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1-1

Quasi-Analytical Approach to the Resonance Phenomenon of Finite Length Solenoid Inductors

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Introduction

To compute the electromagnetic fields, several numerical methods have been proposed and commercial based software packages could be available depending on each of the problems. Even though a lots of packages have been available, it is difficult to evaluate the simple resonant phenomenon of finite length solenoid inductors. This means that an independent solution in each of the Laplace, Poisson, diffusion, wave equations could be easily evaluated but a solution of the mixed problems, e.g., a simultaneous solution of the wave and diffusion equations, is difficult. This leads that there is no commercial based software packages to compute a simple frequency characteristic of finite length solenoid inductors.

T.Takano and et al tried to evaluate the exact skin effect of the finite length solenoid inductors and elucidated that two kind of skin effects are observed in the finite length solenoid inductors. One is a local skin effect observed in each of the cross-sections of the conductors and the other is a global skin effect to reduce the linkage fluxes as possible as small in entire inductors [1].

Y.Watazawa and et al tried to evaluate a quasi-analytical solution of the Laplace, Poisson, diffusion, wave mixed problem and elucidated the fundamental difference between the skin and proximate effects [2].

Xin Hu developed a full wave solver. Probably this is the first general purpose solver to the mixed problems [3].

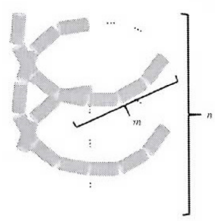
This paper tries to carry out the quasi-analytical solution of the exact spirally wound finite length solenoid inductor. Even though the quasi-analytical solutions are not exactly corresponding to that of experimental ones, it is clarified that the resonant phenomenon is possible to evaluate by means of the quasi-analytical approach proposed in this paper.

Quasi-Analytical Modeling

The most important key idea of the quasi-analytical approach proposed by us is that any of the conductors having complex geometrical shape is divided into small conductor having simple geometrical shape. In the other words, any of the conductors could be represented by a set of large number of small conductors, and each of the small conductors has its own analytical circuit parameters, e.g., resistance, inductance, capacitance. Hence, the solutions of any mixed problems could be reduced into the simultaneous solution of large and extremely complex circuit equations.

Let us consider a simple finite length solenoid inductor shown in Fig. 1(a). At first, a conductor of this inductor is divided into a large number of small conductors as shown in Fig. 1(b).

(a) Finite length solenoid inductor



(b) Subdivisions of the coil

Fig. 1 Model inductor and its coil subdivisions.

The circuit parameters in each of the conductors shown in Fig. 1(b) can be obtained by analytical means. For example, a resistance of a small conductor in Fig. 1(b) is calculated by

$$r = \sigma \frac{l}{\pi a^2}, \quad (1)$$

where σ, l and a are respectively the resistivity, length and radius of the conductor.

The inductance and capacitance are similarly calculated. As a result, it is possible to obtain an equivalent circuit. Fig. 2. shows a simplified circuit model of finite length solenoid inductors.

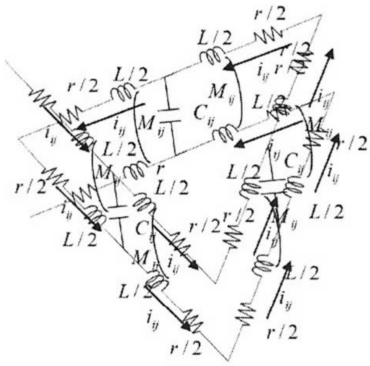


Fig. 2 One of the equivalent circuit.

Fig. 3 shows one of the calculated frequency characteristics of solenoid inductors along with the experimental one. Even though a difference between the calculated and measured resonant frequency is observed, validity of our quasi-analytical approach has been verified.

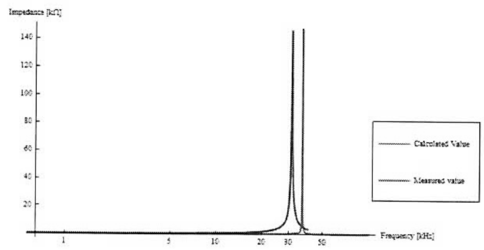


Fig. 3 One of the calculated frequency characteristics of the solenoid inductors along with the experimental one.

