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Fiber optic fused 1×2 coupler as a vibration sensor

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A simple non-contact vibration sensor is designed using a 1×2 plastic optical fiber coupler based on the principle of extrinsic reflection intensity modulation. A single fiber is used as a sensing head for both transmitting and receiving of light from the reflecting surface of the vibrating object and it exhibits a linear region of about 1 mm with the sensitivity of 2.45 mV/μm. The results show that the sensor can measure the frequency of vibrations up to 1300 Hz with an amplitude resolution of 1 μm. In comparison with a dual-fiber and bifurcated-bundle fiber, it eliminates the dark region and front slope, which facilitates easy alignment.

Keywords: vibration sensor, plastic fiber coupler, displacement, LED, photodetector, fast Fourier transform.

1. Introduction

Vibration measurement plays a major role in studying the dynamic behavior and failure of components in machines [1, 2]. Continuous monitoring of vibration reduces not only the maintenance and operating costs but also avoids frequent interruptions of undesirable engine working. In general, vibration is measured by electro-mechanical devices, such as piezoelectric, piezoresistive, or capacitive accelerometers. Such types of measurements require physical contact with the vibrating object. However, some non-contact vibration measurement techniques have been developed with optical interferometric and fiber optics. Especially such non-contact sensors made of optical fibers have already been in use and play a key role in sensing several physical parameters like vibration, displacement and pressure. The advantages attributed to fiber optic sensors are as follows: high sensitivity, immunity to electromagnetic interference (EMI), low cost of maintenance and simple design [3–5]. Reported fiber optic vibration sensors are in general divided into two types according to their working principle of phase or intensity modulation. The phase modulation fiber optic interferometric techniques such as Fabry–Pérot [6], Michelson or Mach–Zehnder [7], self-mixing [8] and Doppler vibrometry [9, 10] were deployed for vibration measurements. These methods exhibit high sensitivity of performance but at the same time a low degree of stability and critical alignment [11]. Consequently, they have a limited practical use. However, the second one, *i.e.*, the intensity modulated technique, takes the advantage of a change in intensity with the vibration using simple fiber optic geometry [12].

In this paper, we report a non-contact simple intensity modulated fiber optic vibration sensor designed with a plastic fiber optic fused 1×2 coupler [13]. It consists of three ports: one port is for coupling of a source, second port acts as a sensing probe and the third port is connected to the photodetector. Here, the single fiber alone guides the light to fall on the reflecting surface glued on a sensing part of the vibrating object and to receive the reflected light. It consists of only a single slope rather than of the two slopes, so the alignment of the sensor is very simple. This is the advantage of the proposed sensor in comparison with the dual-fiber and bifurcated bundle fiber vibration sensors that there is no the dark region and the front slope disappears [14, 15].

2. Theory

The basic principle of the vibration measurement is based on intensity modulation by displacement of the reflecting surface glued on the vibrating target, detected by the sensing fiber port. It consists of a 3dB fiber optic coupler made of PMMA (polymethyl methacrylate) having three ports: one for coupling of a light source, second one acting as a sensing probe and third one receiving reflected light incident on the photodetector. The schematic diagram of the sensor principle is shown in Fig. 1. The LED light is incident on the reflecting surface (glued on the front surface of the microtranslation stage) at a distance x from the sensing fiber probe (port 1) and the reflected light is coupled into the same fiber. The light source of power P_a is coupled to the port 2 of the coupler and directed to the port 1. The light incident on the reflector is of power P_b through the port 1 and the light reflected from the reflector of power P_c is received by the same port, is a function of the gap between the sensing fiber probe (port 1) and the reflector. The light power received by the photodetector via the node 3 is denoted by P_d.

