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Eddy Current Testing Using Square-wave Inverter for Thickness Inspection of Steel Plate

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Eddy current testing (ECT) usually employs a sinusoidal current that flows through an excitation coil. If a square wave instead of a sinusoidal wave is used for excitation, i.e., a square-wave inverter instead of linear amplifiers is used for an ECT system, a handheld ECT system can be developed and the cost can be reduced. In this study, we developed a low-frequency ECT (LF-ECT) system with a square-wave inverter to determine whether an inverter is applicable to estimating the thickness of a thick steel plate in the range from 6 to 19 mm. The developed ECT system has a differential excitation coil and a pickup coil, and these coils are arranged on the steel plate. A square-wave voltage is applied to the excitation coil, and the voltage of the pickup coil is measured. Subsequently, the mutual equivalent resistance and inductance are calculated. Results indicate that the fundamental component of the resistance increases with the thickness when the frequency is approximately 4 Hz. Furthermore, we determined whether the harmonic signals generated by the inverter are also useful. Results indicate that the harmonic components of the resistance also tend to increase with a sufficiently small increase in thickness, i.e., ≤12 mm. This implies that surface and back-surface defects can be simultaneously obtained.

1. Introduction

Maintaining industrial infrastructures, such as roads, bridges, tunnels, and buildings, built during the period of rapid economic growth has become a problem because half a century has passed since then. Additionally, developed countries, including Japan, will become full-fledged aged societies in the future, and the shortage of maintenance personnel is a significant concern. Therefore, accurate, easy, and fast inspection methods are required.

These infrastructures are made of steel. Therefore, eddy current testing (ECT), which is one of the nondestructive testing techniques, is promising for detecting the defects of a metallic structure because it can be conducted at high speeds without the specimen coming in contact with the sensor using a compact instrument with no usage restrictions.(1,2) However, conventional ECT is limited to the detection of surface or subsurface defects, owing to the

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skin effect. Moreover, steel plates with a thickness of 10 mm or larger are often used for large infrastructures. Therefore, low-frequency ECT (LF-ECT) is essential for examining the defects of a thick ferromagnetic object.(3–9)

ECT usually employs a sinusoidal current that flows through an excitation coil.(1,2) In this case, linear amplifiers are used to generate the excitation current. However, if a large excitation current is required to enhance the signal from the eddy current, a linear amplifier requires a large heat sink owing to the low conversion efficiency, and the weight and size of the ECT system increase, which lowers its portability. On the other hand, electrical equipment such as motors often employs an inverter to generate a large current owing to development of power electronics. An inverter is more efficient, smaller, and lighter than a linear amplifier, which contributes to the development of a handheld ECT system and cost reduction.

We previously developed an LF-ECT system using a high-temperature superconducting (HTS) coil and a pulse width modulation (PWM) inverter.(9) Using this system, a steel plate thickness of up to 20 mm can be estimated by measuring the change in coil resistance even when the lift-off is approximately 100 mm, which contributes to the detection of the back-surface corrosion of a thick steel plate.

An inverter is also considered to be applicable to LF-ECT with copper coils as well as HTS coils. In this study, we determine whether an inverter is applicable to LF-ECT with copper coils to estimate the thickness of a steel plate. Note that a square wave contains harmonic sinusoids. Therefore, we also determine whether more information can be obtained simultaneously from harmonic sinusoids as well as a fundamental sinusoid. To investigate the efficacy of harmonic sinusoids, we apply a square wave inverter instead of a PWM inverter.

2. Materials and Methods

Figure 1 shows the developed LF-ECT system with a square-wave inverter. Firstly, a stable DC voltage (5 V) was generated by a DC/DC converter. Then, the square wave was generated by an H-bridge driver (BD6212HFP, ROHM Corp., Ltd.) to excite the coil. The sum of the resistances of the upper and lower arms is 0.5 Ω (typical value). A shunt with a resistance of 0.1 Ω was inserted to measure the current of the excitation coil.

