POF vibration sensor based on speckle pattern changes

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ABSTRACT

A method of sensing vibration using detection of changes in the spatial distribution of energy on the speckle pattern in the output multimode optical fiber is presented and demonstrated. The implementation of sensor consists of a small length of fiber which is isolated and sensitive to ambient vibration. The projection of the speckle pattern is directly recorded by a CCD camera at the outlet end of the fiber and processed changes in the intensity distribution. The sensor is simple, inexpensive and can be implemented to measure vibrations in engine, machines or buildings.

Keywords: multimode fiber sensing, vibration measurements, speckle pattern

1. INTRODUCTION

The speckle pattern is often used in optical sensors [1] and metrology where the granular structure of light is obtained through an optical roughened surface [2]. In these cases, the speckle pattern depends on the properties of coherence of the incident field and surface characteristics Speckle patterns can also be obtained using multimode optical fibers. Early works on the speckle pattern in multimode fibers were made by Takahara [3] and Crosignani [4], in which the effect of visibility, the spectral width of the employed source and the fiber length have been studied. As the speckle pattern in the output fiber is sensitive to any disturbances along the fiber, such as temperature, pressure or vibration, sensing of these measurands is potentially suitable with a proper processing stage of the speckle pattern. In 1989, Spillman et al. demonstrated a method using vibration sensing changes in the spatial distribution of energy at the exit end of a multimode fiber [5]. The authors implemented two experimental setups, the first speckle pattern is spatially filtered and second speckle pattern is projected onto CCD array, where intensity changes observed are related to vibration. Since then, some fiber sensor based on speckle pattern analysis for displacement measurements [6] or micro-cracks in concrete [7] have been proposed.

In this work a multimode fiber sensing system able to measure vibration of structures is proposed. The transducer consists of a multimode optical fiber piece with a tiny CCD camera located at its outlet to capture the speckle pattern. The images processing stage produces an average speckle intensity variation proportional to the transducer fiber vibration. In this paper the sensor concept, its experimental demonstration and the obtained results are presented and discussed.

2. THEORY

Multimode fibers can spread a large number of modes with different phase velocities. The propagation modes corresponding to different optical paths used by the beams coupled into the fiber suffer different phase delays. Output field distribution consists of a sum of all individual contributions of each mode. If the contributions phase delay varies over 2π radians, having a sufficiently coherent source, then interference effects are well structured and can be observed in the intensity distribution through the end of the fiber. The number of modes, M, which supports an optical fiber break index is given by the expression [8] $M=V^2/2$, where V is called normalized frequency given by, $V=(2\pi a/\lambda)(\, n_{co}^2 - n_{cl}^2)^{1/2}$, where a is the core radius, λ wavelength the laser and n_{co} and n_{cl} are the refractive indexes of core and shell, respectively. For a gradient index fiber, the number of modes is: $M\approx V^2/4$. For example, if all modes are excited in the multimode fiber step-index, $n_{co} = 1.492$ and $n_{cl} = 1.402$, and core radius $a=125$ and $490\mu m$, the number of modes that would be about 200,000 and 3 million modes, respectively, when a He-Ne laser ($\lambda = 0.6328\mu m$) is used. Due to the number of speckle dots present in a pattern is approximately equal to M, a speckle pattern adaptable to the needs of the measured variable can be obtained just by choosing a fiber with a suitable diameter and consequently by determining the size of the speckle dots.

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The theoretical development of speckle multimode fiber obtained has been treated in reference [5]. The total intensity of the speckle pattern measured at the output of an optical fiber is approximately constant and is the sum of the individual contributions of each speckle. When the fiber is subjected to a disturbance, the expression of the intensity [5] is:

$$I_i = A_i\{1 + B_i[\cos\delta_i - F(t)\phi_i \sin\delta_i]\} \tag{1}$$

where A_i is the result of mode self-interaction, B_i account for the steady state mode-mode interaction, $F(t)$ is the external disturbance, and ϕ_i is the phase. The intensity I_i was obtained by an integral over the ith speckle pattern. When the system is perturbed, the mode-mode interaction term is modified by ϕ_i. A_i, B_i, δ_i,, which are constant values for any given i. The speckle pattern can be seen as an interference matrix under the same disturbance [5] for each i. Thus, when the conditions of the fiber change due to temperature, pressure or displacement, the speckle pattern is also modified. So with an analysis of the obtained image and with its evolution, the disturbance which affects to the fiber and its characteristics can be obtained. Therefore, the implementation of this method to a vibration sensor may be possible by placing a short length of multimode fiber at the desired vibrating location.

