MEMS VISCOSITY SENSOR USING DUAL SPIRAL SHAPED VIBRATING STRUCTURE

Yasuyuki Yamamoto[1], Sohei Matsumoto[1], Hiroshi Yabuno[2], Masaharu Kuroda[1],
Kenichi Fujii[1]and Tomoko Yamamoto[1]
[1] National Institute of Advanced Industrial Science and Technology (AIST), JAPAN, [2] Keio University, JAPAN

ABSTRACT

We report a development of MEMS based viscosity sensor suitable for in-process measurement for industrial uses. The sensor is based on the principle of the vibrating viscometer. The vibrating body of the viscosity sensor is unique dual spiral structure. The geometry provides a seamless surface and a simple structure of the pseudo-parallel wall in order to create the Couette flow for sensing the viscous stress. On Si wafer, the spiral structure is formed by penetrating trenches(40 µm width, 400 µm depth) which were formed by deep reactive ion etching. In the present study, we verified the principle of viscosity measurement by using the viscosity standard liquids.

KEYWORDS

viscosity, sensor, MEMS, measurement, spiral

INTRODUCTION

Viscosity measurements are universally important in a wide variety of industry and research. Tens of thousands of the conventional viscometer which is rotational, capillary, falling-ball and vibrating viscometer has been used in the world. However, it is well known that many people are not satisfied with the conventional viscometer at the point of usability and portability. Even now, there is no successful compact and portable viscometer as like the handheld digital multimeter for the electric measurements. New approaches of portable viscometer and viscosity sensor are eagerly expected.

Recent development of the technology of the micro electro mechanical system (MEMS) provides new design method and fabrication tool for viscosity sensor. The viscosity sensor based on the MEMS technology has advantages of the downsizing and reducing the cost. However, several problems prevent the MEMS-based viscosity sensor from becoming popular method. The first problem is viscoelastic effect caused by the too high operating frequency of the vibrating body in the sensor. Many reported viscosity sensor is based on the vibrating viscometer. Resonance frequency of micro structure in MEMS device trends to increase corresponding to the scale effect. Some examples of the viscosity sensor work in several kHz, even more MHz. Although the viscoelastic effect is ignored in the principle of the viscosity measurement of the sensor, the effect occurs in the case of high vibrating frequency. Second problem is the fact that calculation of the viscosity needs the density value. Vibrating viscometer using the single plate measures a product of viscosity and density. In general, users in industry wish to measure the viscosity independently.

In order to solve the problem, we have proposed the unique vibrating structure for the MEMS-based viscosity sensor[1]. The proposed shape of the vibrating body is dual spiral structure. The geometry provides a seamless surface and a simple structure of the pseudo-parallel wall in order to measure the viscosity independently. In the present study, we manufactured the micro spiral structure by using the MEMS fabrication methods and verified the principle of viscosity measurement by using the viscosity standard liquids.

THEORY AND EXPERIMENT

Fig. 1 is a photograph of the prototype viscosity sensor. On Si wafer of 400 µm thickness, the spiral structure is formed by penetrating trenches of 40 µm width. The trenches were formed by Deep-RIE(reactive ion etching). The width of the spiral wall is 80 µm. As shown in schematic image of Fig. 2, the dual spiral is composed of the two independent spirals. The red and blue spirals are named vibrating and sensing spiral, respectively. The center of the vibrating spiral is pushed by an actuation pin which joints with piezo element in a sensor holder. Deformation of the vibrating spiral pushed by pin is demonstrated in Fig. 3. The deformation of the spiral is similar to that of the

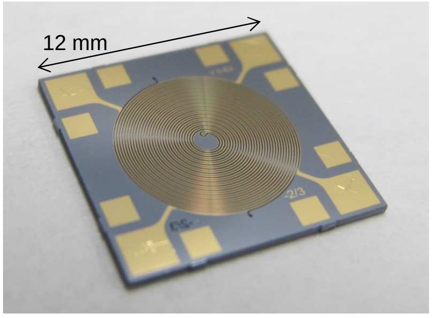

Figure 1 Photo image of double spiral shaped viscosity sensor.

