Effects of Waveform and Frequency of Electric Fields on Vibration Responses of an Electro-Rheological Fluids Based CFRP Cantilevered Beam

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Synopsis

Effects of waveform and frequency of electric fields applied to electro-rheological fluids (ERF) are examined on vibration responses of a CFRP composite cantilevered beam containing ERF. Two types of sinusoidal and rectangular waveforms are used for the vibration tests. As the experimental results, the superposed and the beat responses of the composite beam have been observed if applied the electric fields with frequencies less than the first natural frequency of the composite beam. These peculiar responses are explained in vibration analysis. For this purpose, a simplified mass-spring-damper system is adopted to feature the first flexural mode of the composite beam, where the damping factor is changed in time as a function of electric fields applied to ERF. Numerical analysis is performed to solve the motion of equation.

KEY WORDS: CFRP laminate, ER fluids actuator, smart composites, waveform and frequency of applied electric field, beat phenomenon, superposed response

Introduction

Smart fiber composite materials that incorporate embedded or integrated actuators and sensors during their manufacturing process have recently attracted significant attention for their potential applications in structural vibration control. To successfully apply this new technology, actuator materials play an important role.

One candidate for actuator materials is electro-rheological fluids (ERF)[1]. The apparent viscosity and rheological properties of ERF can be controlled in a wide range by the applied electric field. In addition, the response time is very short (several milliseconds) and the change is reversible. Recently, ERF have been interleaved between aluminum, phosphor bronze plates or CFRP laminates with electrical conductivity to suppress structural vibration [2-5]. However, few studies have been reported on effects of waveforms or frequencies of electric fields applied to ERF on vibration responses of the composite beam. The experimental study was made of effects of waveform and frequency of electric fields applied to ERF[6].

In the present paper, a CFRP composite cantilevered beam containing ERF was prepared and oscillatorily tested by using sinusoidal and rectangular waves with various frequencies of electric fields applied to ERF. An analytical investigation is also given by using a simplified vibration model of the composite beam having an ERF actuator.

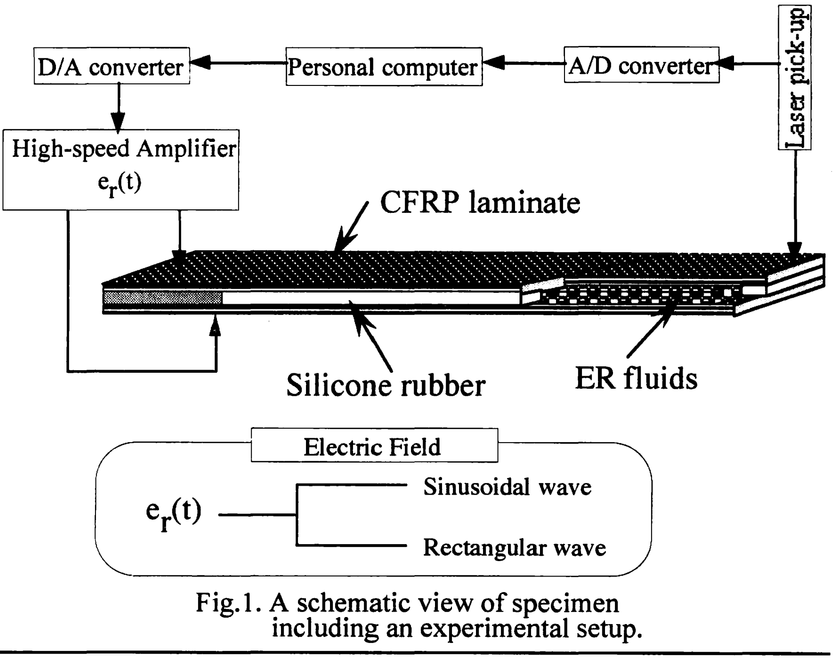

Fig.1. A schematic view of specimen including an experimental setup.

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Table 1. Material properties.

