THREE DIMENSIONAL ANALYSIS OF A CYLINDER-TYPE FLUX CONCENTRATION APPARATUS

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ABSTRACT

This paper deals with three dimensional A-ϕ analysis of a newly developed cylinder-type flux concentration apparatus. We have already examined and analyzed several types of such apparatus, which utilize the flux concentration effect of eddy currents. [1][2][3] The new model treated here, attains compactness in size and high efficiency in flux concentration by assembling a conducting plate just inside one or several excitation windings.

A new four-component direct finite element calculation method is applied to the present analysis, and three dimensional distributions of the flux density; the eddy current and the scalar potential are obtained successfully. The divided direct calculation method is discussed in comparison with our former iterative method.

FLUX CONCENTRATION APPARATUS

An ac flux contentration apparatus, which has been investigated at Kanazawa University since 1981 [4], has changed its style three times. The first fundamental model is the one with two conducting plates placed in parallel between a pair of ac excited coils. The second model is made by placing two more plates just onto the plates of the first one in an orthogonal direction. The present third model is a circular one with some ac coils positioned around one conducting plate. This new type attains compactness in size, as well as high efficiency in flux concentration. Newly-built rims of the conductor for excitation windings enhance the flux concentration effect. In each model, flux concentration appears in the central air part due to the induced eddy currents in the conductor.

DIVIDED DIRECT CALCULATION METHOD

In order to analyze the phenomenon caused by eddy currents circulating in a finite conductor, three dimensional finite element A-ϕ method is indispensable. However, the computer memory necessary for the analysis becomes huge because 4 components are required per node, in addition to the 3-D structure.

In addition, the induced scalar potential makes the system matrix not only huge, but also presents a problem concerning the interpretation of its nature. The role of the scalar potential has been discussed for a long time [5][6][7] and many analysts have considered it to be caused from stored electrical charges as in the electric field. They might have cosidered it to be so because the dimension is the same as the electrical potential and because it has never been calculated for the eddy current diffusion pfoblem due to huge size of the system matrix.

In 1986, we solved the four-component system matrx as it is by using an iterative method.[1] In 1987, we clarified the role of the scalar potential by discussing its distribution.[2][3] This time we develop a divided direct calculation method for two reasons. One is that the iterative method is too time-consuming and the other is that much experience is needed for selecting the convergent coefficient. Moreover, it may be added that the general time sharing system of the large-sized computer is enlarging the memory assigned for an individual user, with the development of the computer technology in capacity and speed.

The divided direct calculation method uses the concept of the Gauss elimination method and two divided calculations for each variable of A_x, A_y, A_z, with one time calculation for ϕ. The division of variables makes the more memory-saving possible. The selection of the number of the division should be considered in connection with the allowed computer memory.

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FIELD ANALYSIS EQUATIONS

For a three dimensional, quasi-stationary, eddy current diffusion problem, Maxwell's electromagnetic field equations together with the definition of the magnetic vector potential are stated as follows:

$$\mathrm{rot}\ \bar{H} = \bar{J}_s + \bar{J}_e \quad (1)$$

$$\mathrm{rot}\ \bar{E}_e = -j\omega\bar{B} \quad (2)$$

$$\mathrm{div}\ \bar{B} = 0 \quad (3)$$

$$\mathrm{div}\ \bar{D} = \rho \quad (4)$$

$$\bar{B} = \mu\bar{H} \quad (5)$$

$$\bar{J}_e = \sigma\bar{E}_e \quad (6)$$

$$\bar{B} = \mathrm{rot}\ \bar{A} \quad (7)$$

where, $\bar{J}_s$ and $\bar{J}_e$ are the impressed current and the induced eddy current densities respectively.
Combining these equations shown above, we obtain two fundamental equations for field analysis, under the assumption of constant μ in the x, y, and z directions.

$$\frac{1}{\mu}\nabla(\nabla\bar{A}) - \frac{1}{\mu}\nabla^2\bar{A} = -\sigma(j\omega\bar{A} + \nabla\phi) + \bar{J}_s \quad (8)$$

$$\mathrm{div}\ \{\sigma(j\omega\bar{A} + \mathrm{grad}\ \phi)\} = 0 \quad (9)$$

From(9), the vector potential $\bar{A}$ is replaced as

$$\nabla\bar{A} = -\nabla^2\phi/j\omega \quad (10)$$

Using (10), (8) can be decomposed into three axis-component equations as shown in (11)-(13). Adding (9), the following four equations should be solved simultaneously.

$$-\frac{1}{\mu}\nabla^2 A_x + j\omega\sigma A_x = J_{sx} - (\sigma\nabla\phi)_x + \frac{1}{j\omega\mu}\frac{\partial}{\partial x}(\nabla^2\phi) \quad (11)$$

$$-\frac{1}{\mu}\nabla^2 A_y + j\omega\sigma A_y = J_{sy} - (\sigma\nabla\phi)_y + \frac{1}{j\omega\mu}\frac{\partial}{\partial y}(\nabla^2\phi) \quad (12)$$

$$-\frac{1}{\mu}\nabla^2 A_z + j\omega\sigma A_z = J_{sz} - (\sigma\nabla\phi)_z + \frac{1}{j\omega\mu}\frac{\partial}{\partial z}(\nabla^2\phi) \quad (13)$$

$$\nabla\cdot(\sigma j\omega(A_x\bar{u}_x + A_y\bar{u}_y + A_z\bar{u}_z) + \sigma\nabla\phi) = 0 \quad (14)$$

The finite element formulation used here, is based on a triangular prism element and the Galerkin method. The structure of the combined global system matrix is shown in Fig.1. It seems not only huge due to the four components, but also sparse due to the introduction of

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the scalar potential. The bandwidth is 3N+ M , if the total number of nodes and the bandwidth are assumed to be N and M, respectively, per each component of $\bar{A}$.

