Original
Received July 7, 2004
Accepted for Publication November 11, 2004

Viscosity measurement in liquids using transient response of the transversal effects of a piezoceramic PZT transducer

Morimasa NISHIHIRA, Morihiro TOKIWA and Kazuhiko IMANO

Department of Electrical and Electronic Engineering, Faculty of Engineering and Resource Science, Akita University, 1-1 Tegata Gakuen-machi, Akita 010-8502, Japan
E-mail : morimasa@ipc.akita-u.ac.jp

The transient response of the transversal effects of a piezoceramic transducer is introduced in measurements of the viscosity of liquids. Viscosities of water-glycerin mixtures and silicone oil were measured from the motional current of transducer at a resonant frequency of 23 kHz and its higher harmonic frequencies of 68, 110 kHz, respectively.

Key Words : Viscosity, Piezoceramic PZT transducer, Transversal effect, Transient response, Higher harmonic resonance

1. Introduction

A vibrating plate technique[1] in liquid is useful to study the dynamic properties of viscous liquids. The measurement frequency, however, is limited to around 100~800 Hz with a piezo bimorph plate[1], to 8 and 13 MHz with a quartz resonator[2] and to 50 MHz with a SAW device[3]. The authors have already demonstrated the measurement of viscosity of liquid with a piezoceramic disk-type PZT transducer using a continuous wave method in the frequency range of 70~430 kHz[4]. In this study, we now introduce the transient response of the transversal effects of the rectangular type PZT transducer into the simultaneous viscosity measurement of liquids at the frequencies of 23, 68 and 110 kHz.

2. Method and Experimental System

When a vibrating plate is contacting with a liquid, the liquid may be dragged along the plate surface. Similarly, when a piezoceramic plate immersed in liquid is being vibrated, a frictional force from the viscosity of the liquid acts as a "resistance" for the vibration. The resonant resistance R_r, as shown in Figure 1, of the piezoceramic plate is changed by the reaction of the frictional force. This fact has already been verified experimentally, and the relationship between the resonant resistance and the viscosity of liquid is given by[4],

$$R_r = \frac{A(2\pi f)^{1/2}}{k^2}(\rho_L \eta_L)^{1/2} \qquad (1)$$

where, k is the electromechanical coupling factor, A the vibrating area, f the frequency, and ρ_L and η_L are the density and the viscosity of liquid, respectively. Therefore, the viscosity can be measured from the resonance resistance R_r. The authors have reported the measurement method[5] for a motional current $I_m(f)$ flowing through the motional admittance $Y_m(f)$ in the transient condition of a piezoceramic transducer. $Y_m(f)$ and $I_m(f)$ have their next relationship as,

$$I_m(f) = Y_m(f) \cdot V(f), \qquad (2)$$

where $V(f)$ is the driving voltage. Figure 2 shows the extracting circuit for the motional current $I_m(f)$[5]. In this circuit, $I_m(f)$ was extracted by subtracting a damped current of C_0 from the total current of the transducer $I(f)$ with the differential mode of the oscilloscope. When a piezoceramic transducer is driven under the

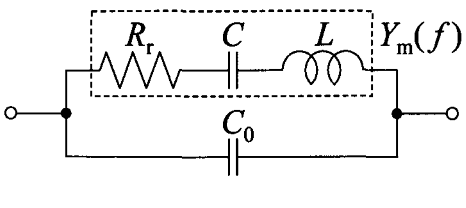

Figure 1 Electrical equivalent circuit of the piezoelectric transducer in contacting with liquid.

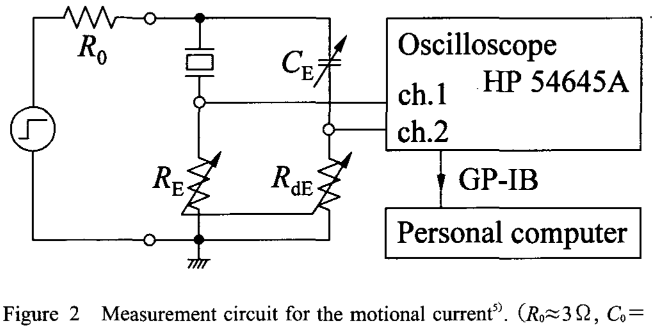

Figure 2 Measurement circuit for the motional current[5]. ($R_0 \approx 3\,\Omega$, $C_0 = C_E$, $R_E = R_{dE}$)

constant-voltage-driven condition, the motional current $I_m(f)$ is directly proportional to the motional admittance $Y_m(f)$. As shown in Figure 1, motional admittance $Y_m(f)$ is expressed as,

$$Y_m(f)=\frac{1}{R_r+j\omega L+1/j\omega C}. \quad (3)$$

At the resonant frequency, $Y_m(f)$ is simply expressed as (4).

$$Y_m(f)\approx\frac{1}{R_r} \quad (4)$$

Therefore, $I_m(f)$ has the information of R_r which is proportional to the product of viscosity η_L and density ρ_L. The frequency spectrum of the motional current $I_m(f)$ is analyzed using the fast Fourier transform of the current waveform $i_m(t)$ in the time domain. Figure 3 shows the experimental arrangement of a piezoceramic PZT transducer in liquid sample. The PZT transducer used was a rectangular type thin plate and was driven by a low impedance ($\approx 3\,\Omega$) step voltage generator. Transversal effect of the transducer, vibration of length direction in this case, was used. A sample cell was filled with the liquid to be tested. Water, water-glycerin mixtures and silicone oil were used as the sample liquids. The transducer was immersed 20 mm into the liquid. This value was empirically determined. One side of the surface of the transducer was electrically isolated by an insulating paint. All experiments were carried out at 20℃.

