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Adaptive Pulse Period Method for Low-Frequency Vibration Sensing With Intensity-Based Phase-Sensitive OTDR Systems

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ABSTRACT The use of intensity-based phase-sensitive optical time-domain reflectometry (φ-OTDR) system to measure low-frequency vibration is the aim of this paper. It is well-known that the laser frequency drift (LFD) and other system noise act as internal vibration that challenge φ-OTDR system to capture external low-frequency vibration. We proposed theoretically and demonstrated experimentally that by adapting the probe pulse repetition rate/pulse period to the frequency of vibration to be measured, consistent intensity change should be always realized in the disturbance region compared to the induced phase-noise change from pulse to pulse. In particular, two different pulse periods were used to demonstrate the effectiveness of the adaptive pulse period method (APP) for detection of low-frequency vibration. Experimentally, the sensing of external vibrations of 5; 1; 0.5 and 0.1 Hz frequencies with intensity-based φ-OTDR system was achieved with good signal-to-noise ratio. Moreover, an approach suitable for measuring low-frequency vibration induced by a PZT through direct acquisition of the Rayleigh intensity in the disturbance region was established. Various driving voltages applied to the PZT confirmed the consistency of the method.

INDEX TERMS Fiber optic sensors, phase-sensitive optical time-domain reflectometry (φ-OTDR), coherent effects, pulse modulation, vibration measurement.

I. INTRODUCTION

The phase-sensitive optical time domain reflectometry (φ-OTDR) technique was firstly testified to use as distributed acoustic sensor (DAS) by Juarez *et al.* [1]. The primitive advantages of the φ-OTDR system such as simple configuration, fully-distributed, high sensitivity, fast response, good spatial resolution early attracted scholar and industrial research interest and the progress in its performance metrics has been demonstrably enhanced [2]–[6]. The φ-OTDR sensor system interprets the Rayleigh back-scattered signal detected in response to highly coherent pulsed light with narrow linewidth injected into a fiber under test (FUT) for the purposes of locating intrusions [1], [7]. The interference of Rayleigh back-scattered signal within a pulse-width detected by a photo-detector (PD) generates a speckle-like trace [8]. Different noise sources in φ-OTDR system including the stochastic nature of Rayleigh back-scattering, laser phase-noise, laser frequency drift (LFD), finite extinction-ratio of the optical modulator, thermal noise in

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electrical and optical components, the polarization dependence of the optical components, influence the stability of the output signal from trace-to-trace and engender measurement errors [7], [9]–[14]. The main drawback of the observed trace-to-trace fluctuations is that they challenge the use of φ-OTDR system to measure low-frequency vibration since they act as a vibration and cannot be distinguished from the external intrusion. Logically, the φ-OTDR system extensively used in structural health monitoring [15], pipeline monitoring [16], cannot find application in the areas where there is need of detection of low-frequency vibration such as galloping monitoring of power transmission line, suspension bridge [17], earthquake wave monitoring [18]. Several research works have demonstrated the impact of the phenomenon on the performance of φ-OTDR sensor system [12], [19]. Additionally, some approaches have been proposed to mitigate these effects. A commonly-used approach to remove the phase-noise fluctuations in φ-OTDR system is to extract the measurement results obtained in the disturbance zone from that in the non-disturbed zone [20], [21]. As well, a double phase difference before and after the vibration location has been proposed to remove the influence of LFD in φ-OTDR system and achieve a phase extraction of 0.1 Hz frequency vibration with high sensitivity [22]. Dissimilarly, most of the proposed approaches in intensity-based φ-OTDR system include the introduction of a hardware component e.g., the use of a laser source with improved characteristics [10], the polarization beam splitters to realize polarization diversity [11], [19], an SOA with high extinction ratio to suppress the coherent intra-noise [23], [24], the tunable wavelength laser source to realize wavelength scanning [24]. These approaches contribute to increase the cost of the φ-OTDR sensor system while reducing the degree of freedom of the system. The method proposed in [22], [25] successfully achieved the phase measurement of 0.1 Hz external vibration assuming the disturbance location was known in advance. Also, the proposed wavelength diversity technique was impractical because more than 90% of the time was used for data-transmission. Likewise, the intensity-based φ-OTDR systems are more convenient for intrusion location because the false alarm rate can be easily eliminated using the moving averaging method [2]. To date, the norm in φ-OTDR system is that the LFD determines the minimum detectable frequency of the intrusion.