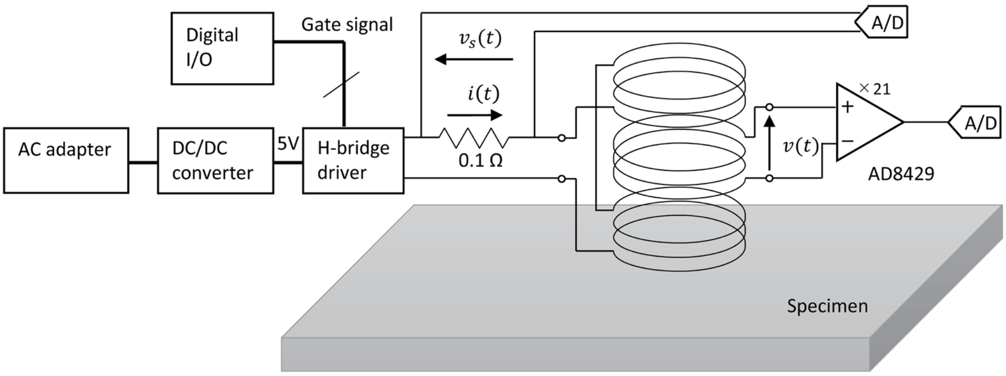


Fig. 1. LF-ECT system with an inverter.

The gate signal of the H-bridge driver was generated by a digital I/O module (NI 9401, National Instruments Corp.). Using the I/O module, we generated a square wave whose frequency was f Hz. The voltage of the pickup coil $v(t)$ was amplified and recorded by an A/D converter (National Instruments Corp., NI 9239; resolution, 24 bit; sampling rate, 50 kS/s). The digital I/O module and the A/D converter were set in the CompactDAQ chassis (cDAQ-9171, National Instruments Corp.), and the modules were controlled using the LabVIEW software.

The lower and upper excitation coils were connected reversely to cancel out the direct flux from the excitation coils and to detect only the flux generated by an eddy current. The voltage of the shunt resistance as well as the pickup coil was recorded by the A/D converter, and the excitation current $i(t)$ was obtained. Subsequently, the n-th harmonic voltage $\dot{V}_n$ and current $\dot{I}_n$ were calculated by applying a fast Fourier transform (FFT) to $v(t)$ and $i(t)$, respectively.

When we assume that the magnetic field is small enough to ignore the nonlinearity and hysteresis characteristics of the steel plate, the relationship between $\dot{V}_n$ and $\dot{I}_n$ can be described as

$$\dot{V}_n = \left(\Delta R_n^M + jn\omega\Delta M_n\right)\dot{I}_n, \tag{1}$$

where ω is the angular frequency ($\omega = 2\pi f$), R_n^M denotes the apparent resistance due to the magnetic flux generated by the eddy current, or equivalent resistance, M_n denotes the mutual inductance between the excitation and pickup coils, and Δ denotes the difference between the values obtained with and without the plate. The parameters ΔR_n^M and ΔM_n were obtained by measuring $\dot{V}_n$ and $\dot{I}_n$.

Figure 2 shows the arrangement of the excitation and detection coils. Table 1 shows the resistances and inductances as well as the dimensions of these coils. These resistance and inductances were measured using an LCR meter (ZM2371, NF Corp.). The distance between the specimen and the lower excitation coil, i.e., lift-off, was 3 mm.

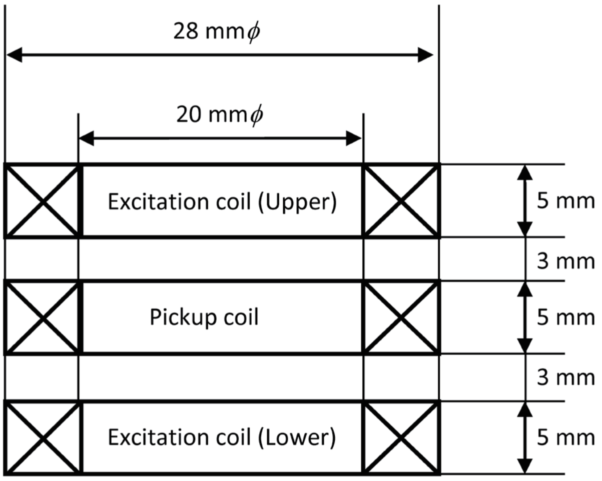


Fig. 2. Arrangement of the excitation and pickup coils.

Table 1
Specifications of the excitation and pickup coils.

