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Linear/Nonlinear Approach on Open-Type Magnetic Shielding Method

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Abstract– Around us, there are many appliances generating electromagnetic noise. The practical measure to shield electromagnetic field is indispensable for our everyday life and protecting our children. An environmental health criterion about magnetic field was published by World Health Organization in last June [1]. But, it is difficult to design the magnetic shield. One of the significant reasons is that all the soft magnetic materials for shield have nonlinear characteristics.

The newly found “open-type magnetic shielding method” has features that its shielding performance can be adjusted finely by changing the kinds of materials, dimensions, intervals and so on. Here this study reports the characteristics of open-type magnetic shielding method and its shielding performance by the approaches with linear and nonlinear numerical analyses.

1. Open-Type Magnetic Shielding Method

Fig. 1(a) illustrates the case in which the magnetic field/flux is generated by electric current and a plate-like material for magnetic shield. To shield magnetic field for reducing the leakage to the front, we have generally placed a plate-like high permeability material between the resource to generate magnetic field and the space to be shielded, because magnetic flux go into it and make a detour [2,3].

In contrast to this conventional method, Fig 1(b) illustrates the open-type magnetic shielding method [4]. This method is different from the conventional method only about the figure of material. All soft magnetic material can be used for it. As shown in Fig. 1(b), strip-like materials are aligned in a line with gaps. It can be air or vacuum in the gaps. Therefore, this wall with open-type magnetic shielding method can pass air, light or objects which are smaller than gaps, but can shield magnetic field. According to the experiment, it is determined that a wall with open-type magnetic shielding method can achieve almost the same effect of magnetic shielding as a wall with the conventional method which is complete plate without any gap [5].

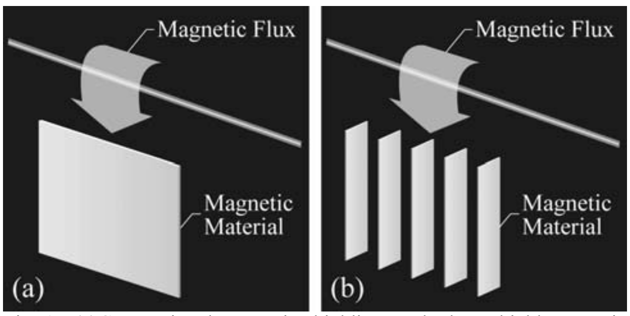

Fig. 1. (a)Conventional magnetic shielding method; to shield magnetic field from the electric wire efficiently, solid plate of magnetic material without any gap has been used. (b)Open-type magnetic shielding method; aligned strips of magnetic material with gaps. Light and air can pass through this magnetic shielding wall.

2. Shielding Model for Consideration

Fig. 2 illustrates a part of the model for consideration in this paper. This model is periodically long enough along the length direction of electric wires. To focus the influence to magnetic shielding performance by linearity/nonlinearity of the magnetic material, it is thought that it should be two dimensional for simplicity.

Two electric wires generate magnetic field and the leakage of magnetic flux density is calculated and measured. A single wall for magnetic shield is made by aligned strips of magnetic material with open-type magnetic shielding method. “L” means the length of magnetic material. “w” means the width. “t” means the thickness. “i” means the interval. “I” means the electric current. And “D” means the distance from the nearer electric wire to the calculation point. In addition, the area from 400 mm to 1600 mm is considered in this paper. Especially about nearer area than 400 mm, the problem

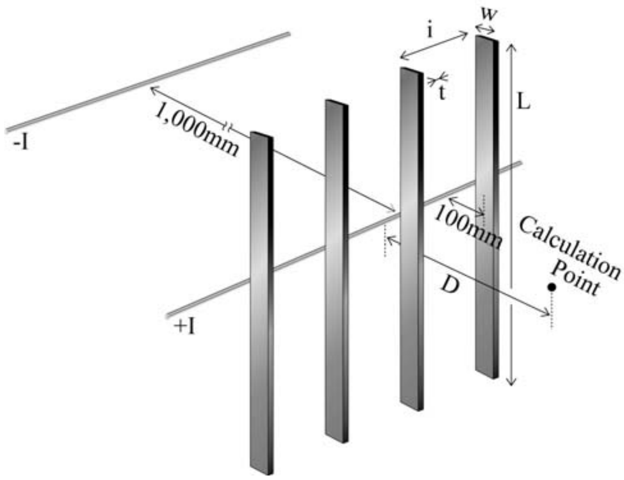

Fig. 2. Illustration about a part of the model for consideration. The model for calculation is repeated this part infinitely to the length direction of electric wires. The experimental model for comparison is 15 m in length.

