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Fiber vibration sensor multiplexing techniques for quasi-distributed sensing

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ABSTRACT

A multiplexing technique for fiber vibration sensors is experimentally investigated using Khazani Syed (KS) code in SAC/OCDMA with direct decoding. The system is proposed to implement vibration sensor multiplexing which can eliminate the Multiple Access Interference (MAI) at low cost and complexity. The results show the proposed system having better SNR, less complex, and low cost when compared with complementary decoding, and higher power level when compared with simplified WDM. A frequency range of 0 to 400 Hz measured shows its suitability for quasi-distributed sensing in bridges, pipelines, transformers, and industrial machine that exhibit low vibrations within this range.

1. Introduction

In the recent years, controversies have surrounded the reliability of the conventional piezo-electric accelerometer used in vibration sensing. This becomes noticeable especially in areas where electromagnetic interference effects becomes unavoidable such as in electrical transformer [1]. Researchers have tapped into the suitability of fiber optic sensors as a replacement due to its capability to eliminate electromagnetic interference effects, chemically inactive, and ability to resist corrosion which are deterrent in several applications of the conventional sensors [2–5]. One other benefit is the ease of multiplexing which makes them suitable for distributed sensing. Unfortunately, quite large numbers of work that have ventured into distributed sensing have only focused on static strain measurement [3] without the timely dynamic counterpart which is suitable in bridges monitoring, pipelines, and crack and vibration detection in steel and concrete structures.

Generally, fiber vibration sensors have been classified into wavelength base, interferometry based and intensity based sensors [4,6], putting into consideration, the parameter that undergo changes when subjected to vibration. Interferometry and wavelength based sensors have history of long usage due to their high sensitivity, accuracy and high resolution but their fragile nature [5] which require frequent replacement therefore, infringes on human labor and the cost of replacement especially in area of higher vibration are somewhat to be considered. Intensity based vibration sensors operates by modulating the intensity of the light passing through them when subjected to vibration. These sensors have existed as contact and non-contact sensors [7]. The non-contact sensors provide ease of vibration sensing without physical contact by interrogating the changes in the intensity of the returning light from measurand using plastic optical fiber. However, this may not be suitable for remote sensing over a long distance due to high dispersion in the plastic fiber and may be difficult to multiplex for distributed sensing due to low SNR in the returning light. Sensing system employing Single Mode Fiber (SMF) has provided comfort of transmitting signal over a very long distance for remote sensing due to their ability to confine the light to the fundamental mode with low dispersion. Other factors that are recently being addressed in sensing are miniaturization and cost efficacy.

Researchers have drawn attention into multiplexing techniques so as to curb the cost of electro-optic, reduce the physical size and effectively utilize the large bandwidth opportunity in fiber optics especially for remote sensing. Time Division Multiplex (TDM) [8–11], Wavelength Division Multiplex [12] and Optical Code Division Multiplex (OCDM) [13–15] have been proposed. Although TDM can support larger network when compared with WDM, it lacks flexibility due to requirement of fixed path length between the multiplexed sensors [16]. Another limitation is the low Signal to Noise Ratio (SNR) due to low reflecting materials being always adopted as well as untimely information which make it not effective for vibration sensing that requires real time information [17]. WDM basically provides simplicity in sensor

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multiplexing but has direct dependency on the spectral bandwidth of the light and in most of the cases required multi-wavelength light source which tends to be costly. Intensity based WDM (IWDM) multiplexing was proposed in [18] in which its multiplexing capacity could double a WDM system due to two extra low reflective grating device used. This is only suitable for distributed strain sensing along a single fiber and could suffer from low SNR and multiple reflections. OCDMA on the other hand has a unique code assigned to individual sensor on the network and provide asynchronous mode of communication while using correlation method to interrogate each sensor at a specific time. However, the issue of multiple access interference (MAI) has limited its applications.

Recently, WDM/SAC [19] was proposed to multiplex fiber vibration sensors aiming to curb the problem of MAI in OCDMA. This however used M-sequence code which has high cross correlation and therefore rely only on balance decoding technique to extract the transmitted signal from the adjacent signals. This tends to add to the cost and complexity [20] of the system considering the added complimentary filters and the attenuators especially, as the sensors grow in number. Therefore, this work proposed intensity based fiber vibration sensor multiplexing using Khazani Syed (KS) code [21] in Spectral Amplitude Coding–OCDMA (SAC–OCDMA) with a direct decoding technique for quasi-distributed sensing.

Section 1 of this paper contains the introductory part while Section 2 describes the architecture of the KS-code used. The system setup is explained vividly in Section 3 meanwhile, Section 4 describes the results and discussions. The concluding part is contained in Section 5.