	CFRP	ER fluids	Silicone rubber
Specific gravity	1.4	1.1	1.5
Storage modulus	48 GPa	100 Pa	1.5 MPa
Loss modulus	1.2 GPa	100 Pa	0.15 MPa

Experiments

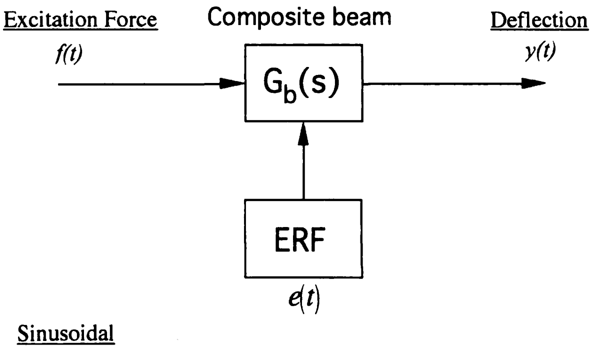
A specimen is schematically shown in Fig. 1, where the experimental set-up is also briefly illustrated including a non-contacting laser displacement pick-up, A/D and D/A converters, a personal computer. Electric fields *e(t)* are produced by a high speed power supply unit. The specimen consists of two CFRP laminated plates (Toray T300/#2500) and an ERF layer (Nippon Shokubai TX-ER2072). The fiber orientation of the CFRP laminates is $[+45^\circ/-45^\circ]_s$. The specimen is 200mm in length and 20mm in width. The thickness of CFRP laminate is 0.5mm and the thickness of ERF layer is 0.2mm. In the specimen, ERF are filled between two CFRP laminated plates and sealed by a silicone rubber in the same manner as proposed by Choi et al.[2]. ERF employed here consist of numerously sulfonated polymer particles (NSP) in silicone oil with volume fraction of 40% [7]. Two CFRP laminated plates are used for electrodes to an apply electric field to ERF, because CFRP laminates are conductive.

In the experiments, the specimen was supported on the shaker under the clamped-free condition and ERF were applied by an electric field of sinusoidal or rectangular wave with various frequencies. These excitation waves were produced by use of a high speed power supply unit controlled by a personal computer. The deflection responses of the free end of the specimen were observed in steady state by using a non-contacting laser displacement pick-up. The tests were carried out under resonant conditions. All tests were performed at the room temperature controlled by an air-conditioner.

Experimental Results

Waveform Effects of Electric Fields

First, the first flexural mode frequency of the cantilevered specimen was examined by a vibration test. It was 12.3Hz, while its predicted value obtained by using Rayleigh's method was 12.0Hz[5]. The material properties used in calculation are listed in Table 1. Secondly, in order to investigate the effects of waveform of electric fields applied to ERF, the deflection responses in resonant state were observed with changing the frequencies, f_e of electric fields applied to ERF. The resonant conditions were produced by tuning the frequency of the excitation force, f_f to the first natural frequency of the composite beam, f_n. Fig. 2 illustrates the relation among the excitation force, *f(t)*, the electric field, *e(t)* applied to ERF and the deflection of the free end of the composite beam, *y(t)*. An example of comparison between steady-state responses subjected to rectangular and sinusoidal waveforms is given in Fig.3, where the response under in electric field is also illustrated. As shown in this example, it was found that the rectangular wave is more effective for control of ER effects than the sinusoidal wave when the amplitude and the frequency of both waves are the same. The



Sinusoidal

$$e(t) = \sqrt{2}\cdot e_r \cdot \sin(\omega_e t + \psi) ,$$

ψ : initial phase

Rectangular

$$e(t) = \begin{cases} e_r & ,\text{for } 0 \le t \le \frac{(2n+1)\pi}{\omega_e} \\ -e_r & ,\text{for } \frac{(2n+1)\pi}{\omega_e} \le t \le \frac{2n\pi}{\omega_e} \end{cases}$$

(n=0,1,2, • •)

Fig.2. Relation among the excitation force, *f(t)*, electric field applied to ER fluids, *e(t)*

amplitude means the effective value. The reason is because the damping effect of the electric field waveform depends on its area in a cycle, as will be explained by Eq. (2) in Section of Analysis and Discussion and therefore the former is more effective than the latter.

