Frequency Response Analysis Considering Non-linearity of Complex Magnetic Permeability employing 3-D FEM

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Abstract — When the flux density of a magnetic material is in the militesla (mT) region, the flux density has a linear relationship with the magnetic field intensity. However in the high frequency region, the magnetic flux is concentrated near the surface of the magnetic material due to the skin effect. Therefore, it is necessary to consider the non-linear magnetic properties of the material because the difference between the magnetic flux density at the surface and at the core of the material is very large.

In this paper, we propose a revised frequency response analysis method that takes into account the non-linearity of the complex magnetic permeability with respect to the magnetic flux density, in order to accurately compute the magnetic flux distribution at high frequency ranges. The validity of the proposed analysis method is verified by comparing the computed data with measurements of a prototype.

I. INTRODUCTION

Frequency Response Analysis (FRA) is conventionally used for linear calculations. We have been studying a computational method for analyzing the characteristics of a linear position sensor and its core material using FRA which also takes into account the Complex Magnetic Permeability (CMP) [1-2].

The magnetic permeability of the magnetic material that is used in the conventional FRA method is a constant value. At high frequencies, the magnetic flux is concentrated near the surface of the material due to the skin effect. However, the magnetic flux density is actually distributed nonlinearly at the core of the material. Thus the magnetic permeability reaches a high value near the surface and a low value inside of the material. Therefore, the FRA approach needs to be revised to account for both the linear variation of the magnetic flux density with respect to time, and the nonlinear variation of the CMP with respect to the distribution within the material.

There have been a few papers in which the analyses were conducted using CMP [3-4]. However, we were able to find just one paper in which the concept of non-linear CMP even existed [5].

In this paper, we propose a revised FRA method that takes into account the non-linearity of the CMP. Moreover, in order to confirm the validity of this computation method, we compared the analyzed results (before and after considering the non-linearity of the CMP) with the measurement of a prototype.

II. ANALYSIS METHOD

The fundamental equation of the magnetic field can be expressed in the frequency domain as follows [1-2].

$$\mathrm{rot}\left(\dot{\nu}\,\mathrm{rot}\,\dot{\boldsymbol{A}}\right)=\dot{\boldsymbol{J}}_0+\dot{\boldsymbol{J}}_e=\dot{\boldsymbol{J}}_0-\sigma\left(j\omega\dot{\boldsymbol{A}}+\mathrm{grad}\dot{\phi}\right) \tag{1}$$

where $\dot{\nu}$ is the magnetic reluctivity, $\dot{\boldsymbol{J}}_0$ is the excitation current density, $\dot{\boldsymbol{J}}_e$ is the eddy current density, σ is the electric conductivity, ω is the angle frequency, $\dot{\boldsymbol{A}}$ is the magnetic vector potential, and $\dot{\phi}$ is the electric scalar potential.

The magnetic reluctivity is expressed as (2) using the complex magnetic permeability $\dot{\mu}$.

$$\frac{1}{\dot{\nu}}=\dot{\mu}=\mu'-j\mu'' \tag{2}$$

where μ' and μ'' are the real and imaginary parts of $\dot{\mu}$, respectively. These parameters are used in the analysis as the DC permeability and hysteresis coefficient, respectively.

In our calculations, we used the measured CMP. However, the measured real and imaginary parts of the CMP include iron loss, especially since the influence of the eddy current is large at high frequencies. Therefore, these parameters were measured at low frequencies because eddy currents are considered in our FEM code.

The electric circuit equation is coupled with the magnetic field equation [1-2]:

$$\dot{V}_0=R\dot{I}_0+j\omega\dot{\psi} \tag{3}$$

where $\dot{V}_0$ is the applied voltage, R is the resistance, $\dot{I}_0$ is the excitation current, and $\dot{\psi}$ is the interlinkage flux of excitation coil. The dot (.) on the letter indicates a complex number.

We account for the nonlinearity of the CMP by recalculating the CMP using the magnetic flux value of the previous step. Then we perform iterative computations until the magnetic permeability and magnetic flux converge.

III. VERIFICATION OF MATERIAL CHARACTERISTICS

A. Analyzed Model

We calculate the frequency characteristics of the CMP by varying the frequency from 30Hz to 100 kHz. The skin effect greatly influences the magnetic flux distribution, especially at high frequencies. Therefore, we generated a very dense finite-element mesh around the core surface to account for the skin effect. The analyzed model is 1/720 of the whole region due to its symmetry. The 3-D mesh of the analyzed model of a toroidal coil is shown in Fig. 1.