3. EXPERIMENTS AND RESULTS

In Figure 1 shown the basic scheme of the system used to record and analyze the changes in the spatial distribution of energy on the speckle pattern caused by the fiber vibrations. A multimode Plastic Optical Fiber (POF) of 250 μm of core diameter is suspended inside a vertical closed tube of a length L. A plastic ring is attached to the lower edge of the fiber. Under the suspended fiber, it is placed a low cost USB camera to which the plastic ring is connected in order to center the speckle pattern into the CCD tiny camera. The end of the fiber is directly attached to the camera to reduce the CCD exposition time and get clearer images under moving conditions. The plastic ring also fixes the lower end of the fiber to the camera maintain the position of the speckle pattern over the camera. With the resulting setup, the suspended fiber is slightly tightened between the upper fixing point and the plastic ring. On the right of Figure 1 shows a photograph of speckle patterns at the output of multimode fibers POF with step index core diameters, (a) 980 μm, (b) 250 μm and gradient index (c) 50 μm.

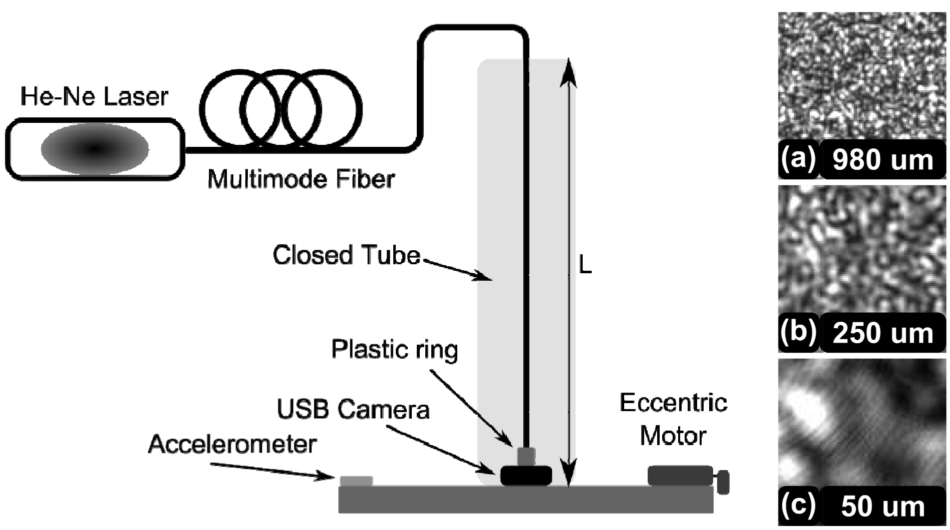

Figure 1. Experimental arrangement used to measure vibration induced optical phase modulation in an optical fiber (left) and speckle patterns of different POFs (right).

A He-Ne laser is attached to the free end of the fiber projecting a speckle pattern into the camera. The whole vertical tube is attached to a table to which is also fixed an eccentric DC motor to generate little and very controlled vibrations with frequencies between 1 and 10 Hz. In order to measure the generated vibrations a ±2G accelerometer (ADXL311) is glued to the table surface to monitor the main axis vibration axis. With the described setup (Fig. 1, left) some sweeps are made varying the DC voltage of the eccentric motor causing different accelerations. Due to the great amount of modes present on the chosen fiber, with a small section of the whole camera image is enough for its later processing stage. For this specific application a 100 by 100 pixels resolution is recorded at 30 frames per second.

For quantifying the vibration a simple differential processing scheme is proposed. For each frame, the difference between the actual and the previous one is computed. The results of a differential processed video sequence are shown on the Figure 2. In this sequence, a 14 steps sweep of different motor voltage is made maintaining the same voltage for 10 sec.