Frequency Effects of Electric Fields

The deflection responses of the free end of the specimen were observed by changing the frequency of electric fields applied to ERF under the same resonant condition. The frequency range of electric fields was from 0.5Hz to 100Hz. If the frequency of electric fields was below the first natural frequency of the composite beam, the superposed responses of the deflection *y(t)* with the first natural frequency and the frequency of electric fields applied to ERF were appeared. Examples of these responses were shown in Fig.4 (a) for 0.5Hz and Fig.4 (b) for 1.0Hz of the sinusoidal wave applied to ERF, respectively. Such a tendency was more significant for the sinusoidal waveform than the rectangular one. The beat phenomena in response of the composite beam have been observed when the frequencies of electric fields close to the 1st natural frequency of the composite beam were utilized to ERF. An example of such a beat phenomenon for the rectangular waveform is shown in Fig.5. If the frequency of electric fields was over the first natural

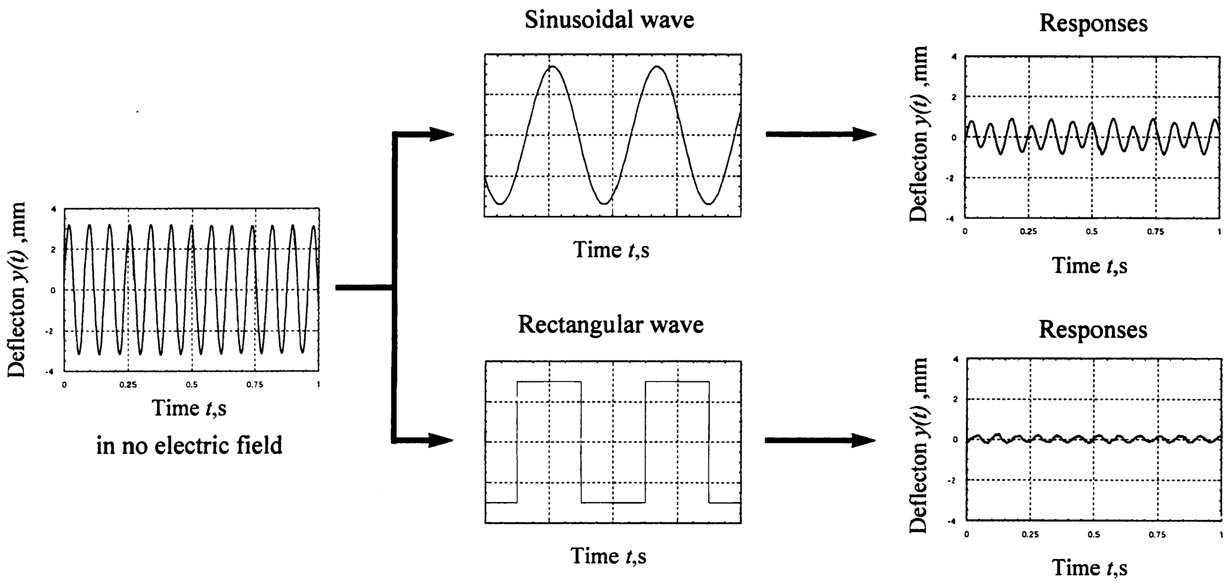
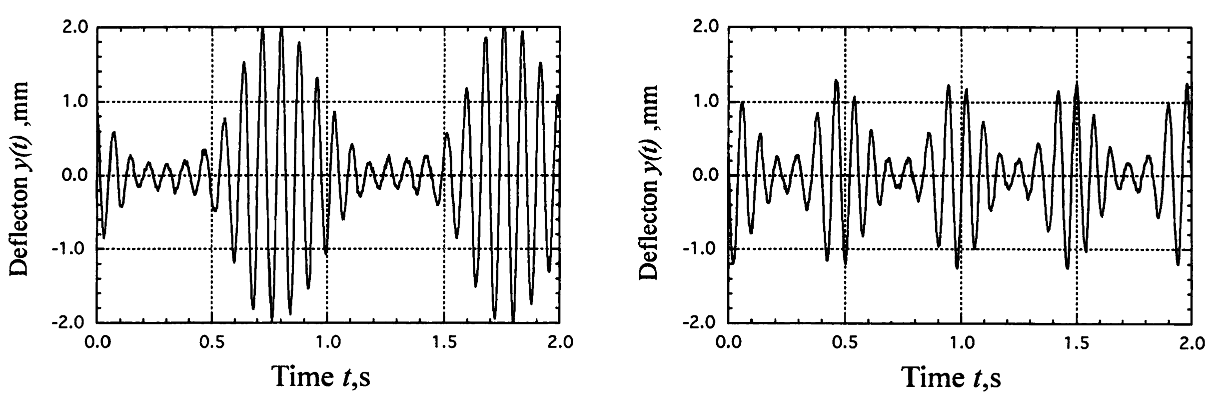


