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Dynamic Distributed Fiber Optic Strain Sensing on Movement Detection

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Abstract—A real-time dynamic Brillouin optical time domain reflectometry (BOTDR)-based system is introduced by using small gain stimulated Brillouin scattering with fast data managing and saving method. The system achieves 2-cm read-out interval, 2-m spatial resolution, and about 7- $\mu\epsilon$ accuracy with about 7 Hz or even faster with 23 Hz continuous monitoring. A movement response on a polymer mat made pavement was successfully monitored by the proposed system. For example, the pace distance at each walking step was detected to be 0.62 m. In addition, the minimum strain difference measured after several human loads is about 10 $\mu\epsilon$ with 7- $\mu\epsilon$ uncertainty and 3- $\mu\epsilon$ repeatability, indicating the possibility of real-time strain monitoring and the movement or trajectory detection by distributed fiber optic strain sensing.

Index Terms—Fiber optics sensors, Brillouin backscattering, time-frequency analysis, dynamic strain sensing, structural health monitoring, real-time monitoring.

I. INTRODUCTION

STRUCTURAL health monitoring (SHM) has attracted significant interest in the past few decades [1], [2]. SHM relies on the quality and the amount of data for better interpretation [3]. Compared to point sensors such as strain gauges that are commonly used in the measurement of infrastructure, distributed fiber optic sensors have the capability of providing distributed sensing data for strain, temperature, and acoustic monitoring, etc. [4], [5]. Particularly, dynamic distributed fiber optic sensing can be applicable to seismic activity detection, perimeter security, traffic and bridge monitoring [6], [7]. Furthermore, dynamic real-time distributed fiber optic sensing data can be used for disaster early warning system of landslides [8], [9]. Another application of the dynamic real-time distributed fiber optic sensing is to detect the people movement which is important for social science to understand human behavior in an infrastructure such as station [3].

Among the distributed fiber optic sensor technologies, the Rayleigh scattering based dynamic fiber optic sensors (phase-sensitive optical time domain reflectometry (Phase-OTDR) [10]–[13] and optical frequency domain reflectometry (OFDR) [12], [14]) are most studied for acoustic

sensing with small strain variation limited to about 2 $\mu\epsilon$ with the frequency in several kHz [10]. However, to achieve dynamic distributed strain sensing, there are several issues in Phase-OTDR or OFDR such as (i) the large trade-off between sensing distance and spatial resolution, (ii) low data density, and (iii) only relative vibration strain (not absolute strain magnitude) can be detected.

In the requirement of structural health monitoring in civil engineering, it is required to have long distance, small spatial resolution, high-density data and actual strain monitoring with dynamic capability. Although Brillouin scattering based optical time domain reflectometry (BOTDR) can be the one to fulfill these requirement as it can detect the distribute strain in long distance, conventional BOTDR cannot take measurements with fast speed [15]. One of the reasons is because conventional BOTDR systems use a frequency scanning method to obtain the Brillouin scattering frequency shift. The frequency scanning method moves the filter to detect the power in each frequency by searching the peak power frequency in the Brillouin scattering spectrum. This operation makes the measurement progress very slow. Another reason is the poor signal noise ratio (SNR) of the Brillouin scattering signal. The poor SNR limits the dynamic performance of BOTDR, and it is affected by the following two factors: (i) the low power of the Brillouin scattering signal and (ii) the large systematic noise which is generated from the optical and electronic circuit design. By carefully designing the components schematic and calculating the used bandwidth, the noise can be reduced but cannot be eliminated. Increasing the number of averages becomes an effective way and is commonly used in the conventional BOTDR system [16]. However, increasing the number of averages reduces the measurement speed as a trade-off and common conventional BOTDR system takes about 5–10 mins. Therefore, it is often used just for static strain measurement.