	Pickup coil	Upper excitation coil	Lower excitation coil
Inner diameter (mm)	20	20	20
Outer diameter (mm)	28	28	28
Number of turns	1200	1200	1200
Resistance (Ω)	200.6	199.5	200.6
Inductance (mH)	40.89	40.94	41.18

The square voltage wave can be described as

$$e(t)=\begin{cases}-E, & -\frac{T}{2}\le t<0,\\ E, & 0\le t<\frac{T}{2},\end{cases} \tag{2}$$

where T is the period ($T = 1/f$) and E is the amplitude ($E = 5.0$ V). By calculating Fourier series coefficients of $e(t)$, we obtain the equation

$$e(t)=\frac{4E}{\pi}\left(\sin\omega t+\frac{1}{3}\sin 3\omega t+\frac{1}{5}\sin 5\omega t+\cdots\right). \tag{3}$$

Therefore, the n-th harmonic voltage of $e(t)$, E_n, can be derived as

$$\dot{E}_n=\frac{2\sqrt{2}E}{n\pi},\ n=1,3,5,\dots . \tag{4}$$

Equation (4) implies that a square wave contains rich harmonics. From Eqs. (1) and (4), we obtain the equation

$$\dot{I}_n=\frac{\dot{E}_n}{R+jn\omega L}=\frac{2\sqrt{2}E}{n\pi\left(R+jn\omega L\right)},\ n=1,3,5,\dots , \tag{5}$$

where R and L denote the resistance and inductance of the excitation coils, respectively. Here, we assume that R and L are sufficiently larger than the changes in these parameters caused by the eddy current. If $R \gg jn\omega L$, i.e., n and ω are sufficiently small, $\dot{I}_n$ is proportional to $1/n$. In this study, the parameters R and L are 400.1 Ω and 71.09 mH, respectively. Thus, the relation $R \gg n\omega L$ holds when $nf \ll 896$.

In the experiment, SM490A steel plates were used. The relative permeability μ_r is approximately 200, and the conductivity σ is 4.1 MS/m. The skin depth δ is

$$\delta=\sqrt{\frac{1}{\pi f\sigma\mu_r\mu_0}}, \tag{6}$$

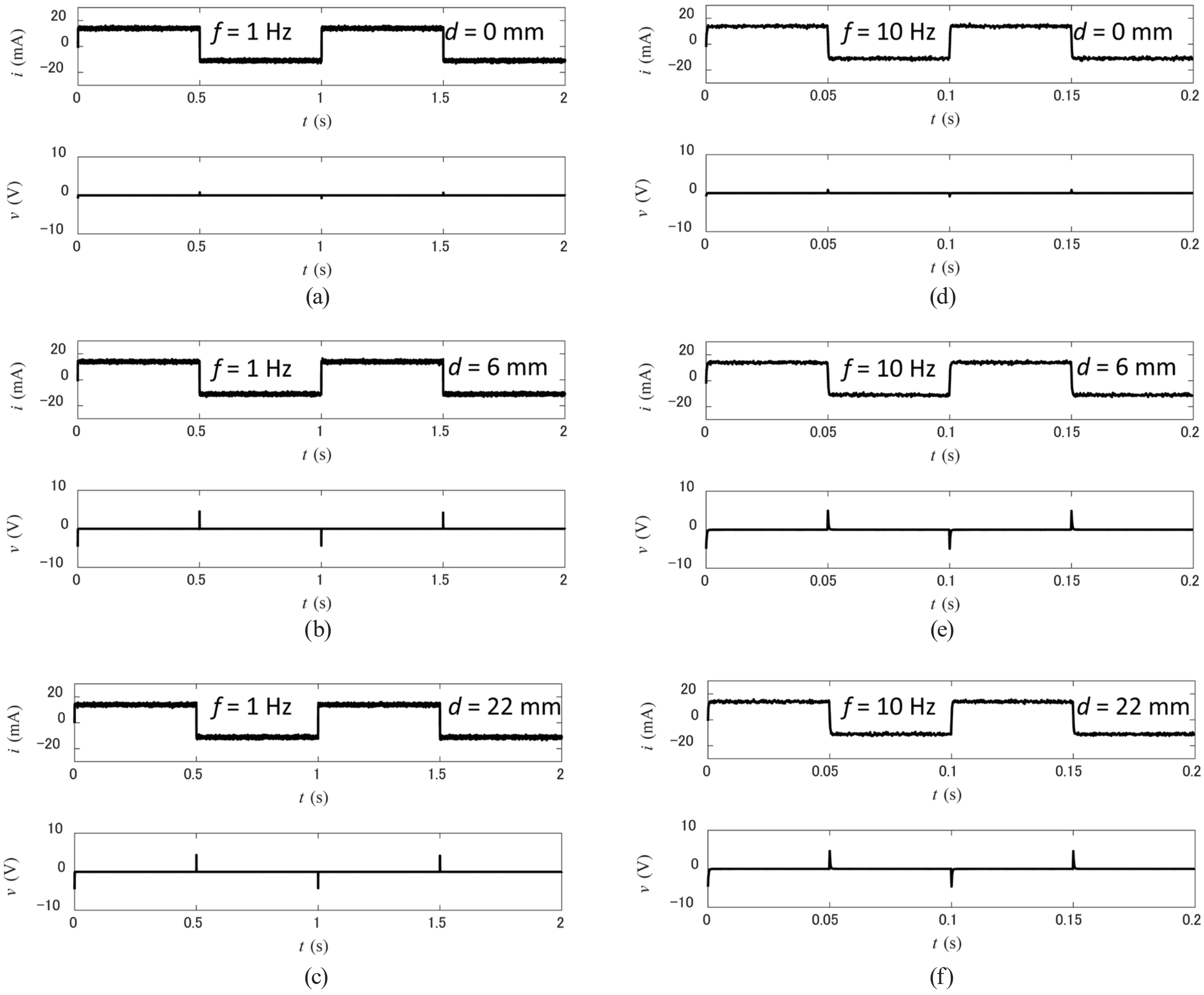
where μ_0 is the permeability of vacuum. Substituting f = 8 into Eq. (6), we obtained δ =