3. Results and discussion

Figure 4 shows an example of the transient motional current of the piezoceramic transducer being immersed in pure water. The motional current waveform $i_m(t)$ and the frequency spectrum of the motional current $I_m(f)$ are shown in Figure 4(a) and (b), respectively. The peaks in the frequency spectrum are observed at the fundamental resonance of 23 kHz and at its higher harmonic resonant frequencies of 68 and 110 kHz. The peak amplitudes at each resonant frequency were measured for the various viscosities of the sample liquids.

Figure 5 shows the experimental results for various viscosities of water and water-glycerin mixtures (viscosity range η_L : 3~1300 mPa・s). The abscissa expresses $(\rho_L\eta_L)^{1/2}$, and the ordinate shows the relative amplitude of the motional current $I_m(f)/I_{water\text{-}max}(f)$, where $I_{water\text{-}max}(f)$ is the amplitude of the motional current of the transducer with pure water at the fundamental resonant frequency 23 kHz. The $(\rho_L\eta_L)^{1/2}$ and $I_m(f)/I_{water\text{-}max}(f)$ relationship has good linearity up to 20 of

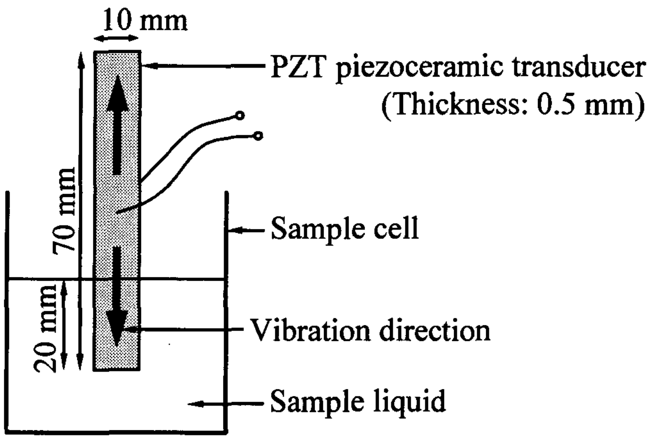

Figure 3 Experimental arrangement of the PZT transducer for the measurements of liquid viscosities. Dimensions : Length : 70 mm, Width : 10 mm, Thickness : 0.5 mm. k=0.4. C_0=22600 pF.

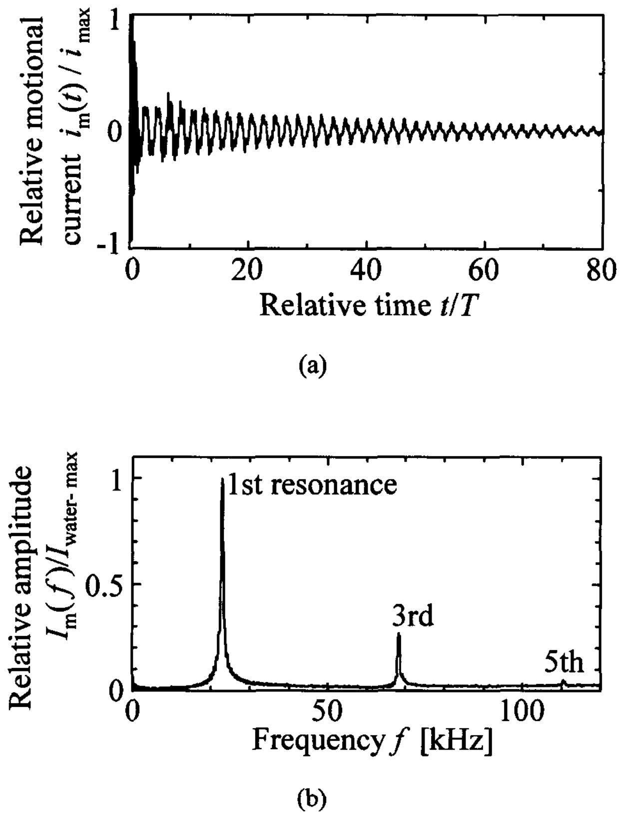

Figure 4 Transient response of a piezoceramic transducer immersed in pure water. (a) is the transient motional current waveform of the piezoceramic transducer, where T is the sound propagation time (=2.2 μs) for the length direction of the transducer. (b) is the frequency spectrum of the motional current waveform of (a).