Compared to the conventional frequency scanning BOTDR working as a spectrum analyzer, a direct sampling method which uses discrete Fourier transform (DFT) to obtain the Brillouin scattering frequency shift profile has been proposed and studied. This leads to much faster measurement speed because of the no need for slow frequency scanning ([17], [18]). In 2016, Luo *et al.* [19] developed STFT based BOTDR and in 2017 Yu *et al.* [20] demonstrated the quadratic time-frequency analytical methods for high accuracy and higher spatial resolution. In the same year, using the same STFT-BOTDR set up, Li *et al.* [21] showed that the Brillouin scattering signal power can be increased by using small gain stimulated Brillouin scattering so that dynamic

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strain monitoring can be achieved. However, at that time, the measurement speed was 60 Hz with 4m spatial resolution and 100 micro-strain. In addition, the measurement time could only last for 100ms, due to the limitation of processing a large amount of data. This measurement time is not enough for the measurement of infrastructure such as bridges. Furthermore, the dynamic performance was not clearly identified.

In this study, the dynamic performance of the new STFT based BOTDR system is verified through the experiment of movement detection. A real-time dynamic monitoring with 2cm read-out, 2m spatial resolution, and about 7 or 14 $\mu\epsilon$ accuracy is proposed by reducing pulse width in the small gain stimulated Brillouin scattering and decreasing the data transmitted that are used for average to achieve 7 Hz or 23 Hz measurement.

II. BACKGROUND/THEORY

Changes in strain or temperature of optic fiber will cause a linear shift of Brillouin scattering frequency (BFS), as shown in equation 1 [5]. By detecting the BFS at each location on the optic fiber, the strain and temperature can be determined.

$$\Delta \text{BFS} = C_\epsilon \Delta \epsilon + C_\alpha \Delta T + C_T \Delta T \quad (1)$$

where ΔBFS is the change of in Brillouin scattering frequency, C_ϵ is the coefficient of strain change, $\Delta \epsilon$ is the change of strain on the optic fiber, α is the thermal induced strain coefficient, ΔT is the change of temperature near optic fiber and C_T is the coefficient of temperature change.

III. SMALL GAIN STIMULATED BRILLOUIN SCATTERING

The limitation of BOTDR technology depends on its poor SNR due to the weak Brillouin scattering signal. To solve the issue on signal power, small gain stimulated Brillouin scattering is used in this work with the sacrifice of measuring distance to less than 1km [21]. Increasing the light power $P_p(f)$ that is launched into the fiber can achieve small gain stimulated Brillouin scattering to increase the scattered signal $H(z, v)$ described by Equation 2 [22].

$$H(z, v) = \int_{-\infty}^{+\infty} P_p(f) \frac{g_b(z) \left(\frac{\Delta v_b}{2} \right)^2}{[v - (f - S_B(z))]^2 + \frac{\Delta v_b^2}{2}} df \quad (2)$$

where $H(z, v)$ is the received Brillouin scattering spectrum, $g_b(z)$ is the Brillouin gain coefficient at position z , Δv_b is the linewidth or full width at half maximum (FWHM) of Brillouin gain, v is the frequency of light, f is the low band frequency of light pulse spectrum, S_B is the Brillouin frequency shift (around 11GHz).

As the SNR increases, the frequency resolution or the measurement accuracy σ becomes higher according to Equation 3 [16]. Therefore, less average can be used to achieve a certain level of the measurement accuracy compared to the system with smaller input light power.

$$\sigma \approx \frac{\Delta v_b \times \delta^{0.05}}{8.5 \times \text{SNR}^{0.25}} \quad (3)$$

where δ is the frequency step resolution, which is determined by the number of data points and the sampling rate in the

DFT system, and Δv_b is the frequency sweeping step in the frequency sweeping system.

IV. FAST DATA SAVING AND PROCESSING METHOD

Because the sampling frequency determines the read-out interval of the measurement as shown by Equation 4, the sampling frequency should be chosen as high as possible for higher data density measurement. In our analyzer, the sampling frequency is 5Gsp/s. However, this large data sampling frequency reduces the data transmitting speed, which in turn limits the performance.

$$\text{Readout interval} = \frac{c}{2nF_s} \quad (4)$$

where c is the light speed in the vacuum, n is the refractive index of the fiber, and F_s is the sampling frequency.

In the previous 60Hz measurement reported in [21], 100 sampling average was used for SNR improvement. This number of averages is not enough for accurate measurement because the accuracy of the strain measurement was about 100 $\mu\epsilon$ with 4m spatial resolution ([21]). In addition, the data was collected continuously with 5Gsp/s and only 100ms data could be continuously measured. The reason for such short measurement time was because it took many times to transfer the data from the digitizer board to the memory and hard disk that were used to store the data. USB 3.0 connection was used for the data transmission with the upper limit speed at 300MB/s. This data transmission speed was not enough for long-term vibration monitoring even with 100 $\mu\epsilon$ with 4m spatial resolution. This is insufficient for accurate monitoring in most of structural health monitoring, because in most of the cases, the strain changes are in hundreds of micro-strains [21].