B. Frequency Characteristic Analysis

The measured magnetic permeability change of the magnetic material SUY with respect to its magnetic flux density (measured at 5Hz) is shown in Fig. 2. As was already mentioned in the Analysis Method, we recalculate the CMP of each element, at each step, using the magnetic flux value of the previous step. The data that was earlier determined and is shown in Fig. 2, is used in this calculation.

We analyzed the frequency characteristics of the CMP

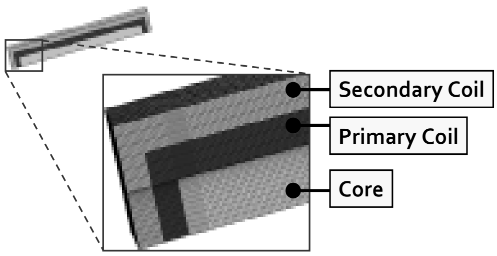

Fig. 1. 3-D mesh of analyzed model (1degree model)

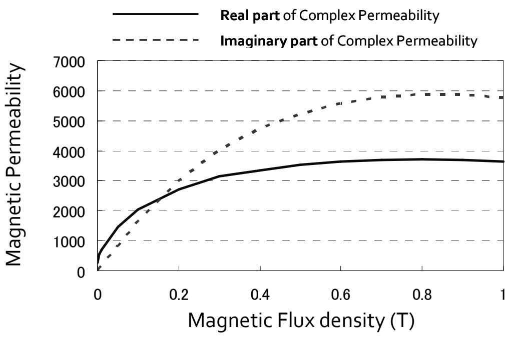

Fig. 1. Magnetic permeability change against Magnetic flux density

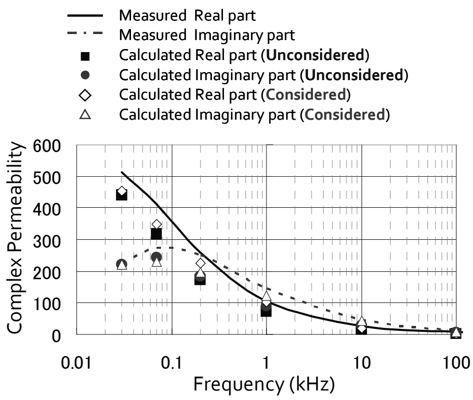

Fig. 2. The comparison between analyzed and measured results of frequency characteristic of complex magnetic permeability ($B_{ave.}$=5mT)

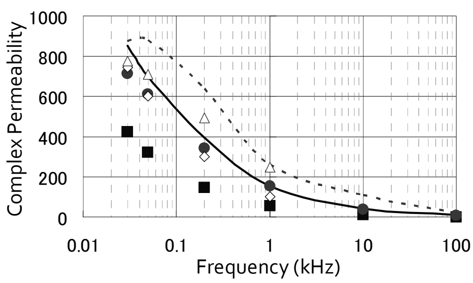

Fig. 3. The comparison between analyzed and measured results of frequency characteristic of complex magnetic permeability ($B_{ave.}$=50mT)

of the core material, SUY, when the non-linearity of the CMP was not considered [2], and when it was considered. These results are shown in Figs. 3 ($B_{aver.}$=5mT) and 4 ($B_{aver.}$=50mT). $B_{aver.}$ refers to the average magnetic flux density in the cross section of the magnetic material.

As can be seen, when $B_{aver.}$ was 5mT, the non-linear analysis results barely showed any improvement compared to the linear analysis results in conforming to the measured results (Fig. 3). However, when $B_{aver.}$ was 50mT, the non-linear analysis results showed a considerably better agreement with the measured results (Fig. 4).

Here, we compared these results in terms of the difference of the real part of the CMP, between the surface and the core of the material at the same frequency, 1 kHz.

In the first case, the real part of the CMP near the surface is about 3 times larger than the core. Thus the difference of the magnetic permeability only had a small effect. On the other hand, in the second case, the difference of the real part of the CMP is about 10 times. Therefore, the effect of non-linearity of the CMP becomes prominent in this analyzed result. This is because the second case induces a larger skin effect than the first case.

It becomes clear that the larger the skin effect, the more advantageous this proposed method is in linear analysis.

IV. CONCLUSION

We proposed a revised Frequency Response Analysis method that accounts for the non-linearity of the Complex Magnetic Permeability. The validity of the analysis is verified through the comparison of the measurement with the prototype.

This analysis method is effective when there is a large difference between the magnetic flux concentration at the surface and the core of the magnetic material. Therefore, it is advantageous for calculations when the skin effect is prominent.

In the full paper, we will discuss about the nonlinear iteration method and more explanations about references and results will be given.

V. REFERENCES

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