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3-1

Stress-Frequency Characteristics of the Complex Permeability

- Fundamental Background-

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Introduction

As is well known, ferromagnetic materials exhibit a lot of complex physical properties, such as the magnetization, magnetostriction and magneto-thermodynamic properties. All of these physical properties are nonlinear processes so that their reproducibility is always low excepting the ultimate condition such as magnetically saturated situation. Only one linear parameter is a complex permeability because it is measured under the sinusoidal field intensity H and also sinusoidal flux density B conditions.

On the other side, a representative ferromagnetic material is iron which is commonly used as frame structural materials of many artificial products. This means that the complex permeability may be considered as one of the possible soundness figure to represent its situation such as under stressed or not in the structural frame materials.

In the other words, if the complex permeability sensitively responds to the external stress as well as residual stress applied to the main frame materials, a stress-frequency characteristic of the complex permeability may be considered as the soundness figure to know the residual and normal stresses in the frame materials used in the various artificial products, e.g., building, tower, bridge, train, automobile and so on.

According to the above mentioned, this paper plans to establish the first firm theoretical background, i.e., theoretical derivation of the complex permeability and its experimental verification.

Theoretical Background

The domain based magnetization model is

$$H = \frac{1}{\mu}B + \frac{1}{s}\left(\frac{dB}{dt} - \mu_r\frac{dH}{dt}\right), \quad (1)$$

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].

The first on the right in (1) represents a static magnetized state and the second represents the dynamic magnetized state, i.e., denoting *v* as a velocity of magnetic domain, the second term can be rewritten by

$$\begin{aligned}\frac{1}{s}\left(\frac{dB}{dt} - \mu_r\frac{dH}{dt}\right) &= \frac{1}{s}B_s\frac{\partial n}{\partial x}\frac{\partial x}{\partial t}\\ &= \frac{1}{s}B_s\frac{\partial n}{\partial x}v\end{aligned}, \quad (2)$$

where B_s, *n*, *x* are the saturated flux density in each of the domains, number of the domains and position, respectively.

Equation (2) means that the induced voltage *dB/dt* in an unit area is composed of the transformer induced $\mu_r(dH/dt)$ and velocity induced $B_s(\partial n/\partial x)v$ voltages.

When we apply a complex notation regarding the constant values of μ, μ_r and *s* to (1), it is possible to derive the complex permeability as

$$\mu_R(\omega) - j\mu_I(\omega) = \mu\left(\frac{s^2+\omega^2\mu\mu_r}{s^2+\omega^2\mu^2}\right) - j\omega\mu\left(\frac{\mu-\mu_r}{s^2+\omega^2\mu^2}\right) \quad (3)$$

where $j=\sqrt{-1}$.

The parameters μ, μ_r and *s* are easily evaluated by considering the $\omega \Rightarrow 0$, $\omega \Rightarrow \infty$ and the peak value of the second term on the right in (3).

Experiment

Figure 1 shows an experimental frequency characteristic of the complex permeability along with the theoretical one.

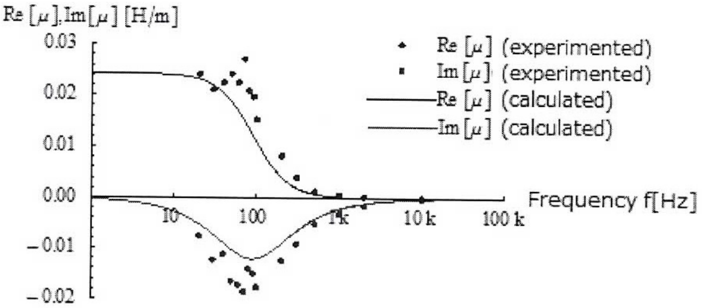

Fig.1 One of the frequency characteristics of the complex permeability.

