Intrusion Detection System based on Speckle Pattern change in Fiber Optic Sensors

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Abstract

The purpose of this paper is to present a fiber optic sensors intrusion system based on the monitoring of the mode distribution change (speckle pattern) in a multimode optical fiber. Detection of vibrations and their parameters is possible through observation the variation in the output speckle pattern from the multimode optical fiber. The implementation of sensor consists of a multimode fiber which is isolated and sensitive to vibration, a CCD camera beam profile, and a computer with specific algorithms for signal processing. The intrusion system is simple, inexpensive and can be implemented to measure vibrations and movement in the protection sites.

1. Introduction

In recent years, there has been growth of interest in fiber optic sensor technology as they offer many advantages, such as increased sensitivity compared to existing techniques and geometric versatility, which permits configuration into arbitrary shapes. Because fiber optic sensors are dielectric devices and small size, light weight, immunity to electromagnetic interference (EMI) large bandwidth, they can be used in high voltage, high temperature, or corrosive environments [1]. Fiber optic sensor technology growing in both interior and exterior security applications with possibility for both detection and location of the intrusion. Intrusion monitoring systems are designed to detect unauthorized intrusion into buildings, protected territories, perimeters, etc. A fiber optic intrusion monitoring systems can detect an attempt to cut, lift, crawl under, and climb over a fence or protected area [2].

In the sensing systems though, information about the measured is primarily conveyed by a change in intensity, frequency, phase, polarization or a measures the change in the speckle pattern [3]. We describe here a fiber optic perimeter intrusion monitoring system based on registration of the speckle pattern in the far-field of a multimode optical fiber. A speckle pattern is a random intensity pattern produced by the mutual interference of a set of wave fronts. The system employs an optical fiber that can be fence-mounted or deployed along the protected perimeter, buried under gravel, etc.

2. Theoretical Concept

A speckle pattern is a map of the energy pattern at the end of a multimode fiber. It appears as a number of almost randomly distributed areas of high energy with spaces in between [4]. When light is sent through the sensing cable, it appears at the end of the cable as a speckle pattern of light and dark patches. However, when pressure is applied to the cable, it changes the way light is distributed through the cable. This change redistributes the speckle patterns of light and dark patches. 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 [5]. The speckle pattern inside the fiber can be detected by projecting it from the fiber ending upon a screen. It consists of large number of small areas with different intensities of light. This is nice visual proof that light indeed travels in many modes throughout fiber if the normalized frequency exceeds 2,405 [6]. Speckle pattern changes slowly in time, but its total summed intensity remains the same. That can be expressed by the following equation:

$$I_T = \sum_{i=١}^{N} I_i \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (١)$$

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 [6]. When the fiber is subjected to a disturbance, the expression of the intensity is [7]:

$$I_i = A_i\{١ + B_i[\cos(\delta_i) - F(t)\emptyset_i \sin(\delta_i)]\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (٢)$$

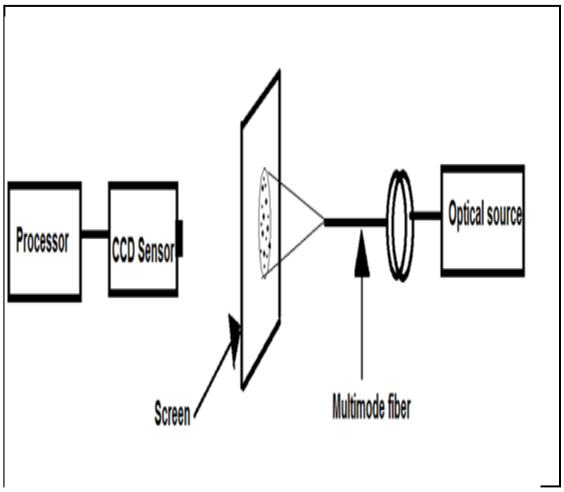
Where A_i is the result of mode self-interaction, (B_i) accounting for the steady state mode-mode interaction, $F(t)$ is the external disturbance, and $\emptyset_i$ is the phase. The intensity I_i was obtained by an integral over the ith speckle pattern. When the system is perturbed, the modification of the mode-mode interaction term is modified by $\emptyset_i, A_i, B_i, \delta_i$, which are constant values [7]. Signal output, in which the absolute value of changes in the intensity pattern is summed, is given by [8]:

$$\Delta I_T = \left[\sum_{i=١}^{N} |C_i \sin(\delta_i)|\right] \left|\frac{dF(t)}{dt}\right| \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (٣)$$

By applying various forces upon the fiber, the way how the modes propagate is changed and therefore their interference distribution is also changed which results in different field pattern at the fiber end [8].

