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Evaluation of mechanical properties using transient vibration excited by acoustic radiation force

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1. Introduction

Vibro-acoustgraphy (VA) is a method of acquiring local mechanical properties of an object using response vibration to ultrasound.[1)] For conventional VA, the distribution of steady vibrations of an object excited by the dynamic acoustic radiation force generated by the amplitude-modulated ultrasound visualizes the mechanical properties.[2)] This method requires to select an appropriate modulation frequency because the contrast of an image depend on the excitation frequency. However, an appropriate frequency for a target is generally unpredictable. To solve this problem, we have proposed VA using transient vibration excited by acoustic radiation force.[3)] In addition, we attempted the proposed method to visualize defects of a thin metal plate, and suggested the feasibility of detecting fine defects that is not be detected by the conventional pulse-echo method.[4)]

The purpose of this study is to consider the feasibility of the estimation of equivalent mechanical properties using our proposed method. VA with transient response measures mode frequencies and damping time which are related to the mechanical properties. In this study, first, we attempted to determine mode frequencies and damping times of transient vibration excited by our proposed method. Then, the estimation of mass, compliance, and mechanical resistance of target are evaluated.

2. Theory

2.1 Acoustic radiation force

We use focusing ultrasound to excite vibration on a sample. However, since focusing ultrasound near a focusing point is assumed to be a plane wave, we estimate an acoustic radiation force based on a plane wave theory.

When a plane sound wave with acoustic energy density E_{inc} is incident perpendicularly from medium 1 of specific acoustic impedance $z_{s1}=\rho_1 c_1$ to medium 2 of $z_{s2}=\rho_2 c_2$, an acoustic radiation force

$$F_{\mathrm{rad}}=\left(1+\left|R_{\mathrm{p}}\right|^2-\frac{z_{s1}}{z_{s2}}\frac{c_1}{c_2}\left|T_{\mathrm{p}}\right|^2\right)SE_{\mathrm{inc}}, \qquad (1)$$

acts on the boundary, where ρ_i and c_i is the density and sound speed of medium i (i =1 and 2), R_{p} and T_{p} is the reflection and transparent coefficients of sound pressure, S is the acting area of sound wave, and $E_{\mathrm{inc}}=P_{\mathrm{inc}}^2/(\rho_1 c_1^2)$ for the incident sound wave with sound pressure of root-mean-square value P_{inc}.

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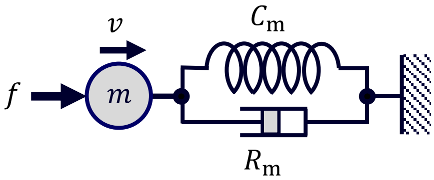

Fig. 1 Vibrational velocity v of equivalent mass-spring-dumper system applied with external force f. m, C_{m}, and R_{m} are the equivalent mass, mechanical compliance, and mechanical resistance, respectively.

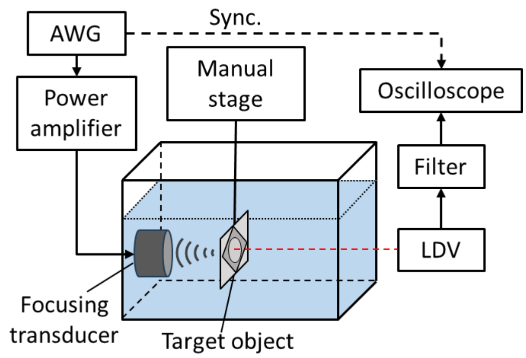

Fig. 2 Experimental setup. AWG; Arbitrary waveform generator, and LDV; laser Doppler vibrometer.

2.2 Transient vibration of mechanical system

In this study, we assume a mass-spring-dumper system (mass m, compliance C_{m}, and mechanical resistance R_{m}) as shown in **Fig. 1** as an equivalent mechanical model of a target sample. When, a step functional force $Fu(t)$ acts on a mass-spring-damper system at $t=0$ s, the transient vibration with velocity

$$v(t)=V_{\mathrm{amp}}e^{-t/\tau}\sin(\omega t), \qquad (2)$$

is exerted for $t>0$ s, where $u(t)$ is a unit step function, $\omega=\sqrt{\omega_0^2-1/\tau^2}$ and $\omega_0=1/\sqrt{mC_{\mathrm{m}}}$ are the mode angular frequencies with and without damping, respectively, $\tau=2m/R_{\mathrm{m}}$ is the damping time, and $V_{\mathrm{amp}}=F/(\omega m)$ is the maximum velocity amplitude. This relationship reveals that the