6.2 mm. We used six plates of different thicknesses, i.e., d = 6, 9, 12, 16, 19, and 22 mm. The dimensions of the steel plates were 200 × 200 mm^2.

3. Results

Figure 3 shows the time waveforms of $v(t)$ and $i(t)$ when f = 1 Hz [Figs. 3(a)–3(c)] and f = 10 Hz [Figs. 3(d)–3(f)].

Figures 3(a)–3(c) show the results obtained when d = 0 (no plate), 6, and 22 mm, respectively. The amplitude obtained when d = 0 mm is approximately 1 V, and those obtained when d = 6 and 22 mm are approximately 4 V. Therefore, the effect of the steel plate can be determined by comparing the obtained amplitudes. In contrast, the amplitudes fluctuate, and there is no correlation between the amplitude and d, e.g., the amplitude obtained when d = 6 mm is less than that obtained when d = 22 mm. Thus, the thickness d cannot be accurately estimated by measuring only the amplitude.



(a) (d)

(b) (e)

(c) (f)

Fig. 3. Time waveforms of $v(t)$ and $i(t)$. (a)–(c) f = 1 Hz and (d)–(f) f = 10 Hz. In the upper row, (a), (d), d = 0 mm, in the middle row, (b), (e), d = 6 mm, and in the lower row, (c), (f) d = 22 mm.

Figures 3(d)–3(f) show the results obtained when $d = 0$ (no plate), 6, and 22 mm, respectively. Here, the tendency observed when $f = 10$ Hz is almost the same as that observed when $f = 1$ Hz. That is, the effect of the steel plate can be determined; however, the thickness cannot be accurately estimated by measuring only the amplitude.

