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Harmonic Balance Analysis for Magnetic Hysteresis under Static and Dynamic Stresses

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ABSTRACT

To evaluate a stress effect to the ferromagnetic properties, this paper proposes a methodology utilizing a frequency response of the domain based magnetization model. A key idea of this approach is based on the following facts that the parameters identification of a domain based magnetization model has been successfully developed by a harmonic balance approach. Since the parameters of the model are extremely sensitive to the various measurement conditions such as temperature, mechanical stress and so on, investigation to the model parameter deflection while controlling a particular measurement condition reveals its controlled parameter effect to the tested ferromagnetic materials. As a result, it is found that the stress effect to a parameter expressing hysteretic property has been clearly deflected its values depending on the externally applied stresses.

KEYWORDS

ferromagnetic material, domain based model, hysteretic property, harmonic balance, Fourier series

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1. Introduction

As is well known, ferromagnetic materials exhibit a lot of complex physical properties, such as magnetization, magnetostriction and magneto-thermodynamic properties. Any of these physical properties are nonlinear properties as, detailed relationships among them are still unknown.

Recently we have tried to identify the parameters of magnetization model by a harmonic balance approach [1-3]. As a result, exact magnetization characteristics have been successfully reproduced from the input field intensity H as well as output flux density B measurements even if the deeply saturated situation. Of course, magnetization model had been essentially required so that we had employed a domain based magnetization model.

To keep the ultimate safety, this paper focuses on a stress effect to the parameters of this model, because most of the mechanical frame structures of the industrial products, e.g., car, aircraft, high speed train and so on are always composed of the iron or its composites, i.e., ferromagnetic materials. Particularly, their nonlinear magnetization characteristics are function of externally impressed stresses. This is because some external physical energy is added to their domain structures so that their structures are essentially stimulated to change[4-6].

Even if a not pressured condition, the magnetic nonlinear problems are extensively solved by means of harmonic balanced approach [7-10].

On the other side, we apply the orthogonal property between the odd and even functions of the Fourier series to decide the parameters of the domain based constitutive equations under both no and pressured conditions, i.e., one of the novel applications of the harmonic balanced approach is proposed in this paper.

At first, we introduce the domain based model and describe the physical meanings in each of its parameters. Second, to determine the coefficients of the domain based model, we apply orthogonal

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properties of the sinusoidal and cosinusoidal functions.

Finally, it is clarified that the most sensitive stress effect factor is a parameter expressing hysteretic property.

2. Domain Based Model

2.1. Domain Based Model and Its Parameters

Previously, we have proposed two types of constitutive models for representing the ferromagnetic properties, i.e., phenomenological and domain based models [1,2]. This paper employs the domain based model [2], and the relationship between the magnetic field H[*A/m*] and flux density B[*T*] is represented by the domain based model as

$$H = \frac{1}{\mu} B + \frac{1}{s}\frac{dB}{dt} - \frac{\mu_r}{s}\frac{dH}{dt} \tag{1}$$

where μ, μ_r and s are the permeability measured in the ideal magnetization curve, reversible permeability measured along with the ideal magnetization curve, and hysteresis coefficient, respectively [1-3].

2.2. Harmonic Balance Method

Let us consider an input and output system shown in Fig.1. When the input and output of this system are respectively given by

$$f(t) = \sum_{i=1}^{n} a_i \sin(i\omega t) + \sum_{i=1}^{n} b_i \sin(i\omega t) \tag{2}$$

$$g(t) = \sum_{i=1}^{n} c_i \sin(i\omega t) + \sum_{i=1}^{n} d_i \sin(i\omega t) \tag{3}$$

We represent this system by a following constitutive equation

$$f(t) = \frac{1}{\mu} g(t) + \frac{1}{s}\frac{dg(t)}{dt} - \frac{\mu_r}{s}\frac{df(t)}{dt} \tag{4}$$

An alternative form of (4) is

$$f(t) = \alpha g(t) + \beta \frac{dg(t)}{dt} - \gamma \frac{df(t)}{dt} \tag{5}$$

To determine the parameter α, β, γ, in (5), multiply the output function *g(t)* to both sides of (5) and integrate from 0 to T yields.