Fig.3. An example of comparison between steady-state responses subjected to rectangular and sinusoidal waves.



(a) For 0.5 Hz.

(b) For 1.0 Hz.

Fig. 4. Superposed deflection responses with the first natural frequency and the frequency of sinusoidal waveform electric fields applied to ERF .

frequency, there appeared no beat phenomena. However, it is shown that less vibration suppression takes place as the frequencies of an electric field increase as shown in Figs.6. In Fig.6 (a), a symbol ◄──► means the range of amplitude variations of the deflection responses which appeared in the case of electric field of the sinusoidal waveform with lower frequencies than the 1st natural frequency of the composite beam.

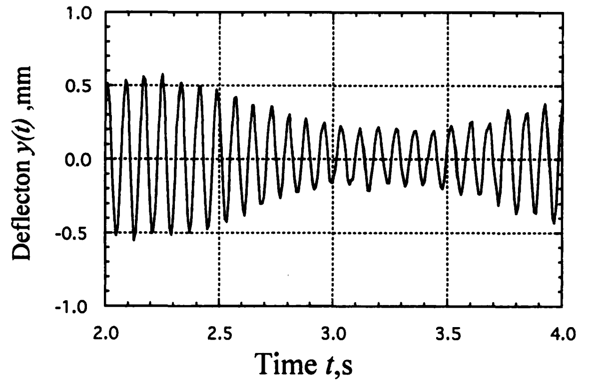
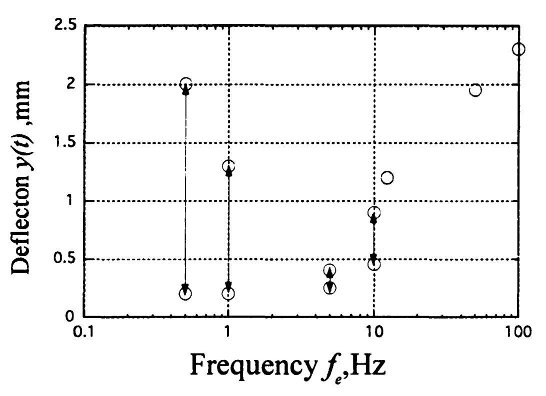
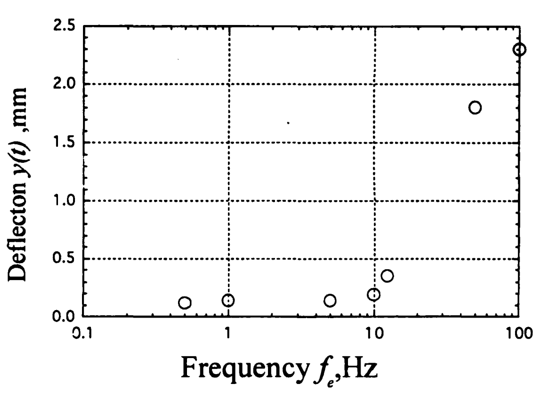


Fig.5. Beat phenomenon of the composite beam due to a rectangular wave with frequency close to the first natural frequency.



