THREE DIMENSIONAL FLOW OF EDDY CURRENTS IN FLUX CONCENTRATION APPARATUS

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ABSTRACT

This paper deals with three dimensional analysis of the eddy current distribution in a cylinder-type flux concentration apparatus by using a four component finite element calculation method. In order to solve z-ward component of eddy currents in a new model with multi-rims, boundary conditions of four components are discussed. We have already examined and analyzed several types of flux concentration apparatus, which utilize the flux concentration effect of eddy currents [1][2][3][4]. However, in these models treated in the references shown above, we do not have to consider the current component perpendicular to the excitation current. In order to obtain three dimensional flow of eddy currents, boundary conditions for four variables should be selected carefully. Boundary conditions especially for z-ward vector potential and the scalar potential are discussed.

INTRODUCTION

We have already analyzed several types of flux concentration apparatus, which utilize the flux concentration effect of eddy currents [1][2][3][4]. By using a four component three dimensional finite element calculation method, we have obtained the distributions of the flux density, the eddy current and the scalar potential. In these references, the role of the scalar potential has also been discussed.

An a.c.-type device for flux concentration, which is investigated at Kanazawa University since 1981, has changed its form four times. The first fundamental model was the one with two conducting plates in parallel between a pair of a.c.-excited coils. The second model was made by placing two more plates just onto the plates of the first model in orthogonal direction. The third model is a circular one with some a.c. coils positioned around one conducting plate. This type attains compactness in size, as well as high efficiency in flux concentration. In each model flux concentration appears in the central air part due to the induced eddy currents in the conductor. However, most models in the references shown above, do not have z-ward component of eddy currents.

To improve the flux concentration effect a new circular-type model with some rims for excitation windings is recently under investigation [4]. Eddy currents flow mainly horizontally along the edge of the conductor, while remaining part flows upward in the rims. Though the z-ward component of eddy currents in the rims has been difficult to obtain, we succeed in getting reasonable distributions of z-ward eddy currents.

The existence of the z-ward component of eddy currents demands proper combination of boundary conditions for four variables. Especially, boundary conditions for z-ward vector potential and the scalar potential are essential. Examination using computation results has been made.

FIELD ANALYSIS EQUATIONS

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

$$\mathrm{rot}\ \bar{H} = \bar{J}_s + \bar{J}_e \tag{1}$$

$$\mathrm{rot}\ \bar{E}_e = -j\omega\bar{B} \tag{2}$$

$$\mathrm{div}\ \bar{B} = 0 \tag{3}$$

$$\mathrm{div}\ \bar{D} = \rho \tag{4}$$

$$\bar{B} = \mu\bar{H} \tag{5}$$

$$\bar{J}_e = \sigma\bar{E}_e \tag{6}$$

$$\bar{B} = \mathrm{rot}\ \bar{A} \tag{7}$$

where, J_s and J_e are the density of exciting current and the induced eddy current density, 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.

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

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

The finite element formulation used here, is based on a triangular prizm element and the Galerkin method. The structure of the combined global system matrix is shown in Fig.1. The system of the equations is solved by using our divided direct calculation method [4].

Z-WARD EDDY CURRENTS

Eddy currents can be obtained from the following relation.

$$J_e = -j\omega\sigma\bar{A} - \sigma\ \mathrm{grad}\ \phi \tag{10}$$

Three components of eddy currents are

$$J_x = -j\omega\sigma A_x - \sigma(\mathrm{grad}\phi)_x \tag{11}$$

$$J_y = -j\omega\sigma A_y - \sigma(\mathrm{grad}\phi)_y \tag{12}$$

$$J_z = -j\omega\sigma A_z - \sigma(\mathrm{grad}\phi)_z \tag{13}$$

In the flux concentration models described in [1][2][3], there are no z-ward excitation currents and conductors used are flat. As a result, z-ward eddy currents do not exist and we do not have to consider the z-ward vector potential. The cylinder-type model we are now developing has multi-rims to improve the flux multification factor. It consists of one or several excitation coils and one conductor with multi-rims. The multi-rims for excitation windings work to improve concentration efficiency by making the flux linkage between the conductor and windings denser.