$$\int_0^T g(t) f(t) dt = \alpha \int_0^T g(t) g(t) dt + \beta \int_0^T g(t) \frac{dg(t)}{dt} dt - \gamma \int_0^T g(t) \frac{df(t)}{dt} dt \tag{6}$$

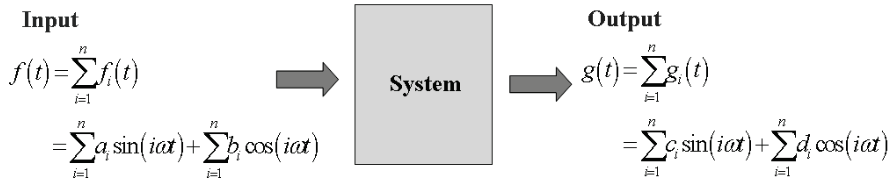


Fig. 1. Simple input and output system.

Similarly multiply the time derivative of output function *dg(t)/dt* to both sides of (5) and integrate from 0 to T yields

$$\int_0^T \frac{dg(t)}{dt} f(t)dt = \alpha\int_0^T \frac{dg(t)}{dt} g(t)dt + \beta\int_0^T \frac{dg(t)}{dt}\frac{dg(t)}{dt}dt - \gamma\int_0^T \frac{dg(t)}{dt}\frac{df(t)}{dt}dt \quad (7)$$

Further, multiply the input function *f(t)* to both sides of (5) and integrate from 0 to T yields

$$\int_0^T f(t)f(t)dt = \alpha\int_0^T f(t)g(t)dt + \beta\int_0^T f(t)\frac{dg(t)}{dt}dt - \gamma\int_0^T f(t)\frac{df(t)}{dt}dt \quad (8)$$

Substituting the input (2) and output (3) functions into the equations (6), (7) and (8), it is possible to set up a system of equations for *i*-th harmonics as

$$\begin{bmatrix} a_ic_i + b_id_i \\ b_ic_i - a_id_i \\ a_i^2 + b_i^2 \end{bmatrix} = \begin{bmatrix} c_i^2 + d_i^2 & 0 & -i\omega(a_id_i - b_ic_i) \\ 0 & i\omega(c_i^2 + d_i^2) & -i\omega(a_ic_i + b_id_i) \\ a_ic_i + b_id_i & -i\omega(a_id_i - b_ic_i) & 0 \end{bmatrix} \cdot \begin{bmatrix} \alpha_i \\ \beta_i \\ \gamma_i \end{bmatrix} \quad (9)$$

Input and output relation for *i*-th harmonics is given by

$$f_i(t) = \alpha_i g_i(t) + \beta_i \frac{dg_i(t)}{dt} - \gamma_i \frac{df_i(t)}{dt} \quad (10)$$

Let us introduce a phaser notation, i.e., a symbol ^ refers to complex quantities, then (10) could be reduced into

$$\left(1 + ji\omega\gamma_i\right)\hat{f} = \left(\alpha_i + ji\omega\beta_i\right)\hat{g}, \quad (11)$$

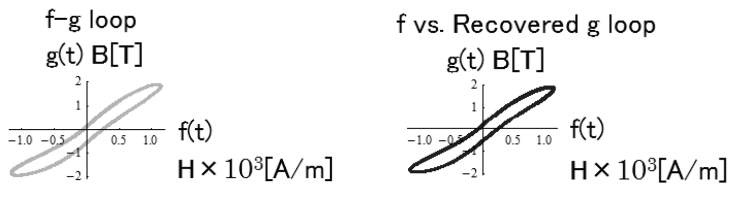
where

$$j = \sqrt{-1} \quad (12)$$

Thus, the output is

$$g(t) = \sum_{i=1}^{n}\sqrt{\frac{1+(i\omega\gamma_i)^2}{\alpha_i^2 + (i\omega\beta_i)^2}}\sqrt{f_{i,r}^2 + f_{i,\mathrm{Im}}^2}\cos\left(i\omega t - \tan^{-1}\frac{f_{i,\mathrm{Im}}}{f_{i,r}} + \tan^{-1} i\omega r_i - \tan^{-1}\frac{i\omega\beta_i}{\alpha_i}\right) \quad (13)$$

Entire sum of the output (13) for *i*-th harmonics gives the output *g* of (3).