This paper suggests an intensity-based φ-OTDR system that maintains its simple configuration and capable of measurement of low-frequency vibration. Through numerical simulations, we realized that the intrusion induced intensity change in the case of low-frequency vibration grows with time and frequency. This observation constitutes the basis for the adaptive pulse period (APP) method for detection of low-frequency vibration with intensity-based φ-OTDR system. Besides, we demonstrated an approach suitable for measurement of low-frequency vibration through direct acquisition of the Rayleigh intensity in the disturbance zone. We established that when a low-frequency sinusoidal external vibration is induced by a PZT, the Rayleigh intensity output from the φ-OTDR system is a summation of sinusoidal signals with amplitude given by Bessel function of $2n^{\text{th}}$ order with frequencies of $2n$ times (n is an integer) the frequency of the external vibration. Experimental results were consistent with the theoretical analysis in both direct and coherent detection schemes.

II. INFLUENCE OF LASER FREQUENCY DRIFT ON THE PERFORMANCE OF Φ-OTDR SYSTEM AND DERIVATION OF THE PRINCIPLE OF ADAPTIVE PULSE PERIOD METHOD

A. INFLUENCE OF LASER FREQUENCY DRIFT ON THE PERFORMANCE OF φ-OTDR SYSTEM

The basis of the working principle in φ-OTDR system is the Rayleigh back-scattering phenomenon in single mode-fibers that can be quite well illustrated with one-dimensional impulse response [8]. The φ-OTDR sensor system gates into the FUT highly coherent pulse light and receives continuously from the PD the interference signal of Rayleigh back-scattered light within a pulse-width along the FUT. Assuming negligible the fiber loss, the time evolution of the optical intensity signal can be expressed as [26]:

$$I(t) = \left[\sum_{i=1}^{M} a_i.\cos(\omega_0.t + \varphi_i)\right]^2 = \sum_{i=1}^{M} a_i^2 + 2\sum_{i=1}^{M-1}\sum_{j=i+1}^{M} a_i a_j.\cos(\varphi_{ij}), \tag{1}$$

where $I(t)$ is the normalized form of the received optical intensity, a_i and φ_i represent respectively the amplitude and phase of the i^{th} scattering center, ω_0 symbolizes the nominal frequency of the laser output and M denotes the total number of scattering centers within a pulse-width.

A local phase change caused by any external intrusion directly impacts on the received optical intensity signal. A routine approach used in intensity-based φ-OTDR system to detect the intrusion location is the intensity differential method:

$$\Delta I = I_s(\Delta f).\left\{\cos\left(\varphi_{ij} + \Delta\theta\right) - \cos\left(\varphi_{ij}\right)\right\}, \tag{2}$$

with ΔI, the subtraction of the intensity detected in the disturbance zone from that of non-disturbed region of the FUT, $I_s(\Delta f) = \sum_{i=1}^{M-1}\sum_{j=i+1}^{M} a_i a_j$, which is dependent on the LFD Δf. $\Delta\theta$ corresponds to the phase change induced by the intrusion. In relation (2), it should be observed that there is a challenge between the external vibration $\Delta\theta$ and the system noise induced phase fluctuation φ_{ij} which are the two variables. A critical condition for the φ-OTDR system to be practical is the laser to have low LFD, which is the dominant noise source [10].

To gain insight into the effects of LFD on the performance of φ-OTDR system, we performed some numerical simulations considering the relation (2) in the condition of non-existence of external intrusion and assuming the only change observable in the OTDR trace is due to the LFD. In those conditions, the relation (2) becomes:

$$\Delta I_{LFD}=I_s\left(\Delta f\right).\left\{\begin{array}{l}\cos\left[2\pi.\Delta f.t_{ij}+2\pi\left({}^{c}/_{\lambda_0}\right).t_{ij}\right]-\\ \cos\left[2\pi\left({}^{c}/_{\lambda_0}\right).t_{ij}\right]\end{array}\right\}, \tag{3}$$

with $\varphi_{ij} = 2\pi(c/\lambda_0).\ t_{ij}$. The parameters for the numerical simulations are listed in TABLE 1 above:

TABLE 1. List of parameters used in the numerical simulations.

Parameters	Symbol	Value
Light Wavelength	λ_0	1550 nm
Celerity of light	c	3.10^8 m.s^{-1}
Pulse- width	τ	100 ns
Pulse period	T	50 µs
LFD	Δf_1; Δf_2; