SICE Annual Conference 2014
September 9-12, 2014, Hokkaido University, Sapporo, Japan

Preliminary Study on Noncontact Internal Structure Sensing by Resonant Mode Excitation Using Airborne Ultrasound Radiation Pressure

Masahiro Fujiwara[1†] and Hiroyuki Shinoda[2]

[1]Department of Information Physics and Computing, Graduate School of Information Science and Technology, The University of Tokyo, Tokyo, Japan
(Tel : +81-4-7136-3777; E-mail: masahiro_fujiwara@ipc.i.u-tokyo.ac.jp)
[2]Department of Complexity Science and Engineering, Graduate School of Frontier Sciences, The University of Tokyo, Tokyo, Japan
(Tel : +81-3-5841-6926; E-mail: hiroyuki_shinoda@k.u-tokyo.ac.jp)

Abstract: In this paper, we perform the first study of noncontact internal structure sensing based on mechanical resonance mode excitation of an elastic object. The vibration is excited by airborne ultrasound acoustic radiation pressure. It is confirmed by using the noncontact sensing system that the lowest resonance frequency of the measured displacement amplitude frequency response decreases as the increasing object height.

Keywords: Sensors and Transducers; Signal Processing; Noncontact Measurement; Acoustic Radiation Pressure.

1. INTRODUCTION

Noncontact measurement of internal structure is a challenging problem. In medical applications, magnetic resonance imaging (MRI) and X-ray computed tomography (X-ray CT) are widely used representative techniques for imaging of internal anatomy. These noncontact methods measure the whole body easily at high spatial resolution.

Ultrasonography [1] and elastography [2-3] are lower invasive techniques which adopt ultrasound propagating through a body. Ultrasonography visualizes discontinuity of acoustic impedance due to the internal organs in the body. Elastography visualizes elasticity distribution in the body by using ultrasound acoustic radiation pressure phenomenon [4]. These methods measure internal anatomy at high temporal resolution by using a contact ultrasound probe.

We have proposed a noncontact surface compliance distribution sensing method [5] which visualizes surface elasticity using airborne ultrasound radiation pressure. In this paper, we perform the first study of internal structure estimation by our surface compliance sensing system. As a preliminary experiment, the heights of uniform urethane gel samples on a metal base are examined by mechanical resonance frequency shift. The resonance frequency shift is compared with predicted value by longitudinal vibration model of a rod.

2. METHODS

2.1 Rod model of elastic body

Our sensing system [5] consists of an ultrasound phased array for vibrating an object surface and a laser displacement sensor for measuring surface vibration. The surface compliance distribution is measured as the ratio of the surface vibration amplitude to the applied force amplitude for each point on the surface. The pressurization frequency is chosen within a range which is higher than low frequency background noise band and is lower than the attenuation range of the target object for compliance sensing.

† Masahiro Fujiwara is the presenter of this paper.

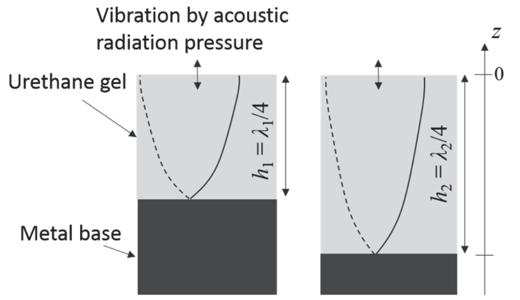

Fig.1 A mechanical resonance mode in a urethane gel samples based on longitudinal vibration assumption of a rod.

For height estimation of an elastic object, we measure the mechanical frequency response. The frequency response includes various properties such as boundary conditions, elasticity, viscosity, density, and their distribution. The height of the target object is a part of the boundary conditions.

For this fundamental survey, we assume a longitudinal vibration model of a uniform elastic rod. Fig. 1 shows the supposed situation. A spot area on the object top surface is vibrated in a direction perpendicular to the surface.

The vibration mode of this model is formularized as follows under the condition of small deformation. For this model, the displacement occurs only in the z-direction and the internal stress $t_{zz} \neq 0$ and $t_{ij} = 0$ when $i \neq z$ or $j \neq z$. The kinematic equation for the z-direction is

$$\rho \frac{\partial^2 u_z(z,t)}{\partial t^2} = \frac{\partial t_{zz}(z,t)}{\partial z}, \tag{1}$$

where ρ is the density of the object and u_z is the z-direction component of the displacement. The stress and the displacement are related by Hook's law as follows

$$t_{zz}(z,t) = Y \frac{\partial u_z(z,t)}{\partial z}, \tag{2}$$

where Y is the Young's modulus. By substituting Eq. (2)

into Eq. (1), a wave equation of the displacement is obtained:

$$\frac{1}{c^2}\frac{\partial^2 u_z(z,t)}{\partial t^2} = \frac{\partial^2 u_z(z,t)}{\partial z^2}, \tag{3}$$

where $c = \sqrt{Y/\rho}$ is the wave speed.

The sinusoidal solution of the Eq. (3) is written as

$$u_z(z,t) = (A\cos kz + B\sin kz)\sin(\omega t + \varphi), \tag{4}$$

where ω, φ, and $k = \omega/c$ are the angular velocity, initial phase, and wave number, respectively. A, B are constants decided by boundary conditions. The boundary conditions in this situation are

$$t_{zz}(0,t) = Y\left.\frac{\partial u_z(z,t)}{\partial z}\right|_{z=0} = 0, \qquad u_z(-h,t) = 0, \tag{5}$$

for any time t, where h is the height of the pillar element under the pressed surface area. If u_z is non-trivial solution, the wave number k is restricted as $k = (n + 1/2)\pi/h$ for zero or a positive integer number n. Thus the natural frequency f_n for this situation is

$$f_n = \frac{c}{2\pi/k} = \frac{1}{2h}\sqrt{\frac{Y}{\rho}}\left(\frac{1}{2}+n\right). \tag{6}$$

The amplitude of ultrasound radiation pressure is modulated to swept-sine wave and the resonance mode frequency is extracted from measured amplitude frequency response of the surface displacement.

2.2 Frequency response measurement by swept-sine method

We utilize swept-sine method [6] for frequency response measurement of elastic objects. Generally, when a known time discrete signal x_n (n = 0, 1, …, N - 1) is input to a linear time-invariant (LTI) system, a measured output signal y_n is represented as

$$y_n = h_n \otimes x_n \tag{7}$$

where h_n is the impulse response of the LTI system, which is the inverse Fourier transform of the frequency response. The symbol "$\otimes$" means circular convolution. So the frequency response of the system H_k (k = 0, 1, 2,…, N - 1) is simply found by $H_k = Y_k / X_k$,

$$H_k = \frac{Y_k}{X_k} \tag{8}$$

where X_k and Y_k are discrete Fourier transforms of x_n and y_n, respectively. For well-defined measurement in a sufficiently wide frequency range, it is ideal that $|X_k|$ is constant independently of the frequency parameter m. Impulse signal δ_n is an ideal input signal, which has flat frequency property, and the impulse response is directly obtained as the output signal y_n.

The swept-sine method uses a sine signal which has a rising or falling instantaneous frequency instead of the impulse signal. We use a linear swept-sine signal which has following frequency representation:

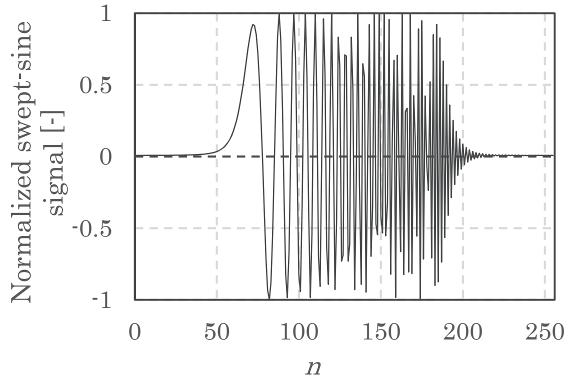

Fig.2 Swept-sine signal of rising instantaneous frequency (N = 256, m = N/4 = 64).

$$X_k = \begin{cases} \exp\left(j4\pi m\frac{n^2}{N^2}\right) & (k = 0,1,\dots,N/2) \\ X^*_{N-k} & (k = N/2+1,\dots,N-1) \end{cases}, \tag{9}$$

where m is an integer parameter which decides effective signal length J as $J = 2m$. The corresponding input signal x_n in time domain is a sine wave which has linearly rising instantaneous frequency as shown in Fig.2. This swept-sine has advantages of high SN ratio by time stretched impulse signal and low crest factor, which is ratio of peak value to effective value. Because $|X_k| = 1$, Eq. (8) is rewritten as

$$H_k = Y_k X_k^* \tag{10}$$

and the impulse response h_n is obtained by inverse discrete Fourier transform of H_k. In this case, the required amplitude response $|H_k|$ is equal to $|Y_k|$ concisely.

2.3 Swept-sine pressing by modulated acoustic radiation pressure

Convergent ultrasound beam for modulated pressurization is generated by a phased array system [7]. The ultrasound beam pushes spot area on a target surface by positioning the focal point to the area. The phased array controls amplitude of output ultrasound by pulse width modulation (PWM). And the pressing force by the ultrasound acoustic radiation pressure [4] on the target surface is represented as

$$F = \int_S \frac{2p_0^2}{\rho_0 c^2} dS \tag{11}$$

where ρ_0 is air density, c is the speed of sound, and p_0 is RMS value of the ultrasound, S is the pressed area. Thus the swept-sine signal of Eq. (9) is applied to the target surface by controlling ultrasound amplitude.

3. EXPERIMENTS

3.1 Experimental setup

The measured samples are 11 urethane gels (Exseal corp., Japan, Asker C hardness 0) which have a base of 30 mm× 26 mm area and height from 4mm to 18mm as

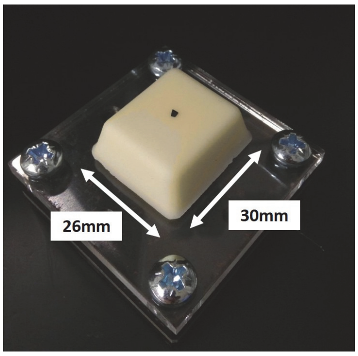

Fig.3 A urethane gel sample of 12mm height. A sufficiently thin black tape is put on the center of the top surface.

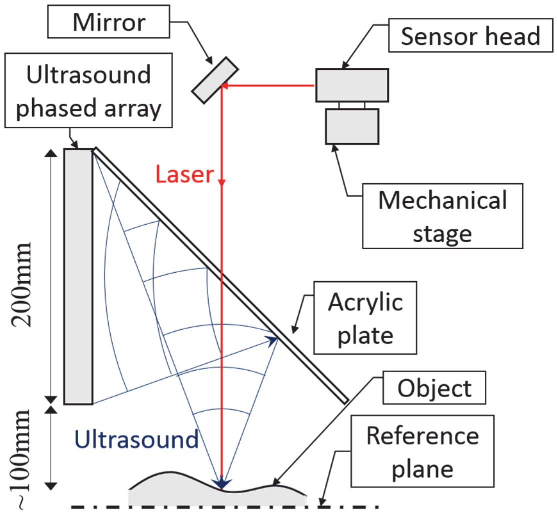

Fig.4 Experimental setup of the prototype measurement system using an ultrasound phased array and an optical displacement sensor.

shown in Fig. 3. Sufficiently thin black tapes are put on the gel samples as an optical reflector for stable displacement measurement by an optical sensor.

The sample gels are vibrated by an ultrasound phased array, which is used in [5], from about 30 cm distant as shown in Fig. 4. Because of the acrylic plate, the ultrasound beam and the laser of the displacement sensor shares the identical axis. Thus the more robust measurement is achieved for vertical displacement.

The ultrasound frequency is 40 kHz and the pressed area on the surface is about 8.5 mm diameter circle. The maximum value of the acoustic radiation force through the swept-sine signal is about 16 mN. The sampling frequency of pressing waveform is 200 Hz. Therefore the nominal maximum pressurization frequency is 100 Hz, which is equal to Nyquist frequency. The signal number N = 256, integer parameter $m = N/4$ = 64, and so the signal length is 1.28 sec. Because the radiation pressure value is always positive or zero and suction force does not occur, the input swept-sine signal is

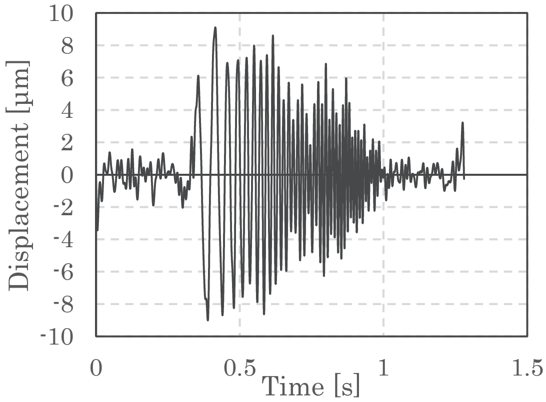

Fig.5 Measured displacement of the 12 mm height gel sample for swept-sine modulated pressurization.

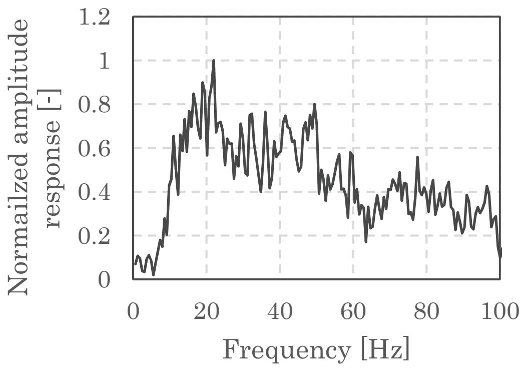

Fig.6 Amplitude frequency response of a surface on urethane gel of 12 mm height. The peak frequency in the range below 100 Hz is 22.0 Hz.

biased to the half of the maximum output.

The surface vibration by modulated pressing is measured by a triangulation-type laser displacement sensor (LK-G500, Keyence corp., Japan) from about 40 cm distant. The sampling frequency is 10 kHz at 2 μm repeat accuracy. Because the pressing interval is 1.28 sec, measured displacement number in a single response is 12800. The measured data include extremely low frequency drift resulted from background noise. And the frequency components of more than Nyquist frequency of pressing signal does not include pressing response for a LTI system. Thus the measured displacement is filtered by FIR band pass filter of length 4097, lower cutoff frequency is 10 Hz, and higher cutoff frequency is 100 Hz as shown in Fig. 5. The band pass filter is designed by inverse discrete time Fourier transform of shifted rectangular function. The obtained filter coefficients are multiplied by Hanning window for reduction of filtering side lobe. The amplitude response is calculated by DFT of the filtered data.

