Fiber-Optic Vibration Sensor Based on Multimode Fiber

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Abstract. *The purpose of this paper is to present a fiber-optic vibration sensor based on the monitoring of the mode distribution in a multimode optical fiber. Detection of vibrations and their parameters is possible through observation of the output speckle pattern from the multimode optical fiber. A working experimental model has been built in which all used components are widely available and cheap: a CCD camera (a simple web-cam), a multimode laser in visible range as a light source, a length of multimode optical fiber, and a computer for signal processing. Measurements have shown good agreement with the actual frequency of vibrations, and promising results were achieved with the amplitude measurements although they require some adaptation of the experimental model. Proposed sensor is cheap and lightweight and therefore presents an interesting alternative for monitoring large smart structures.*

Keywords

Optical sensors, vibration measurements, multimode fiber.

1. Introduction

In recent years, there has been growth of interest in optical fiber sensors as they offer many advantages compared to conventional electric ones. Most of the advantages of fiber sensors are the same as the advantages of optical communication technology: light weight and small size, inherent immunity to electromagnetic fields and high-voltages, long measuring distances (in kilometers), etc. In addition, fiber sensors are attractive solution due to the possibility to integrate a large number of sensors using multiplexing and interrogation techniques in the photonic domain.

In scope of this article we shall present vibration sensor that could be used in smart structures or, in other words, for bestowing self-sensing capabilities upon materials, or whole structures [1]. This capability could reduce maintenance costs that are often very significant. The proposed sensor could be used to measure natural frequency and degree of damping - parameters that may change as damage is inflicted upon materials, thus information about integrity of a structure may be obtained by studying these characteristics.

2. Theoretical Background

Multimode fiber, as a result of its large core diameter, has a relatively large number of modes that travel simultaneously through the fiber. Each mode travels with its own group velocity and propagation constant, but interferes with other modes as they share the same medium. There are around 500 modes in a typical multimode fiber [2].

The speckle pattern inside the fiber can be detected by projecting it from the fiber ending upon a screen. It consists of a large number of points with different intensities of light (Fig. 1).

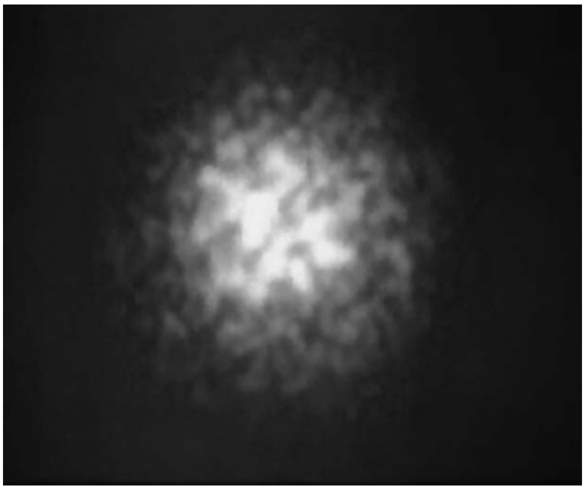

Fig. 1. Speckle pattern (distribution of light intensities).

This is a nice visual proof that light indeed travels in many modes throughout the fiber whose normalized frequency exceeds 2,405 [2]. Speckle pattern changes slowly in time, but its total summed intensity remains the same. That can be expressed by equation (1),

$$I_T = \sum_{i=1}^{N} I_i \tag{1}$$

where I_T is the total intensity, I_i is the intensity of each point (small area) in the speckle pattern and N is the number of points. In reality N is the number of photo detectors inside a CCD camera.

The light intensity inside the multimode fiber can be represented as [2], [3]:

$$I(r,\phi) = \frac{1}{2} Y \sum_{m=0}^{N`} \sum_{l=0}^{N`} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) \cdot \cos(n_n \phi) \cos(n_l \phi) \exp(-i(\Delta\beta_{ml} z - \Delta\phi_{ml})) \quad (2)$$

Here m and l represent the index of each propagating mode, A_m and A_l are the amplitudes of each mode, $\Delta\beta_{ml}$ and $\Delta\phi_{ml}$ are the difference between the propagation constants and the phase of two modes, u_m and u_l are equal to $u_m = \sqrt{\beta_0^2 n_1^2 - \beta_{z,m}^2}$, and Y is proportionality constant.

This expression can be rearranged as follows:

$$\begin{aligned} I(r,\phi) = \frac{1}{2} Y \sum_{m=0}^{N`} \Big[ & A_m^2 J_{n_m}^2 (u_m r) \cos^2(n_m \phi) \\ & + 2 \sum_{l=m+1}^{N`} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) \\ & \cdot \cos(n_m \phi) \cos(n_l \phi) \cos(\Delta\beta_{ml} z - \Delta\phi_{ml}) \Big] \end{aligned} \quad (3)$$

If the fiber is exposed to some force $F(t)$, the propagation constant of each mode changes in correlation with that force, and the difference $\Delta\beta_{ml}$ is proportional to the applied force

$$\delta(\Delta\beta_{ml} z) \propto F(t). \quad (4)$$

The corresponding change of intensity is equal

$$\begin{aligned} I(r,\phi) = \frac{1}{2} Y \sum_{m=0}^{N`} \Big\{ & A_m^2 J_{n_m}^2 (u_m r) \cos^2(n_m \phi) \\ & + 2 \sum_{l=m+1}^{N} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) \cos(n_m \phi) \\ & \cdot \cos(n_l \phi) \cos\left[\Delta\beta_{ml} z - \Delta\phi_{ml} + \gamma_{ml} F(t)\right] \Big\} \end{aligned} \quad (5)$$

where γ_{ml} is the constant of proportionality. The intensity (actually optical power) detected at one detector of the CCD camera can be calculated by integrating the intensity over the area a of the detector

$$I_i = \int_{a_i} I \cdot da_i \, . \quad (6)$$

In practice, the product γ_{ml} $F(t)$ is a small number. Consequently,

$$\begin{aligned} I_i = & \frac{1}{2} Y \sum_{m=0}^{N`} A_m^2 \int_{a_i} da_i J_{n_m}^2 (u_m r) \cos^2(n_m \phi) \\ & + Y \sum_{m=0}^{N`} \sum_{l=m+1}^{N`} \cos(\Delta\beta_{ml} - \Delta\phi_{ml}) A_m A_l \\ & \cdot \int_{a_i} da_i J_{n_m}(u_m r) J_{n_l}(u_l r) \cos(n_m \phi) \cos(n_l \phi) \\ & - F(t) Y \sum_{m=0}^{N`} \sum_{l=m+1}^{N`} \gamma_{ml} \sin(\Delta\beta_{ml} z - \Delta\phi_{ml}) A_m A_l \\ & \cdot \int_{a_i} da_i J_{n_m}(u_m r) J_{n_l}(u_l r) \cos(n_m \phi) \cos(n_l \phi) \end{aligned} \quad (7)$$

The equation (7) can be written as

$$I_i = A_i \left\{ 1 + B_i \left[\cos(\delta_i) - F(t) \theta_i \sin(\delta_i) \right] \right\} \quad (8)$$

where A_i is the result of mode self-interaction, and the next two terms represent the mode-mode interaction, the first one (B_i) accounting for the steady state, and the second one θ_i signify the modification of the mode-mode interaction if the system is perturbed. Signal output, in which the absolute value of changes in the intensity pattern is summed, is given by

$$\Delta I_T = \left[\sum_{i=1}^{N} \left| C_i \sin(\delta_i) \right| \right] \left| \frac{dF(t)}{dt} \right| . \quad (9)$$

By applying various forces upon the fiber we change the way modes propagate and therefore their interference conditions, which results in different field distribution at the fiber end. While calculating exact changes of propagation parameters for each mode resulting from applying the force is an extremely complex task, good results can be obtained merely by studying changes in speckle pattern at the fiber end.

From these changes we can, quite easily, not only detect vibrations, as has been demonstrated in [4], but we can also obtain information about the vibration parameters such as the amplitude and the frequency. Furthermore, a sensor system with these characteristics can be built using cheap and widely available components that are at the same time lightweight, which makes it an interesting product in the sensor market for integration in, already mentioned, smart structures.

3. Sensor Design

In Figs 2 and 3 we have the basic block scheme of the system used to record and analyze the changes in the distribution of light caused by the vibrations of the fiber.

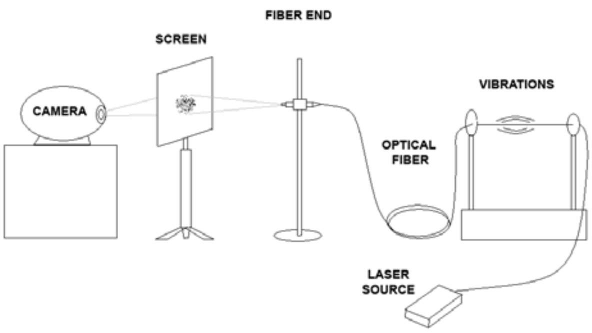

Fig. 2. Basic sensor system scheme for detecting vibrations.

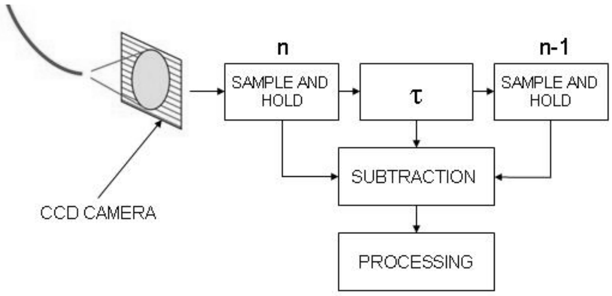

Fig. 3. Processing side of vibration sensor.

The signal coming from the light source (in our case a laser operating in visible spectrum) travels through the multi-mode fiber. Output signal from the fiber end is projected on the screen, and is recorded by a simple CCD camera.

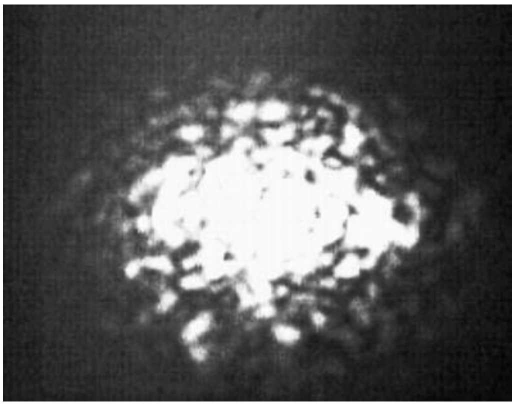

Fig. 4. A single frame extracted from the video signal, areas of higher light intensity are white.

Since the data is recorded in video signal mode, it is first broken down to frames (25 per second) and then analyzed as a set of consecutive frames that each represent a matrix of speckle pattern point intensities in time (see Figs. 4-6.). After data preparation, analysis takes place in Matlab where necessary functions are implemented. Different analysis steps include loading images in memory, calculating total intensities, differences between images, functions for calculation of spectral components from differences between images, and functions for extracting amplitude of vibrations.

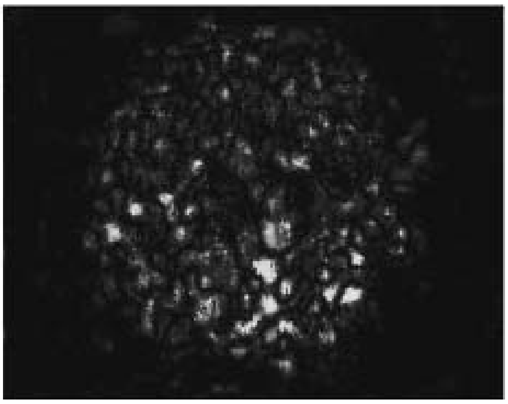

Fig. 5. A difference picture between two consecutive frames when the vibrations are present.

Fig. 6. A difference picture between two consecutive frames when the vibrations are not present

Multimode fiber is exposed to mechanical vibrations in one point. If multipoint vibrations are present some difficulties arise as we can analyze only image at the fiber end where influences from all vibration points interfere. Maximum detectable frequency is tied, via Nyquist criteria, by sample frequency of detector – in our case a web camera. As its sample frequency was around 25 frames per second, we could measure vibrations with frequencies up to approximately 12 Hz. By constructing custom CCD sensor greater frequencies can be detected. Higher sampling rate increases memory footprint requirements and complexity of calculations so some tradeoffs between processing requirements and maximum detectable frequency are present.

3.1 Measurements

The measurements were made using several different vibration sources. In the first couple of measurements it was not possible to obtain a vibration source that was controllable in the means of amplitude of the vibrations and their frequency at the same time, so different sources were used with the ability to control one of the parameters.

The first vibration source was a small electromotor with the help of which the system's ability to detect vibrations was tested. In Fig. 7 the period of vibrations (first half of the experiment) and the period when vibrations were not present are clearly visible. Since this ability was confirmed, the next step was detecting the parameters of vibrations. By lightly tapping on the optical fiber with a precise frequency (using a time signature device – a metronome) frequency controlled vibrations were produced. However, the amplitude of such vibrations was not controllable. The data analysis was performed using the Fourier transformation of the matrix representing the intensity difference between elements on the same location in consecutive images (see Eq. (9) and Fig. 9). Since the image sampling frequency was known, we were able to determine the frequency of light modulation produced by the vibrations. The results were very accurate for a number of different frequencies.

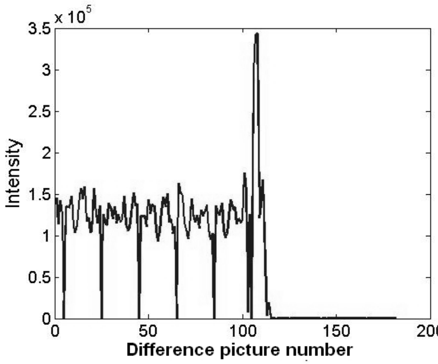

Fig. 7. Detecting the presence of vibrations (the vibrations were present in the first half of the graph).

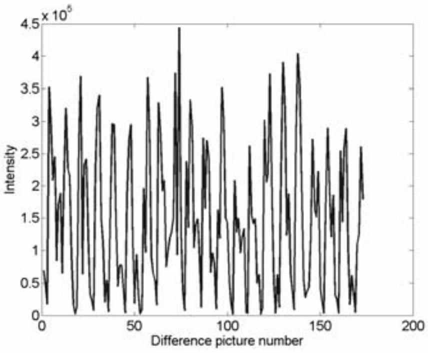

Fig. 8. Detecting the presence of 3 Hz vibrations.

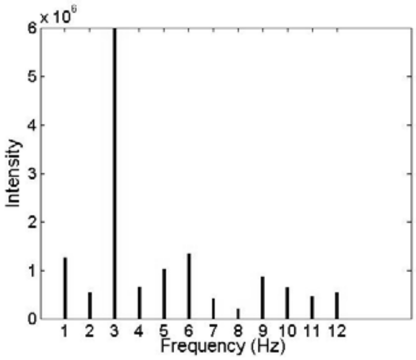

Fig. 9. Results of the Fourier analysis for the 3 Hz vibration excitation.