Our divided direct method avoids zero submatrices unnecessary for the calculation, using the concept of the Gauss elimination method. Both of the forward elimination process and the backward substitution process, are divided into four stages. In the forward elimination process, at the first stage submatrices of AA, SA and PP are treated in the main processor, at the second, submatrices of BB, SB and PP are treated, at the third, submatrices of CC, SC and PP are treated in the main processor and so on. As to the backward substitution process, at the first stage only PP, at the second, SC and CC, at the third, SB and BB, at the last stage, SA and AA are manipulated in the main processor.

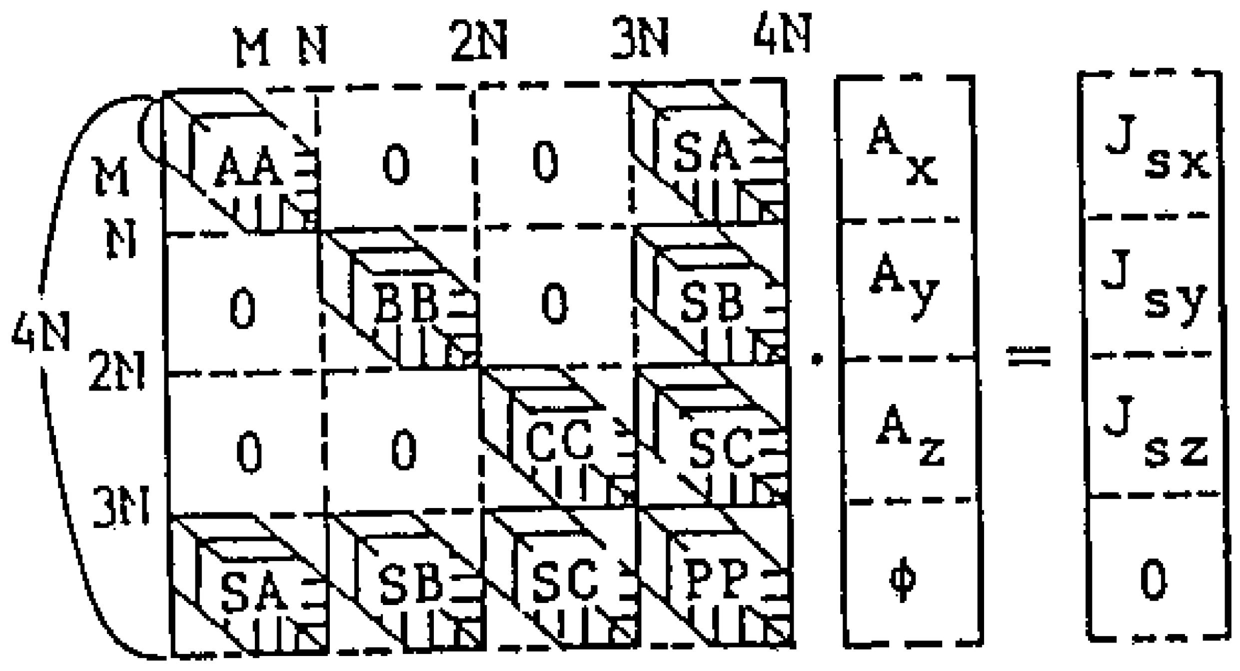


Fig.1 Structure of Global System Matrix