3. Experimental work

The main experimental set-up is represented in (Fig.1). It consists of a multimode optical fiber sensor, a LED light source, a CCD beam profile detector, and a PC with a speckle image processing program. The probing light from a laser source is injected into the input end face of the fiber and at the output end face of the fiber the far-field distribution of the probing light intensity (the speckle pattern) is registered. When a physical perturbation hits the fiber, the speckle pattern varies. The CCD is used for registration of variations in the speckle pattern of the multimode fiber.



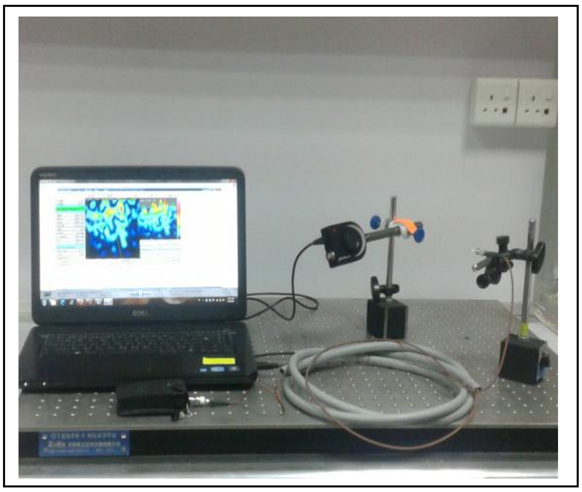


Fig.1: The set-up of system used to record and analyze speckle patterns.

The probing light source is a He-Ne laser (650 nm), A (3 m length) multimode optical fiber with a parabolic refractive index profile and a core diameter of 50 μm was used as a sensing element which terminated both ends with ST type connectors where the typical Insertion Loss for matched ST connectors was 0.25 dB . The speckle pattern was registered by using CCD beam profile detector from Genetic Electro-Optics [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, but we can also obtain information about the vibration parameters such as the fiber end 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.

4. Results and Discussion

Since the data is recorded in video signal mode, it is first broken down to frames (30 per second) and then analyzed as a set of consecutive frames that each represent a matrix of speckle pattern point intensities in time. After data preparation, analysis takes place in computerized algorithm using 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 (2, 3, 4 lift side) showed speckle pattern distribution in three dimensions changed with any vibration occur on the fiber. In the same time CCD camera can translated this distribution to intensity distribution in two dimensions as show in the fig (2, 3 and 4 right side). The change in intensity distribution is clear and can be dependent in security process.

Using multimode fiber of 650 nm of a study state (no event) fig.2, which can be considered as a result for other measurement of fine and hard events when the fiber exposed to any intruder.

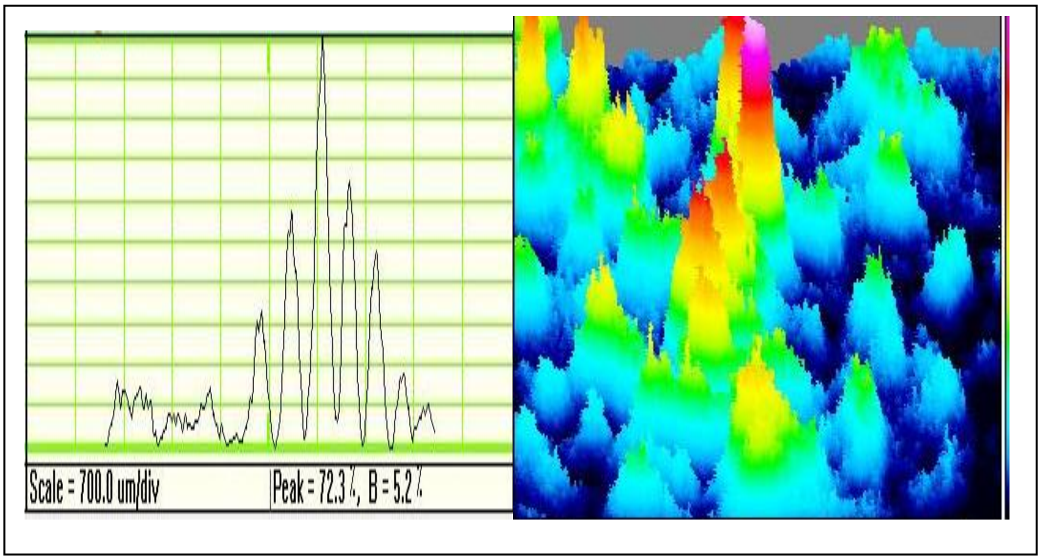


Fig.2: Speckle pattern alarm signal in the steady state using CCD beam profile detector.

Fig.3 showed that the multimode fiber of 650 nm when exposed to fun (slow intruder), intensity peak of each mode are different than intensity peak of study state. In this case we can determine the alarm from the degree of change in intensity for each mode, and this is done through compared the change speckle pattern with reference case (steady state).

