Laser-induced surface displacement detection instrument for measuring viscosity of liquids with Doppler shift composed of optical fibre

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Abstract. This article proposes a laser-induced surface displacement detection instrument for measuring the viscosity of liquid. The features of this instrument can obtain the absolute value of time-resolved surface displacement with an adjusted-free and non-calibration. The constitution method of our proposed apparatus and its trial prototype are shown, and experimental results are demonstrated. Finally, our proposed scheme that estimates liquid viscosity is described briefly.

1. Introduction

Since liquid viscosity is a significant physical property for industrial and medical situations, a technique is required that can measure it quickly. Recently, several laser-applied techniques have been proposed for measuring liquid viscosity [1], [2]. These techniques include non-contact with samples and micro-liter sample volume, both of which provide significant advantages in terms of actual applications. But optical benches are expensive and massive, and advanced skill is required for their operation since the measurement apparatus is extremely complicated. To overcome these problems, we address a new laser-induced surface displacement detection instrument that is composed of an adjusted-free, optical fiber system. Our proposed technique analyzes the time-resolved frequency of the Doppler shift by elastic waves in liquid induced by periodical expansion.

Expansion can be generated by the following two phenomena. The first is that light incident into liquid increases its momentum, which is caused by the difference in the refractive index at the boundary between air and liquid, and gives the surface an upward force as a reaction when a laser beam is not absorbed practically in a liquid, i.e., because a laser beam is rarely converted to a thermal state [2]. This phenomenon is called a laser pickup. The second phenomenon is that thermal expansion on a liquid’s surface is caused when the laser beam is mostly absorbed in a liquid in a phenomenon called photothermal expansion [1]. First, we describe the constitution method of our proposed apparatus and its trial prototype and then demonstrate experimental results that were measured with cases of the above two phenomena. Finally, we briefly describe our proposed scheme that estimates liquid viscosity.

2. Measurement system

Figure 1 illustrates the sensing head. The incident laser beam is focused on the boundary surface between the air and the liquid by a spherical lensed fibre (SLF), which returns part of the beam reflected with the surface to the fibre. The distance between the SLF tip and the boundary surface (the gap) was adjusted commonly to the SLF’s focal length. The distance between the air and the liquid is changed transitionally when the surface is lifted due to the above two phenomena. Consequently, the reflected beam, whose frequency is shifted due to the Doppler effects, is returned to the fibre.

Figure 2 shows a block diagram of our proposed system. We used a laser diode module with a 1.47-μm wavelength and 120-mW fibre output power as the light source of the pumping beam. A
1.55-μm, DFB laser diode module was used as the probe beam. We chose a wavelength for two beams because these modules and their peripheral parts are commercially available for optical communication systems. The probe beam is CW and is branched to two routes by a fibre coupler (FC). The side beam is a reference beam that is fed to an acoustic optical modulator (AOM) to generate a frequency shift of 80 MHz for optical heterodyne detection. The other side beam is fed to a wavelength-division multiplexing (WDM) FC that functions as a dichroic mirror and is unified with a pumping beam. The two unified beams are fed to a sensor head through a circulator, and the probe beam is mixed with the frequency-shifted reference beam for heterodyne detection after the reflected (residual) pumping beam is eliminated with an interference filter. Consequently, we believe that the frequency transition due to the Doppler effect, which is associated with a velocity transition of the surface deformation, can be time-resolved measured by a modulation domain analyser (MDA) [3].

In our setup, Doppler shift frequency $\Delta f$ is given by:

$$\Delta f = \frac{2\nu}{\lambda}$$

where $\nu$ and $\lambda$ is a velocity of deformation and a wavelength of probe beam, respectively. Accordingly, an absolute value of $\nu$ can be obtained easily without a peculiar calibration.

Figure 3 represents a trial prototype of our instrument shown in Fig. 2. Its main components are enclosed by dotted lines. Our instrument features a miniaturized apparatus, a portable one, and an adjusted-free one. Furthermore, it can be installed easily to a universal 19-inch rack.

3. Experimental results

Figure 4 shows an example waveform of a Doppler shift frequency $\Delta f$ measured by MDA. This is the waveform caused by the laser pickup phenomenon, because we used an optical non-absorbed liquid (ethanol) at the pumping beam’s wavelength, which was observed with the modulation of the pumping beam. The positive value of $\Delta f$ and the negative value of $\Delta f$ respectively correspond to the frequency shift at the start of pumping, i.e., surface lifting, and the pumping cut-off, i.e., lifting recovery. Here since $\Delta f$ is proportional to the perfect, absolute velocity of the surface displacement, we can simply obtain the time-resolved surface displacement (lifting) value from the data shown in Fig. 4 with a numerical integral calculation by the Simpson method. For reference, Fig. 5 shows the relationship between 10 μs-interval time and surface displacement (lifting), i.e., timewise differential values of the displacement. As can be seen in this figure, it was demonstrated that the lifting value per time is decayed moderately after it has a radical ascent. The reason for this is believed to be a viscosity and specific gravity.
Fig. 3  Trial prototype of instrument.

Fig. 4  Example waveform of a Doppler shift frequency $\Delta f$.

Figures 6(a) and (b) show the relationship between the elapsed time and the surface displacement value for the laser pickup and photothermal expansion, which respectively uses ethanol and distilled water as sample liquids. The circles and triangles correspond to the displacement values for lifting the surface by starting the pumping and recovering with a pumping cut-off. The displacement gradually increases (decreases) as time passes and eventually becomes saturated. We also confirmed that the tendency (i.e., decay constants) is different for each sample because of different relaxation times due to different viscosities.

Fig. 5  Timewise differential values of displacement.

Fig. 6  Relationship between elapsed time and surface displacement value for (a) laser pickup and (b) photothermal expansion.
4. Discussions

Dotted lines drawn in Fig. 7 intend a curve fit of exponential decay concerning plots corresponding to Fig. 6 in case of a recovering of surface displacement. As can be seen in this figure, it was confirmed that the displacement with a sample of distilled water is closely match with an exponential curve. This is because the effect of thermal diffusion is dominant compared with that of laser pickup. On the other hand, the displacement with a sample of ethanol is designated a combination of several exponential curves. The reason for this is believed that the viscosity of liquid is symbolized with infinite connections of elastic model, as shown in Fig. 8. Namely, the mighty spring of wave number functions dominantly as the displacement of liquid surface is larger, and the weak spring of one functions dominantly as it is smaller. Incidentally, it is recognized that it is useful for applying an error function in this case, as defined relatively by [2]:

$$S(t) = 1 - 2\Gamma t e^{\Gamma t} \text{erfc}(\Gamma t)$$  \hspace{1cm} (2)

where \(t\), \(S\) and \(\Gamma\) is time, displacement and relaxation constant, respectively. Furthermore, \(\Gamma\) is associated with a viscosity and surface tension of liquid.

5. Summary

We proposed a laser-induced surface displacement detection instrument with a Doppler shift composed of optical fibre. The features of this instrument can obtain the absolute value of time-resolved surface displacement with an adjusted-free and non-calibration facility. We also produced a miniaturized, portable prototype instrument. We believe that a liquid’s viscosity can be estimated in the future from the experimental data shown in Fig. 7.

References

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