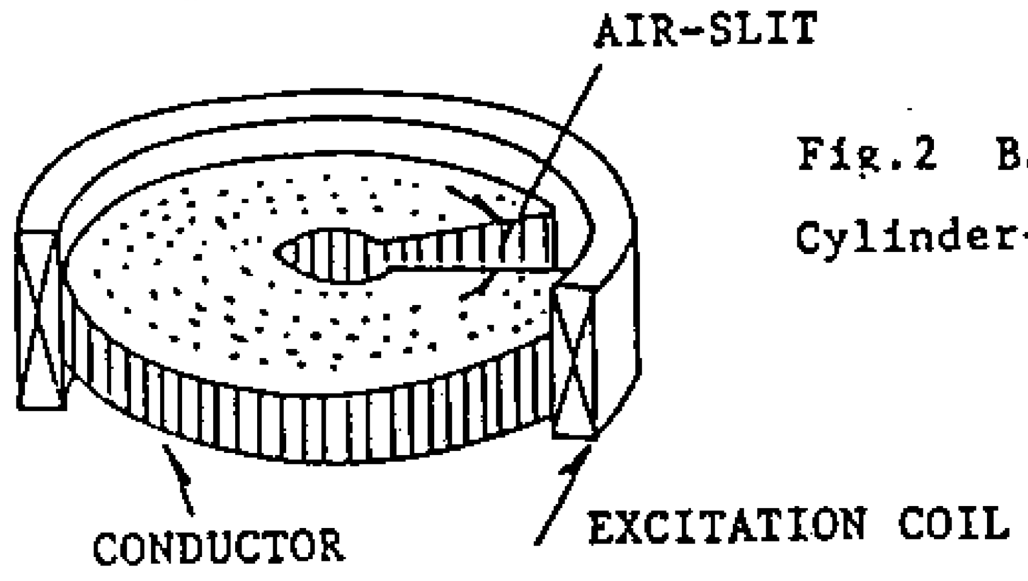


Fig.2 Basic Cylinder-type Model

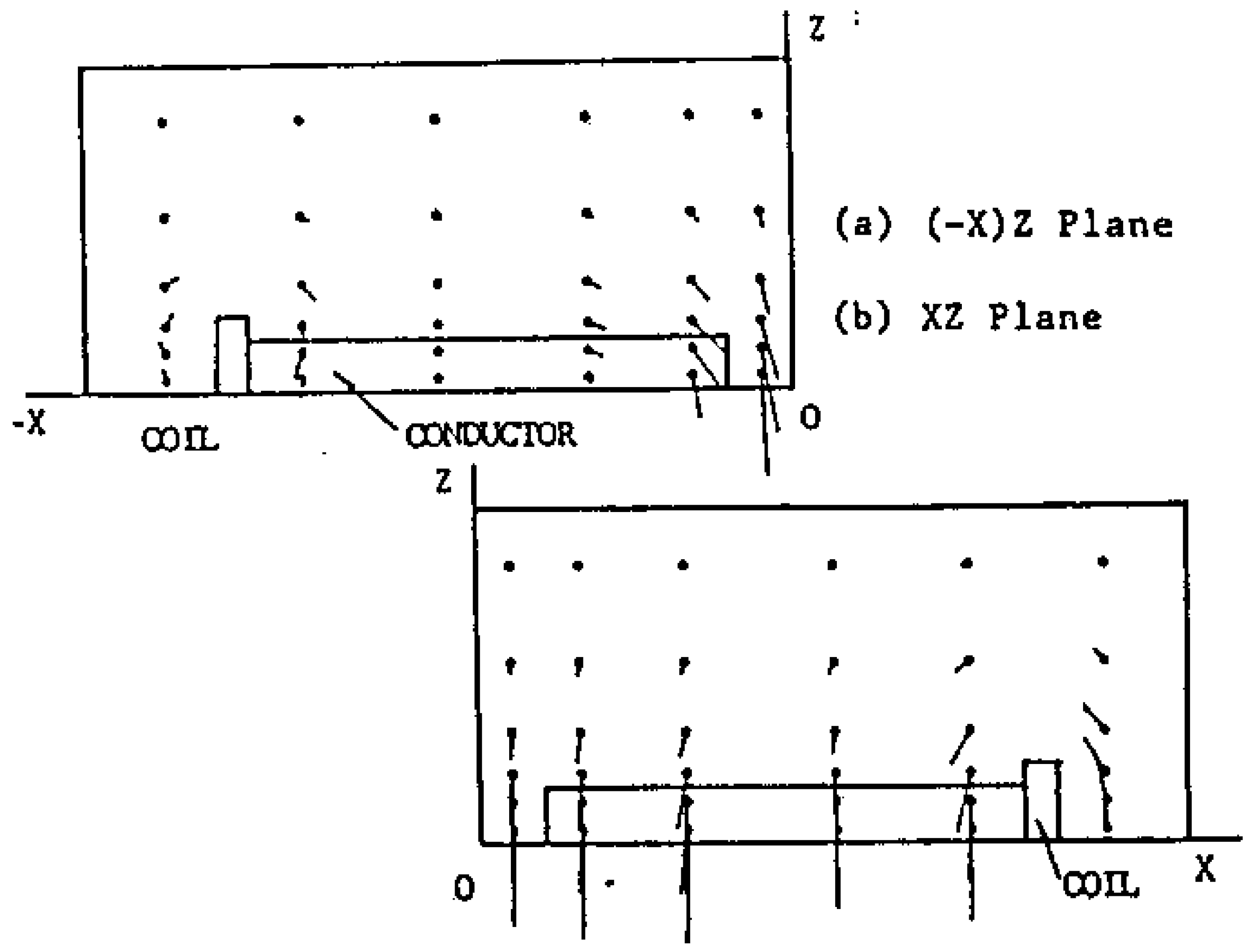


Fig.3 Flux Density Distribution (SDEG=3.75°)

BASIC CYLINDER-TYPE MODEL

Fig.2 shows a basic model of the cylinder-type flux concentration apparatus. It consists of one or several excitation coils and one conductor with a tiny hole and one air-slit in the radial direction.
Ac excitation induces eddy currents in the conductor, which results in concentrating the flux in the central hole. The model attains higher efficiency and makes the structure more compact, compared with the former ones. The reason is because existence of excitation windings just around the conducting plate makes the flux linkage between a conductor and coils denser.