(a) Original (b) Recovered

Fig 2. Validity check of the model (4) or (5)

Figure 2 shows one of the examples of the recoverbility of our domain based harmonic balance solution. According to the result shown in Fig.2, it is obvious that the nonlinear magnetization characteristics exhibiting the hysteretic properties of ferromagnetic fields could be solved by means of phaser transform method.

3. Experiment

3.1. Experimental Verifications

Figure 3 shows an experimental device and Table 1 lists its various constants. The tested specimens are the silicon steels with the 0.35mm thickness, 30mm width and 100mm length. The tested specimen was put on the upper two head surfaces of U shape ferrite core wound the 300 turns exciting coil. The specimen in Fig.3 is excited by an alternating current having 0.35A peak value through this exciting coil.

Table 1 Specification of the measurement devices

Specimen	U shape ferrite core
Material: silicon steels Length: 100cm Width: 30mm Thickness: 0.35mm Number of coil turns: 300 turns Diameter of conductor: 0.2mm	Material: ferrite Number of coil turns: 300 turns Diameter of conductor: 0.6mm

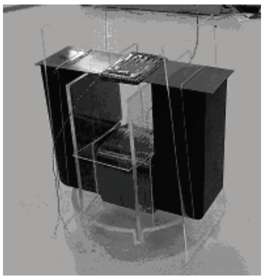
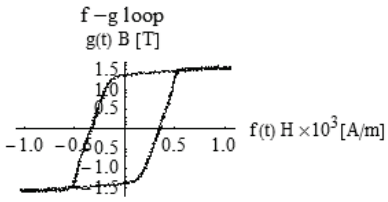
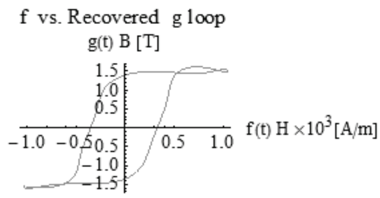


Fig 3. Specimen and U shape ferrite core



(a) Experimented



(b) Recovered by(13)

Fig 4. Comparison between the experimental and recovered hysteresis loops

Figure 4 shows a comparison between the experimented and recovered hysteresis loops. Recovered hysteresis loop by (13) is well corresponding to experimental one. A correlation coefficient between the Figs. 4(a) and 4(b) is over 0.99. This means that the hysteretic nonlinear magnetization problems in ferromagnetic fields could be solved by means of the harmonic balance approach.

3.2. Stress Visualization

Figure 5 shows an experimental schematic diagram to visualize the applied stress. A U shape ferrite core wound the exciting coil just same as shown in Fig.3. The specimen wound the search coil is put on the upper two head surfaces of U shape ferrite core. The stress was applied to the specimen by putting on the wood weight to the specimen as shown in Fig 6. The used weight is 900g.

Figure 6 shows the hysteresis loops when applied the 900g stress. Figures 6(a), 6(b) and 6(c) show the hysteresis loops when impressing low, middle and high voltages, respectively.

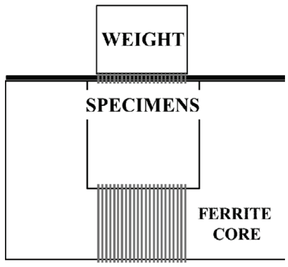
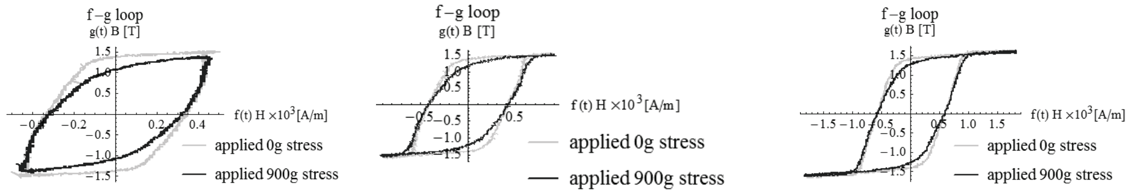