The results in Fig. 1 verifies the validity of our complex permeability model. The frequency characteristic of the complex permeability depends on only three parameters, i.e. permeability μ, reversible permeability μ_r and hysteresis coefficient s so that the effect caused by the external stress may reflect on these parameters.

Thus, the first stage of our stress measurement project employing the stress-frequency characteristics has been successfully established, i.e., the careful measurement of the parameters μ, μ_r and s has reproduced the frequency characteristic of the complex permeability.

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5-2

Defect Searching in the Curved Surface by the Film ∞ Coil

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Introduction

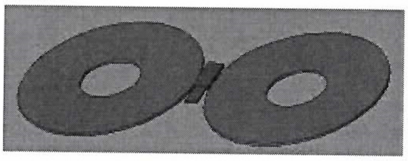
Previously we have succeeded in developing a new ECT sensor called ∞ coil [1,2]. This new ECT sensor ∞ coil is composed of two exciting coils. These exciting coils are arranged in two column wise finite length solenoid coils. When an alternating current is flowing in series through these two coils, both coils yield magnetic fields. One becomes a south pole and the other becomes a north pole. Therefore, there is a zero magnetic field zone. One of the most beautiful key points of the ∞ coil is that a sensing coil wound around a ferrite bar is set to this zero magnetic field zone, which is extremely sensitive to the magnetic fields caused by a defect in the target specimen.

However, the ∞ coil confronts to a serious difficulty to apply the curved surface targets. To overcome this difficulty, this paper has worked out a film ∞ coil whose shape exhibits a surprising flexibility so that the film ∞ coil changes its shape to adjust any curved surface targets.

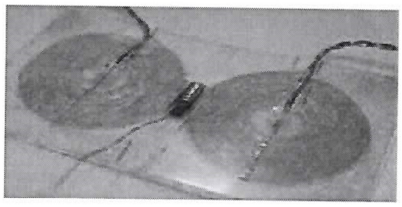
Intensive numerical simulations employing 3D FEM package were carried to show the usefulness of the film ∞ coil. Experimental results verified the validity of the numerical simulations as well as the versatile capability of the ∞ coil.

The Film ∞ Coil

Before to work out the exact film shape ∞ coil, we worked out the flat coil ∞ coil. Fig. 1 shows a model film ∞ coil and its corresponding flat ∞ coil.



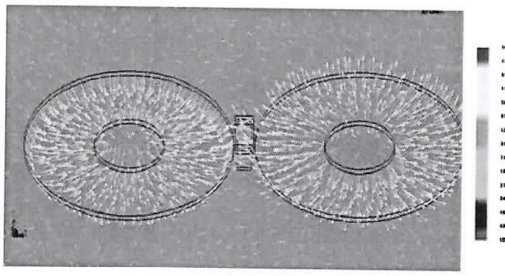
(a) Model film ∞ coil



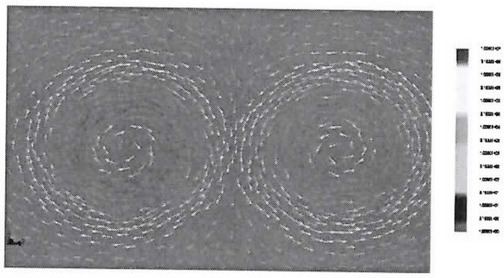
(b) Film ∞ coil

Fig.1 A model film ∞ coil and its corresponding flat ∞ coil.

Fig. 2 shows one of the computed magnetic field intensity distributions and the eddy current vectors distributions.



(a) A computed magnetic field intensity distribution



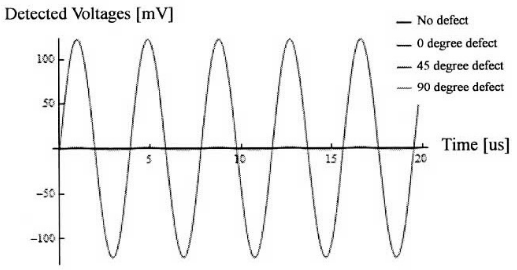
(b) The eddy current vectors distributions.