(a) In case of sinusoidal wave.



(b) In case of rectangular wave.

Fig.6. Effect of frequency of electric fields applied to ERF on vibration suppression.

Analysis and Discussion

Recently, M.Yalcintas et al. have given a series of reports on analytical studies of ER material based adaptive model [8,9]. In their papers, they use a basic model for multi-layered damped composite beam, where structural adaptability is incorporated by assuming that the complex shear modulus of the ER material is a function of electric field. However, a simplified mass-spring-damper system is here available only to feature the first flexural mode of the cantilevered composite beam which is used in our vibration tests. That is, the lumped mass system of the composite beam can be decomposed to the concentrated mass system of one degree-of-freedom in which the damping factor is changed in time as a function of the waveform of electric fields.

Then, the equation of motion of the composite beam is given by

$$\ddot{y} + 2 \cdot \zeta(t) \cdot \omega_n \cdot \dot{y} + \omega_n^2 \cdot y = \frac{1}{m} \cdot f(t) \quad , \qquad (1)$$

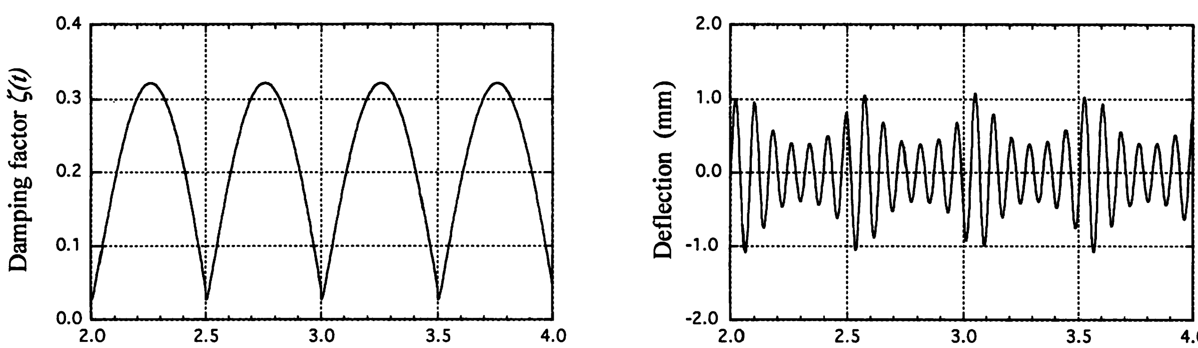
where $m = 12.2 \times 10^{-3}$ kg and $\omega_n = 77.3$ rad/s .

The damping factor $\zeta(t)$ includes the damping ratio of the composite beam ζ_0 and the ER effect $e(t)$ as follows:

$$\zeta(t) = \zeta_0 + |e(t)| \quad (\zeta_0 = 0.028) \quad . \qquad (2)$$

First, referring to the waveform of Fig.2 used in the experiments, let an electric field *e(t)* for the sinusoidal waveform be represented by Eq.(3). This function is adopted taking acount of a little bit time lag between the ER effect and the input of electric field. That is, a first-order lag element between them is assumed with time constant of 8ms which was given by the other measurement method. Thus, damping factor ζ (t) due to sinusoidal waveform with a frequency of 1Hz is illustrated in Fig.7(a). Numerically solving Eq.(1) by using the Runge-Kutta method, we have an example of a superposed response of the composite beam with