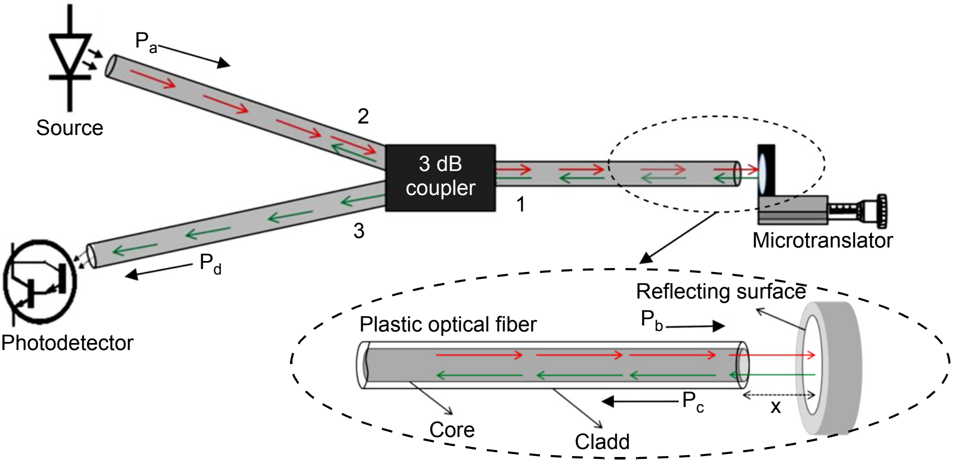


Fig. 1. Schematic of the fiber optic coupler vibration sensor working principle.

The light transmitted from the source with the power of light P_a through the fiber to the sensing fiber port 1 is given by [16]

$$P_b = \left(1 - \mathrm{cr}\right)\left(10^{-0.1L} - 10^{-0.1D}\right)P_a \tag{1}$$

where cr, L and D are the coupling ratio, the excess loss and the directivity of the fiber coupler, respectively.

The reflector is kept parallel to the sensing fiber cross-section and then the power of light is coupled back, and next received by the sending fiber probe. The power is given by

$$P_c = P_i\left[1 - \exp\left(-\frac{2a}{W^2(x)}\right)\right] \tag{2}$$

where $P_i = kP_b$ is the light power coupled to the sensing fiber at $x = 0$, a is the core radius of the fiber, $W(x) = 2x\tan(\theta) + a$, $k = 1.15$ and $\theta = \sin^{-1}(\mathrm{NA})$ is the divergence angle of the fiber [16]. Substituting Eq. (1) into (2), we have

$$P_b = k\left(1 - \mathrm{cr}\right)\left(10^{-0.1L} - 10^{-0.1D}\right)P_a\left[1 - \exp\left(-\frac{2a}{W^2(x)}\right)\right] \tag{3}$$

The light power detected by the photodetector from the sensing port through the port 3 is given by

$$P_d = \mathrm{cr}\left(10^{-0.1L} - 10^{-0.1D}\right)P_b \tag{4}$$

Substituting $W(x)$, Eq. (3) into (4) yields

$$P_d = k\mathrm{cr}\left(1 - \mathrm{cr}\right)\left(10^{-0.1L} - 10^{-0.1D}\right)^2\left\{1 - \exp\left[-\frac{2}{\left(\dfrac{2x\tan(\theta)}{a} + 1\right)^2}\right]\right\}P_a \tag{5}$$

therefore

$$P_d = P\left\{1 - \exp\left[-\frac{2}{\left(\dfrac{2x\tan(\theta)}{a} + 1\right)^2}\right]\right\}P_a \tag{6}$$

where $P = k\mathrm{cr}(1 - \mathrm{cr})(10^{-0.1L} - 10^{-0.1D})^2$.

For a large value of $2x\tan(\theta)/a$, Eq. (6) can be written as

$$P_d = \frac{P}{2}\left\{\frac{(2a)^2}{\left[2x\tan(\theta)\right]^2}\right\}P_a \tag{7}$$

This equation is the correlation function of the displacement sensor with the multimode fiber coupler. It states that the power received by the photodetector is directly proportional to the square of the diameter of the fiber and inversely proportional to the square of the distance between the fiber and the reflector [17].

A simple photodetection circuit is used to convert the light intensity into equivalent voltage. Generally, the output voltage with respect to the intensity of light incident on the photodetector P_d is given by [18]

$$V_{\text{out}} = R_\lambda P_d R_E \tag{8}$$

where $R_\lambda = \eta g\lambda/1.24$ is the responsivity of the photodetector, R_E is the feedback resistance, η, λ and g are the quantum efficiency, the wavelength of the incident light and the photoconductive gain, respectively. For a given photodetector, the values of η (< 1) and g are the constants, therefore the responsivity (sensitivity) is completely dependent on the wavelength of the light.

