Sensors and Actuators A 209 (2014) 154–160

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Frequency characteristics of hetero-core fiber optics sensor for mechanical vibration

Michiko Nishiyama[a,*], Kazuhiro Watanabe[b]

[a] Structures Research Group, Institute of Aeronautical Technology, Japan Aerospace Exploration Agency, 6-13-1 Ohsawa, Mitaka, Tokyo 181-0015, Japan
[b] Information Systems Science, Faculty of Engineering, Soka University, 1-236 Tangi, Hachioji, Tokyo 192-8577, Japan

ARTICLE INFO

Article history:
Received 22 July 2013
Received in revised form
19 December 2013
Accepted 5 January 2014
Available online 30 January 2014

Keywords:
Fiber optics sensor
Vibration sensor
Natural frequency
Hetero-core fiber

ABSTRACT

In this paper, we present characteristics of a hetero-core fiber optic sensor in mechanical vibration based on rigid supported beam property for vibration monitoring in fault diagnosis of the industrial equipments. A first configuration of the hetero-core fiber optic vibration sensor was rigidly supported at two fixed ends as curved setting without tension to the fiber. In order to tune the range of the detectable frequencies to be higher of the vibration sensor, a second configuration was evaluated, in which the hetero-core fiber optics was linearly-arranged with tension to the fiber. As a result, the both types of the proposed hetero-core fiber optic vibration sensors could pick up the free vibration from an impact force. Analytical natural frequencies were calculated based on an FEM fiber beam model. It was indicated that the natural frequencies from the experimental results of the 1st configuration were appropriate to the FEM results and a typical beam property, and could be tuned by the length between two fixed ends. Additionally, the 2nd configuration of the vibration sensor with tension to the fiber enabled its detectable frequencies to be dramatically higher than without tension.

1. Introduction

Vibration monitoring and analysis for early detection of failures in plant machineries and gas turbine engines have been proposed in various industrial fields [1,2]. In fact, each machine defect produces vibrations with distinctive characteristics. The diagnosis for identification of unfault and fault conditions has been implemented by comparing the actual device model with these mechanical vibration spectra [3]. The vibration monitoring for on-line monitoring and fault diagnosis requires capability of real-time frequency-domain analysis, to be permanently mounted to the machine for the continuous monitoring without burden on the machine. For these demands, the vibration analysis approaches have been proposed and developed for the machine fault diagnosis, which are the FFT analysis based on DSP for rotating machine monitoring [3] and multi-channel vibration analyzer based on a low cost FPGA for motor failures [4]. The target frequency for the machine fault diagnosis is with ranging from a few tens to a ten thousand Hz, and changes with characteristics of the machine [3].

Conventional vibration monitoring techniques have been widely used based on capacitive or piezoelectric accelerometers and displacement sensor [5,6]. The accelerometer usually has a seismic mass, which induces a force with a given acceleration. The other conventional sensor, such as a magneto-elastic resonator, has been proposed to detect extremely localized changes in the magnetic field from the vibrations [7,8]. However, the vibration sensors for the industrial applications are preferred to be unaffected from the electro-magnetic interference (EMI) noise.

On the other hands, a fiber optic sensor is superior to the conventional electric sensors for the vibration monitoring. This is because that it is not necessary to supply the power at the sensor itself, and they are resistant to corrosion and fatigue and immune to electromagnetic interference. Therefore, it is suitable for the fiber optic sensor to be permanently mounted to the machine for continuous monitoring. Additionally, the fiber optic sensors have the stable transmission line, which enables them to be used for remote sensing. A poly methyl methacrylate (PMMA) fiber [9] has been used for the vibration monitoring by means of the displacement sensing technique. However, it seems to be affected by pressure and bending to the transmission fiber line because of its multi-mode propagation characteristics. Additionally, the displacement characteristics of the PMMA fiber sensor has positive and negative slope, so a calibration process is needed in order to select the proper slope for the vibration detection. A Fabry–Perot interferometer (FPI) and in-line fiber etalon techniques for vibration sensing have been proposed [10,11]. These techniques have attractive features since it can easily be configured within a fiber-optic probe, however, FPI sensors are sensitive to measurement errors caused by external vibration, temperature fluctuation and acoustic waves.

* Corresponding author. Tel.: +81 50 3362 5858; fax: +81 422 40 1434.
E-mail addresses: nishiyama.michiko@jaxa.jp (M. Nishiyama), kazuhiro@soka.ac.jp (K. Watanabe).

0924-4247/$ – see front matter
http://dx.doi.org/10.1016/j.sna.2014.01.008

As an alternative to these technologies, we have been developing hetero-core fiber optic sensors, which have been used in displacement and pressure sensing [12,13], for deformation sensing [14]. The hetero-core optical fiber sensors aremade up of a stable single-mode (SM) fiber and can detect bending curvature change of a few tenth millimeter in optical loss change. It is also insensitive to temperature changes of the sensor portion because the length of the sensing region is as long as a few millimeters so as not to be affected from the silica thermal expansion.

In this paper, we present characteristics of a newly-developed hetero-core fiber mechanical vibration sensor for simple fault diagnosis of the machine. Picking up the target frequency behavior enables to monitor the machine status for identification the fault or unfault conditions. The proposed technique with high robustness under the harsh environment has possibility in achieving a simple and real-time fault diagnosis system.

Since the hetero-core fiber optic sensor sharply induces the optical loss change to curvature change of the fiber, the minute deformation due to the free vibration of the fiber fixed at the two ends can be detected by the hetero-core fiber optic sensor. The uniform cylindrical fiber plays a role as a beam due to its rigidity from a silica glass and acrylate coating.