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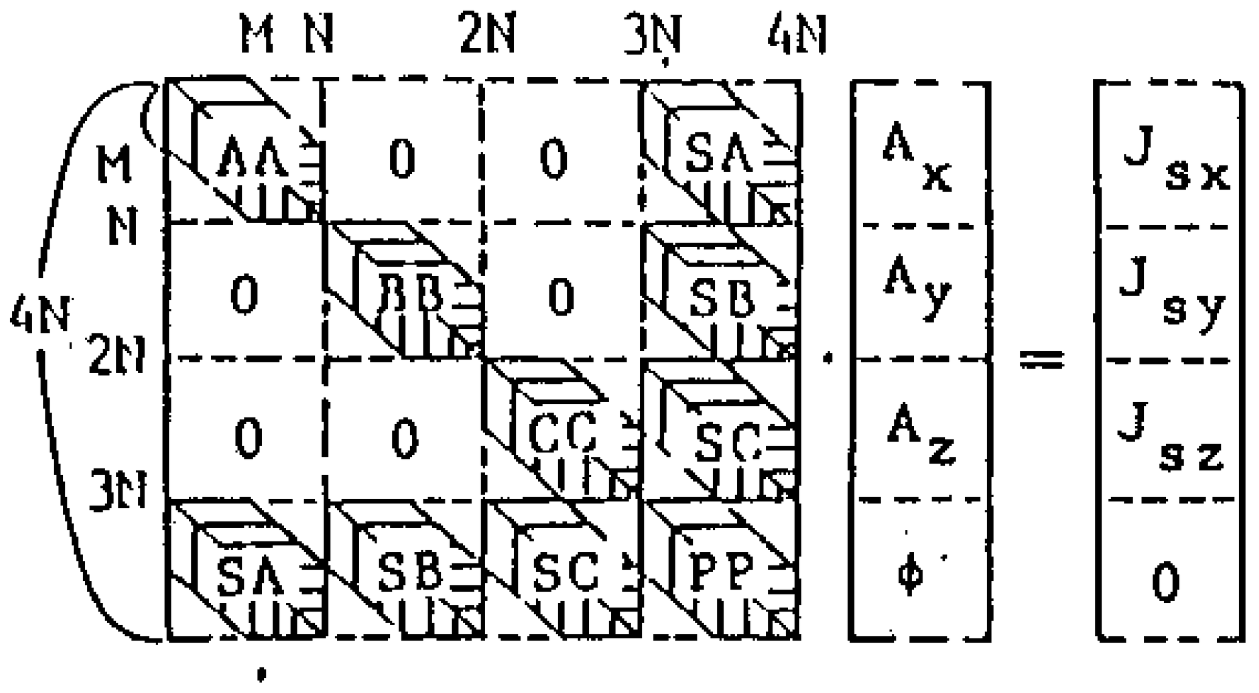
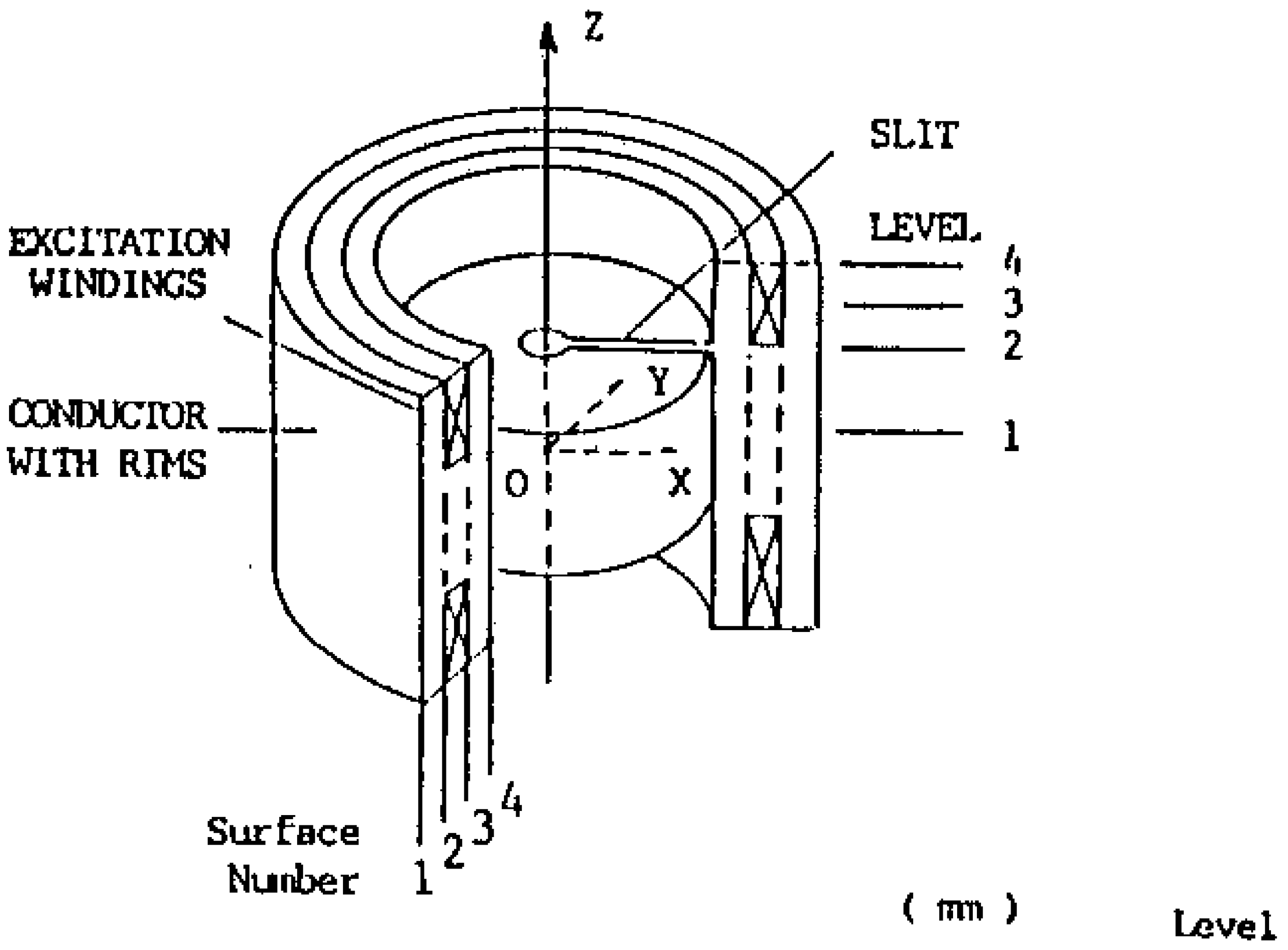