In this study, to overcome the limitation of data transmission speed, data was designed to be collected segmentally. Instead of collecting the continuous data and saving all the data in the memory and hard disk, the data was cut into different pieces. Each piece indicates one reading of a certain number of samples from the digitizer. The data management includes two parts: data acquisition/transmission in the digitizer card and data processing in the processing board or PC.

In each dynamic measurement, the measurement consists of multiple readings. The digitizer is controlled by MATLAB software and is set to 5Gsp/s which provides 0.2cm sampling interval (read-out interval) in distance. Determined by the fiber length L , N samples ($N = L/0.2\text{cm}$) are digitized. After K times of the N samples reading are digitized, each $K \times N$ samples data is averaged in time series and an averaged N samples data can be obtained. The data is then allocated as an $N \times M$ matrix with M averaged N samples data. The matrix is transmitted to a processing board or PC. During the data transmission, the sampling progress is stopped and waited until the next trigger is made from PC to restart the sampling progress.

The details of the work flow presented in Fig. 1 are given below:

1. Take samples in the time domain according to the fiber length under test. The number of samples N is equal to $\frac{cL}{2nF_s}$, where c is the light speed in a vacuum,

Fig. 1. The algorithm of the data digitizing method flow chart.

L is the fiber length, n is the refractive index, and F_s is the sampling frequency. Repeat taking the time domain signal. Each of them has N samples data. Store K readings of N samples data in the memory of the digitizer.

2. Take the average of the K readings to obtain N samples averaged data.
3. Repeat step 1 and 2 M times to have an $N \times M$ data matrix.
4. Send and save the $N \times M$ matrix to PC using USB 3.0 connection.
5. Trigger the digitizer to repeat from step 1 for another reading.
6. On the PC, transform each of the N samples in the $N \times M$ matrix to the time-frequency domain by STFT.
7. Average the M time-frequency domain result to one time-frequency domain readings for the Brillouin scattering frequency shift peak detection and use this as one dynamic reading per measurement.

Compared to the conventional data transmission that has $P \times N \times K \times M$ data, the new approach transmits $N \times M$ data each time and transfer P times. Therefore, the time consumption is smaller than the conventional method. The total number of readings is limited in the original method because the size of the memory disk in the digitizer is usually small.

Because one reading has an $N \times M$ matrix and the data is sent in each $N \times M$ matrix, the data size that needs to be transmitted each time is smaller, compared to transmitting all the readings after a continuous sampling in the previous paper [21]. Hence, the data transmission speed is faster and can be used in real dynamic long-term monitoring.

V. EXPERIMENT

To verify the effectiveness of the proposed fast data saving and processing method, measurements of movement detection using the dynamic fiber optic strain sensing system were conducted. The temperature was assumed to be not changed during the experiment, so that only one tight-buffered single mode optic fiber with diameter of 0.9 mm (Nanzee Ltd.) was

Fig. 2. The experimental set up of the movement experiment. (a) The setup of the Yoga mat. The white cable is connected in the center of the mat. In the walking experiment, the adult walked along the arrow direction (b) the prototype of the Dynamic-BOTDR box. (c) The schematic of the Dynamic-BOTDR block diagram.

attached to a 10 mm thick PVC mat, as shown in Fig. 2 (a). When an adult walked or stepped on the mat, the change in strain was dynamically detected via the fiber optic sensor. Five pieces of PVC mats were connected and fixed as a flat surface by a pink rubberized fabric. The optic fiber was attached on top of the mat by a transparent rubberized fabric. The length of the mat was 9 m in total. A total length of the cable was 34.7 m (a 9m fiber section attached on the mat, 10m fiber between the analyzer and the mat, and another 15.7 m fiber after the mat section). The fiber was connected to the STFT based BOTDR system which provided dynamic Brillouin scattering based optical time domain reflectometry with 2cm read-out and 2m spatial resolution (see Fig. 2 (b)). The average number was set to 5000 or 1000 times for a high strain resolution so that the measurement speed was 7 or 23 Hz.