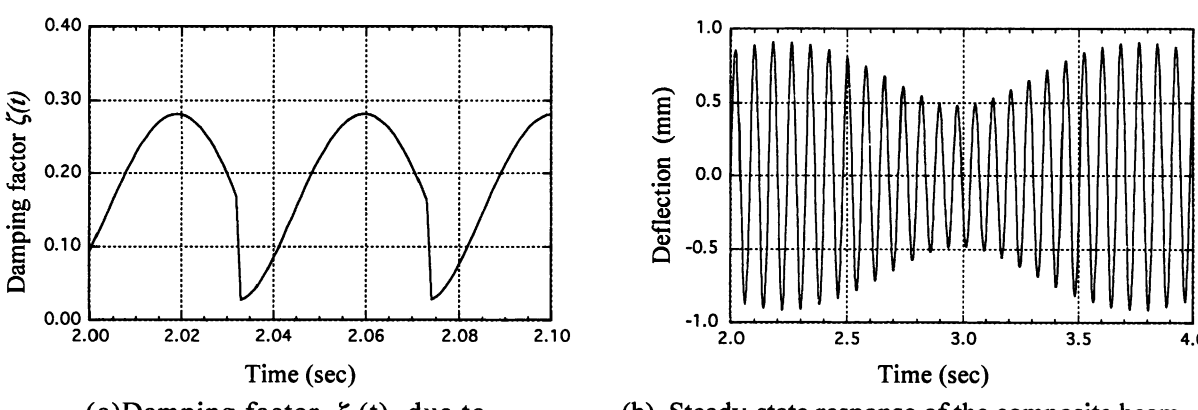
$$e(t)=\begin{cases} \sqrt{2}e_r\cdot\dfrac{T\cdot\omega_e}{1+\left(T\cdot\omega_e\right)^2} \times\left\{e^{-\frac{t}{T}}-\cos\left(\omega_e\cdot t\right)+\dfrac{1}{T\cdot\omega_e}\cdot\sin\left(\omega_e\cdot t\right)\right\} & ,\text{for } 0\le t<\dfrac{(2n+1)\pi}{\omega_e} \\ 0 & ,\text{for } t=\dfrac{(2n+1)\pi}{\omega_e} \end{cases} \tag{3}$$



(a) Damping factor ζ (t) due to a sinusoidal waveform

(b) Steady-state response of the composite beam.

Fig7. An analytical example of steady-state response of the composite beam in case of a sinusoidal waveform (superposed), for f_f=f_n and f_e=1 Hz.

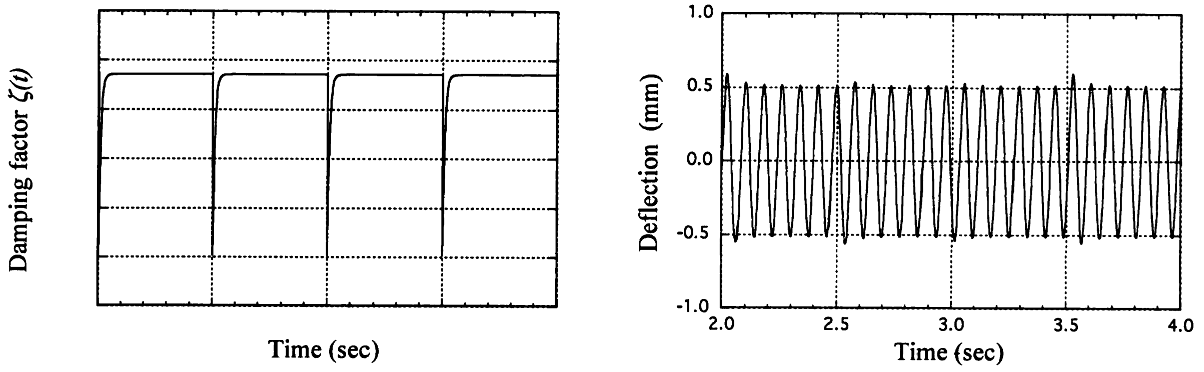


(a)Damping factor ζ (t) due to a rectangular waveform

(b) Steady-state response of the composite beam.

