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Evaluations of Iron-based Material Expressed by Magnetic Transfer Function

***Abstract**. We have been investigated a basic concept of material constant evaluation using transformer type probes in an a.c. field range between 20Hz and 200kHz. The probes are consisted of 2 transformers with open magnetic poles attached to the material surface under estimation and attached to the reference material, respectively. The output voltage of each transformer is connected in series and reverse to cancel the offset voltage caused by the leakage flux. The analyses are performed by using a.c. magnetic resistance theory of magnetic circuit. We attained the high sensitivity of conductivity and permeability changes in the material without direct contact as that in d.c. measurements. The transfer function of material in general was defined by the experimental results of the excitation current of the probe, operation frequency and the output voltages, independent of the characteristics of the transformer materials.*

***Streszczenie**. Badano koncepcję stałej materiałowej przy badaniu próbki transformatorowej w pasmie 20 Hz do 200 kHz. Próbka składała się z dwóch otwartych transformatorów, z których jeden przyłożony był doi badanego materiału a drugi do materiału porównawczego. Wyjścia połączono szeregowo i przeciwsobnie. Określono funkcję przetwarzania umożliwiającą ocenę badanego materiału. (**Ocena materiału ferromagnetycznego wyrażona przez funkcję przetwarzania**)*

Keywords: NDE, Iron-based material, non-contacting probe, ac magnetic probe, eddy current, permeability
Słowa kluczowe: badania nieniszczące, materiał ferromagnetyczny

Introduction

Iron-based structural materials in general are used in atomic power stations, where it is very important to detect the fatigues of the structural material, far before the collapses in fatal destructions. We have been investigating the non-destructive evaluations (NDE) of these materials by using ac magnetic probes with non-contacting method. So many electrical and magnetic tools of NDE methods have been developed by researchers in these several decades of years [1-3]. We have been developing many diagnostic tools as resistance observations, internal residual stresses by using electro-microscope, Vickers test, optical surface observation by using a laser interference method, magnetization observation and magnetic leakager flux observation etc [4-14]. However, the methods hitherto developed were not adopted in the atomic power plant, not only due to the conservative constitutions of the factories but also to the sophistications of the electromagnetic tools. Therefore, it is necessary to develop some simple and easy tools to undestand the physical mechanism. In addition to these reasons, the tools for NDE should be non-contacting without any stains at the material surface as in that dc resistance measurements. Here, in this study, we show a diagnosis tool to observe the permeability and conductivity at the material surface, just by attaching magnetic probes of transformers. For this purpose, we developed a transformer type probe with open poles at the material surface under evalution, and analysed the frequency characteristics of the material by observing the difference signals between that obtained for a material and that for a reference material, respectively, or between those at the two positions in the same material. By using transformer type probes with each specific frequency dependence, we performed analyses of the magnetic permeability and conductivity of the material as a function of frequency to discriminate the eddy current loss from the magnetic dispersion. In this analysis, the general properties of the permeability and the conductivity in the material were obtained by normalized characteristics of the transformer probes themselves. Therefore, using single probe, we characterized the frequency response of materials such as iron plates, magnetic amorphous sheet and copper plates in a frequency range between 20Hz and 200 kHz. Three discrete components in the a.c. magnetic circuit were determined in general, composed by (1) a resistance representing the leakage flux around the probe transformer core, (2) the air gap between the poles and the material and (3) a resistance of material, respectivly.

Experiments

The experimental apparatus was tentatively set-up as shown in Fig.1. The magnetic probes (Pr1,Pr2) were re-constructed with pulsed transformers by removing the one side of the loop-core. The primary coils of the probe were connected in series to generate exactly the same a.c. magnetic field at the poles, and the second coils were connected in reversed to generate the difference signal between the two probes where open poles was set at one side of the material and the other at reference material. The signal generator was connected both with the coil excitation and with the lock-in amplifier as a reference. In case of the low frequency response in time domain and when the the phase information is not necessary, the ac output voltages of Pr1 and Pr2 were rectified by diodes and connected in reverse by bridge circuit. In this case, the signal to noise ratio became very high to detect just the difference of the two amplitude difference in the two probes.