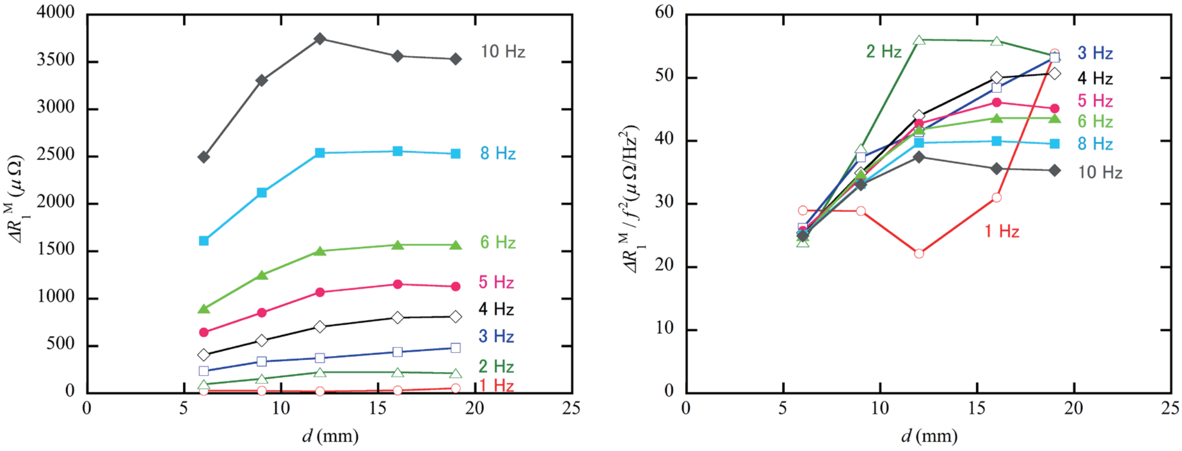
Figure 4(a) shows the relationship between the fundamental mutual equivalent resistance (ΔR_1^M) and the thickness of the steel plate (d) when f changes from 1 to 10 Hz. Here, ΔR_1^M increases with f. Thus, it is difficult to recognize the tendency of the result when f is small. When we assume that the hysteresis loss in the steel plate is sufficiently lower than the eddy current loss and the skin effect is small, ΔR_1^M is proportional to f^2.

Figure 4(b) shows the result obtained when ΔR_1^M is normalized by dividing f^2. Here, ΔR_1^M monotonically increases with d when $f = 3$ Hz. Therefore, the thickness d can be estimated by measuring ΔR_1^M even when a square wave is used for excitation instead of a sinusoidal wave. In other words, an inverter is applicable to ECT to estimate the thickness of the steel plate.

If the frequency is lower, i.e., $f = 1$ and 2 Hz, the signal from the eddy current becomes smaller. Thus, ΔR_1^M did not monotonically increase with d when $f = 1$ and 2 Hz. That is, it is difficult to estimate d when f is lower. In contrast, if the frequency is higher, i.e., $f \geq 4$ Hz, the domain that shows a monotonic increase decreases owing to the skin effect. For example, ΔR_1^M monotonically increases in the domain $6 \leq d \leq 12$ mm when $f = 10$ Hz.

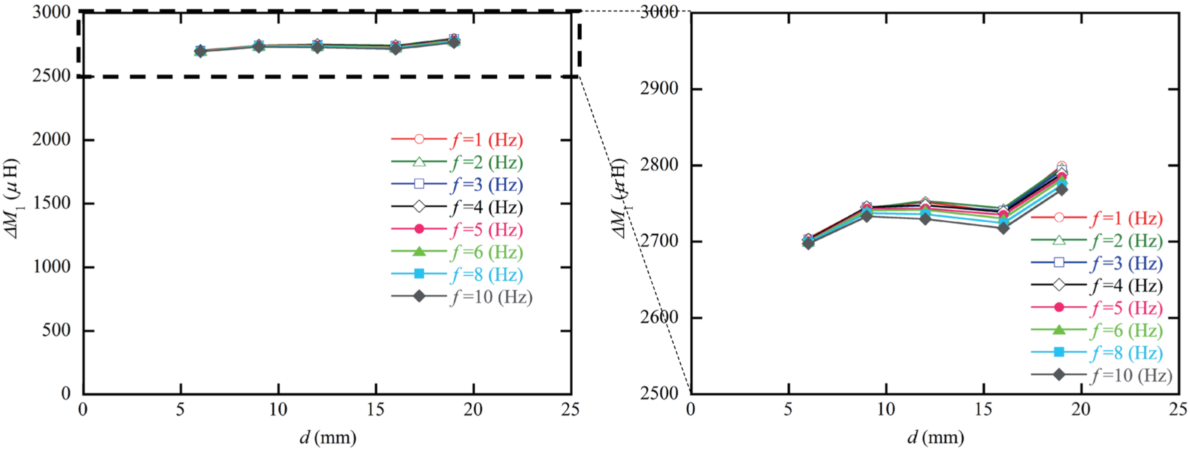
Figure 5 shows the relationship between the fundamental mutual inductance (ΔM_1) and d when f changes from 1 to 10 Hz. Here, ΔM_1 is almost constant even when d and f change. Thus, ΔM_1 is independent of d.