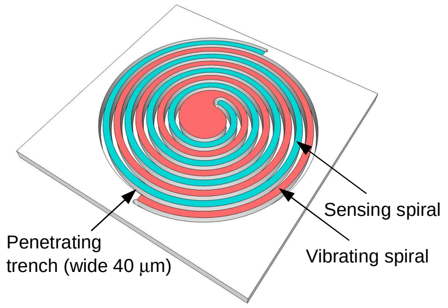

Figure 2 Schematic image of dual spiral

Figure 3 Simulated deformation mode of spiral form.

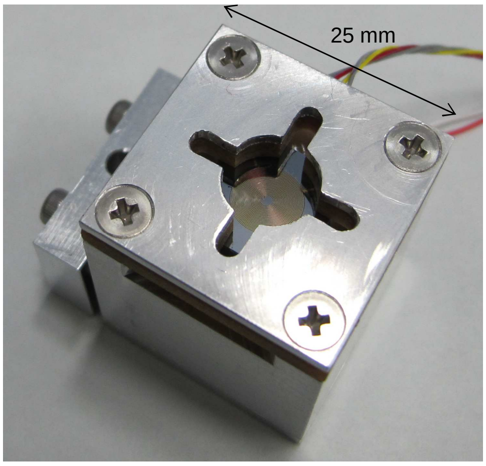

Figure 4 Photo image of piezoelectric holder unit.

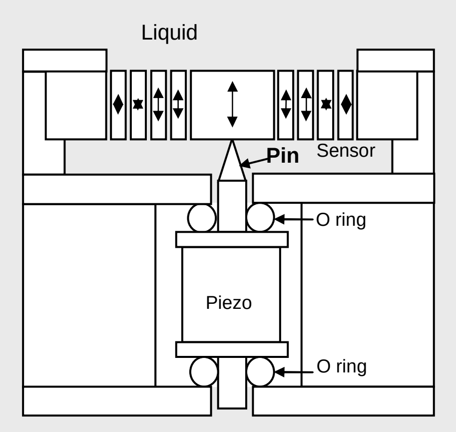

Figure 5 Schematic cross-section view of piezoelectric holder unit.

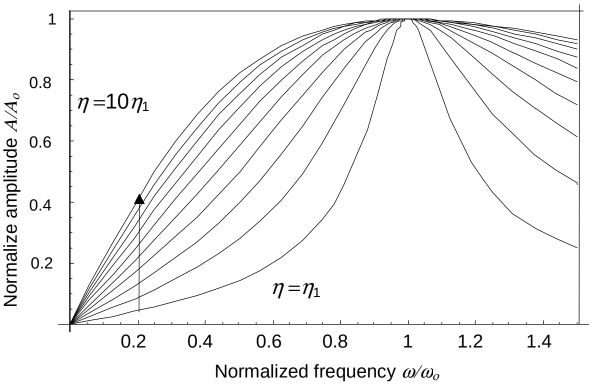

Figure 6 Typical theoretical curves of frequency response of the sensing spiral.

volute spring. The movement of the sidewall of the vibrating spiral is pseudo-parallel motion to the sidewall of the sensing spiral in the case of relatively small displacement of the center of the vibrating spiral. If test liquid fills up the gap between the spirals, the shear motion of the spiral-walls creates shear flow in the liquid. The shear flow courses viscous force on the spiral-walls.

The sensor chip is mounted in the holder in Figs. 4-5. The holder includes the piezo actuator and the pin in order to actuate the center of the vibrating spiral. In experiment, the whole holder is dipped in test liquid. Although the present size of the sensor and holder are 12×12×0.5 mm and 25×25×25 mm, it is easy to downsize in the future.