3.2 Results and discussion

The measured amplitude response of 12 mm height sample is calculated by Eq. (10) and shown in Fig. 6 as

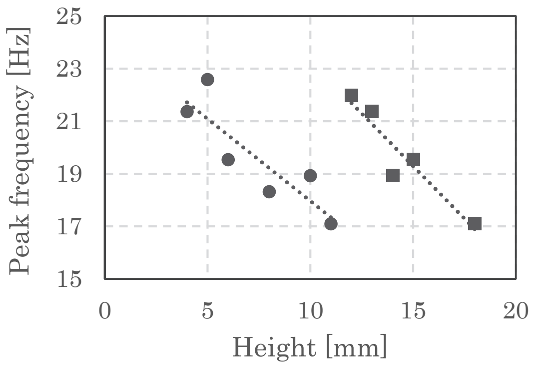

Fig.7 Peak frequencies for amplitude responses of each urethane gel. The dotted lines indicates different trends of the frequency decrease.

one of results. For high frequency range, the amplitude components decrease because of the viscosity of the urethane gel. Although the spectrum shape includes some perturbations, the peak component is observed at about 22 Hz. The higher order resonance frequencies are not seen. The peak frequencies observed for eleven samples are plotted in Fig. 7. There are two trends in the result and the trends are switched between 11 mm and 12 mm height. It is considered that the higher order resonances are observed for the samples of 12 mm or higher since the too low frequency components are cut off by the high pass filtering. For each trend, the frequency decreases as the height increases. This qualitative property corresponds the theoretical analysis.

In quantitative evaluation, however, these frequencies are lower than predicted resonance frequencies by the longitudinal vibration model of a rod and typical parameters of the urethane gel (Y = 177 kPa, ρ = 1.04× 10^3 kg/m^3, f_0 = 326 Hz at h = 10 mm). In this experimental setup, it is seemed that other resonance modes are excited. Nevertheless, there is a possibility of internal structure sensing because the corresponding frequencies reflects the height of the objects.

4. CONCLUSION

In this paper, the first study of noncontact internal structure sensing using airborne ultrasound acoustic radiation pressure was performed. The lowest mechanical resonance frequencies of elastic objects with uniform elasticity put on a rigid plate depend on the height. These frequencies are lower than predicted values from the longitudinal vibration model of a rod. As a further work, we will clarify the reason of the frequency shift.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Number 25-9627.

REFERENCES

[1] J. A. Noble, D. Boukerroui, “Ultrasound image segmentation: a survey”, *IEEE Transactions on Medical Imaging*, Vol. 25, No. 8, pp. 987 - 1010, 2006.

[2] L. Sandrin, B. Fourquet, J. M. Hasquenoph, S. Yon, C. Fournier, F. Mal, C. Christidis, M. Ziol, B. Poulet, F. Kazemi, M. Beaugrand, R. Palau, “Transient elastography: a new noninvasive method for assessment of hepatic fibrosis”, *Ultrasound in Medicine & Biology*, Vol. 29, No. 12, pp. 1705-1713, 2003.

[3] J. Bercoff, M. Tanter, M. Fink, “Supersonic shear imaging: a new technique for soft tissue elasticity mapping”, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency control*, Vol. 51, No. 4, pp. 396-409, April 2004.

[4] J. Awatani, “Studies on Acoustic Radiation Pressure. I. (General Considerations)”, *Journal of the Acoustical Society of America*, Vol. 27, pp. 278-281, 1955.

[5] M. Fujiwara, H. Shinoda, “Coaxial noncontact surface compliance distribution measurement for muscle contraction sensing”, *in Proc. of 2014 IEEE Haptics Symposium* (*HAPTICS*), Houston, TX, USA, pp. 385-389, Feb. 2014.

[6] M. A. Poletti, “Linearly Swept Frequency Measurements, Time-Delay Spectrometry, and the Wigner Distribution”, *Journal of Audio Engineering Society*, Volume 36, Issue 6, pp. 457-468, June 1988.

[7] T. Hoshi, M. Takahashi, T. Iwamoto, and H. Shinoda, “Noncontact Tactile Display Based on Radiation Pressure of Airborne Ultrasound”, *IEEE Transactions on Haptics*, Vol. 3, No. 3, pp.155-165, 2010.