3. Experiment

Figure 2 shows the schematic experimental setup of the fiber optic vibration sensor. It consists of a LED source (IFE-96, i-fiberoptics) of centre wavelength 650 nm and is driven by a simple circuit with a regulated power supply. A 3 dB plastic optical

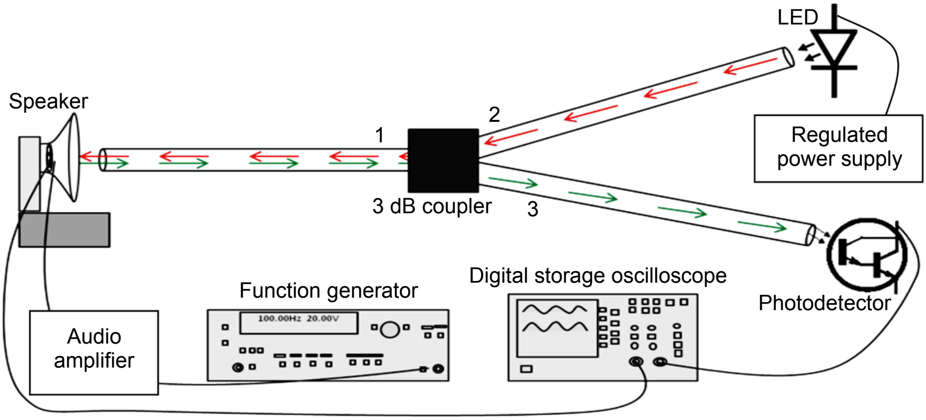


Fig. 2.. Schematic of the experimental setup.

fiber 1×2-coupler (IF-562, i-fiberoptics) is used to configure the sensor to detect the vibration of the vibrating object; a photodetector (IFD-93, i-fiberoptics) with a detection circuit is used to convert the light intensity into an equivalent electrical signal. A well regulated power supply is used to drive the LED source. A synthesized function generator (HM8130, Scientific) and a commercial speaker with a reflector attached at its centre are used to test the sensor response. To record and monitor the vibration of the speaker at different frequencies and amplitudes, a digital storage oscilloscope (SM1060, Scientific) is used.

Figure 1 shows the method of calibrating the amplitude of sensor vibration: a small reflector is pasted on the surface of a rectangular block and it is fixed to the microtranslation stage perpendicular to the sensing head of the fiber. A digital multimeter is used to measure the output light power in terms of the voltage with respect to the displacement between the reflector and the sensing head (node 1) in steps of 10 µm over a span of 4000 µm. Figure 3 shows the experimental and theoretical displacement characteristic curve for the parameter values of $P_a = 200$ µW, $a = 490$ µm, cr = 0.5, $L = 1.6$ dB, $D = 25$ dB, NA = 0.51 by substituting these values in Eq. (8) for the proposed sensor and both are in a good agreement. It follows the inverse square law as given by Eq. (7).

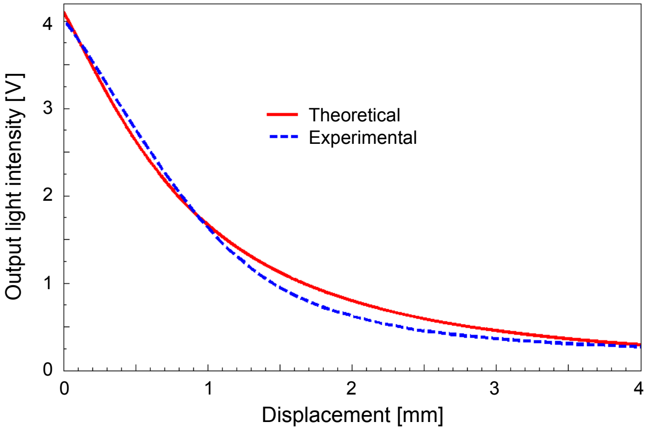
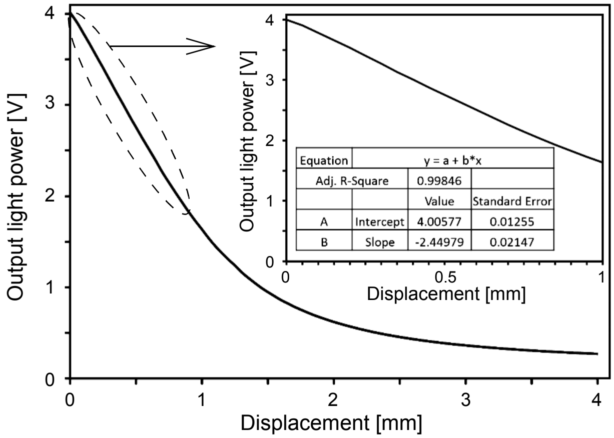


