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Vibration-based specklegram fiber sensor for measurement of properties of liquids

Eric Fujiwara*, Yu Tzu Wu, Carlos Kenichi Suzuki

UNICAMP—The State University of Campinas, Faculty of Mechanical Engineering, Laboratory of Photonic Materials and Devices, R. Mendeleiev, 200, Campinas, Sao Paulo 13083-970, Brazil

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A B S T R A C T

A specklegram fiber sensor for the measurement of properties of liquids is proposed. The laser speckle field formed at the output of a multimode fiber is modulated by a vibrating microbending transducer. Once the transducer is placed in vessel filled by the sample, the frequency response of the specklegrams can be correlated to the properties of the liquid. The system was applied on the measurement of the mass and viscosity of water and ethanol samples, by processing the inner product of speckle patterns with artificial neural networks. The sensor provided measurements with absolute error lower than 0.5 g and 0.1 mPa s on the prediction of mass and viscosity, respectively, with potential application on the determination of the concentration of liquid mixtures.

1. Introduction

The measurement of physical and chemical properties of liquids is essential for many applications in engineering, such as the process monitoring and quality control in food, pharmaceutical and chemical industries, as well on the laboratorial analysis and research activities [1]. In this sense, the application of optical fiber sensors on the measurement of liquids has been widely reported, particularly motivated by its unique advantages, such as high sensitivity, lightweight, and immunity to electromagnetic interference [2]. Nowadays, several properties of liquids can be detected by different fiber-based sensing principles, for example, the measurement of refractive index, concentration or viscosity by Fresnel reflectometry [3,4], fiber Bragg gratings [5], long period gratings [6,7] and surface plasmon resonance [8].

On the other hand, a new category of sensors defined as fiber specklegram sensors was proposed, in which the speckle hologram (specklegram) generated at the output of a multimode optical fiber due to the modal interference, is used to quantify the physical status of the waveguide. These sensors provide attractive features, such as high sensitivity (comparable to interferometric fiber sensors), relative low cost and multiplexing capabilities [9]. Currently, some of the applications of FSS can be found on the detection of sub-micrometric displacements [10], vibration detection [11], and refractive index sensing [12].

In this research, a vibration-based fiber specklegram sensor for the measurement of properties of liquids is reported. The sensor response is demonstrated first for the detection of the mass of the sample, and later on the prediction of the concentration and viscosity of ethanol–water mixtures. In addition, the frequency-variant specklegram signals are processed by artificial neural networks (ANN) models.

2. Sensor design

2.1. Specklegram fiber sensors

When the light from a coherent laser source is propagated through a multimode fiber, a complex speckle pattern is formed in the fiber output as a consequence of constructive and destructive interferences between the propagating modes. However, the modal noise is a serious limitation to optical communication systems; the speckle field carries the spatial information of the fiber status, since the pattern is particularly very sensible to mechanical disturbances along the optical fiber. In this sense, the spatial information can be retrieved by the analysis of the speckle hologram generated in the fiber output.

According to [9], given a 2D complex speckle field $A(x,y)$ denoted by

$$A(x,y)=\sum_{m=0}^{M} a_m(x,y)\exp[j\phi_m(x,y)], \tag{1}$$

* Corresponding author. Tel.: +55 19 3521 3337; fax: +55 19 3289 3722.
E-mail addresses: fujiwara@fem.unicamp.br (E. Fujiwara), suzuki@fem.unicamp.br (C.K. Suzuki).

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where M is the number of modes, and a_m and ϕ_m are the amplitude and phase distributions related to the m-th mode, the specklegram intensity $I(x,y)$ measured by the CCD is given by

$$I(x,y) = |A(x,y)|^2. \tag{2}$$

In order to exploit the complex information of the speckle fields, which provides a more sensible detection [10], the normalized intensity inner product (NIPC) is calculated by

$$\mathrm{NIPC} = \iint I_0(x,y) I(x,y) dxdy \Big/ \left[\iint {I_0}^2(x,y) dxdy \iint I^2(x,y) dxdy \right]^{1/2}, \tag{3}$$

where I_0 is the intensity corresponding to the initial fiber status.

2.2. Sensor configuration

A schematic of the fiber sensor is shown in Fig. 1. The light emitted by the HeNe laser source (633 nm) is launched into ~3 m length standard multimode fibers coated with polymer buffer. A microbending transducer is connected to the optical fibers and then placed on a cylindrical acrylic vessel (Ø87 × 16 mm), that is filled up with the liquid sample. The transducer, Fig. 2(a), consists of a pair of deformer plates, in which the bending mechanism is provided by 0.5 mm graphite rods spaced in a periodic fashion. The upper plate is kept in a stationary position and is attached to an external static support, whereas the lower part is connected to the bottom of the vessel. Additionally, the initial distance between the deformer plates can be adjusted by a translation stage. In order to excite the transducer with acoustic waves, a speaker is installed below the vessel. Sine sweep signals are generated by a MATLAB routine, and then electronically amplified. Finally, the specklegrams projected at the fibers ends are acquired by a CCD with a 15 Hz sampling rate, and then post-processed in MATLAB. Furthermore, the stability of laser source is monitored by a reference ~3 m length multimode fiber, whose specklegram is simultaneously measured by the same CCD.