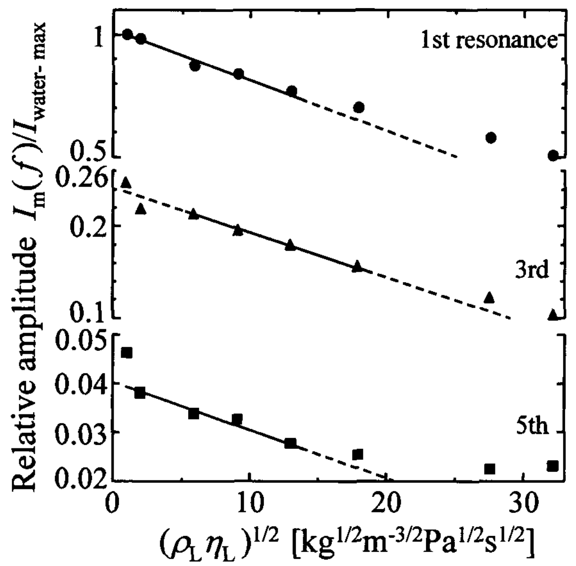

Figure 5 Experimental results of the motional current $I_m(f)$ for various values of $(\rho_L\eta_L)^{1/2}$ for water-glycerin mixtures.

$(\rho_L \eta_L)^{1/2}$ at each resonant frequency. In our experiments, however, it is not obvious whether the change of the motional current $I_m(f)$ depends on the viscosity or the density of the liquid, because both density and viscosity of the water-glycerin mixtures vary with their volume fractions. To clarify this, an experiment with silicone oil was carried out, since it has an almost constant density $(0.93 \times 10^3 \sim 0.97 \times 10^3$ kg/m$^3)$ for various viscosities (9～1100 mPa・s), and the contribution of viscosity in $I_m(f)$ became clear. Figure 6 shows the experimental results for various viscosities of silicone oil. The amplitude of the motional current $I_m(f)$ at each resonant frequency almost shows linearity with $\eta_L^{1/2}$ up to 0.4. Therefore, we can conclude that the motional current $I_m(f)$ is dominantly changed by the viscosity, and our method would be useful for simultaneous viscosity measurements of liquids at multiple different frequencies in the frequency range of 20～110 kHz. The sensitivity for the viscosity is reduced at the higher harmonic frequencies. This problem can be improved by selecting an appropriate material or an optimum shape of the transducer.

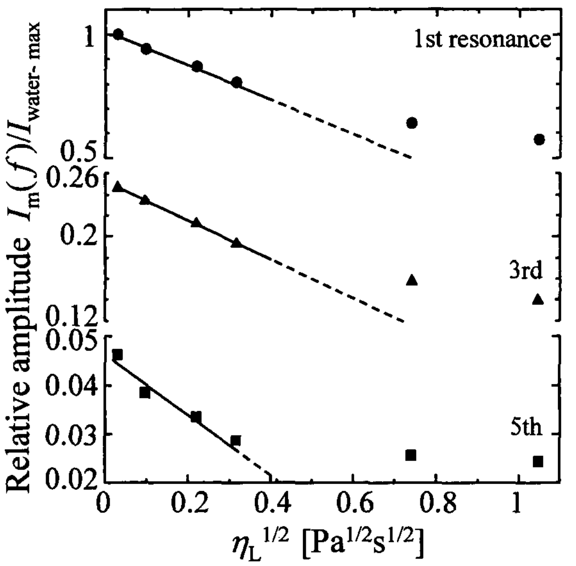

Figure 6 Experimental results of the motional current $I_m(f)$ for various values of $\eta_L^{1/2}$ for silicone oil.

4. Conclusion

Measurement of the viscosity of liquid using the transient response of a piezoceramic PZT transducer has been achieved. The motional current extracted from the transient response can be used to measure the viscosity. The advantage of the transient method compared with the continuous method is exhibited by the simultaneous measurement of viscosity at multi frequencies. Future work of this study is to examine the design for optimized sensor.

References

1) Kobayashi, T., Tai, H. and Ueha, S. (1997) : Vibrating-plate viscometer using a triangular bimorph transducer, *J. Acoust. Soc. Jpn.*, Vol. E18, pp. 223-228.

2) Muramatsu, H., Tamiya, E. and Karube, I. (1988) : Computation of equivalent circuit parameters of quartz crystal in contact with liquids and study of liquid properties, *Anal. Chem.*, Vol. 60, pp. 2142-2151.

3) Kondoh, J., Hayashi, S. and Shiokawa, S. (2001) : Simultaneous detection of density and viscosity using surface wave liquid phase sensors, *Jpn. J. Appl. Phys.*, Vol. 40, pp. 3713-3716.

4) Momozawa, S. and Imano, K. (2001) : Viscosity measurements in liquid using transversal effects of piezoceramic disk type transducer in the frequency range 70-430 kHz, *Jpn. J. Appl. Phys.*, Vol. 40, pp. 3654-3655.

5) Nishihira, M., Kaido, M. and Imano, K. (2002) : Experimental determination of piezoelectric constants of transversal effects of $Pb(Zr,Ti)O_3$ transducer using transient response, *Jpn. J. Appl. Phys.*, Vol. 41, pp. 3354-3355.