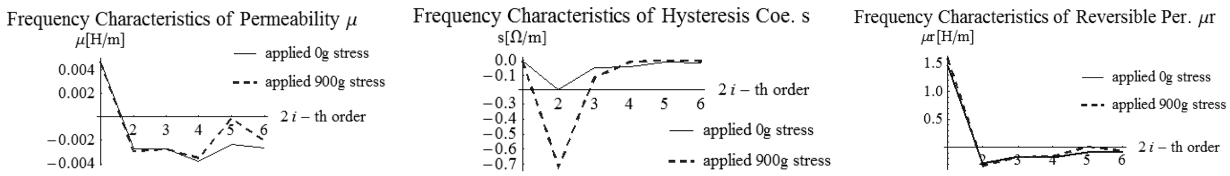
Fig 5. Schematic diagram of the stress impression



(a) Low voltage (b) Middle voltage (c) High voltage

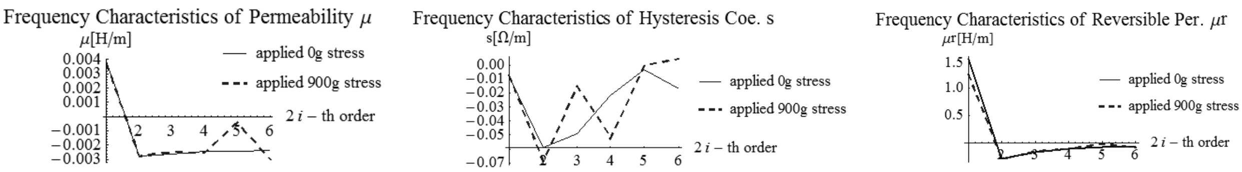
Fig 6. Difference of the hysteresis loops between the no mechanical stress and 900g stress conditions.

Observe the results in Fig. 6 reveals that the hysteresis loop*s* are changing in accordance with the 900g stress impression.



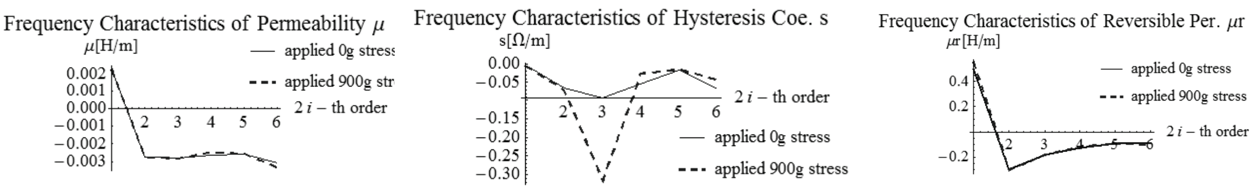
(a) Permeability μ (b) Hysteresis coefficient s (c) Reversible Permeability μ_r

Fig 7. Parameters μ, s, and μ_r values in each of the harmonics when impressing low exciting voltage.



(a) Permeability μ (b) Hysteresis coefficient s (c) Reversible Permeability μ_r

Fig 8. Parameters μ, s, and μ_r values in each of the harmonics when impressing middle exciting voltage.



(a) Permeability μ (b) Hysteresis coefficient s (c) Reversible Permeability μ_r

Fig 9. Parameters μ, s, and μ_r values to each of the harmonics when impressing high exciting voltage.

Figures 7-9 show the parameters μ, s, and μ_r values to each of the harmonics when impressing the low, middle and high exciting voltages. According to the variation of *s* shown in Figs. 7(b), 8(b), 9(b), it is found that the parameter *s* is highly sensitive to the applied stress.

Observe the hysteresis coefficient s in Figs. 7-9, it is obvious that the hysteresis parameter s greatly depends on the externally impressed stress while the other parameters μ, μ_r. are keeping the similar values independent to the stress. This means that the hysteresis loss becomes larger in values when keeping the same magnetic flux density.

Thus, the external stress gives a large effect to the magnetic hysteresis, i.e., iron loss may be greatly increased by the externally applied stress.

4. Conclusion

The hysteretic nonlinear problems in ferromagnetic fields could be solved by means of the harmonic balance approach. The parameters μ, μ_r and *s* in the domain based model could be determined in each of the harmonics by the Fourier approach.

According to our approach, it has been revealed that the parameter representing the hysteretic property of the domain based model is highly sensitive to the applied stress. Namely, the iron loss in the electrical machines distributes depending on the stress distribution and may take the large in value at the highly stressed positions.

Design of the electrical machines essentially requires the efficiency item, which is directly related to the iron loss, because about 60% in the entire loss is the iron loss. In particular, thermal design of the electrical machines requires the exact iron loss distribution to work out the compact high power electrical machines.

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