Fig. 3. The displacement characteristic response of the sensor.

Figure 4 presents a linear region of 0–1000 µm with a slope of 2.45 mV/µm (shown in the sub-plot) and it is used to measure the amplitude of vibration. The calibrated weightless reflector is glued on the speaker front surface and then the sensor head is placed in front of the reflector in such a way that they are perpendicular to each other. The speaker is adjusted to be placed within the linear region of the displacement curve from the sensing head. The light from the LED is coupled to the port 2 of the coupler and directed to the port 1. The light incident on the reflector via the port 1 and the reflected light modulated by the vibration of the speaker are received by



Equation		y = a + b*x	
Adj. R-Square		0.99846	
		Value	Standard Error
A	Intercept	4.00577	0.01255
B	Slope	-2.44979	0.02147

Fig. 4.. Linear region of the displacement characteristic curve of the sensor for vibration measurement.

the same fiber (port 1). The light power received by the photodetector is converted into its equivalent voltage signal by a simple receiving circuit and is recorded or stored by a storage oscilloscope. The FFT technique is used to convert the time domain signal into the frequency domain to analyse the vibration in terms of frequency of the object and also to measure the amplitude of vibration. The experiment is repeated for different frequencies of the amplitude of vibration to measure the detectable maximum frequency and amplitude resolution of the sensor and also to test the reliability of the sensor.

4. Results and discussion

The whole setup is mounted on a vibration free table (Newport). The sine wave applied to the speaker (CH1) and the response of the sensor (CH2) are recorded by the oscilloscope as shown in Fig. 5. The FFT of both signals gives the frequencies of the applied signal and the output of the sensor. It is evident from Fig. 5 that there is a perfect matching in frequencies between them. The peak-to-peak voltage of the output signal gives the amplitude of vibration using the slope of the calibration curve which

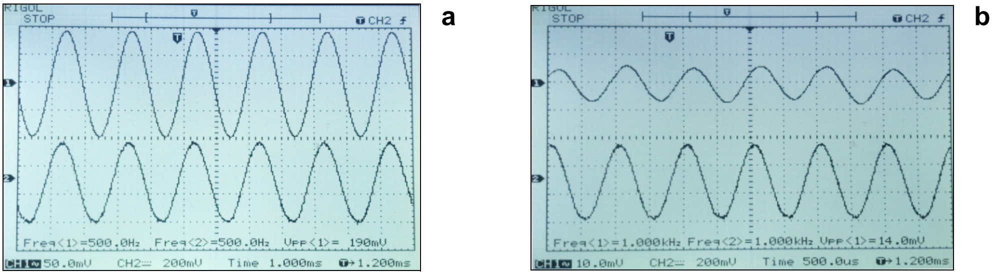


Fig. 5. Experimental results of the sensor at 500 Hz (**a**) and 1000 Hz (**b**).

corresponds to the displacement amplitude d_p. For a given frequency f_p, the peak velocity v_p and the peak acceleration a_p can be computed by:

$$v_p = 2\pi f_p d_p \tag{9}$$

$$a_p = 4\pi^2 f_p^2 d_p \tag{10}$$

Figure 6 illustrates the relation between the frequency applied to the speaker and the frequency provided by the sensor output. At a constant amplitude of vibration, that is at a constant driving voltage, the frequency range of 0–1400 Hz is applied to the speaker and corresponding frequency is measured by the sensor. The obtained results show that up to 1300 Hz there is a perfect matching between the frequencies applied to the speaker and those measured by the sensor output. In between 1300 Hz to 1400 Hz, the sensor vibration measurements uncertainty is ±5 Hz and beyond 1400 Hz there is no response from the sensor, it is giving a dc signal.