Figure 6 shows the relationship between the fundamental mutual inductance (ΔM_1) and d when the lift-off z changes from 3 to 13 mm. Here, ΔM_1 is almost constant even when d and f change, whereas ΔM_1 decreases with z. This suggests that the lift-off can be determined by measuring ΔM_1.(8)



(a) (b)

Fig. 4. (Color online) Relationship between the fundamental mutual equivalent resistance (ΔR_1^M) and the thickness of the steel plate (d) when f changes from 1 to 10 Hz. (a) Resistance and (b) normalized resistance.



(a) (b)

Fig. 5. (Color online) Relationship between the fundamental mutual inductance (ΔM_1) and the thickness of the steel plate (d) when f changes from 1 to 10 Hz.

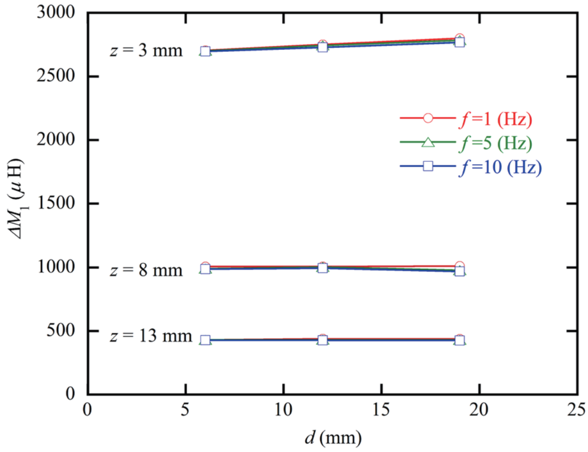


Fig. 6. (Color online) Relationship between the fundamental mutual inductance (ΔM_1) and the thickness of the steel plate (d) the lift-off z changes from 3 to 13 mm.

Figure 7 shows the relationship between the normalized fundamental and harmonic equivalent mutual resistance ($\Delta R_n^M/(nf)^2$) and d when $f = 1$, 2, 3, and 4 Hz. The tendency of $R_n^M/(nf)^2$ ($n > 1$) is almost the same as that of $\Delta R_1^M/f^2$. For example, when $nf \geq 4$ Hz, the skin effect appears, and ΔR_1^M monotonically increases in the domain $6 \leq d \leq 12$ mm.

4. Discussion

Firstly, we determined whether a square-wave inverter is applicable to ECT to estimate the thickness of the steel plate. The result shown in Fig. 4 demonstrates that d can be estimated by measuring ΔR_1^M using a square-wave inverter if f is appropriately chosen. This result