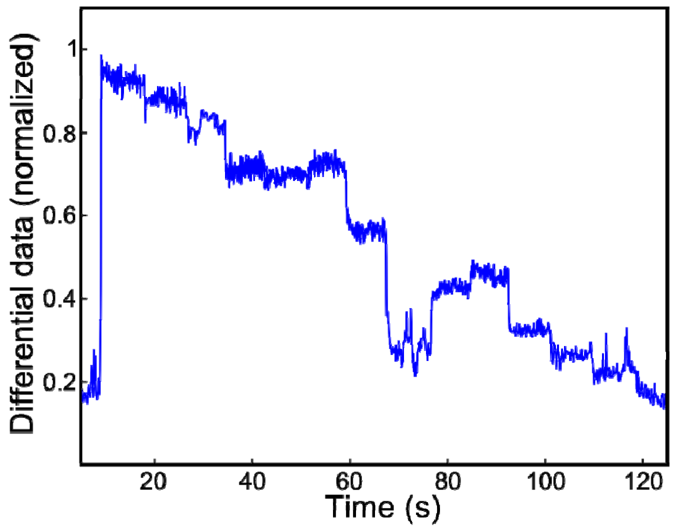

Figure 2. Differentially processed data of a 14 steps vibration sweep.

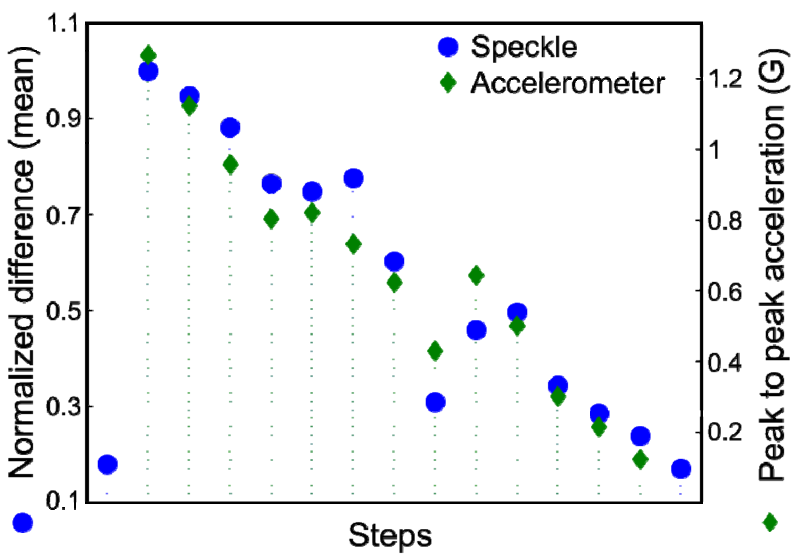

Figure 3. Averaged samples of each step of the vibration sweep.

Once the video is differentially processed, some of the obtained samples are averaged to reduce the noise. For this sequence the chosen averaging window is 100 samples taken in the center of each step. These averaged samples are compared against the acceleration measured over the main axis on the Figure 3.

The speckle vibration measures (circles) are compared to the measured peak to peak acceleration (diamonds).The first and final speckle processed points (circles) are measured under non vibration induced condition, so it is the less sensitivity achieved under the test conditions. The same trend is observed in both measurement sets being pretty linear against the motor control voltage (different steps). The observed dropped value for the t=70 seconds step is due to the resonance frequency of the motor fixing piece as it is shown by the two measures. Apart from the structure response, the accelerometer measurements have a very high noise component introducing an uncertainty around ±0.05G so, the presented results are just included for indicating the vibration trend.

4. CONCLUSION

A method of sensing vibration using changes in the spatial intensity distribution of speckle pattern obtained at the output of a multimode plastic optical fiber has been demonstrated. The developed prototype is relatively simple and cost-effective, consists of a short length of multimode POF ended by a tiny CCD camera. The average speckle intensity variation causes an electric signal proportional to the transducer fiber vibration. The results from a broad variety of experimental vibration experiments follow properly the expected simulations.

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