender rotational shape. The loci of the ***H***-vectors were quite different from those of the ***B***-vectors, and the shapes were dependent on the grain size and its location. There were large differences in loci of ***H***-vectors at each position. The ***H***-vector is always not parallel to ***B***-vector. Though the misorientation is very small, the magnetic proprieties differ by the place. Especially, to get the uniform ***B***-vector distribution, the ***H***-vector is largely influenced considerably surrounding the situation. From the facts described above, we may conclude that the magnetic properties is not uniform in the sheet by effects of grain orientation, grain boundary shape, the missing grain in the large grain.[3][4][5]

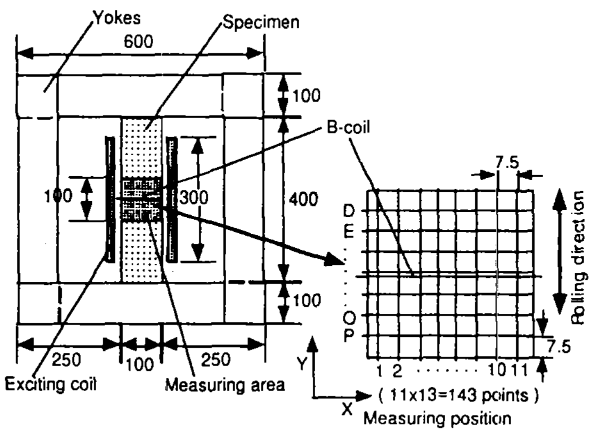
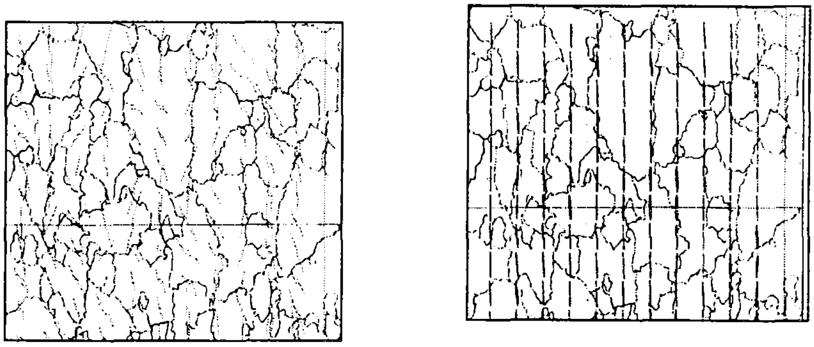


Fig. 5 Measuring apparatus and area.



(a) The loci of *H*-vect (b) The loci of *B*-vector.

Fig. 6 The loci distribution of **H**- and **B** – vector in f=50 [Hz]

Figs. 7 and 8 show the relation between the magnetic domain structure and vector magnetic properties. From these results, we can indicate the effect of the grain boundary on iron loss.