As the piezo actuator is activated, the vibrating spiral is oscillated. When the displacement x_2 of the center of the vibrating spiral is described as follow equation,

$$x_2 = A_2 \sin \omega t \tag{1}$$

the viscous force in steady-state, F_η , on the wall of the sensing spiral is described as follow,

$$F_\eta = S\frac{\eta}{d}\left\{1+2\sum_{n=1}^{\infty}\left(\frac{\left(\zeta/(n\pi)^2\right)^2}{1+\left(\zeta/(n\pi)^2\right)^2}\right)\right\}\frac{\partial x}{\partial t} - S\frac{\eta}{d}\cdot 2\sum_{n=1}^{\infty}\left\{\frac{\left(\zeta/(n\pi)^2\right)^2}{1+\left(\zeta/(n\pi)^2\right)^2}\frac{\omega(n\pi)^2}{\zeta}\right\}x(t) \tag{2}$$

$$\zeta = \frac{d^2\omega}{\nu}, \qquad x = x_2 - x_1$$

where S: effective surface area [m^2], d: gap distance [m], η: dynamic viscosity [Pa s], ν: kinematic viscosity [m^2/s], x_1: displacement of the center of the sensing spiral [m]. The terms related to the parameter ζ are inertial effect caused by the liquid density. If the parameter ζ is smaller than 0.1 ($\zeta < 0.1$), the terms of the inertial effect can be ignored. In the case of $\zeta < 0.1$, the viscous force F_η is simplified as follow.

$$F_\eta = S\frac{\eta}{d}\frac{\partial x}{\partial t} \tag{3}$$

The sensing spiral is pulled by the viscous shear force. The movement of the sensing spiral is written as following equation of motion,

$$m_1\frac{\partial^2 x_1}{\partial t^2} = m_1 g + \eta\frac{2S}{d}\frac{\partial\left(x_2 - x_1\right)}{\partial t} - k_1 x_1 \tag{4}$$

where, m_1: effective mass of sensing spiral [kg], k_1: spring constant of sensing spiral [N/m]. The eq.(4) does not include the density of test liquid. Therefore, we can measure the viscosity of liquid independently. The displacement x_1 of the sensing spiral is given by,

$$x_1 = \left(\frac{2\eta S}{m_1 d}A_2\omega \middle/ \sqrt{\left(\omega_o{}^2 - \omega^2\right) + \left(\frac{2\eta S\omega}{m_1 d}\right)^2}\right)\cos\left(\omega t - \tan^{-1}\left(-\frac{2\eta S}{m_1 d}\frac{\omega}{\omega_o{}^2 - \omega^2}\right)\right). \tag{5}$$

where ω_0 is natural angular frequency [rad/s]. The amplitude of the displacement x_1 depends on the viscosity and angular frequency. Typical frequency response curve of the displacement x_1 of the sensing spiral is shown in Fig. 6. As the viscosity of liquid increase, the peak of the response curve is broader. The broadening of the curve depends on the parameter: $2S\eta/m_1 d$. The sensor parameter: $2S/m_1 d$ can be calibrated by the reference liquid of which the viscosity value is known. The parameter: $2S\eta/m_1 d$ is obtained by curve fitting of the frequency response. The viscosity of the sample liquid can be calculated by using the obtained parameter: $2S\eta/m_1 d$ and the calibrated sensor parameter: $2S/m_1 d$.

For examination of the measurement principle, a testing system which has a laser displacement sensor was built. Fig. 7 is schematic illustration of the testing system. Sample liquids are Japanese standard reference liquids. The properties are listed in Table 1.

RESULTS AND DISCUSSION

Observed natural frequency is 102 Hz. The frequency is relatively lower than the other MEMS devices which have vibrating body. The spiral structure realizes the flexible spring easily. The characteristic of the spiral structure is suitable for the vibrating body of viscosity sensor which has to avoid the high frequency.

Experimental results of the frequency response are collected in Fig. 8. Both of the axes are normalized by the fitting value of the resonance frequency ω_0 and peak of amplitude A_{peak}. Parameter of the sensor is calibrated using the fitting value of the JS10 one of the reference liquid. By using the fitting value of the others, measurement values of the viscosity are calculated. The measurement results and deviations are summarized in Table 1. The results agree with the reference values less than 10 %. Although the deviations of the values are not sufficiently small, the experiment verified that the proposed dual spiral-shaped structure can be applied to the viscosity measurement.