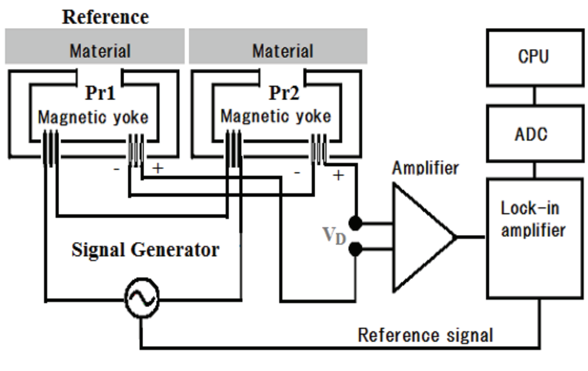

Fig. 1: The experimental set-up of a.c. magnetic parameters using the two transformer type probes.

Note here that the ADC(Analogue to Digital Converter) in this figure was 24 bits, 2-channel to record the material response as a function of positions of sample surface. Here, we performed the basic experiment to characterize a probe output (V_0) as a function of frequency (f). For this purpose, we define the a.c. magnetic circuit just as that in the a.c. circuit theory as

$$\Phi(\omega) = \frac{N I(\omega)}{\sum_j R_j(\omega)}, \qquad (1)$$

where, N stands for the primary coil turns, $I(\omega)$, the current and $\omega(=2\pi f)$, angular frequency, respectively. The magnetic resistance $R_j(\omega)$ is defined as frequency dependent and complex variable, and the suffix (j) runs over several circuit elements. The current I is also dependent on frequency as $I_0 \exp(-i\omega t)$, $(i \equiv \sqrt{-1})$. Therefore, we obtain the output voltage V_0 as

$$Vo(\omega) = i\frac{nN\omega I(\omega)}{\sum_j R_j(\omega)}. \qquad (2)$$

Here, n stands for the winding turns in the secondary coil. Now, transfer function $C(\omega)$ is defined by

$$C(\omega) \equiv K\frac{V_0(\omega)}{\omega I(\omega)} = \frac{1}{\sum_j R_j(\omega)} \qquad (3)$$

Here, K stands for a constant ($=-i\ 1/Nn$). It is easily understood that $C(2\pi f)$ reflects the flux conductive properties as that in the d.c. magnetic circuit.

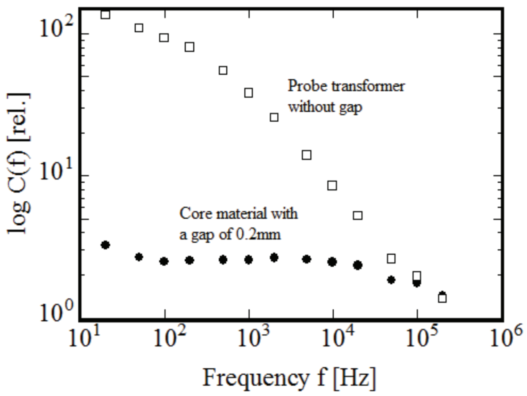

Fig. 2. The experimental characteristics of a transformer type probe with completely closed magnetic circuit, immersed with the original transformer core (open circle), and a probe with open magnetic poles attaching at the same core surface (closed circle).

Fig. 2 shows the drastic change of the magnetic transfer function $C(f)$ describing the role of the air-gap of about 0.2mm. Namely the magnetic transfer function denoted by $C(f)$ shows monotonic behaviour in a low frequency range below 10kHz. By using the probe in this study, we can obtain the stable value of magnetic susceptibility in magnetic metal without the effects of eddy current loss in the low frequency range less than 1 kHz as shown in Fig.3. In the lower figure, the eddy current losses in copper plates are enhanced in a range larger than 1kHz. Note here that $C(f)$ is normalized by that in air without material. Hence, the value of $C(f)$ larger than unity means that the magnetic field inside the probe increased than that in air. In other words, we can determine the magnetic susceptibility and conductivity precisely by this method. In this figure, a magnetic dust-core with 3mm thickness, a supermalloy sheet with 10μm and a soft iron sheet of 1mm show values larger than unity, respectively. In contrast to these results, the several copper sheets with different thicknesses show the large frequency dispersions depending on the thicknesses. In the d.c. operation obtained by rectifying the output voltages in Pr1 and Pr2, we attained the resolution of 0.5% for conductance changes in conductive materials and the susceptibility changes of 1 % for magnetic materials, respectively.