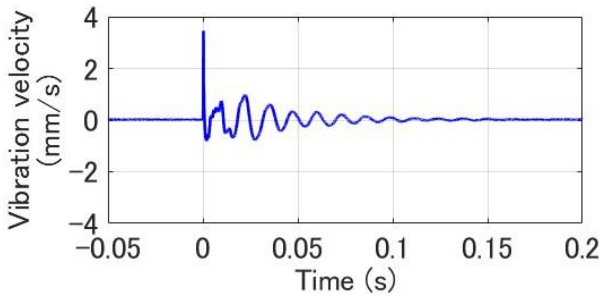

Fig. 3 Vibration velocity of transient response. Ultrasound impinging on the target surface at 0 s (strictly delayed by the propagation time 34 μs)

mechanical properties are estimated from the frequency, damping time, and amplitude.

3. Experimental method

The experiment was conducted in a water ($\rho_1 = 1000$ kg/m^3 and $c_1 = 1500$ m/s). **Figure 2** shows the experimental setup. A focused ultrasound transducer with a radius of curvature of 51 mm radiated 5-MHz tone-burst ultrasounds of the maximum sound pressure $P_{\mathrm{inc}} = 605$ kPa and a beam width of 1 mm. As a target object, silicone rubber (ρ_2=1000 kg/m^3 and c_2 =1000 m/s) with a thickness of d=1 mm fixed by two acrylic plates with a hole of 40 mm in diameter was arranged perpendicular to the beam axis at the maximum sound pressure point.

The vibration velocity of the center of silicone rubber was measured with a laser Doppler vibrometer via a bandpass filter of 50–5000 Hz. Since it is hard to extract mode frequencies from Fourier analysis of the observed signal containing several peaks, mode frequencies and damping times are extracted from the observed velocity signal using an autoregressive model.

4. Results and discussion

Figures 3 and 4 show an example of the vibration excited at the ultrasound impinging time t =0 s and the frequency characteristics, respectively. The transient vibration is observed at the rise of the step-functional radiation force. Observed frequency peaks correspond to the mode vibration of the target samples.

Here we take the lowest-order mode, and determine the mode frequency of $\omega/(2\pi)$ =74 Hz and damping time of τ =0.03 s. From Eq. (1), the radiation force acting on the object is determined to be F =5.1×10^{-5} N. We estimate the equivalent mass m, compliance C_{m}, and mechanical resistance R_{m} to be 8.0×10^{-5} kg, 5.6×10^{-2} m/N, and 5.4×10^{-3} Ns/m, respectively. Although these values are equivalent

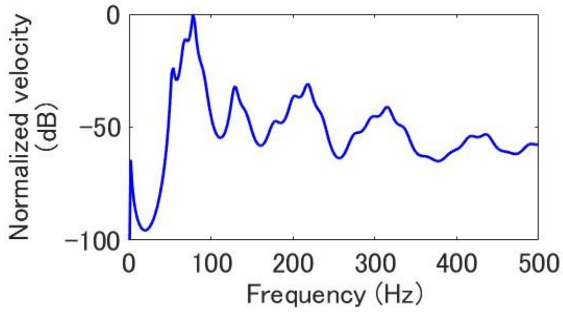

Fig. 4 Frequency characteristics of vibrational velocity signal in Fig. 3.

parameters, they seem to be far from the actual ones. For example, the mass of the portion of the sample excited by the ultrasound incident with the cross-sectional area S is $\rho_2 S d$ =7.9×10^{-7} kg, and is two-order smaller than the estimated mass. One possible cause of this discrepancy would be that the mediums are considered infinite thickness when estimating the radiation force as described by Eq. (1). Another possibility is that the assumption that the excitation area of the radiation force equals the beam size is inappropriate. Assuming the vibration area is 10 mm, the mass is consistent with the estimated value.

5. Conclusion

In this study, we experimentally considered the feasibility of the estimation of equivalent mechanical properties using the VA with transient response. The results showed the possibility of obtaining equivalent mechanical properties from the transient response, although the values are not accurately estimated.

In the present study, we used the value of radiation force at an exciting point to evaluate mechanical parameters, although this value is not always obtained for practical uses. In order to resolve this problem, the proposed method must be improved.

Acknowledgment

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