REFERENCES

[1] Y. Yamamoto, S. Matsumoto, H. Yabuno, M. Kuroda, K. Fujii and T. Yamamoto, 2012 Material Research society spring meeting (MRS-S 2012), pp. 108.

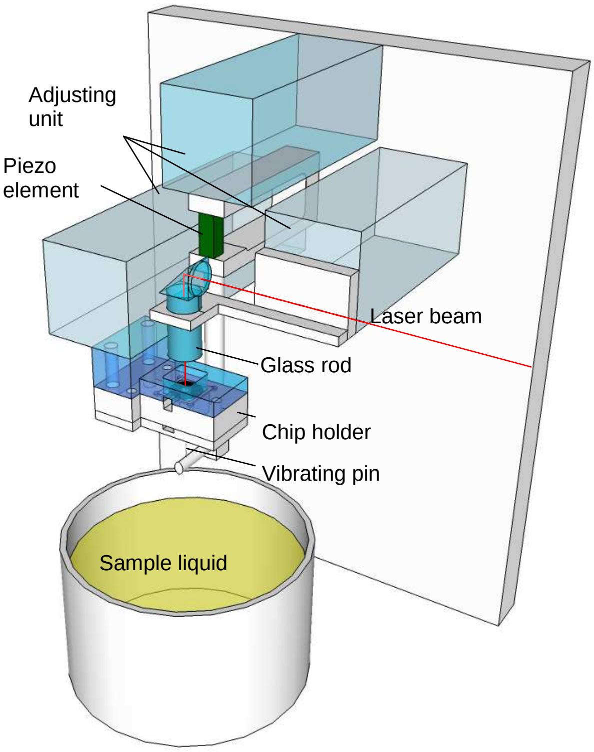

Figure 7 Schematic view of the testing system.

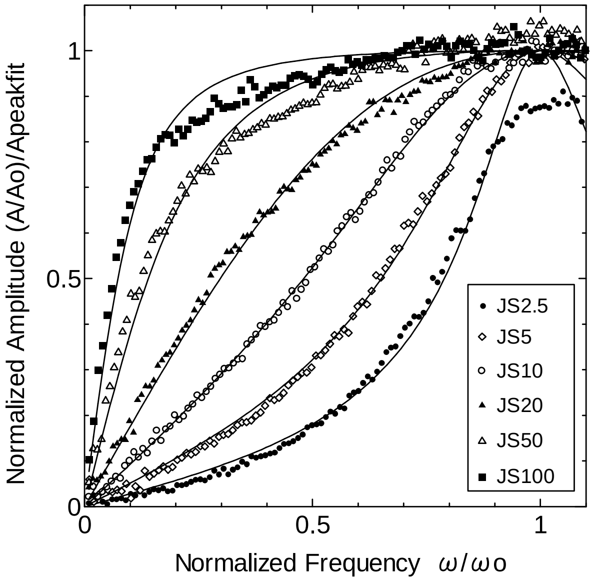

Figure 8 Normalized spectra using the piezoelectric holder.

ACKNOWLEDGEMENT

This research is granted by the Japan Society for the Promotion of Science (JSPS) through the "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)," initiated by the Council for Science and Technology Policy (CSTP).

Table 1 Experimental results in experiment of the piezo unit and the reference value of the standard liquid.

	Kinematic viscosity	Dynamic Viscosity	Density	Dynamic Viscosity	Deviation
24 ℃	calibrated value	calibrated value	calibrated value	measurement	
	mm2/s	mPa・s	kg/m3	mPa・s	%
JS2.5	2.295	1.773	0.773	1.66	−6.3
JS5	4.483	3.62	0.807	3.96	9.4
JS10	8.927	7.334	0.822	−	0
JS20	17.16	14.29	0.833	15.62	9.3
JS50	41.25	34.87	0.845	34.63	−0.7
JS100	80.55	68.77	0.854	63.1	−8.2

CONTACT

Yasuyuki Yamamoto: yamamoto-yasu@aist.go.jp