Fig.1 . Structure of Global System Matrix



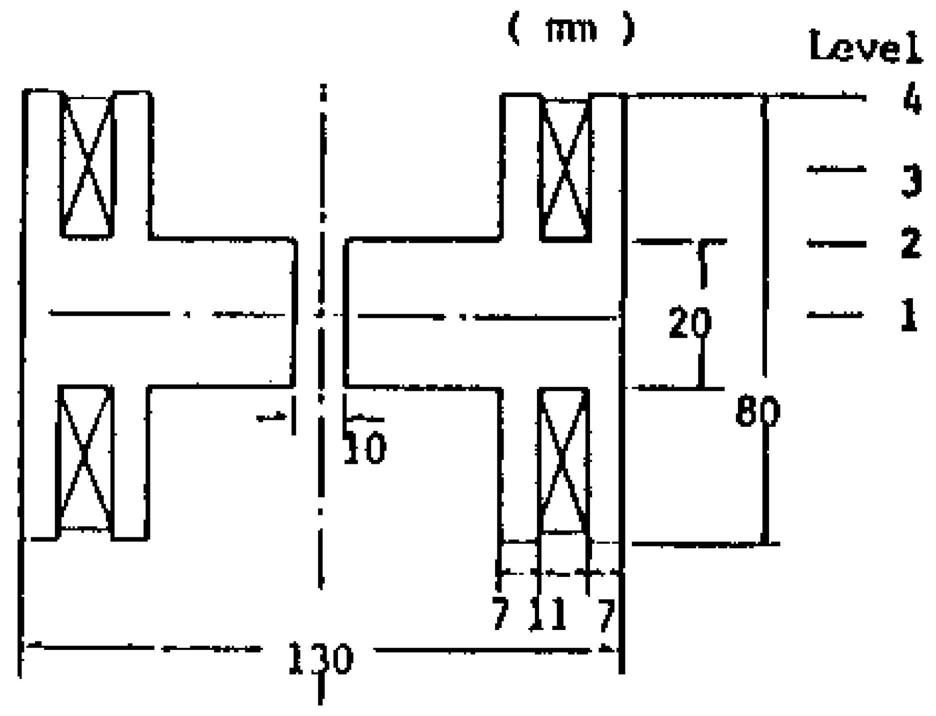


Fig.2
Model
Configuration

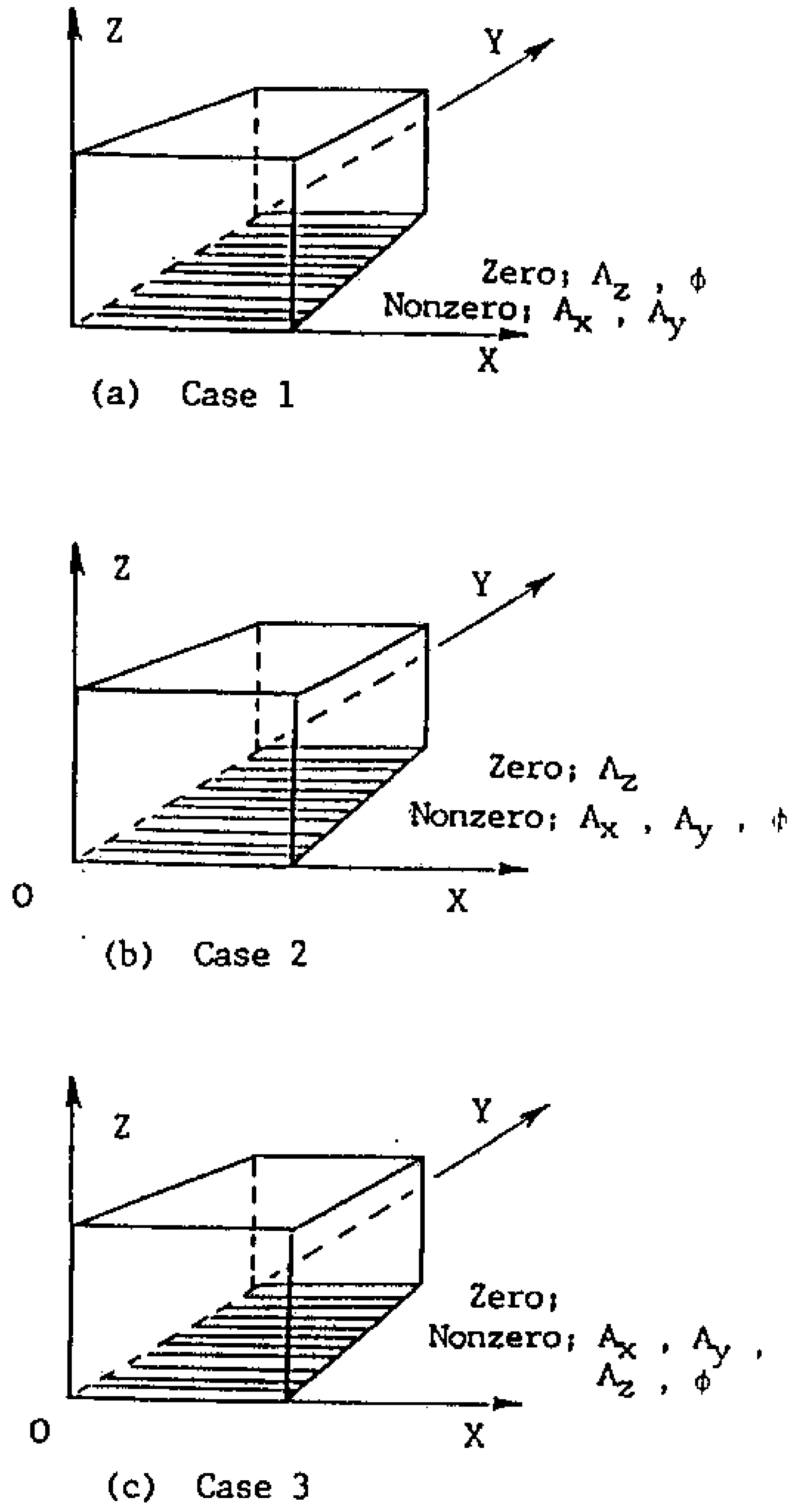


Fig.3 Boundary Conditions on X-Y Plane

In such a model, z-ward eddy currents begin to appear in the rims.

COMBINATION OF BOUNDARY CONDITIONS

To analyze z-ward currents, z-component of the vector potential and the scalar potential play important roles. The main problem is to prescribe the boundary conditions for the magnetic vector potential A and the scalar potential ϕ. In this paper the problem is examined by calculation.

Fig.2 shows a circular-type flux concentration model with two rims and one winding. Two symmetry planes of X-Y and X-Z make a one fourth region need to be calculated. Different combinations of boundary conditions for the two symmetry planes give different results.
In order to consider the problem, a one fourth model is taken as shown in Fig.3. As for the boundary conditions on X-Z vertical plane, zero values may be set on A_x , A_z and ϕ from the viewpoint of the symmetry. On the other hand, it is unknown how to select the values of A_z and ϕ on X-Y horizontal plane.
Mutual influence of z-ward vector potential and the scalar potential makes the problem difficult. We examine three following cases using computation.

Case 1: Zero A_z and zero ϕ on the horizontal symmetry plane.
Case 2: Zero A_z and nonzero ϕ on the horizontal plane.
Case 3: Nonzero A_z and nonzero ϕ on the horizontal plane.

(a) Case 1
The boundary conditions on the X-Y plane lead to the result shown in Fig.4. While there appear z-ward eddy currents in two rims, the density of eddy currents in the horizontal part of the conductor is very weak and the flux density is also very weak in the central hole. This conclusion is in contradiction to the fact we obtain experimentally.