becomes complicated because of the leakage from gap between strips. This area is out of scope in this paper.

3. Numerical Analysis Method

The commercial software for electromagnetic field analysis named MagNet ver.6 is used for calculation of the model of Fig. 2. MagNet is developed by Infolytica Corporation in Canada utilizing the finite element method with regard to T-Ω method. It divides the space for analysis to suitable meshes, makes approximate solution by polynomial about electromagnetic field in each mesh and solves the matrix equation with the conjugate gradient method. When magnetic material is treated as nonlinear, MagNet utilizes Newton-Raphson method.

The feature of the model in this paper is that the figure of magnetic material is very thin like 0.35 mm which is the thickness of electrical steel sheets. The finite element method is not so good at dealing with this kind of problem, but MagNet has special "thin plate" finite elements which are flat (two-dimensional) elements that can be used in a 3D analysis to represent the effects of the thin structures [6,7].

In this paper, the approximation of second degree is used as polynomial order. The properties of magnetic material are isotropic for all analyses. The current in electric wires are DC and the solver for 3D static magnetic field is used. In addition, the periodical boundary condition is applied to the length direction of electric wires.

4. Nonlinear and Linear Approach of Permeability

All soft magnetic materials for magnetic shield have the properties magnetizing nonlinearly responding to an applied magnetic field. In other words, permeability which is inclination of B-H curve varies with magnetic field. Permeability is generally also a function of frequency and it is complex when frequency is not zero. Our purpose in this paper is to present the fundamental and significant characteristics of open-type magnetic shielding method by nonlinear and linear approach. Therefore we deal with permeability of material as real number for zero frequency.

4.1. Nonlinear Approach

Fig. 3 indicates the material data of grain-oriented electrical steel sheet. The line "B for Nonlinear" with the left axis is B-H property. The line "μ_r for Nonlinear" with the right axis represents the relative permeability of "B for Nonlinear." Increasing the applied magnetic field from zero, the permeability becomes higher once and becomes lower after the maximum point. In other words, the degree of magnetization in magnetic material becomes higher once, but saturates beyond certain strength of magnetic field in which the material does not works effectively any more as magnetic shield.

4.2. Linear Approach

The straight line "B for Linear" with the left axis is selected for the linear approach which is the maximum permeability. The permeability is approximately 60,000 $\times \mu_0$ H/m. Here, μ_0 is $4\pi \times 10^{-7}$ H/m and means the permeability of vacuum. Their inclination does not vary with the strength of magnetic field.

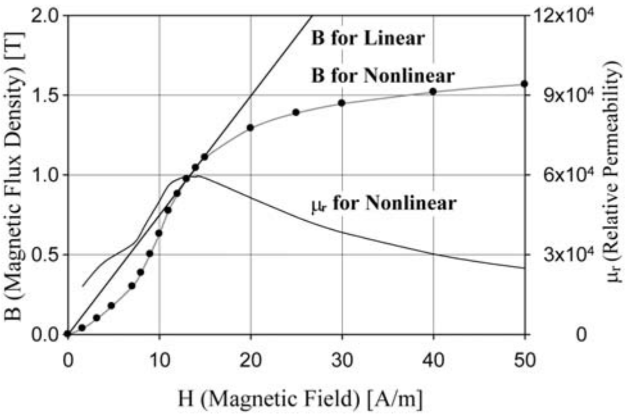

Fig. 3. Material data with linear deal and nonlinear deal. The nonlinear data is measured and read from the catalog about 35Z155 which is grain-oriented electrical steel sheet produced by Nippon Steel Corporation.