The system architecture of the dynamic BOTDR is shown in Fig. 2 (c). A 1550 nm narrow-linewidth laser is followed by a 90/10 coupler which splits the light into two branches. One continuous-wave light is modulated by an electro-optic modulator (EOM), which is driven by a pulse generator to produce a 20ns pulse width, 2MHz repetition rate pulse light signal. The pulse light signal is then amplified by an erbium-doped fiber amplifier (EDFA) and launched into the fiber during the measurement which is glued on top of the flat mat. The peak pulse power that goes into the fiber under test is about 3.12W for the small gain stimulated Brillouin scattering [21]. The Brillouin scattering from the fiber is guided by the circulator and 50/50 coupled with the other branch from a polarization scrambler, which provides random polarization of continuous-wave light coming from the other branch of the laser light. The mixed Brillouin scattering signal and random polarization continuous light are then interfered and detected by a photodetector. The Brillouin scattering signal's frequency

Fig. 3. (a) The adult stood on and off to provide load periodically. (b) The load is on for 3s and off for 3s as one period.

Fig. 4. (a) The Brillouin scattering spectrum in one of the readings. (b) The Brillouin scattering frequency shift profile when one adult stood on the mat and nobody stood on it.

is amplified and down-converted to intermediate-frequency for a 5Gbps digitizer to capture. The data acquisition board is controlled by a MATLAB software. The collected data is transmitted to a laptop in real time for data processing.

A. Standing Experiment

In the first experiment, a person stood at the center section of the mat. The weight was about 70 kg, whereas the foot size was about $550 \times 125 \text{ mm}^2$. Readings were made using the dynamic readings of the analyzer when he stood on the mat. One reading for this experiment took 2ms (500 Hz equivalent).

B. Walking Experiment

In the second experiment, a person walked on the mat from the beginning to the end as shown in Fig. 2(a). The movement was from point 1 to the joint between mat 4 and 5 and the total distance of movement was about 5 m in 11s. The analyzer took 72 readings during this 11s duration (about 7 Hz).

C. Standing On-Off Experiment

In the third experiment, a person stood on the mat after the reading started. He stood at the center section of the mat shown in Fig. 3(a) for about 3 s and left the mat for about 3 s as shown in Fig. 3 (b). He then came back to the mat as one cycle. This periodical operation lasted about 34 s and the analyzer took 216 reading for this experiment (about 7 Hz).

VI. RESULT

Fig. 4 (a) shows one of the Brillouin scattering spectrum distribution results for the first standing experiment. The

Fig. 5. (a) The strain change while the person is walking at the six location on the mat. (b) The change of normalized Brillouin peak frequency shift at 6 locations with time.

shifted frequency is due to pre-tensioning of the optic fiber when it was glued on the mat. The result in Fig. 4 (b) shows the strain change profiles before and after the person was on the mat. The feet length (two feet in a line) is about 550 mm and the length of the measured strain due to the feet standing on the mat is about 2m width, which is equal to the spatial resolution. The read-out interval is every 20 mm so that there are 100 points within the 2m spatial resolution section. The peak strain generated by standing on the mat was about $400 \mu\epsilon$.

In the second walking experiment, three different measurement speeds were trialed. The strain vs time with 7 Hz measurement at 6 different locations on the mat is shown in Fig. 5. By taking the beginning (i.e. when a person was standing on the mat) as baseline, the change of strain while the person was walking on the mat is shown in Fig. 5 (a). Because the initial strain varied at different locations after the optical fiber was attached on the mat, the measurement Brillouin scattering frequency shift values were normalized by dividing the maximum frequency shift measured in the experiment, shown in Fig. 5 (b). The point from 1 to 6 is the point at Mat 1 to Mat 6 as shown in Fig. 2(a). Initially, the person

Fig. 6. (a) The strain changes at different locations on the mat while the person is walking from the beginning to the end. (b) The result of the time-distance plot of the normalized Brillouin peak frequency.

stood at point 1 and then moved to point 2 and finally stopped at point 6. After he left point 1, the strain at point 1 decreased as the mat recovered to the original flat position. During the movement from point 1 to point 2, the strain at point 2 increased as the optic fiber at point 2 suffered a larger tensile strain because the shape change section on the mat is closer to point 2. While the person kept moving further, the same repetitively happened at point 3, 4, 5 and 6.