A first configuration of the hetero-core fiber optic vibration sensor is proposed to be a curved setting so as to be without tension to the fiber. The natural frequency of the fiber is tunable with the length between two fixed ends. In order to expand the natural frequency range of the fiber, the linearly-arranged fiber with tension to the fiber is evaluated as a second configuration. It is reported that the tension to the fiber enabled the detectable frequency range to be dramatically higher compared to without tension, so that the hetero-core fiber optic vibration sensor can detect the mechanical vibration with ranging from a few thousand to a ten thousand Hz.

2. Natural vibration frequency of beam model

Since the cross section of the fiber has double structure of silica glass and acrylic coating with uniform material along the fiber axis, Young's modulus and the area moment of inertial can be considered to be constant along the fiber axis.

The differential equation of the vibrating beam of uniform cross section is [15]

$$\frac{\partial^4 \eta}{\partial t^4} + \frac{EI}{\rho A} \times \frac{\partial^4 \eta}{\partial_{X^4}} = 0 \quad (1)$$

where, η is the vertical distance from the neutral line, which is a horizontal line across the cross section through its center of gravity, E is the Young's modulus, I is the area moment of inertial, ρ is the mass of the beam per unit length, A is the area of the cross section. Assuming a sustained free vibration at a frequency ω, we have

$$\eta(x, t) = \phi(x)\exp(i\omega t) \quad (2)$$

using the coefficient μ, the differential equation leads the natural frequency, ω, which is

$$\omega = \sqrt{\frac{EI}{\rho A}}\mu^2$$

For each fixed end of the beam, there are two conditions, which are

$$\eta = 0, \frac{\partial \eta}{\partial x} = 0 \rightrightarrows \phi(0) = 0, \phi(L) = 0, \frac{\partial \phi(0)}{\partial x} = 0, \frac{\partial \phi(L)}{\partial x} = 0 \quad (3)$$

where, L is the length between the two fixed ends.

Under the condition of rigidly supporting ends, the coefficient μ is inversely proportional to the beam length, L. Therefore, the natural frequency is inverse to the square of the beam length, $1/L^2$

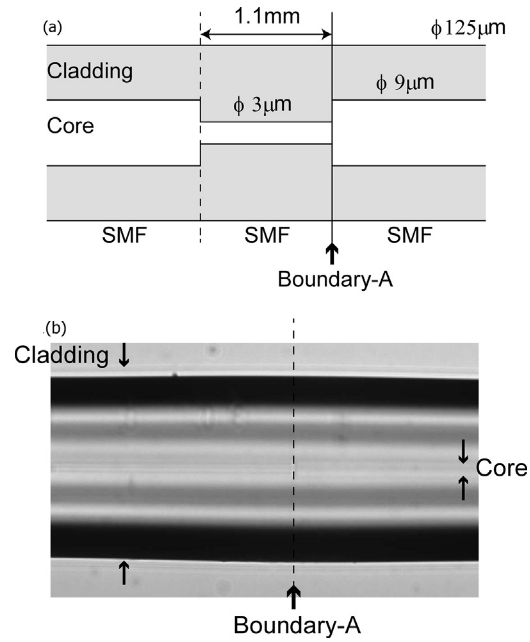

Fig. 1. Structure of a hetero-core fiber optic sensor, whose cores of a transmission line and an inserted hetero-core portion are 9 and 3 μm in diameter, respectively: (a) a diagram and (b) a photo of cross section along the optical axis.

3. System configuration

3.1. Mechanical vibration measurement using hetero-core fiber optic sensor

The hetero-core fiber optic sensor consists of a SM transmission fiber and an inserted fiber portion in a smaller core diameter than the transmission fiber, as shown in Fig. 1(a). The name of hetero-core means the difference between the core diameters of transmission fiber and inserted fiber segment. The fiber segment with the small core is inserted into the transmission fiber by cleaving and fusion splicing. Fig. 1(b) shows a photo of a hetero-core splicing boundary-A, which is indicated in Fig. 1(a). As shown in Fig. 1(b), the hetero-core spliced boundary is uncracked, as a result, seems to keep the retention of strength. A transmitted light partially leaks into the cladding region at the boundary of the inserted fiber segment which is a sensor portion. The core diameters of the transmission line and the inserted fiber segment were employed to be 9 and 3 μm, respectively. Fig. 2 shows characteristics of hetero-core fiber optic bending sensors with the core diameters of 9 and 3 μm, and 9 and 5 μm in the optical loss change. As shown in Fig. 2, the optical loss monotonically increases with the bending action of the sensor portion. A length of the inserted fiber is 1.1 mm.Our previous work [16] also showed that the hetero-core fiber sensor with the core diameters of 9 and 3 μm had higher sensitivity to the curvature change than the core diameter combination of 9 and 5 μm. Additionally, focusing on the small curvature less than 0.03, the sensor with the hetero-core diameter of 3 μm is sufficiently sensitive to curvature change. Therefore, the hetero-core fiber optic sensor with the core-diameter of 9 and 3 μm has possibility to detect minute deformation of the fiber by the mechanical vibration.

Fig. 3 shows that configurations of the hetero-core fiber optic mechanical vibration sensor with the two fixed ends. In the first configuration shown in Fig. 3(a), the hetero-core fiber optics was arc-like arranged, in order that the fiber could keep tensionless along the fiber axis. The hetero-core sensor portion was located at the center between the two fixed ends. A free supporting point was put at the center between the two fixed ends on the base, which