Fig8. An analytical example of steady-state response of the composite beam in case of a sinusoidal waveform (beat phenomenon), for f_f=f_n and f_e=12.3 Hz.

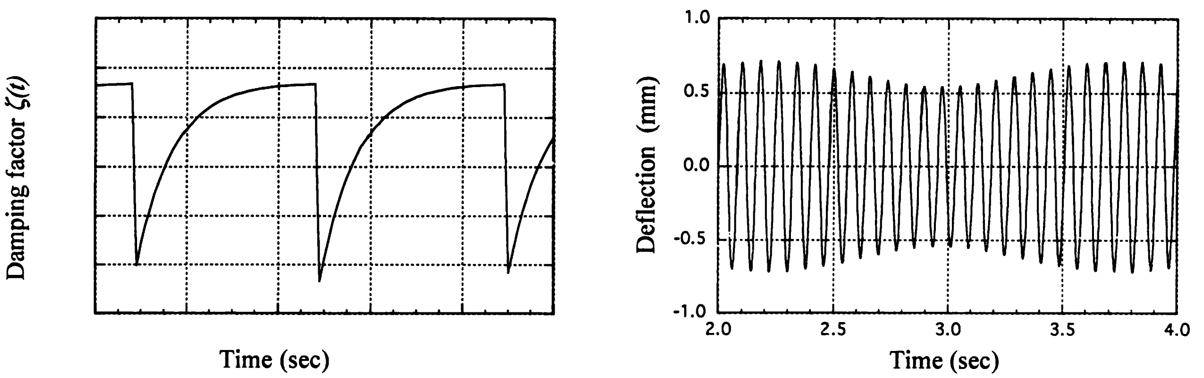
$$
e(t)=\begin{cases} e_r\left\{1-e^{-\frac{t}{T}}\right\} & ,\text{for} \quad 0\le t<\frac{(2n+1)\pi}{\omega_e} \\ 0 & ,\text{for} \quad t=\frac{(2n+1)\pi}{\omega_e} \end{cases} \tag{4}
$$



(a) Damping factor ζ (t) due to a rectangular waveform

(b) Steady-state response of the composite beam

Fig.9 An analytical example of steady-state response of the composite beam in case of a rectangular waveform for $f_f=f_n$ and $f_e=1$ Hz.



(a) Damping factor ζ (t) due to a rectangular waveform

(b) Steady-state response of the composite beam

Fig. 10 An analytical example of steady-state response of the composite beam in case of a rectangular waveform (beat phenomenon), for $f_f=f_n$ and $f_e=12.3$ Hz.

frequencies of 1Hz and 12.3Hz as illustrated in Fig.7(b). This case is corresponding to experimental result shown in Fig.4. For the case of 12.3Hz shown in Fig.8(a), the beat phenomenon of the response can be simulated similarly by waveform function of Eq.(3). Next, by using an electric field *e(t)* for the rectangular waveform represented by Eq.(4) in the same manner, analytical results are given in Figs.9 and 10. In cases of rectangular waveform, no superposed phenomenon appeares for a frequency of 1Hz, but for the case of 12.3Hz, the beat phenomenon can be seen as shown in Fig. 10(b). This is corresponding to experimental results shown in Fig.5.

Conclusion

A CFRP composite beam with an ERF actuator was tested subjected to electric fields of two types of waveforms with various frequencies. Analytical examinations were made by using a simplified vibration model having the time-dependent damping factor. These results are summarized as follows;

(1) The rectangular waveform is more effective for control of ER effects than the sinusoidal wave.
(2) The superposed deflection responses with the first natural frequency and the frequency of electric fields applied to ERF appear for the frequency of electric fields below the first natural frequency of the composite beam. Such a tendency is more significant for the sinusoidal waveform than the rectangular one.
(3) The beat phenomena in response of the composite beam have been observed subjected to the electric fields with frequency close to the natural frequency of the composite beam.

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