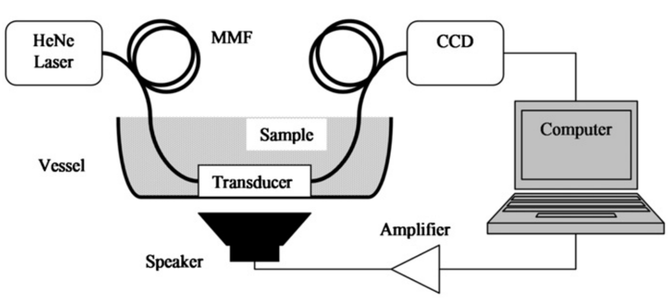

Fig. 1. Configuration of the fiber sensor.

2.3. Principle of operation

As the vessel is disturbed by an acoustic wave, the lower plate is displaced, causing the fiber to be pressed by the microbending mechanism, and resulting in the modulation of the speckle patterns. On the other hand, if the vessel is filled by the liquid sample, the vibration response of the system is also affected by the properties of the liquid. A simplified model of the transducer, shown in Fig. 2(b), can be described as a function of the time t by

$$F = (m + m_s)\ddot{u}(t) + (d + d_S)\dot{u}(t) + ku(t) \tag{4}$$

where F is the acoustic excitation, u is the position of the bottom plate, m, d and k are the mass, damping coefficient and spring constant related to hardware parameters, such as fibers, transducer materials, geometry and preload, and the vessel, whereas m_S is the mass and d_S is the viscous friction coefficient of the liquid. The acoustic excitation is of the form

$$F = A\sin(2\pi f(t)), \tag{5}$$

where A is the amplification, and $f(t)$ is the frequency of vibration, which increases from an initial to a final value with a constant rate. Therefore, since the specklegram intensity changes according to $u(t)$ and, consequently, as a function of the vibration frequency f(t), the frequency response of $I(x,y)$ and NIPC can be correlated to the sample coefficients m_S and d_S.

3. Experimental

3.1. Experimental setup

In order to verify the frequency response of the fiber sensor, a preliminary experiment was carried out by filling the vessel with 50 g of distilled water and then adjusting the system to produce a 20 s duration signal with frequency increment from 0 to 600 Hz.

Next, the effect of the mass of liquid was evaluated by filling the vessel with amounts from 20 to 50 g of distilled water. In this case, the signal generator was adjusted to produce a sine sweep varying from 0 to 250 Hz in 15 s.

Finally, the influence of the liquid composition was analyzed by testing the sensor for ethanol–water mixtures, by using solutions with the same mass (30 g), but different concentrations, ranging from 0 to 100 wt% of ethanol. The system was also set to generate a 15 s signal ranging from 0 to 250 Hz.

For all experiments, the samples were prepared and measured at room temperature (~22 °C). The stability of the laser source was granted by monitoring the intensity of reference fiber, and system was kept out of possible external effects, such as mechanical disturbances or temperature fluctuations, in order to avoid uncontrolled changes in the speckle patterns.

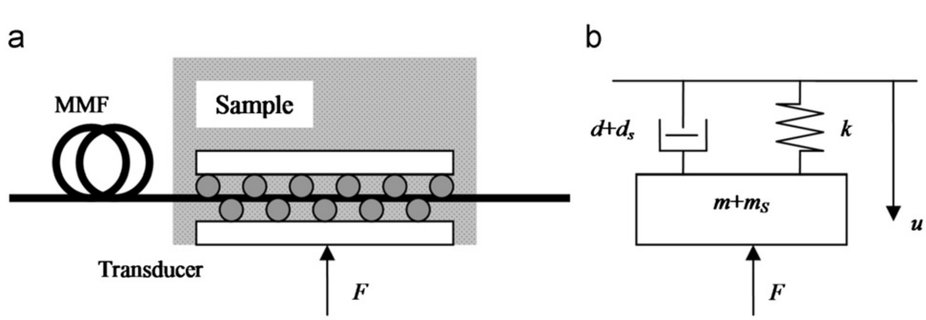

Fig. 2. (a) Detail of the microbending transducer, and (b) equivalent mechanical model.