At each point in Fig. 5 (b), there are two peaks close to each other. By measuring the time difference and calculate the movement speed of the person, the distance of the two peaks is about 0.62 m. The two peaks are the result of the pace distance between the two feet while the person was moving forward. In addition, due to the viscoelastic behavior of PVC, the strain recovery of the PVC mat was slow compared to the rate of strain generation during step loading.

Fig. 6 (a) shows the strain change due to the walking person in a distance vs time plot. The strain at $t = 0$ s is about $300 \mu\epsilon$ and then the strain profile shift along the walking as time passes. The arrows show the change of the walking speed at different locations on the mat. Because the initial strain level is different, contour of the normalized strain change is shown in a distance vs time plot in Fig. 6 (b). Larger strain in tension

Fig. 7. (a) The result of the respond of the strain change with the cycle load. (b) The strain changes due to the cycle load of the steps in the distance vs time plot.

reflects yellow color. At the beginning ($t = 0$ s), the person stood at location 13 m and caused a large strain at that location. After he started to move, the yellow points moved to the right. At the beginning between 0 to 4 s, he moved slowly with big step distance from 13 m to about 13.8m. The walking speed is about 0.2m/s. He then walked faster and took 3s walking from 13.8 m to 16 m with speed about 0.73m/s. Then he slowed down again and took 4s walking from 16 to 18 m with speed of about 0.5m/s. Because the person moved slower with small steps, the deformation of the mat became larger and also it took longer time for the mat to restore. Therefore, at the later stage of moving, the strained section became wider comparing to the strained section at the beginning.

Results show that the 23Hz sampling rate measurement gave $14 \mu\epsilon$ accuracy and $5.7 \mu\epsilon$ precision, while the 7 Hz sampling rate measurement gave $7 \mu\epsilon$ accuracy and $3 \mu\epsilon$ precision. This was demonstrated by taking the standard deviation of the slack section of the optic fiber where no strain was applied during the experiment.

In the third cyclic stand on-off experiment, the load was applied for 3 s and then removed for 3 s. This was continued for 6 times. In this experiment, 216 readings are taking in 34s by using 5000 average (i.e. 7Hz). At the slack section of the optic fiber where no strain change is applied, the precision or the repeatability was approximately obtained as $3.12 \mu\epsilon$. Meanwhile, by taking the standard deviation of the strain readings at the 10m slack section where the strain is ideally the same across the whole section, the accuracy of the

measurement at this section was $7 \mu\epsilon$. Fig. 7 (a) shows the strain development due to the loading cycles. At the beginning, the strain increased to $240 \mu\epsilon$ while the person stood on the fiber and decreased to $120 \mu\epsilon$ while he left the mat. Because of viscoelastic nature of the mat, the strain did not go back to zero before the second step was applied. The second step caused about $80 \mu\epsilon$ tension strain change and relaxed about $55 \mu\epsilon$ strain change. The following steps caused smaller tension change and smaller tension strain was released in the following unloading cycle. In general, the change of the strain was detected successfully under 7Hz sampling speed and change of strain was smoothly detected. After 6 steps, the analyzer successfully detected less than $10 \mu\epsilon$ change of strain at the finally cycle. Fig. 7 (b) shows the spatial variation of strain changes due to the loading which provided the cycle load. The history of footprint (two feet within one 1 m distance) can be observed based on 6 loading cycles.

VII. CONCLUSION

In this study, the effectiveness of the proposed fast data saving and processing method of the dynamic-BOTDR was investigated. It successfully monitored the dynamic movement of the external forces applied on the mat. The strain-distance variation with time allows monitoring of the moving object. The proposed system was able to detect the feet distance between steps to be 0.62 m with a detectable change in strain of less than $10 \mu\epsilon$. When the sampling speed is about 7Hz, the accuracy is about $7 \mu\epsilon$ and the repeatability precision is about $3 \mu\epsilon$. The spatial resolution is about 2 m. By taking the advantage of the 20 mm readout resolution, the system was able to provide high-density data for trajectory tracking.

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