(b) Case 2
The boundary conditions of zero A_z and unknown ϕ on the X-Y plane yield the computation result shown in Fig.5. Z-ward eddy currents also appear as shown in Fig.5 (a). But they differ from those in Fig.4 (a). We have noticed following three differences.
(1) The z-ward flow of eddy currents is not so large compared with the corresponding one in Fig.4 (a).
(2) The density of eddy currents is the strongest on the innermost surface(S4).
(3) In the edge facing the air-slit downward eddy currents appear to exist. This has

close relation with the fact that the horizontal flow on the top surface has some backward component near the edge. Fig.5 (c) shows concentrated flux density in both the central hole and the air-slit, while Fig.4 (c) shows little flux density in the corresponding parts.

(c) Case 3
The boundary conditions of nonzero A_z and nonzero ϕ on the X-Y plane yield almost the same result as the one shown in Fig.5. This is inferred to be caused from the fact that values of A_z are comparatively small in this model. No existence of z-ward excitation leads to the smaller values of A_z .

What combination of boundary conditions is desirable should be considered with other models. From the theoretical standpoint, the variables of A_x, A_y and ϕ take the same symmetrical values in both split regions divided by the X-Y symmetry plane, while values of A_z take negative. This indicates zero A_z should be set on the X-Y plane. But if we took zero A_z on the X-Y horizontal plane, z-ward eddy currents in the lower half would become different from those in the upper half region. Therefore, we think the boundary condition of Case 3 should be adopted in this case. This confusing matter should be continued to discuss from now, probably with the model containing z-component of excitation.