Fig.2 One of the computed magnetic field intensity distributions and the eddy current vectors distributions.

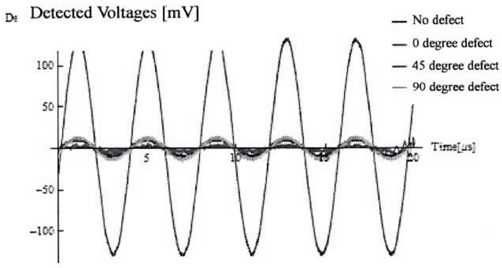
Simulated and Experimented Results

To verify our ∞ film coil, we compared the simulated and experimented results. Fig. 3 shows the simulated results along with the experimented results.

Time [us]



(a) Simulated detected voltages in the sensing coil.



(b) Measured detected voltages in the sensing coil.

Fig.3 Comparison simulated results with measured results related to detected voltages in the sensing coil.

Although the small detected signals are observed in Fig. 3(b), both of the detected signals to a defect is well corresponding each other.

Conclusion

We have succeeded in exploiting the film ∞ coil. According to our laboratory work, it is clarified that the practical film ∞ coil may be produced by the printing processes.

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5-3

First Order Frequency Fluctuation Analysis of the Barkhausen Signals

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Introduction

Barkhausen signal is popularly observed in any of the ferromagnetic materials having the magnetic domain structures, e.g. iron, nickel, cobalt and garnet, when they are magnetizing. Also, it is well known that the Barkhausen signals are very sensitive to the physical external input, such as mechanical stress and radioactive damage, to the ferromagnetic materials [1].

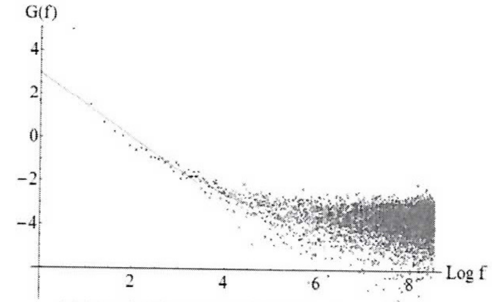
According to the past researches concerning to a relationship between the Barkhausen signal and applied mechanical stress, it has been revealed that Barkhausen signals are very sensitive to the mechanical stress and radioactive damage but any deterministic regularity has not been found.

This paper concerns with the stress detection problems on the ferromagnetic materials by means of the frequency fluctuation analysis of the Barkhausen signals emitted from the ferromagnetic materials. Major ferromagnetic magnetic material is iron and its composites which are used extensively as the structural frames of various artificial products such as car, train, bridge and sky scraper buildings. So that we apply our frequency fluctuation analysis method to the Barkhausen signals to inspect whether the structural frames are stressed or not [2].

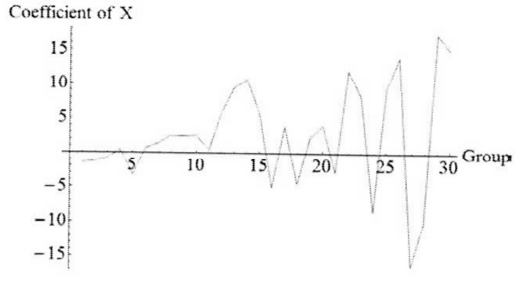
Until now, we have tried to detect the stress characteristic from the Barkhausen signals under stressed ferromagnetic materials. As a result, it has been clarified that the stress characterizing signals are contained at low frequency range in the Barkhausen signals. However, its 1st order frequency fluctuation method has some drawback, i.e., the frequency range containing the stress characterizing signals should be artificially extracted [3].

To overcome this drawback, we apply one of the optimum methodologies, i.e., k-means method, to the Fourier power spectrum of the Barkhausen signals under stressed.