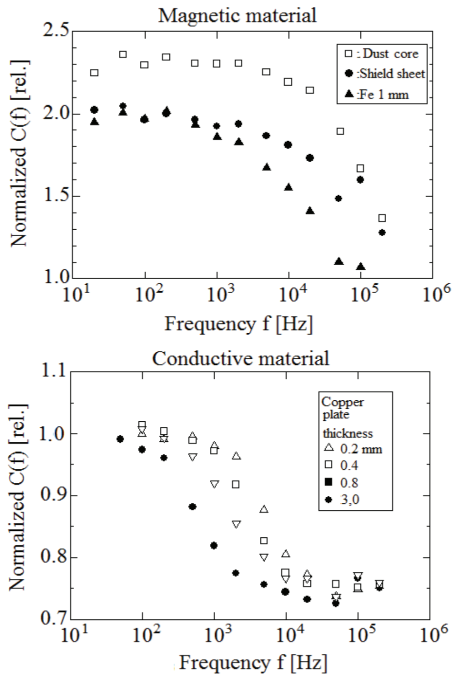

Fig.3. The permeance $C(f)$ of several magnetic materials (the upper figure) observed for a magnetic dust-core, a sheet of supermalloy, a soft iron plate and copper plates with different thicknesses (the lower figure), respectively.

Here in Fig.3, the several copper plates with various thickness are examined for the system calibrations, by which experiment the relationship between the conductivity, the thicknesses and the frequency dispersions become clarified. Fig. 4 shows the difference outputs in the d.c. output operation, observed for a SUS304 sample with a residual strain caused by a tensile stress of 600MPa, as a function of positions with probe A at the grip-hand and B at the different positions as shown in Fig.5.

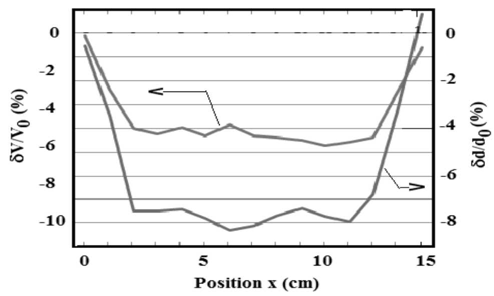

Fig. 4 The thickness deformations and output voltages detected for a SUS304 sample with a tensile stress up to 600MPa as a function of positions along the elongation direction.

Fig.4 describes the results of the output voltages and the thickness deformation as a function of positions for an elongated SUS304 sample with a tensile stress. In this material, both the magnetic susceptibility increase caused by the martensitic transformation and the conductivity decrease happen together [16, 17, 18].

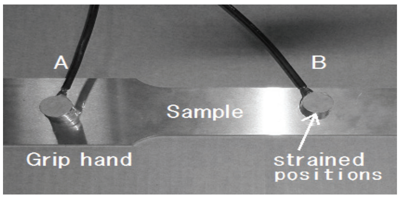

Fig.5 The setting of probes at the sample surface

In addition to these results, the phase shifts of output voltages deviated from the excitation current were also observed by an a.c. operation after removals of diode arrays.

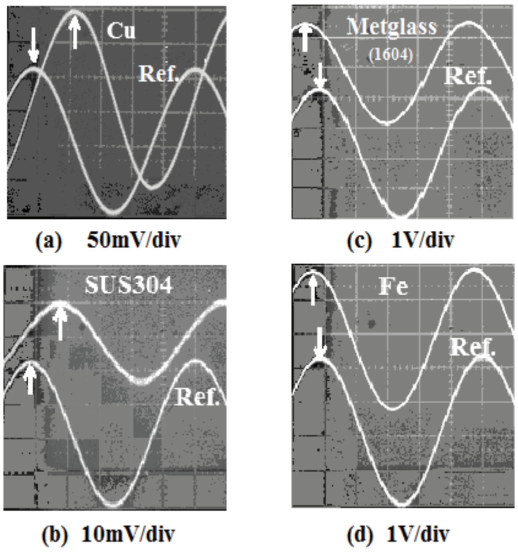

Fig. 6 The phase shifts in different materials observed by the difference outputs between the two probes in the a.c. operation. (Ref. signal: *I(t),* Horizontal axis: 0.1ms/div)

Note here that the phases in Fig.6 are not the real phase shifts but the difference of the two outputs of Pr1 and Pr2 in ac operation. Namely, V_D for conductive materials retarded from I by the phase shifts about of $\pi/2$ degree as shown in Fig.6 (a),(b), and V_D for ferromagnetic materials the phase advance by that for *I(t)* with small angles<0 as in Fig.6 (c),(d). Therefore, in this apparatus, the phase shifts in V_D could display the enlarging phases to clarify the material properties. Namely, the difference output voltages (V_D) could characterize the ratio of the eddy current loss to the magnetic permeance in this device, because that the phase shift of V_D from I proportionally reflects the composition of that by magnetic permeability and that by the conductivity, respectively. On the other hand, by rectifying the secondary coil voltages, the output voltages (V_D) show the amplitude variations with a high sensitivity and with a slow temporal response.