2. KS code architecture

The KS code used in this system has been compared earlier with some other codes like MQC [22], OOC, and Hardamad and show better performance over them [21,23]. It is a unified code based on modified double weight (MDW) and has in-phase correlation of one. The code is derived mathematically as follows [21]

$$C_\alpha = \cup_{i=}^{w/2} \cup_{j=i}^{w/2} C(i, \alpha(i,j) : \alpha(i,j)+2) = [1\ 1\ 0]\} \tag{1}$$

$$C_\beta = \cup_{i=}^{w/2} \cup_{j=i}^{i} C(i+1, \beta(i,j) : \beta(i,j)+2) = [0\ 1\ 1]\} \tag{2}$$

The two subcodes C_α and C_β are then combined in the form of $C_\alpha \cup C_\beta$.

The number of sequences K_B and the sequence length N_B are as follows[21,24]

$$K_B = \frac{w}{2} + 1 \tag{3}$$

$$N_B = 3 \sum_{i=1}^{w/2} i \tag{4}$$

where w is the code weight.

Another unique property of the code is the existent of two chips beside each other [20,21,25]. This enables two chips to be filtered by a single FBG of double bandwidth and in the process, reduce the number of filter that will be required. The ease of increasing the number of users by simply increasing the number of mapping (m) without corresponding change in the in-phase correlation also makes the code preferential for our proposed work.

For a system with weight 4, the number of sensor point is calculated thus

$$K_{max}(m) = m * \left\{ \frac{w}{2} + 1 \right\} \tag{5}$$

while the length of the code sequence increases to

$$N_{kmax}(\mathrm{m}) = 3 * m * \sum_{i=1}^{w/2} i \tag{6}$$

where $m=2$ is the number of mapping, the sequence of code generated will be

$$m1 = \begin{cases} C1 & 1\,1\,0\,1\,1\,0\,0\,0\,0 & 0\,0\,0\,0\,0\,0\,0\,0\,0 \\ C2 & 0\,1\,1\,0\,0\,0\,1\,1\,0 & 0\,0\,0\,0\,0\,0\,0\,0\,0 \\ C3 & 0\,0\,0\,0\,1\,1\,0\,1\,1 & 0\,0\,0\,0\,0\,0\,0\,0\,0 \end{cases}$$

$$m2 = \begin{cases} C4 & 0\,0\,0\,0\,0\,0\,0\,0\,0 & 1\,1\,0\,1\,1\,0\,0\,0\,0 \\ C5 & 0\,0\,0\,0\,0\,0\,0\,0\,0 & 0\,1\,1\,0\,0\,0\,1\,1\,0 \\ C6 & 0\,0\,0\,0\,0\,0\,0\,0\,0 & 0\,0\,0\,0\,1\,1\,0\,1\,1 \end{cases}$$

3. Principle of operation and system setup

Fig. 1(a) and (b) shows the proposed system setup for two sensor points. The light from the Agilent Amplified Spontaneous Emission (ASE) source is split into two with each arm launched into each encoder. An encoder comprises a circulator, an array of FBG which reflect a range of wavelength from the launched light. In order to encode the signal launched to sensor point A, with inscription A(1 1 0) denoting λ_1, λ_2 and λ_3, FBGs of center wavelength 1552.0 nm and 1552.4 nm with 0.4 nm bandwidth are used while 1552.4 nm and 1552.8 nm are used on sensor B with B(0 1 1) as denoted in Table 1. The presence of a FBG with the corresponding wavelength is denoted by chip "1" while "0" shows that the supposed FBG is absent.

The reflected spectrum from the array of the FBG collected through the circulator is then guided to the sensors where it is modulated. The sensor head is fabricated by using two collimators [19], coupled and aligned in such a way that the light from one collimator is launched into the other one. Collimators produce a parallel image of the light launched into them at infinity and thereby make it possible to couple the light from one collimator to another with minimal loss. The sensors are then installed on vibrating boxes built with a D.C motor concealed inside them and driven by variable D.C voltage in order to generate varying vibration. The collimators are aligned on their axis by fixing one collimator with permanent gum while another is fixed with a flexible gum for ease of resonating and modulating the intensity of the light passing through them. The output lights from the two sensor points are then coupled using a 2×2 star coupler.

At the receiving end, the coupled light is further split into two for the two decoders (Fig. 2). As a result of direct decoding technique employed, each decoder only filters the chip that is not overlapping with other chips in the code sequence [20]. In order to decode the signal from sensor A, an FBG of center wavelength 1552.0 nm corresponding to λ_1 is used while 1552.8 nm which is λ_3 is used to decode signal from sensor B. The decoded signals which contain the modulated spectrum are detected using Positive-Intrinsic-Negative (PIN) photo-detectors. The output spectrums are obtained on the 2-channel digital oscilloscope in sinusoidal time domain waveforms which are eventually converted to the corresponding frequency response using Fast Fourier Transform (FFT).

A D.C voltage range between 0 and 30 V is applied at 3 V intervals to the D.C motors installed inside the boxes. In order to prevent the movement of the boxes so that the vibration signal will solely be determined by the vibration generated in the box, the two boxes are fastened onto the optical table as shown in the figure. As a result of this, the minimum D.C voltage that could trigger the sensors is 12 V. Thus, all the applied voltage below 12 V are considered as 0 V. As the applied voltage is varied, there is