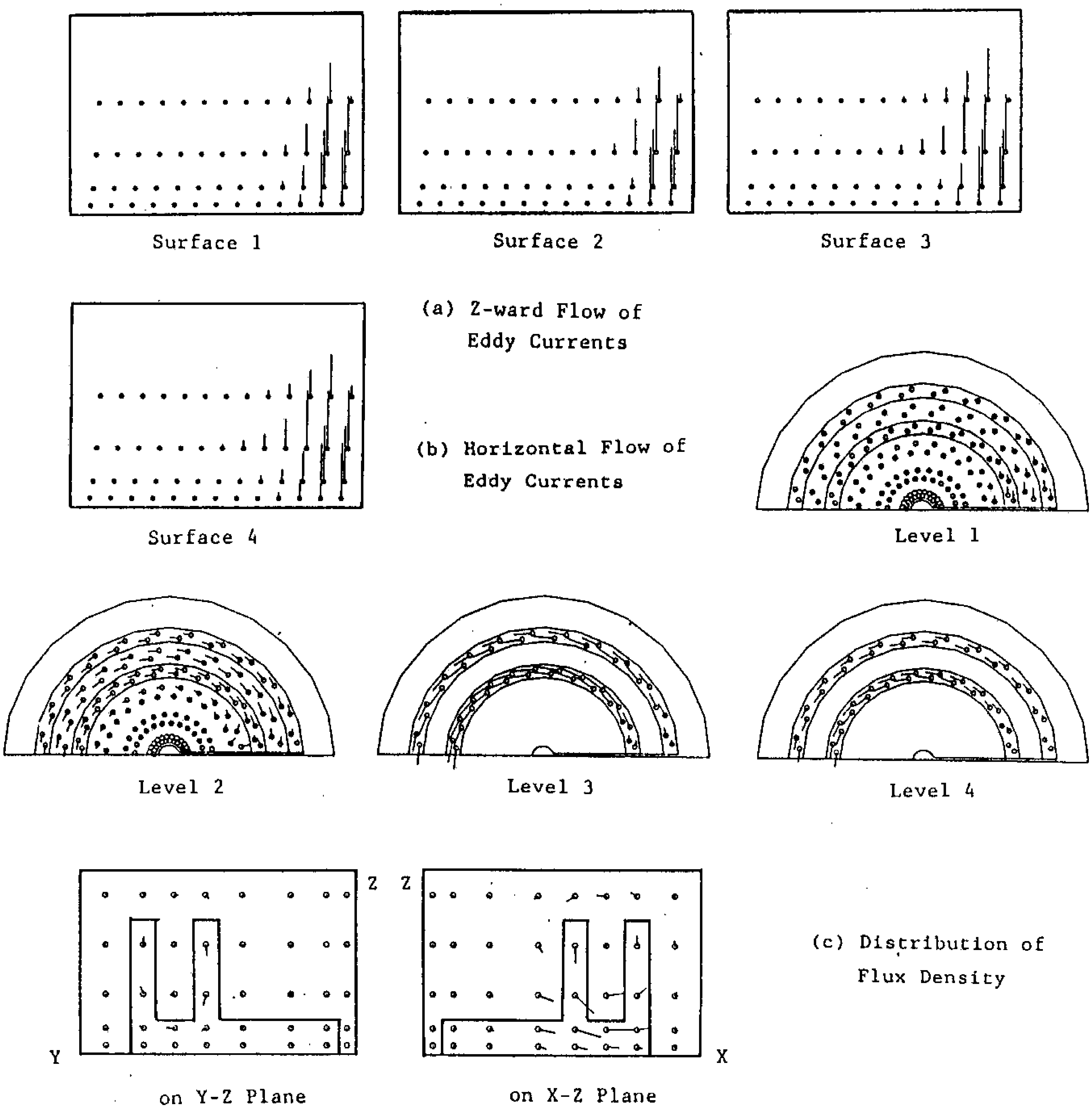


Fig.4 Computed Results for Case 1

CONCLUSION

Three dimensional eddy current problem in flux concentration apparatus with multi-rims is discussed. To decide z-ward eddy currents in the rims, z-ward vector potential and the scalar potential are found to play a great role. Though computation results do not show clearly what combination of boundary conditions should be selected, adoption of the boundary conditions of nonzero A_z and ϕ on the X-Y symmetrical plane is inferred to be reasonable.