The next step was to try to control the amplitude and the frequency of the vibrations. The idea was to use a low frequency speaker, and a tone generator to create low frequency vibrations in the fiber by attaching it directly to the speaker membrane. Although it was expected to be able to control both frequency and amplitude in this manner, it turned out that the frequencies in question (12 Hz) were too low for the speaker to reproduce, and it's response to such an excitation from the tone generator was unknown. Still, the amplitude of vibrations was controlled by changing the excitation signal voltage. Finally, in cooperation with the Faculty of Civil Engineering, University of Zagreb, a vibration source with controllable frequency and amplitude was put to our disposal. The dynamic press machine, usually used for structural testing, was used to produce controlled vibrations of a known amplitude and frequency (see Fig. 10). Although the conditions in which the measurements were made were not ideal, and the system, being of an experimental nature, was not adapted for an out of laboratory use, some progress was made, and theoretical ability to measure (not just compare) amplitudes of vibrations was confirmed (Fig. 11). A linear approximation of the intensity difference to vibration amplitude was made (Fig. 12). Conditions in which measurements took place, and the number of points of measurements don't allow us to be completely satisfied with the result, but even from these preliminary testing it can be seen that spackle pattern changes in multimode fiber vary with vibration intensity changes.

Fig. 10. The dynamic press machine.

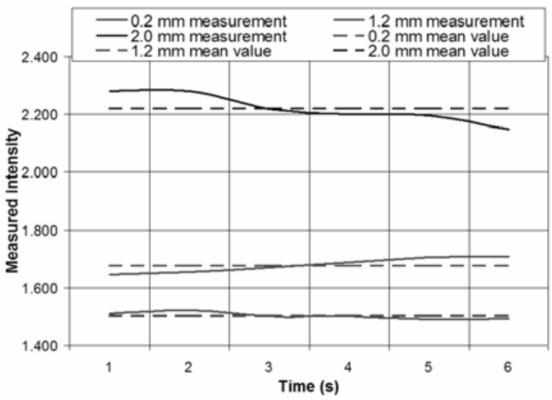

Fig. 11. Measured values for different amplitude vibrations.

If measurements were to be repeated with slight modification to the system much better results could be obtained. The biggest problem in outdoor testing proved to be the influence of the environment lightning that significantly raised noise in system. By constructing closed camera detecting system better results are to be expected.

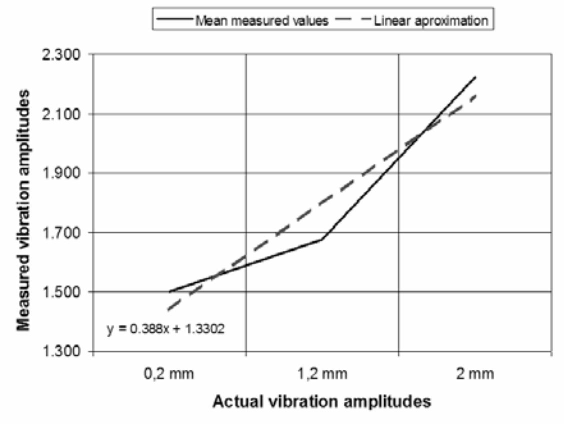

Fig. 12. Measured values in proportion to real values with a linear approximation trendline.

4. Conclusion

It has been demonstrated that it is possible to detect vibrations and measure their parameters using the sensor based on measuring the change in speckle pattern in multimode fiber. The frequency parameter has been successfully measured and compared to known values, while there has been some difficulty with the amplitude parameter of the vibrations. Those difficulties can be overcome by building a closed camera detecting system. With such model, measurements using the dynamic press machine as a vibration source should be repeated, and the final conclusion concerning amplitude detection could then be made. For now it is possible to claim that the system is capable of comparing different amplitude vibrations. The range and resolution of the system have not been determined, since the task was just to show the possibilities of such a system. These parameters should be determined in the future.

In contrast to other sensors, this cheap variant has some drawbacks. Mainly inability to locally isolate vibrations and to multiplex more sensor points connected to the same multimode fiber via techniques introduced in communication applications, namely WDM.

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