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Equivalent-Network Modeling of a Liquid-Level Sensor Operating in Backward-Wave-Type Trapped-Energy Vibration Modes

周波数上昇型エネルギー閉じ込めを利用した液面レベルセンサの等価回路表現について

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1. Introduction

A novel approach for detecting a small-scale variation in liquid level that employs a piezoelectric thickness vibrator operating in a trapped-energy mode has been studied by the authors[1-8]. It has been demonstrated that the evanescent field created in both conventional and backward-wave-type[9,10] trapped-energy resonators can be utilized effectively for this purpose. The sensors have been modeled[6-8] by an equivalent electric network representing the propagation of thickness-vibration modes[10,11]. However, the network model for the sensor utilizing a backward-wave-type trapped-energy mode was not applicable for the case in which a liquid covered the un-electroded region[8]. In this paper, an improved model is presented and some results of simulation are shown.

2. Geometry of the Sensor Utilizing Trapped-Energy Resonator for Backward-Wave Mode

In backward-wave thickness-vibration modes, the dispersion relation between the angular frequency ω and the wave number γ along the plate around the cut-off frequency takes the form presented in **Fig. 1(a)**. A novel and unique technique to realize energy trapping for this type of vibrational modes was presented by the authors[9-10]. In this technique, the surrounding region of a piezoelectric plate is electroded and short-circuited as presented in **Fig. 1(b)**. An additional capacitance C_A is connected in series with the central excitation electrodes to ensure energy trapping. By dipping the evanescent region of the resonator in a liquid, a depth-dependent variation in the electric admittance Y will occur at the resonance frequency.

3. Equivalent-Network Modeling and Results of Analyses

The sensor configuration and the corresponding equivalent-network representation are shown in **Figs. 2 and 3**, respectively. In the formally reported model[8], only the outer electroded portion may be dipped in a liquid. In the new model presented here, the liquid surface may be either on the gap or on the outer electrodes. In the sensing side, two transmission lines representing the unelectroded gap of the length $2l'$ are connected serially to the network elements corresponding to

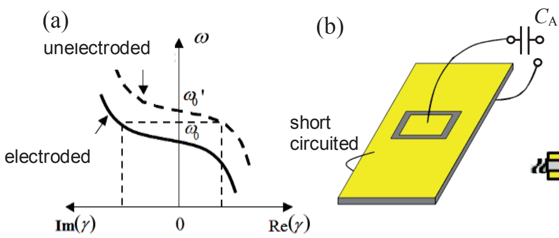

Fig.1 Dispersion curve (a) and electrode configuration (b) for backward-wave energy trapping.

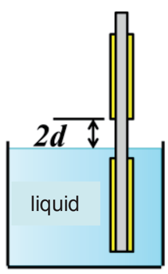

Fig. 2 Arrangement of trapped-energy vibrator for liquid-level sensing.

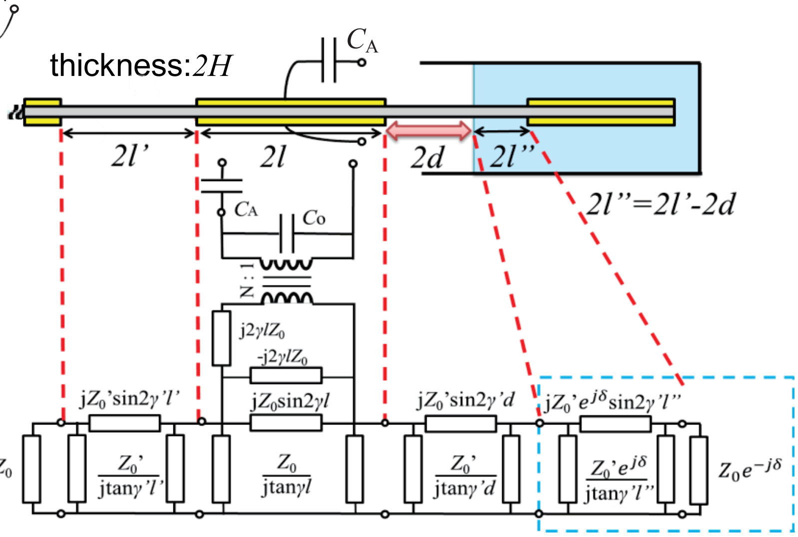

Fig.3 Equivalent network for the sensor utilizing backward-wave energy trapping.