5. Comparison between Measured and Calculated Values

Fig. 4 indicates the comparison between measured and calculated values. Basically, the values of magnetic flux density are decreasing with the distance from the nearer electric wire, because magnetic field has the property reducing with the distance from the resource. It is worthy of note that the black triangles representing "Measured (with shield)" and the gray line representing "Calculated (Nonlinear)" coincide with each other. The black dashed line representing "Calculated (Linear)" is bellower than other shielding cases. The shielding performance is better because of the higher permeability.

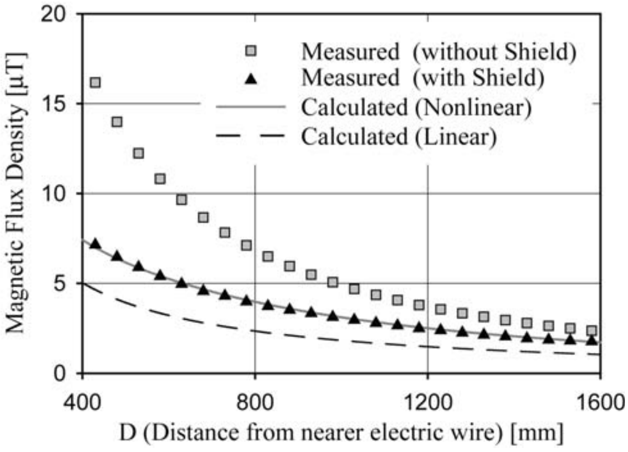

Fig. 4. Comparison between the measured values and the calculated values. L is 900 mm. w is 20 mm. t is 0.35 mm. i is 100 mm. I is 50 A.

6. Magnetic Flux Density inside Magnetic Material

Fig. 5 indicates the magnetic flux density inside a magnetic shielding strip. The difference between linear/nonlinear analyses is seen on the height of mountain curves, but not seen on the general figures. And it is interesting that the magnetic flux density is very small near the ends of strip. This cause could be the angle between the direction of magnetic field and that of magnetic shielding strips. The shielding performance of open-type magnetic shielding method becomes better when the magnetic shielding strips are parallel to the magnetic field. But if they are not parallel, the shielding performance becomes worse [4]. In other words, when the direction of magnetic field is not parallel to the direction of magnetic shielding strips, less amount of magnetic flux is taken into them.

Fig. 6 represents the part in the B-H curve utilized for calculations. 0.41 T for "B for Linear" and 0.37 T for "B for Nonlinear" corresponds to the values on the tops of two mountains in Fig. 5. From the point of view about B-H properties, the difference between linear/nonlinear is so large. But it is thought that the difference about magnetic flux density inside materials and shielding performance is not so large. These features may be seen only about the zone in which applied magnetic field is small.

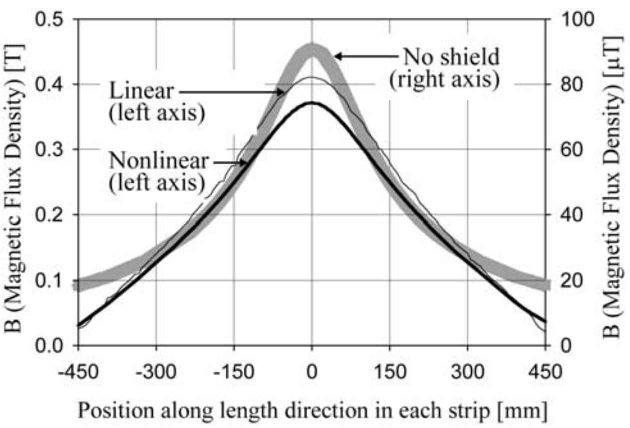

Fig.5. Magnetic flux density inside a magnetic shielding strip. All data is calculated under the same condition as Fig.4. Zero of horizontal axis means the center position of magnetic strips. 450 mm and -450 mm mean the ends of strip. The data of "No shield" is calculated about space without magnetic shield along the same line of shielded cases.