Discussions

We presented many NDE tools in this study together with the additional experiments on the ac magnetic diagnosis tools. In this discussion, we examine the validity of a.c. magnetic circuit and the experimental results. Namely, we suppose the complex variables of the magnetic resistance $R(\omega)$ as $Z(\omega)$ in the conventional circuit theory [15,16]. Further, 3 components are proposed in each probe of Pr1 and Pr2 as shown in Fig. 7.

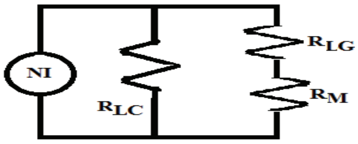

Fig.7 Equivalent magnetic components composed of the core stem, the gap at the poles and the material, respectively.

Namely Fig. 7 shows an equivalent component of R_{LC}, originated by the leakage flux around magnetic core positions ranging from the winding coil, R_{LG}, by the air-gap between the magnetic poles and sample surface, R_M, by the sample, respectively. The dependence of gap resistance on the frequency could be neglected as a pure resistance (real number). Now, in general, the difference signal between Pr2 and Pr1 (=$\Delta C_{21}(f)$) is exactly expressed by each component of R_{LG1}, R_{M1}, R_{LG2}, R_{M2}, in Pr2 and Pr1, respectively as

$$(4)\quad \Delta C_{21}(f) \approx \frac{1}{R_{LG}}\left[\frac{R_{M2}}{R_{LG}+R_{M2}} - \frac{R_{M1}}{R_{LG}+R_{M1}}\right]$$

Note here that $R_{LG1}=R_{LG2}$ ($\equiv R_{LG}$) due to the exactly the same current flows in the primary coils of the two probes with the same structure. Now, $\Delta C_{21}(f)$ behaves always positive due to the increasing function of R_M in the case of inequality of $R_{M2}>R_{M1}$. We can simplify the inequalities of these resistances for magnetic materials as

$$(5)\qquad |R_{LC}| >> |R_{LG}| >> |R_{LM}|\ .$$

In this case, the difference permeance $\Delta C_{21}(f)$ is expressed by

$$(6)\qquad \Delta C_{21}(f) \approx \frac{1}{R_{LG}^{\ 2}}(R_{M2} - R_{M1}).$$

Equation (6) shows the difference permeance between the material constants at the position "1" and "2", or different material "1" and "2", respectively.
By considering frequency dispersions of the magnetism and the conductivity of the material, R_M is exactly expressed by

$$(7)\quad R_M(f) \approx 2\pi f^{E} R_{M0} \exp(-2\pi f \tau_M)\ .$$

Here R_{M0} stands for a complex number depending on the magnetic susceptibility, *E,* an adjustable parameter to fit experimental data with that for eddy current loss or the magnetic dispersion. The relaxation time constant (τ_M) might be fitted well with the experimental results as shown in Fig.3, where apparently the frequency dispersions were observed. The total response of the *C(f)* is limited between the largest value by $(R_{LC}//RLG)^{-1}$ and the smallest by $(R_{LC})^{-1}$as easily understood by Fig. 7,.where the leakage flux around at the primary coil could not be neglected.

Conclusions

We emphasize here, that the analytical results could be normalized and calibrated by the sample properties, thickness and by the surface area. After these corrections, we can obtain the general and absolute material constants of the susceptibility, the conductivity as a function of frequency and the sample thickness, respectively. In addition to this information, the anisotropy of the material might be obtainable by the structure of the magnetic poles in the probe. The phase shift analysis of the output signals will make it possible to decompose the contributions by the susceptibility and by the conductivity in the material. The most important feature in ac magnetic probe is the non-contacting manner to the sample surface. Especially in the atomic power station, all the material should not be injured by the diagnosis. Even in case of small digs caused by the measurement, might enlarge the injuries from the surface.

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