the central excitation electrode part. One is the transmission line representing the out-of-liquid portion of length $2d$, wave number γ' and characteristic impedance Z_0'. The other is the line of length $2l''$ ($=2l'-2d$) representing the portion in the liquid. The wave number and the characteristic impedance in this part should be complex to take the leakage loss into consideration. However, only the characteristic impedance is set to be complex by giving a phase angle δ because the gap width is usually small. The outermost metallized region is supposed to have an infinite length and is therefore expressed by the characteristic impedance $Z_0\exp(-j\delta)$.

A backward-wave-type trapped-energy resonator composed of a thickness-poled $PbTiO_3$ plate is assumed as a model. The ratio of the central electrode width $2l$ to the plate thickness $2H$ is supposed to be 4.0 and the normalized gap width l'/H is supposed to be 0.5. The ratio of the damped capacitance C_0 to the series capacitance C_A is 1.0. A small amount of resistance is added at the electric port to take the material loss into account which is not considered intrinsically in the model.

As an example of the computation results, the variations in the electric admittance characteristic are shown in **Fig. 4** for d/H values of 0 to 2.5. Here, the horizontal axis is the normalized frequency Ω ($=\omega H/v_l$, v_l: longitudinal wave velocity), the vertical axis is the normalized admittance $|Y|/(v_l C_0/H)$ in dB, and δ is assumed to be 0.3. Note that a smaller d/H (higher liquid level) gives a lower peak level at the resonance. The variation in the electric admittance level corresponds to the variation in the quality factor Q_m. Therefore, the variation in $|Y|/(v_l C_0/H)$ with the normalized distance d/H at the resonance frequency is computed. The result is shown in **Fig. 5**. Here, the vertical axis is normalized to the $|Y|$ value for the liquid-free condition. In this figure, the portion where $d/H<0.5$ is newly computed with the model. Note that continuous variation in the electric admittance on the liquid level is obtained.

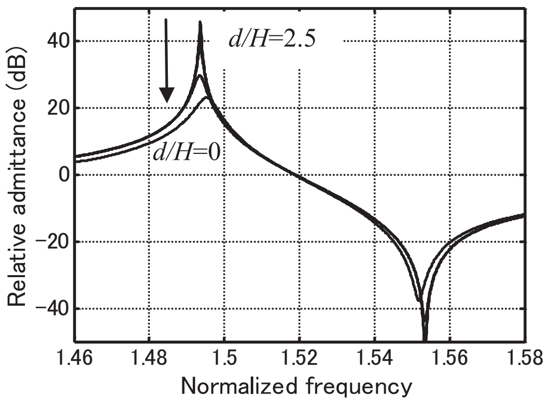

Fig.4 Admittance characteristics computed for d/H of 0 to 2.5.

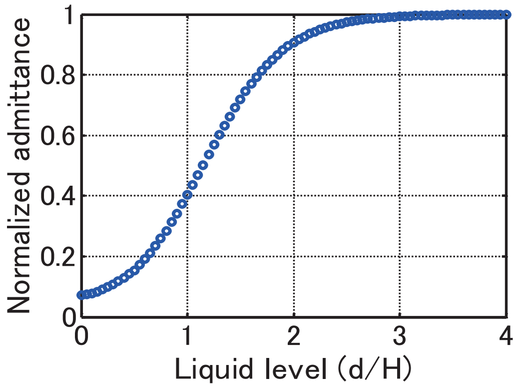

Fig. 5 Variation in $|Y|$ with the liquid level at resonance.

4. Conclusions

An extended equivalent-network model is presented for the liquid-level sensor operating in a trapped-energy-mode thickness vibration of backward-wave type. Continuous variation of the electric admittance on the liquid level is obtained. However, more precise treatment of the wave number and characteristic impedance with the variation of the liquid level should be considered.

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