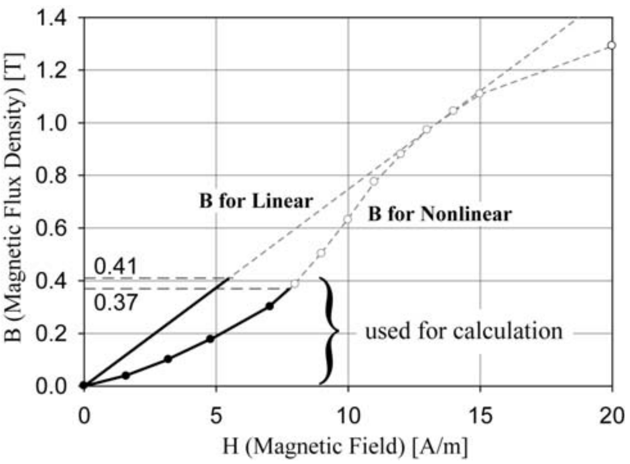

Fig. 6. The part in the B-H curve utilized for calculations under the conditions in this paper. The real lines in black are the part utilized for calculation. Especially for nonlinear calculation, the linear interpolation is used between the points indicated by the circles in black.

7. Necessary Length of Shielding Strips

In the latter part of this paper, the influences to the magnetic shielding performance of open-type magnetic shielding method by some parameters are considered. Fig. 7 shows the leakage of magnetic flux density when length of strips changes. For all case of D, magnetic flux density does not change when L is larger than 3000 mm. It is inferred that the part of the strips over 1500 mm far from the center does not work for magnetic shield.

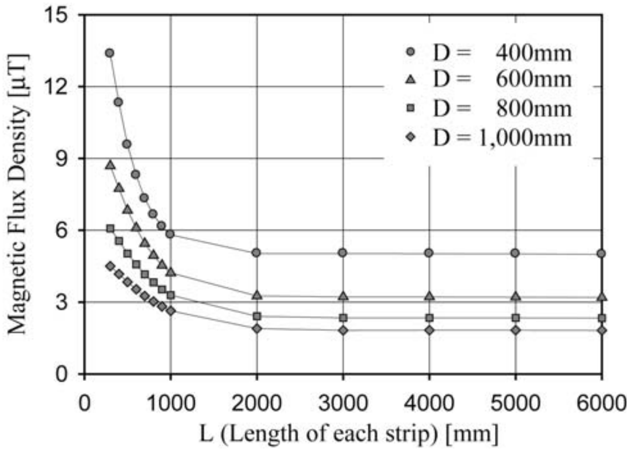

Fig. 7. Calculated result about linear material when L changes from 300 mm to 6000 mm. μr is 60000. w is 20 mm. t is 0.35 mm. i is 100 mm. I is 50 A.

8. Shielding Performance When the Strength of the Applied Magnetic Field Changes

Fig. 8 indicates the magnetic shielding performance in the case of linear material when the current of electric wires changes. For all cases about current and D, shielding factor S does not change. Here, S means the magnetic flux density is reduced to 1/S. It is found that S is uniform against the strength of applied magnetic field in the case of linear material.

On the other hand, Fig. 9 shows the magnetic shielding performance in the case of nonlinear material. Increasing the current of electric wires, S is increasing once but decreasing in the area larger than 150 A. It is inferred that magnetic material for shield saturated because of strong magnetic field. In the case of linear material, this kind of saturation is not seen at all. In addition, S is different in each D. S of near position like D = 400 mm is large, but it becomes smaller at far position like D = 1000 mm. The reason is not clear. More detail consideration is necessary about this result.