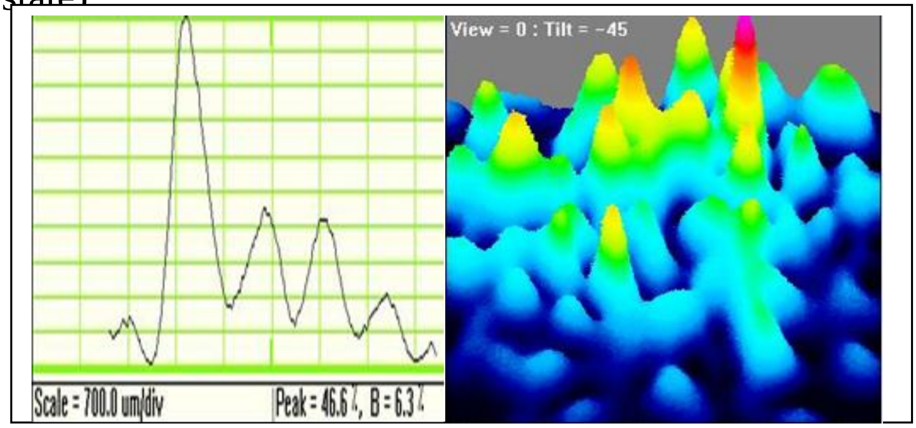


Fig.3: Speckle pattern alarm signal in the slow intrusion using CCD beam profile detector.

Fig.4 illuminates the multimode fiber for 650 nm in the hard vibration. As mentioned in the previous case we can identify the alarm from the degree of change in intensity for each mode, and as we shown from the fig (4) the change of intensity is stronger than the previous cases. From this result we can recognize between the real and the warning alarm.

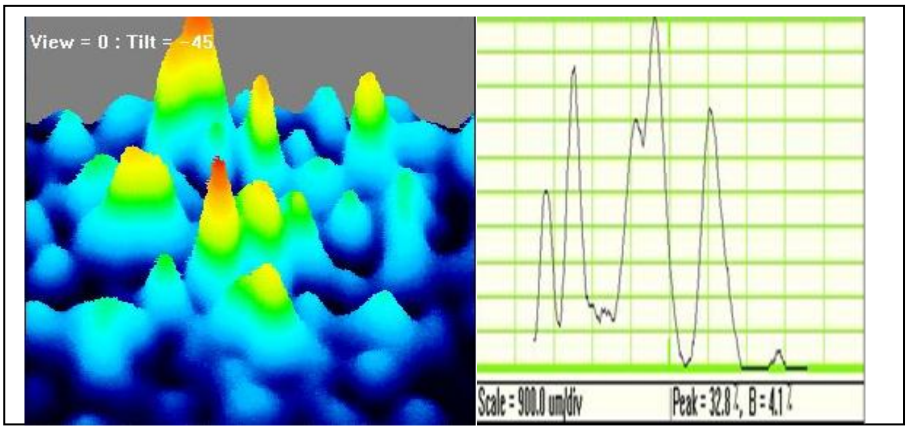


Fig.4: Speckle pattern alarm signal in the hard vibration using CCD beam profile detector.

5. Conclusion

It has been demonstrated that it is possible to detect & sensing vibration using changes in the spatial intensity distribution of speckle pattern obtained at the output of a multimode optical fiber. The developed prototype is relatively simple and cost- effective, comprises a multimode optical fiber connected to a coherent light source, a CCD detector, and a processor for generation of the output signal. The system is based on the principle of variation in the speckle pattern in the far field of a multimode optical fiber under the action of mechanical perturbation. The average speckle intensity variation causes an electric signal proportional to the transducer fiber vibration. By processing the speckle pattern, one can derive the amplitude of the output signal. Intrusion monitoring systems can be applied in surveillance of civilian and military objects, deposits of radioactive or chemical waste materials, etc. The results from a broad variety of experimental vibration experiments follow properly the expected simulations.

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نظام كشف التسلل باستخدام متحسسات الالياف البصرية المعتمدة على تقنية التغير في نمط البقعة

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الخلاصة

الغرض من هذا البحث هو تقديم نظام متحسسات الالياف البصرية للتسلل بالاعتماد على رصد تغير توزيع النمط (نمط البقعة) في الليف البصري ذي النمط المتعدد. الكشف عن الاهتزازات والمعلمات الخاصة بها ممكن من خلال مراقبة التغير في نمط البقع الخارجة من الليف البصري المتعدد النمط. جهاز التحسس يتألف من ليف متعدد النمط والذي يكون عازل وحساس للاهتزاز, كاميرا نوع CCD لشكل الحزمة, وكمبيوتر مع برمجيات خاصة لمعالجة الاشارة. النظام بسيط, غير مكلف, ويمكن تطبيقه لقياس الاهتزازات في المواقع المحمية.