Fig.3-5 shows the results for the model of slit angle SDEG=3.75°, total nodes NP=595 and total elements NE=858. Fig.3 shows distributions of the flux density, (a) for (-X)Z plane, (b) for XZ plane. It is observed that the flux is reflected over the conductor and perpendicular to XY plane along the air-slit. Fig.4 is the distribution of the eddy current density in the central plane. Fig.5 shows the circumferential distribution of the scalar potential. It serves the eddy currents to circulate in the conductor.

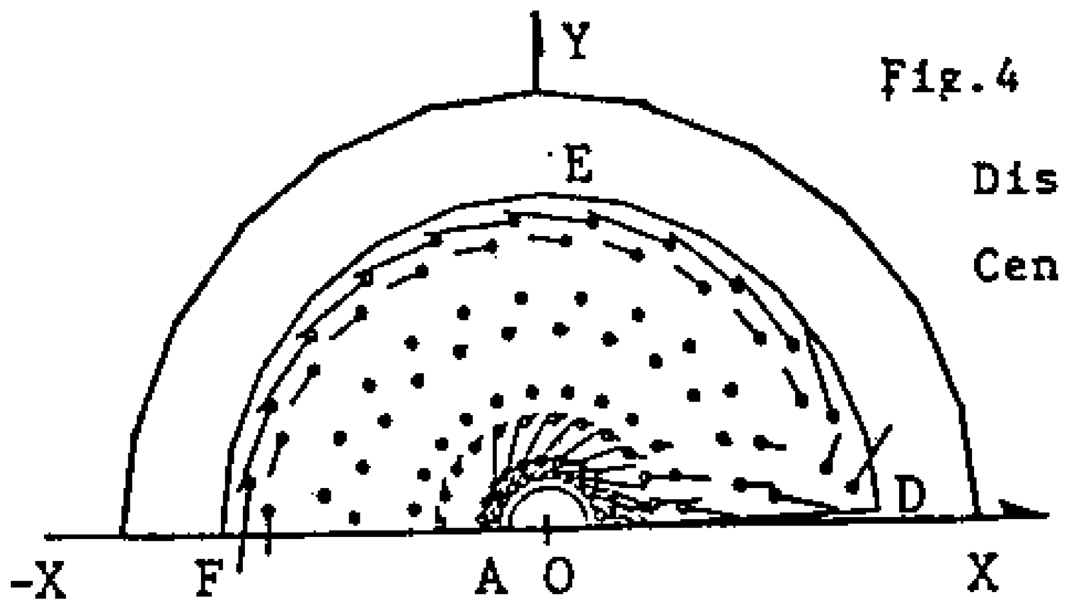


Fig.4 Eddy Current Distribution in Central Plane

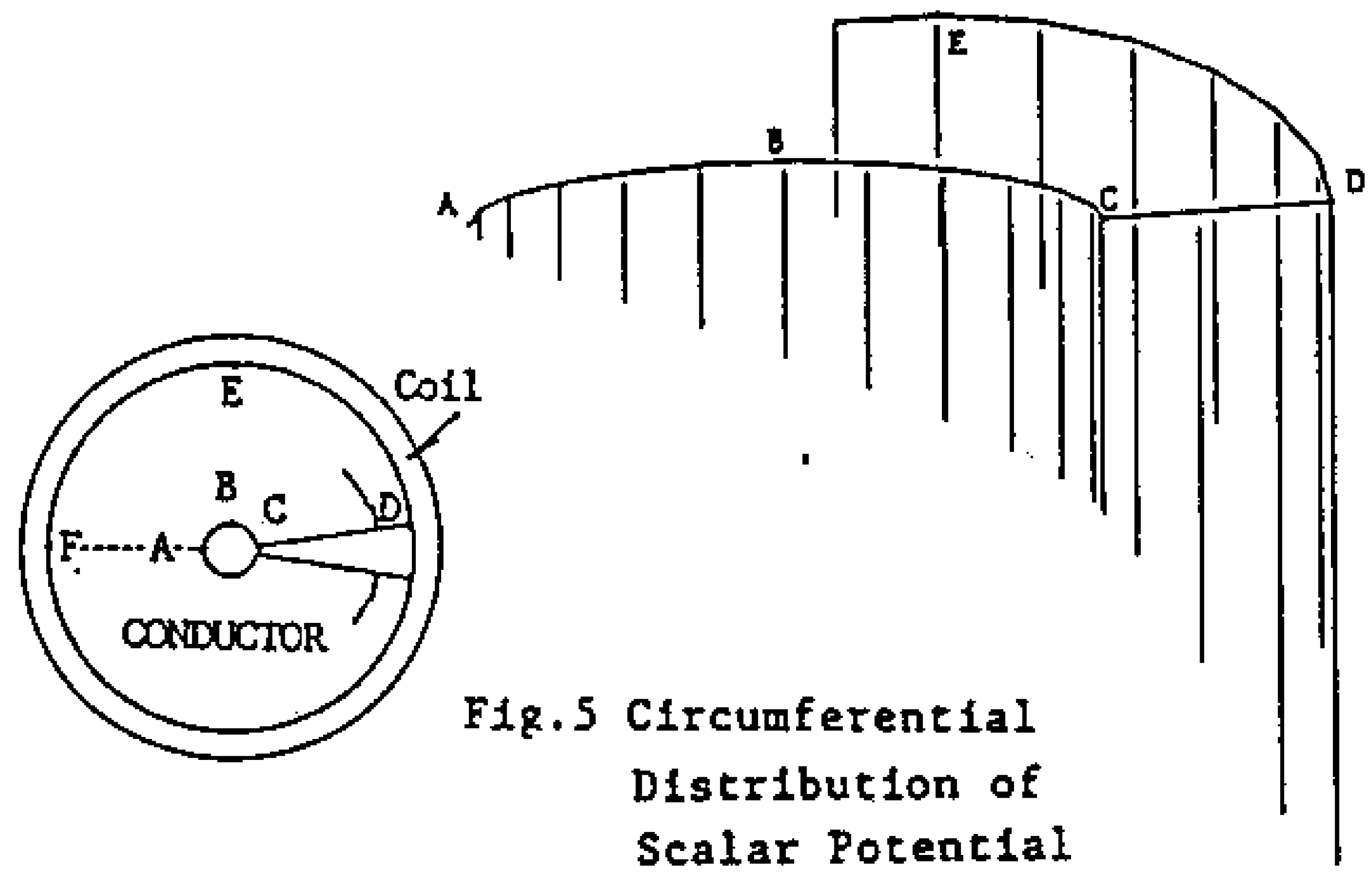


Fig.5 Circumferential Distribution of Scalar Potential

MODEL WITH MULTI-RIMS

In order to improve the degree of flux concentration, several rims and multi-windings are found effective. Fig.6 shows the relation between the number of windings and the factor of flux concentration (or flux density). FEM calculation is made on the model with three rims and two windings as shown in Fig.7.
One fourth of the model of total nodes NP=1098 and total elements NE=1625 is analyzed. The Dirichlet boundary condition is imposed on the outer boundary surface with zero vector potential along z-axis.
As for the boundary condition of the scalar potential, zero values are set on the (-X)Z plane. Frequency of the impressed current is 60 Hz, the conductivity of the copper plate 8.62×10^7 S/m, the width of the slit 3.0 mm, and the ampere turn of the coil 2.0×10^{-12} AT/mm^2.