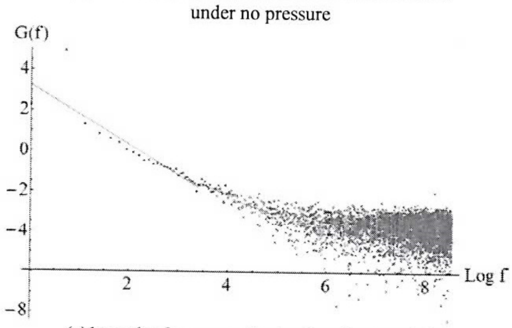
Thus, we have succeeded in detecting the stress characterizing signal from the Barkhausen signals under stressed by combining the 1st order frequency fluctuation analysis and k-means method.



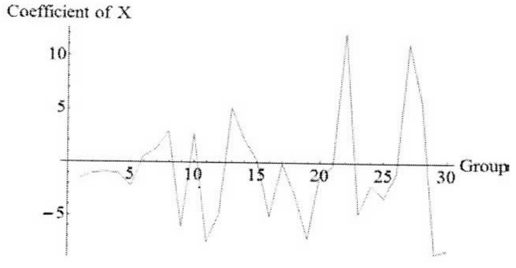
(a)1st order frequency fluctuation characteristics under no pressure



(b)1st order gradient vs. frequency characteristics under no pressure



(c)1st order frequency fluctuation characteristics under 1026g pressure



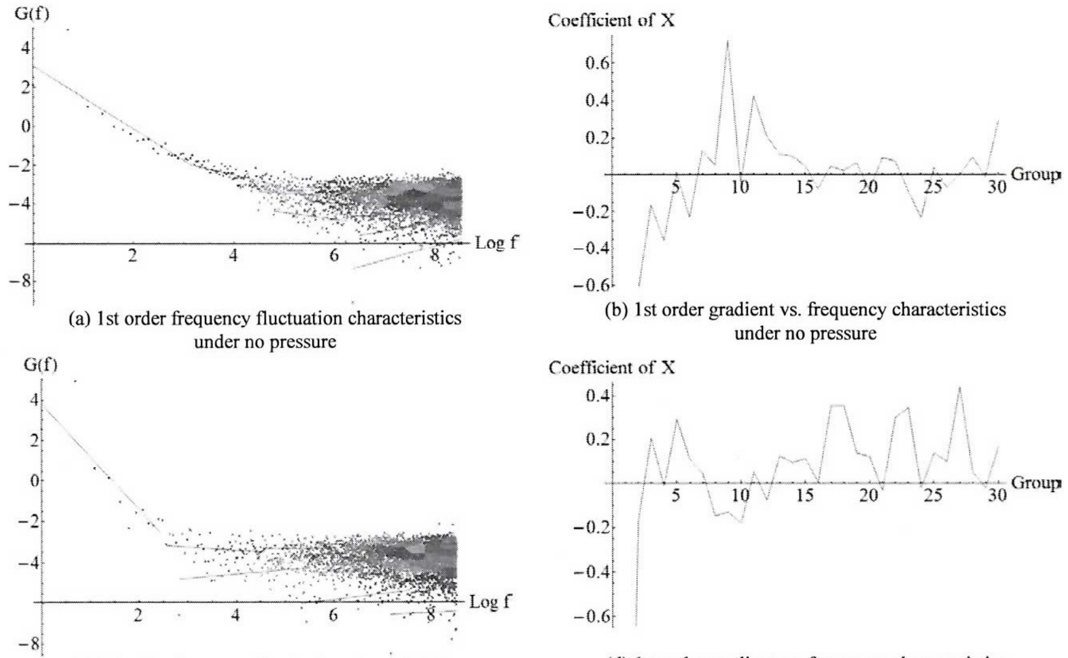
(d)1st order gradient vs. frequency characteristics under 1026g pressure

Fig. 1 1st order frequency fluctuation characteristics obtained by the equispaced clustering. method

Clustering by k-means approach

We confronted to a serious difficulty, i.e., how to decide the frequency range for which to be computed the frequency fluctuation characteristic. This problem is solved in this paper by employing one of the optimization methods, i.e., k-means method based on Euclidean distance [4].