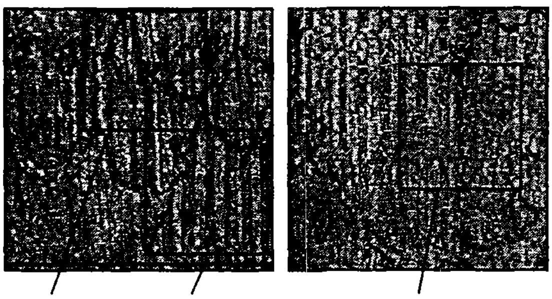


Fig. 7 Magnetic domain structure at some measurementpoints

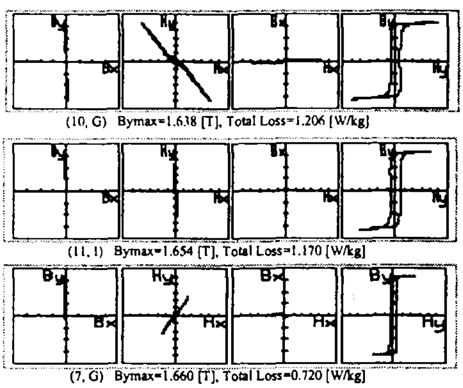


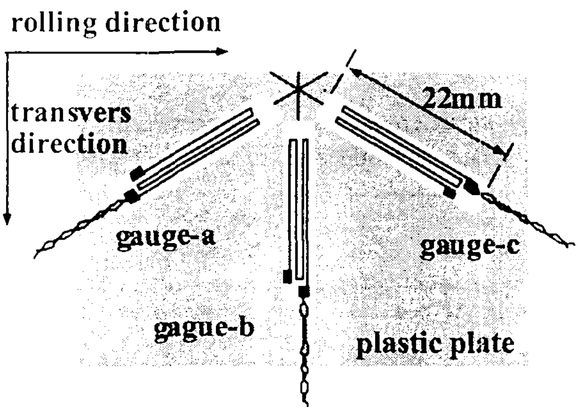
Fig. 8 The loci of B- and H-vectors and the hysteresis loop for the X,Y components atsome measuring position. The axis of B is 0.5 ([T]/div.). The axis of H is 50 ([A/m]/div.).

V. VECTOR MAGNETOSTRICTION[6][7][8]

Let show the definition of magnetostriction from new viewpoint. Conventional measurement method is not useful for the grasp of the whole behavior, because the behavior of magnetostriction depends on both direction and magnitude of ***B***-vector. We have introduced tensor method for the determination of exact behavior of magnetostriction.

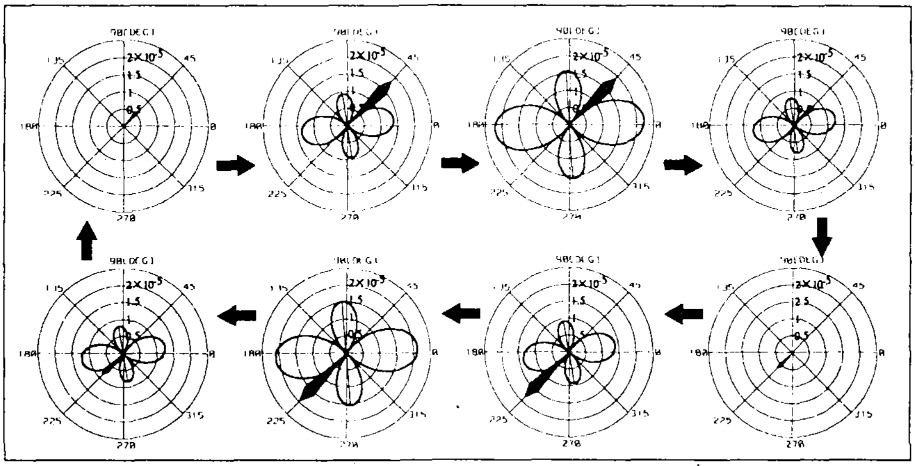
In general, it is indicated that the direction of the main magnetostriction usually differs from that of the flux density ***B***-vector. It is therefore necessary to use the three-axis strain gage in those measurements. We have developed a new gage that can remove the influence of outer magnetic field and applied it to measuring the two-dimensional magnetostrictions with two-dimensional magnetic measurement apparatus. The results show that the new gage is very useful in measuring the rotational properties. Fig. 9 shows the new strain gage construction (SKF-5964), which can measure three components of magnetostrictions.

Fig.10 shows the two-dimensional behavior of magneostriction by two-dimensional magnetic measurement methcd. Magnetostriction increases with increasing magnetic flux density, but it is not parallel to the direction of magnetic flux density ***B***-vector. As shown Fig. 10, though the magnetostriction of parallel direction component in the ***B***-vector is very small, in the different direction from the ***B***-vector, the large strain is generated. This result is completely different from the conventional result.