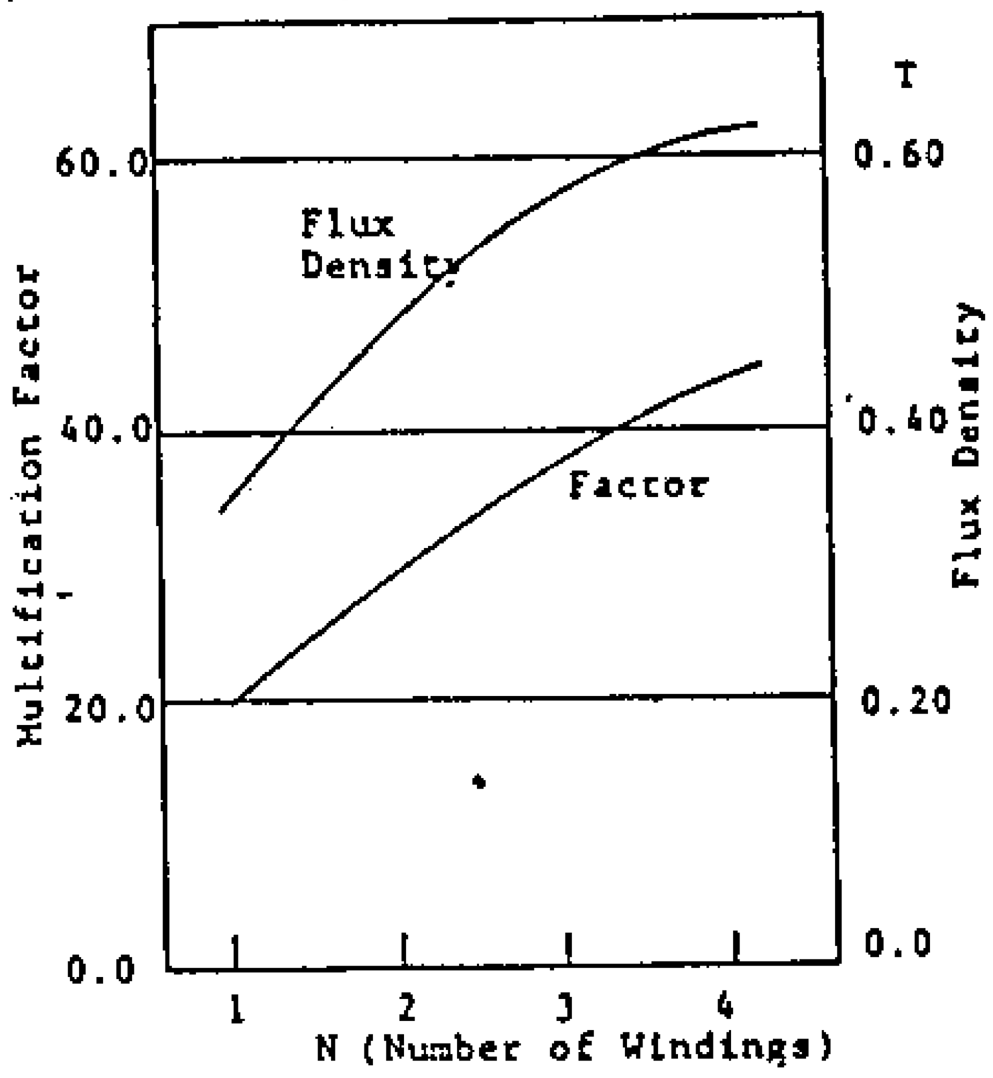


Fig.6 Flux Density vs. Number of Windings (at 100 V)

