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On the Use of Trapped-Energy Mode of Backward-Wave-Type Thickness Vibration for Liquid-Level Sensing

周波数上昇型エネルギー閉じ込め振動モードの利用による液面レベル・センシング

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1. Introduction

The measurement of liquid level on the millimeter scale or less has become an important subject in biological and chemical fields. However, the well-known pulse-echo method is inadequate for measurement in a very small distance range. As an alternative to the pulse-echo method, the authors have presented a new technique[1)] that employs a piezoelectric thickness vibrator operating in a trapped-energy mode[2)] for detecting a small-scale variation in the liquid level. There exists another type of energy-trapping that should be applied to the backward-wave-mode thickness vibrations[3,4)]. This type of energy-trapping can provide single-resonance characteristic with no spurious response around the anti-resonance frequency. In this paper, some results of the application of the backward-wave-type energy-trapping to the liquid level sensing are presented.

2. Dispersion Relation and Energy Trapping

Conventional trapped-energy-mode thickness vibrator[2)] is shown in **Fig. 1(a)**. The corresponding dispersion relation between the angular frequency ω and the wave number γ along the plate around the cut-off frequency for the related mode is shown in **Fig. 1(b)**. In this case, γ in the central electroded region is real, whereas that in the surrounding unelectroded region is imaginary. In some kind of thickness vibration modes, however, the dispersion curve takes a different form such as shown in **Fig. 2(a)**. In this case, the corresponding vibration, having the cut-off regime above the cut-off frequency, becomes a backward-wave mode. To realize the energy-trapping in such a case[3,4)], the surrounding region should be electroded and short-circuited so that the wave number there becomes imaginary, such as shown in **Fig 2(b)**. In the trapped-energy mode of this type, spurious-free characteristic is obtained around the anti-resonance frequency. Therefore, the use of anti-resonance may be effective for the liquid-level sensing.

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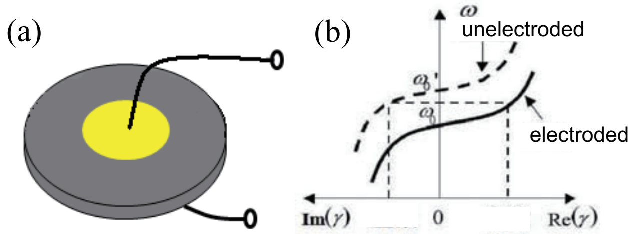

Fig. 1 (a) Conventional trapped-energy resonator, and (b) corresponding dispersion curve.

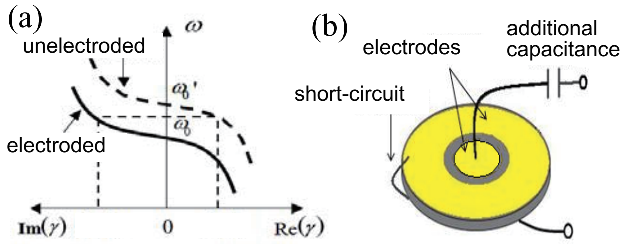

Fig. 2 (a) Dispersion curve for backward-wave mode, and (b) electrode configuration for energy-trapping.

3. Experiments

Thickness-poled $PbTiO_3$ plates of 30 mm in diameter and 1 mm in thickness (Fuji Ceramics M-6) were employed as the vibrator material because their fundamental thickness-extensional vibration is the backward-wave mode. Experiments were carried out for the following two resonators having different electrode geometry; one having the inner electrode of 6 mm in diameter and the unelectroded gap of 1 mm in width (resonator A), and the other having the inner electrode of 4 mm in diameter and the unelectroded gap of 2 mm in width (resonator B). The anti-resonance frequencies were 2.08 MHz and 2.06 MHz, and the *Q*-factors were about 64 and 400, respectively. For comparison, a conventional trapped-energy resonator of the same dimension having the central electrode of 4 mm in diameter (NEPEC-6, TOKIN) was prepared (resonator C).

The plates were supported vertically by clamping their fringes and dipped in a liquid to be tested, as shown in **Fig. 3**. The test liquids employed were water, glycerin, castor oil, and honey. The depth *h* was varied using a pulse-motor

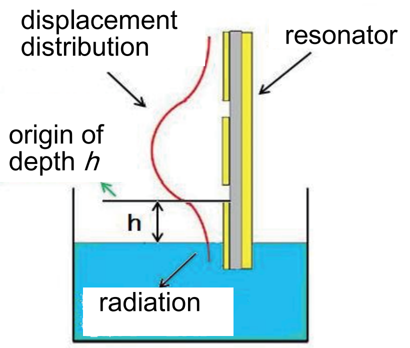

Fig. 3 Experimental arrangement for liquid-level sensing.

stage moved in the vertical direction. The real part R of the electric impedance (or G of the admittance), against h at the anti-resonance (or resonance) point was measured using an impedance/material analyzer (Agilent E4991A) because it corresponds to the variation in Q-factor.