REFERENCES

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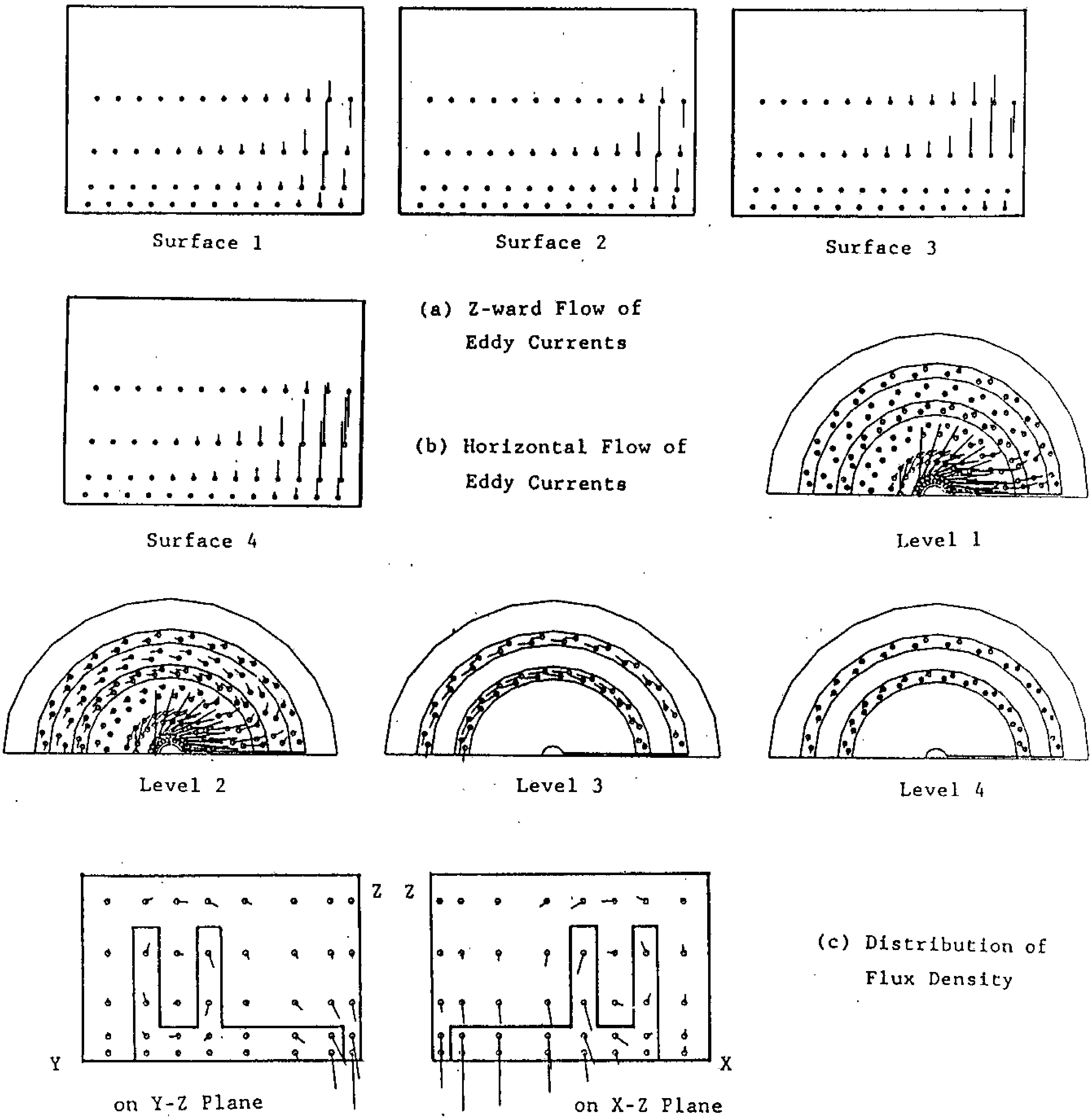

Fig.5 Computed Results for Case 2