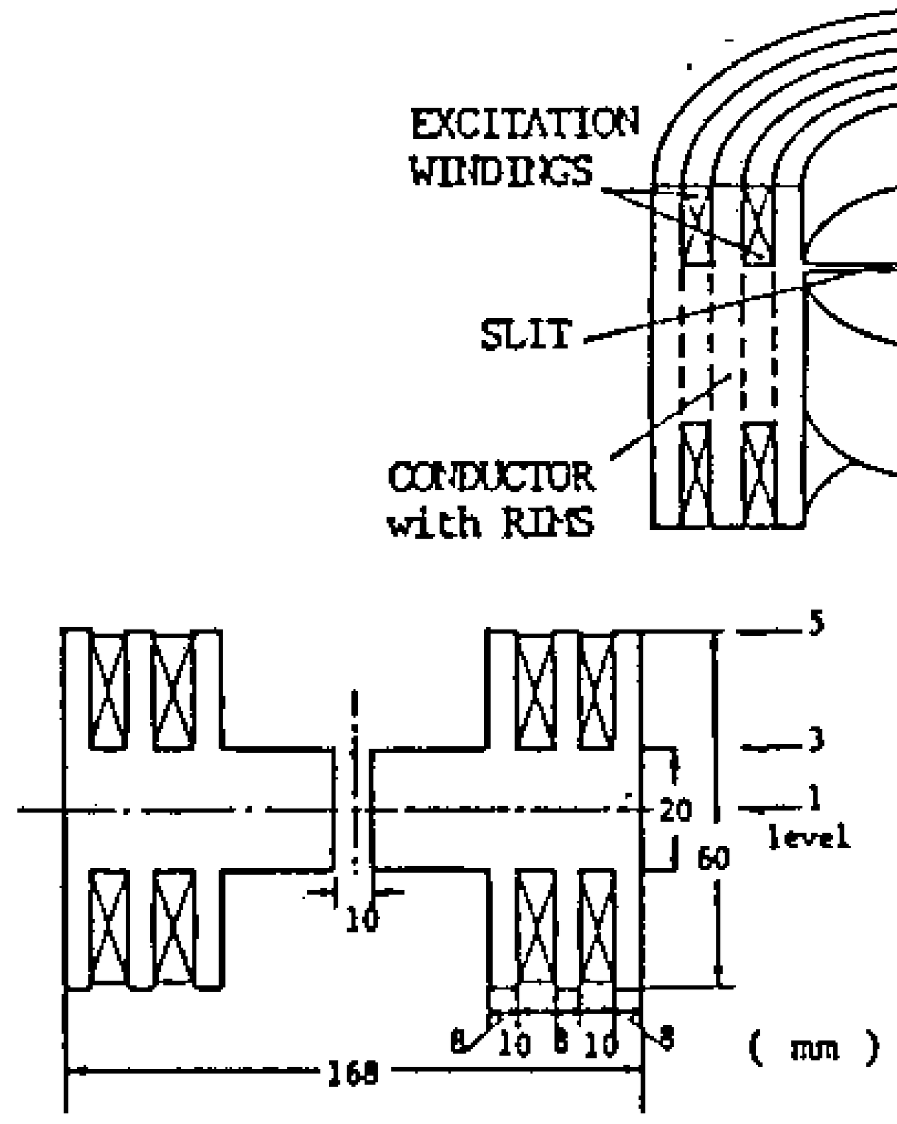
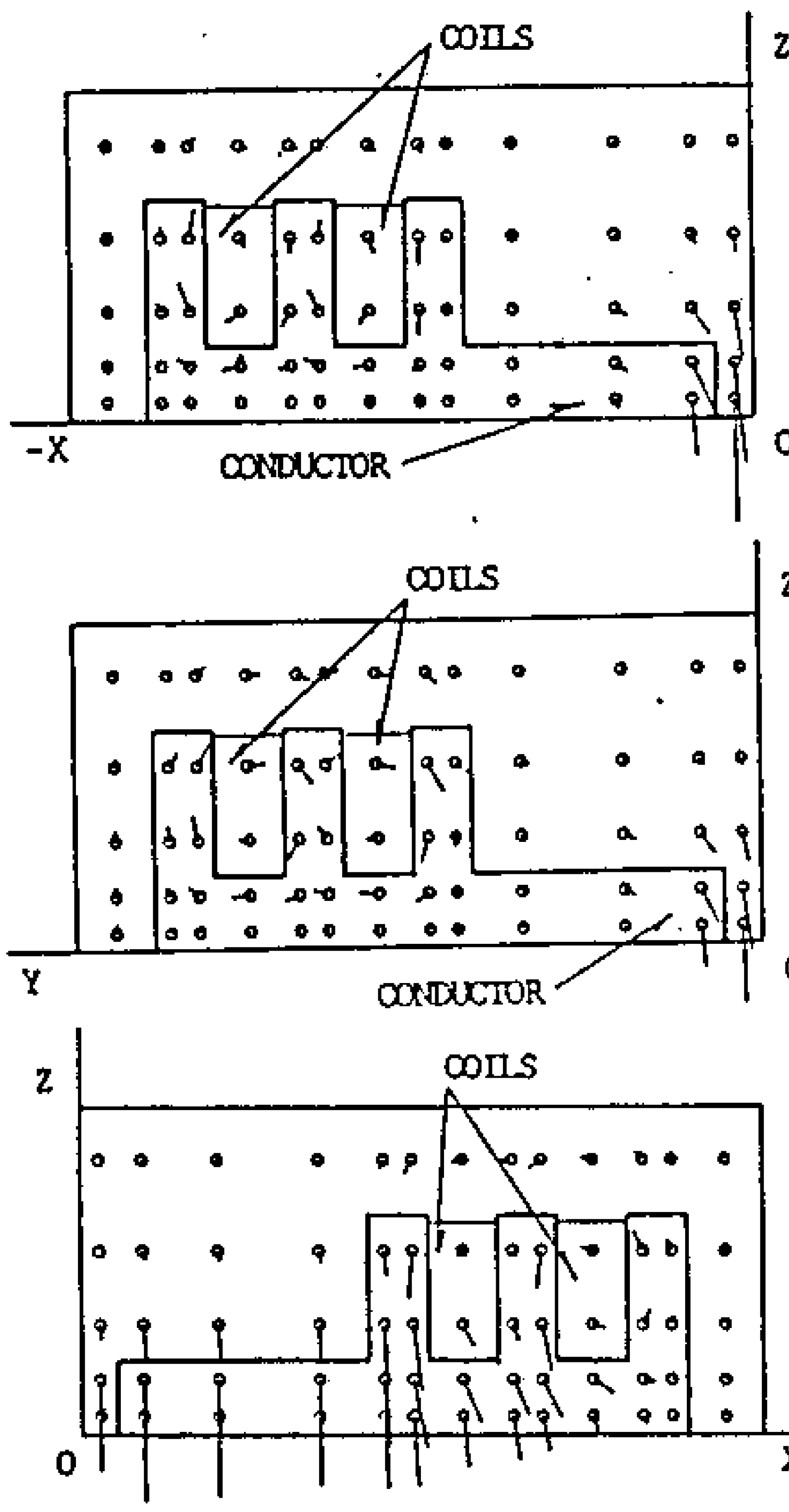