4. Results

Figures 4 to 7 show the variations in R (or G) obtained by resonators A to C for the four different kinds of liquids. The vertical axis is normalized to the maximum values R_{max} (or G_{max}) for each of the liquids. The origin of the horizontal axis corresponds to the outer boundary from which the exponential decay (evanescent field) starts. Figure 4 shows the results for the anti-resonance frequency, and Fig. 5 shows those for the resonance frequency, both obtained by resonator A. In Fig. 5, a capacitor was connected in series with the central electrode. It is noted that the variations of R (or G) are gradual when the liquid surface is on the surrounding electroded region, whereas it becomes steep when the liquid surface is on the unelectroded gap. These two regimes might be selected depending on the purpose, i.e., for either wide-range measurement or high-sensitivity measurement. Figure 6 shows the characteristics obtained by resonator C at the anti-resonance frequency. The variation is almost the same as that obtained at the resonance described in the former report[1]. Figure 7 shows the results obtained by resonator B, having a wider unelectroded gap. Compared with the results shown in Fig. 4, slight difference is seen depending on the liquid. Further investigation is required for clarifying this reason.

References

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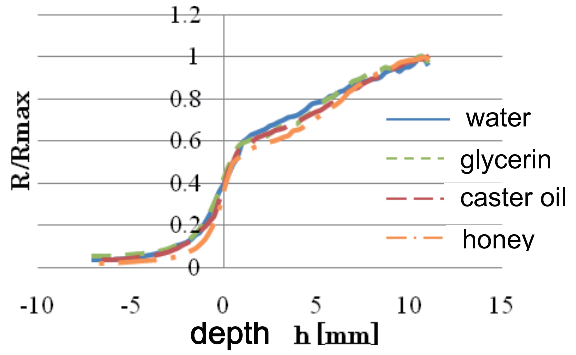

Fig. 4 Results obtained by resonator A at antiresonance.

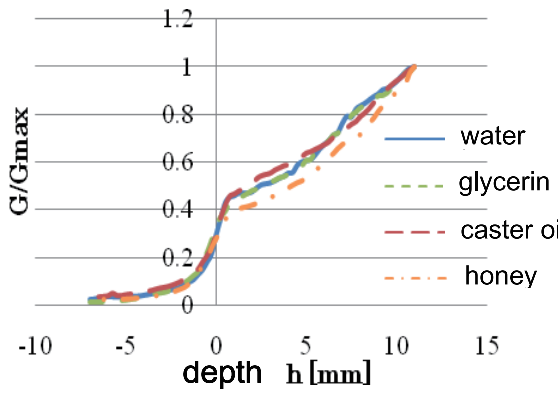

Fig. 5 Results obtained by resonator A at resonance.

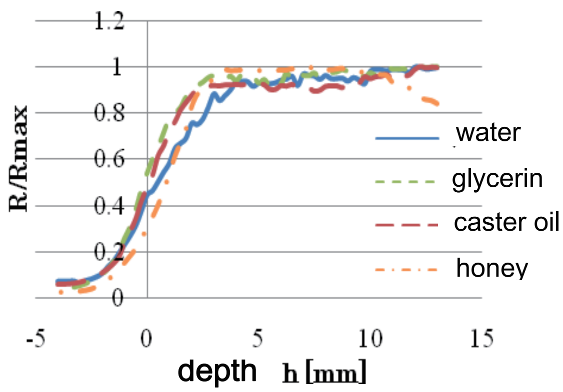

Fig. 6 Results obtained by resonator C (conventional trapped-energy resonator) at antiresonance.

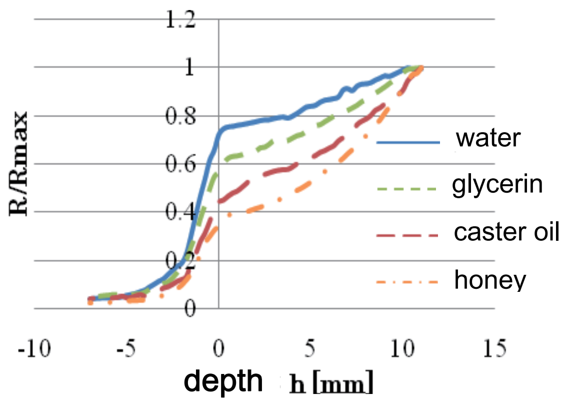

Fig. 7 Results obtained by resonator B at antiresonance.