Fig. 1 shows the equispaced clustered frequency fluctuation characteristics under no and 1026g stresses. It is obvious that it is difficult to detect a distinct difference between the no and 1026g stresses from the results in Fig.1.



(a) 1st order frequency fluctuation characteristics under no pressure

(b) 1st order gradient vs. frequency characteristics under no pressure

(c) 1st order frequency fluctuation characteristics under 1026g pressure

(d) 1st order gradient vs. frequency characteristics under 1026g pressure

Fig. 2 1st order frequency fluctuation characteristics obtained by the k-means clustering method.

Fig. 2 shows the k-means clustered frequency fluctuation characteristics under no and 1026g stresses. In Fig.2, it is revealed that an entire 1st order coefficients becomes the positive values when 1026g stress is applied to the target silicon steel, i.e., the 1st order frequency fluctuation characteristics along with the k-means clustering method takes a different tendency of the frequency characteristics by applying the stress to the target steel.

Conclusion

Thus, we have succeeded in detect the stress to the ferromagnetic materials by the 1st order frequency fluctuation analysis along with the k-means clustering method.

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5-4

A Study on Backside Defect Searching by Low Frequency Excitation of the ∞ Coil

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Introduction

Modern engineering products such as air-plane, automobile, smart building, high speed train and so on are essentially composed of metallic materials for forming the shape of product, suspending the mechanical stress and constructing the structural frames. In particular, the mass transportation vehicles, e.g. large air plane, high-speed train, express highway bus, carrying a large number of peoples are required ultimately high safety as well as reliability. To keep the high safety and reliability, nondestructive testing to the metallic materials is one of the most important key technologies, because most of the structure materials are composed of the metallic materials. Various nondestructive testing methods, such as eddy current testing (ECT), electric potential method, ultrasonic imaging and x-ray tomography are currently used for the modern airplane, high-speed -train and express high bus. Among these methods, ECT does not need the complex electronic circuits and direct contact to the targets. More of that most of the targets whose major frame parts are composed of conductive metallic materials can be selectively inspected by ECT [1-3].

Operation principle of ECT is fundamentally based on the magnetic field distribution change detecting capability due to the defect in the targets. To realize this principle, we have two methodologies. One detects the magnetic field change caused by the detour eddy currents flowing around the defect as a change of input impedance of the exciting coil [2,3]. The other equips a sensing coil to detect the magnetic field change caused by the detour eddy currents flowing around the defect. The former and latter are called the impedance sensing and sensing coil types, respectively.

The sensing coil type is further classified into two variations. Most popular sensing coil type employs a differential coil, and also the other type sets the sensing coil surface perpendicularly to those of the exciting coil. As is well known that the differential coil detects the uniformity of the magnetic field distribution. Similarly the perpendicularly installed sensing coil surface to those of exciting coil detects only the magnetic fields caused by the detour eddy currents due to the defect in the target.

Our developed ∞ coil belongs to the latter type, i.e., detects only the magnetic fields caused by the detour eddy currents due to the defect in the target. A key idea of our ∞ coil is that the sensing coil wound around a ferrite bar is installed at the lowest magnetic field intensity region between the north and south poles of exciting coils [1].

In the present paper, to search for the backside defect of a target, we have employed the ∞ coil. As a result, it is revealed that the ∞ coil has versatile capability, i.e., low frequency excitation of the ∞ coil along with the signal processing method enhancing the S/N ratio makes it possible to detect the backside defects.

Experiments

At first, we have carried out the intensive numerical simulations employing 3-dimensional finite elements method to check the possibility of backside defect searching by low frequency excitation of our ∞ coil. After a series of numerical experiments changing the exciting frequencies. We carried out the practical experiments. As a result, we have confronted to the high frequency noise problem caused by various electrical and electronic devices located around the work bench. To overcome this difficulty, we employed two signal processing methodologies. The first is the averaged sum method which requires the multiple signal samplings to the same target. Second is a Fourier transform method which deletes the higher frequency components than the exciting frequency from the detected signals.