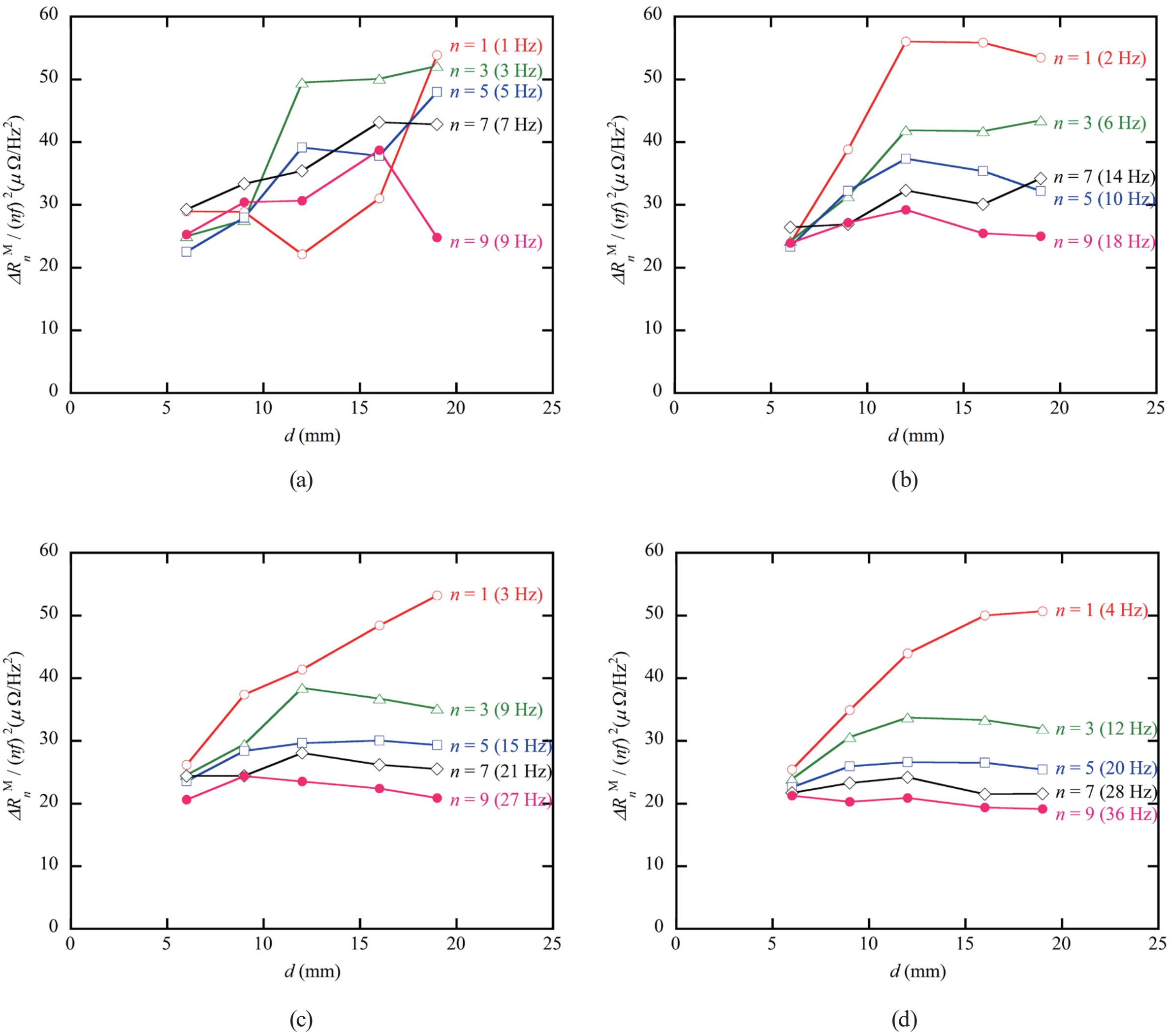


Fig. 7. (Color online) Relationship between the normalized fundamental and harmonic mutual equivalent resistance $[\Delta R_n^M/(nf)^2]$ and d when f = (a) 1, (b) 2, (c) 3, and (d) 4 Hz.

corresponds to that in a previous study when the sinusoidal wave is chosen for excitation.(8) Therefore, the result of this study supports the validity of adopting a square-wave inverter for ECT instead of a linear amplifier.

Secondly, we determined whether more information can be obtained simultaneously from harmonic sinusoids as well as a fundamental sinusoid by using a square-wave inverter instead of a PWM inverter. The result shown in Fig. 7 demonstrates that the tendency of the harmonic signal is almost the same as that of the fundamental signal wiht the same frequency. This suggests that harmonic signals and a fundamental signal can be obtained simultaneously using a square excitation wave.

On the other hand, it has been reported that ECT enables us to obtain much information simultaneously using multifrequency data.(11–13) In our future work, we will determine whether the harmonic signals generated by using the square excitation wave are applicable to obtaining much information simultaneously.

In this study, we chose a small excitation current for the experiment only to determine whether a square-wave inverter is applicable or not. In our future work, we will inspect the effectiveness of LF-ECT with a square-wave inverter when the lift-off is large.

5. Conclusions

In this study, we developed an LF-ECT system to determine whether a square-wave inverter is applicable to estimating the thickness of a steel plate. The result obtained by using the LF-ECT system demonstrates that a square-wave inverter is applicable to estimating the thickness by measuring the fundamental component of the mutual equivalent resistance. Moreover, we determined whether more information can be obtained simultaneously from harmonic sinusoids as well as a fundamental sinusoid. The result suggests that harmonic signals and a fundamental signal can be obtained simultaneously using a square excitation wave.

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