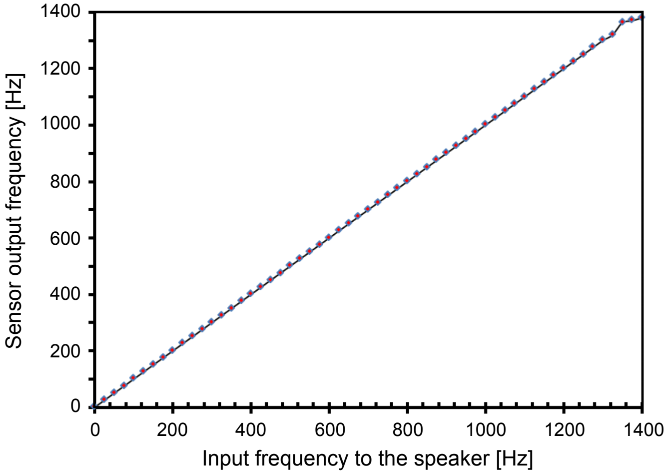


Fig. 6. Frequency response of the vibration sensor.

The amplitude response of the sensor between the driving voltage to the speaker and the FFT peak voltage of the output signal at different frequencies is plotted in Fig. 7. It is observed that the amplitude of vibration is linear with the correlation coefficient of 0.99, in response to the driving voltage to the speaker. The resolution of the sensor is calculated from the minimum amplitude of vibration detected by the sensor at maximum frequency. The sensitivity of the vibration sensor is found to be 2.45 mV/μm from the slope of the displacement characteristic curve. Experimentally, the minimum amplitude resolvable by the sensor is 2 mV, which corresponds to the resolution of around 1 μm. The experiment is repeated to test the reliability of the system and the response of the sensor is found to be consistent.

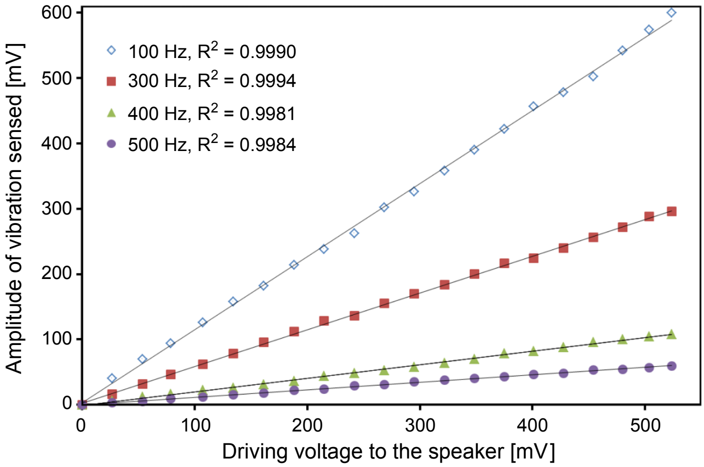


Fig. 7. Amplitude response of the sensor at different frequencies.

The possible measurement errors may be as follows: the fluctuation in the source of light, the stray light effect and dust formation on the mirrors. To reduce the fluctuations in the source of light, a well regulated power supply is used. A hollow cylindrical protection tool is mounted on the reflector so that the stray light cannot interfere with the source light, and to avoid formation of dirt on the mirror. The sensor is positioned very close to the vibrating target within the sensing linear region and does not require special optics. Thus it is especially suitable in embedded applications.

5. Conclusions

In this paper, a simple intensity modulated non-contact vibration sensor has been presented using a 1×2 fiber optic fused coupler. A single fiber is used as a sensing probe and it consists of only one slope with high sensitivity of 2.45 mV/µm, which facilitates easy alignment and accurate measurement. The sensor is capable of measuring the vibrations of frequencies 0–1300 Hz with 1 µm resolution amplitude of vibration. The experimental results show that high sensitivity, good linearity and non-contact measurement are useful for the health condition monitoring of the vibrating objects in industries, especially useful where conventional in-contact sensors fail to install. The designing of the sensor using optical fibers has advantages of fiber sensors and is useful for sensing applications in embedded situations.

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