Fig.7 Model with 3 Rims and 2 Windings

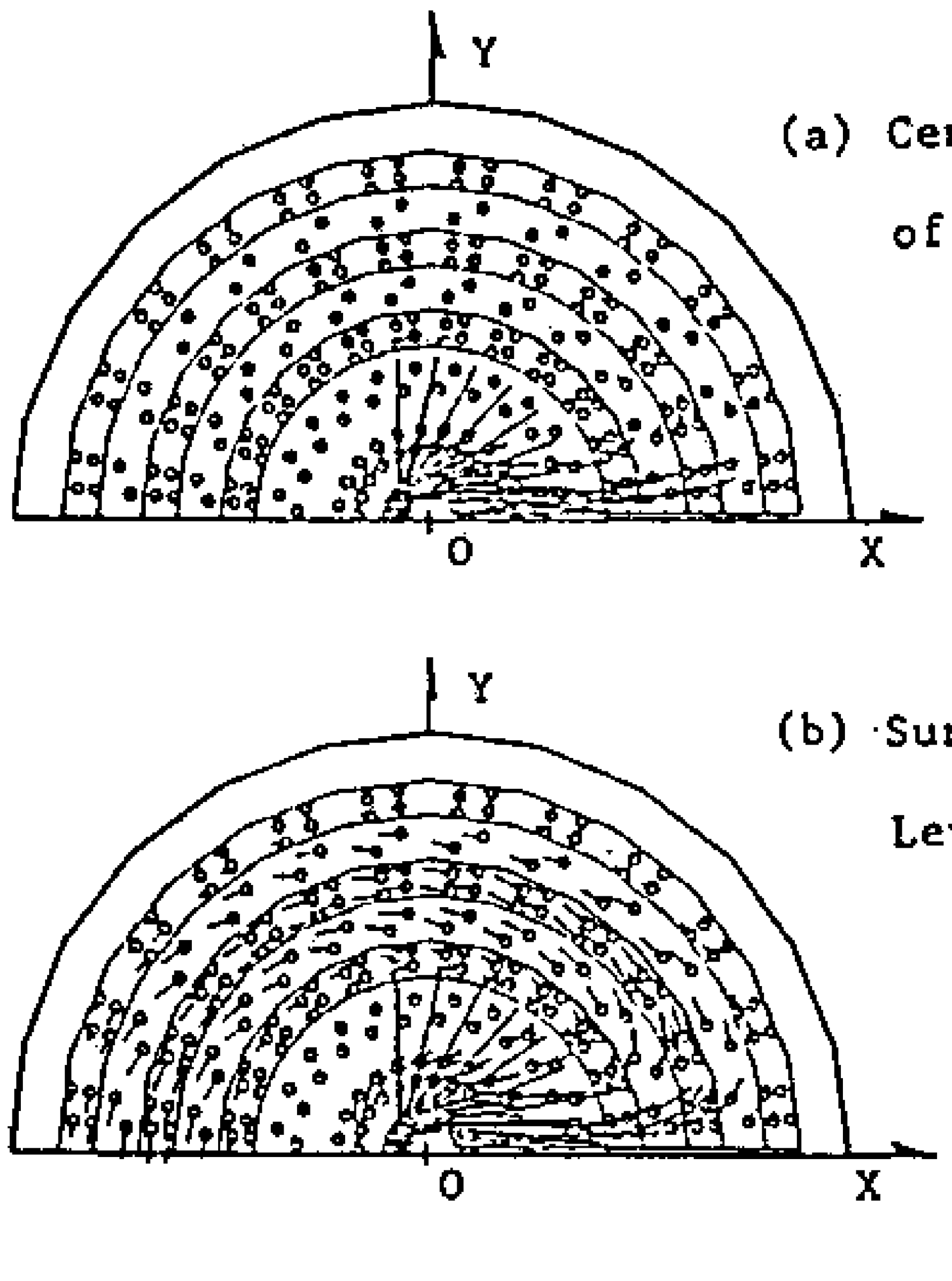


(a) (-X)Z Plane

(b) YZ Plane

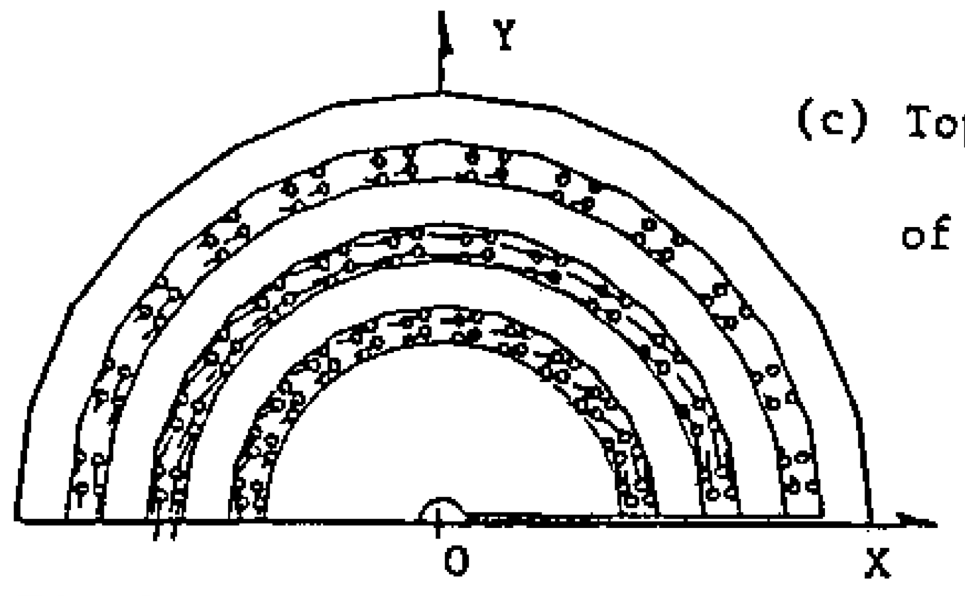
(c) XZ Plane

Fig.8 Flux Density Distribution



(a) Central Plane of Level 1

(b) Surface of Level 3



(c) Top Surface of Level 5

Fig.9 Eddy Current Distribution

Fig.8 shows the distributions of the flux density, (a) for (-X)Z plane, (b) for YZ plane, (c) for XZ plane. It is also observed that the flux density is higher in the left side in the hole. Fig.9 shows the distributions of the eddy current density, (a) for the central plane of level 1, (b) for the surface of level 3, (c) for the top surface of level 5.
In this analysis, one fourth of the model should be treated, because of the existence of two symmetric planes. Every submatrix in this analysis comes to have the bandwidth of about two times as that in the case that one eighth region is treated. As a whole, this model is memory-consuming.

CONCLUSION

Two models of the cylinder-type flux concentration apparatus are analyzed by applying a newly developed 3-D divided direct method of calculation. In spite of the memory consuming model, we obtained the distributions of the flux density and the current density, as well as the scalar potential. It is observed that eddy currents concentrate in the inner circumference of the conductor and contribute to strengthen the flux density in the hole, especially in the left side. The distribution of the scalar potential is confirmed to correct the flow of the eddy current not so as to flow out of the conductor. It is also confirmed that multi-rims are usefull to intensify the flux concentration effect by increasing the linkage of the magnetic field.

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