Gauge length :15 mm Gauge resistance :350 - 2.5, Gauge factor : 2.02 - 2.0%

Fig. 9 Construction of new type stain gauge for measurement of vector magnetostriction



Specimen : 30ZH Inclination angle : 45 [deg]

Alternating flux condition Bmax : 1.0 [T] . λaxis : 2.5 A10^{-5}(full scall)

: Magnetic flux density vector ------: Direction of maximum magnetostriction

Fig. 10 Two-dimensional magnetostriction (30ZH Alternating flux conditions)

VI. ROTATIONAL BARUKHAUSEN SIGNAL AND CHAOS.

A new phenomenon was discovered, which is called Rotational Barkhausen Noise by using special sensor. [9][10][11][12] This signal is very useful in detecting internal stress of magnetic material and sensitive, too.

Fig. 11 shows the Barkhausen noise under alternating and rotational flux conditions, which are called "*Alternating Barkhausen Signal* (conventional Barkhausen signal)" and "*Rotational Barkhausen Signal*". This Rotational Barkhausen Signal is continuous signal in different from alternating one. **Fig. 12** is FFT's result in the case of non-oriented silicon steel sheet. These signals are imported in computer system through the wave memory analyzer. By analyzing this signal, we have found the chaos attractor as shown in **Figs. 13(a) and (b).**

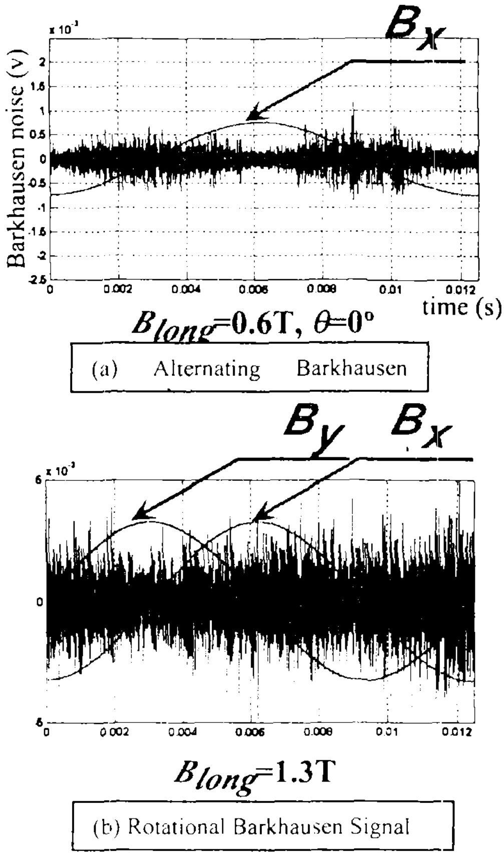


Fig. 11 Barkhausen Signal.

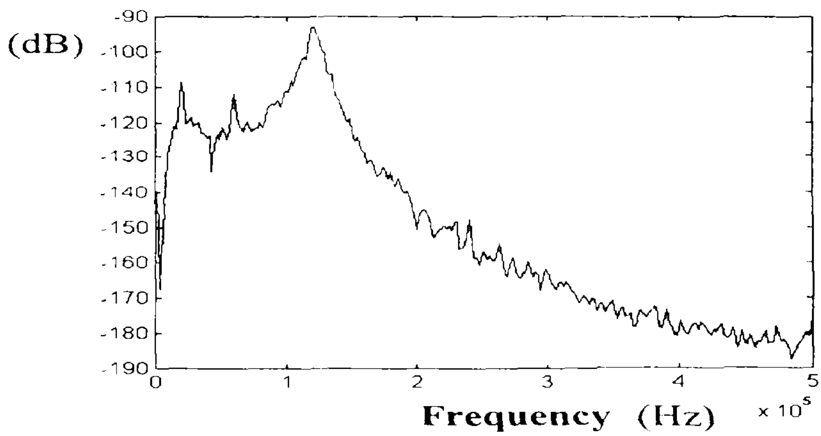
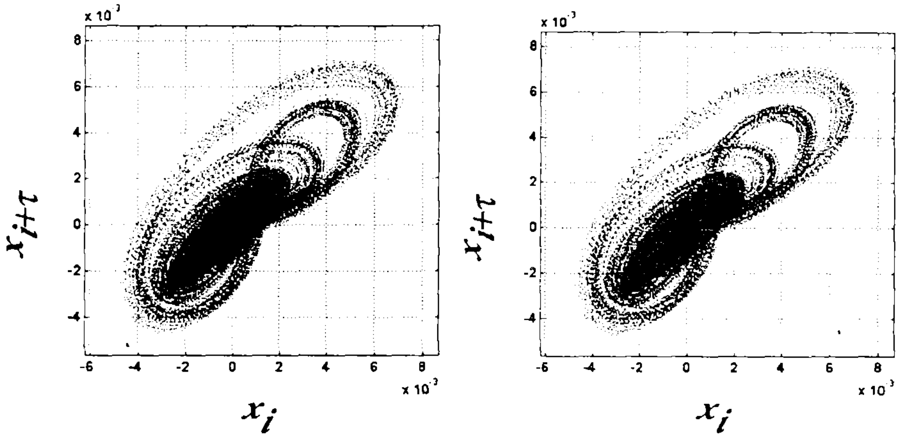