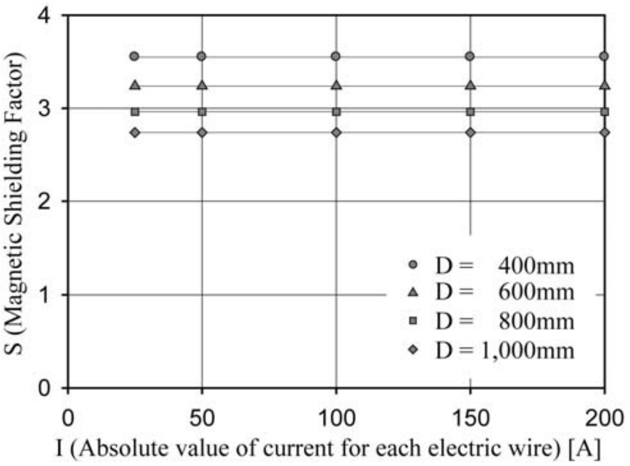

Fig. 8. Calculated result about linear material when current I changes from 25 A to 200 A. μr is 60000. L is 3000 mm. w is 20 mm. t is 0.35 mm. i is 100 mm.

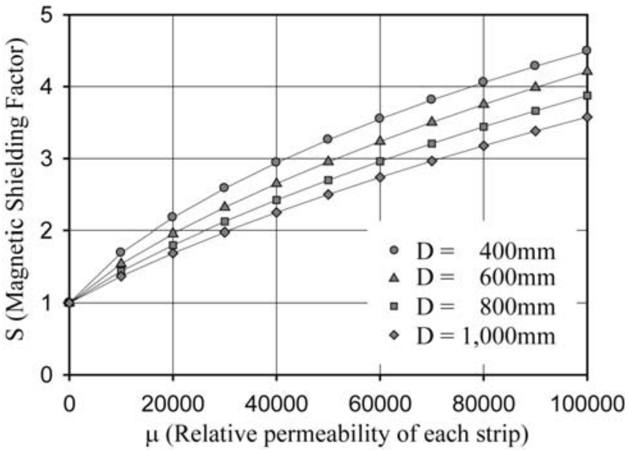

Fig. 10. Calculated result about linear material when relative permeability of magnetic material changes from 0 to 10000. L is 3000 mm. w is 20 mm. t is 0.35 mm. i is 100 mm. I is 50 A.

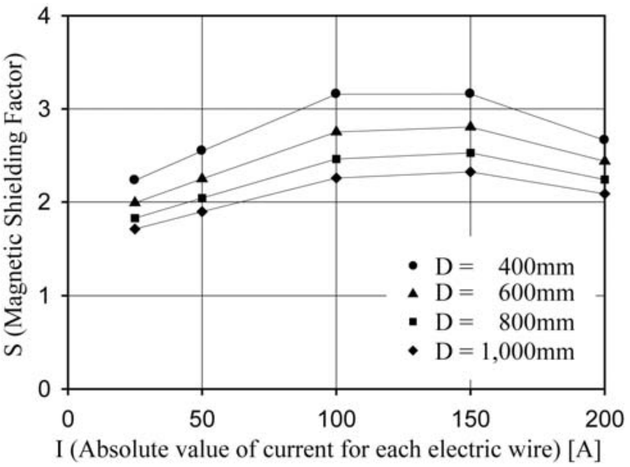

Fig. 9. Calculated result about nonlinear material when current I changes from 25 A to 200 A. L is 3000 mm. w is 20 mm. t is 0.35 mm. i is 100 mm.

9. Shielding Performance When the Permeability of Magnetic Material Changes

Fig. 10 indicates the shielding performance in the case of linear material when the relative permeability of magnetic material changes. It is interesting that S does not have complete proportional relationship to relative permeability. This reason is also not clear. More detail consideration is necessary also about this result.

10. Conclusion

All soft magnetic material for magnetic shield is nonlinear in practice. But if they are dealt with as linear, we can consider the magnetic shielding phenomena as simple problems without some complexities.

It is found that shielding factor S is uniform against the strength of applied magnetic field if magnetic material is linear. But S does not have complete proportional relationship against the change of relative permeability, though it is linear completely. More detail studies are necessary about these kinds of issues.

It is obvious that nonlinear approach is very effective to make sure about coincidence between calculation and real phenomena. But it is very difficult to understand physics inside or general properties. On the other hand, linear approach is very effective to understand the fundamental characteristics and useful for shielding design. For future investigations, Parameter studies with both approaches about width, thickness and interval of shielding strips could be also worthwhile.

Acknowledgments

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