Thus, we have succeeded in our low frequency exciting approach of the ∞ coil to the backside defect searching problems. Fig.1 shows the illustrative figures whose left and right are the schematic diagram of the numerical experiments and an experimental picture denoting the measurement pitch (5mm) by yellow color, respectively.

The red and blue rings on the left in Fig.1 are the exciting coils which yields the exciting magnetic fields. Also in the same figure, a small ferrite bar wound around a sensor coil located at the just adjacent part of the red and blue colored exciting coils. The defect searching area is a 20mm as shown in the right on Fig.1.

Fig.2 shows the result of backside defect searching by the low frequency driving of the ∞ coil. The left and right on the Fig. 2 are the induced voltages in the sensor coils evaluated by the numerical and practical experiments, respectively. Obviously, No. 3 location has a backside defect in the target.

Thus, we have elucidated that our ∞ coil makes it possible to search for the surface as well as backside defects by driving the low frequencies.

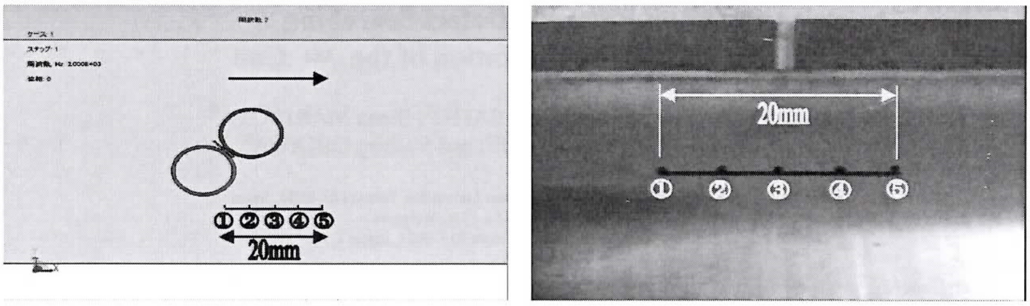

Fig. 1. A line flaw detection model.
The left and right figures denote the scanning direction and measured locations, respectively.

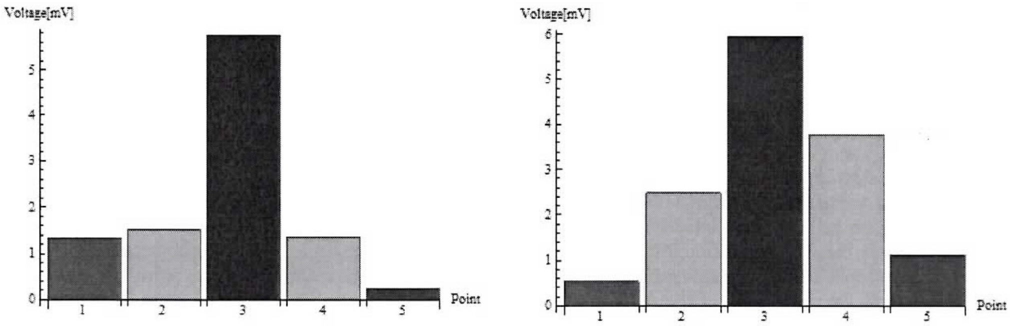

Fig. 2. Sensor output voltages vs. measured points.
The left and right figure refer to the simulation and measurement results, respectively

Conclusion

In the present paper, we have employed the low frequencies for the ∞ coil excitation to search for the backside defect of the metallic target. As a result, it has been clarified that the low frequency excitation of the ∞ coil along with the signal processing procedures enhancing the S/N ratio makes it possible to search for the backside defects.

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[2]Hiroki Kikuchihara, Yoshifuru Saito, Enhance the Sensibility of the ECT Sensor, Journal of the Japan Society of Applied Electromagnetics and Mechanics, Vol.21, No.3, 2013.

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