Fig. 12 FFT's result of Rotational Barkhausen Signal.

Furthermore, we discussed this attractor by using *Lyapunov exponent*. We concluded that this signal had chaotic and original attractor



(a) f =4000 [Hz], non-oriented sheet. (b) f = 5000 [Hz], non-oriented sheet.

Fig. 13 Attractor of rotational Barkhausen noise.

VII. CONCLUSIONS.

In this paper some interesting phenomena concerning two-dimensional magnetic properties which are magnetic properties as a vector quantity, localized distribution of two-dimensional magnetic properties, three dimensional behavior of magnetostriction, development of rotational Barkhausen signal called as "*Rotational Barkhausen Signal*". We claimed that magnetic property is the relationship between magnetic field strength ***H***-vector and magnetic flux density ***B***-vector. We cannot design the efficiency machine and new development by new material without our concept of vector magnetic properties. In conventional analysis, some results were obtained by using scalar quantity in spite of vector field analysis. Almost behaviors between ***H***- and ***B***-vector have nonlinear relation on not only magnitude but also spatial phase.

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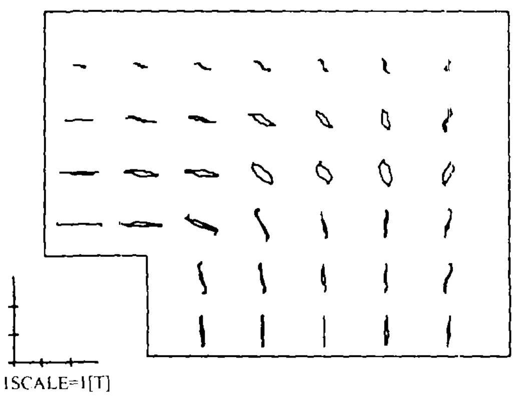
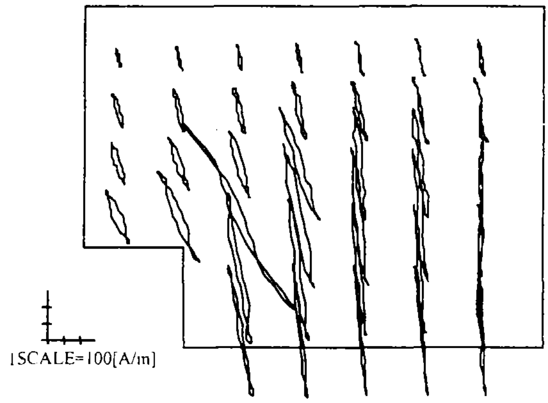
APPENDIX

Figs A and B show the measured results by the two-dimensional measurement sensor of model core in Fig. 2.



(a) Loci of ***B***-vector



(b) Loci of H-vector

Fig. A. Loci of measured B- and H-vector.

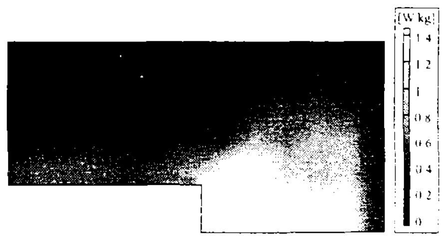


Fig. B. Distribution of measured iron loss.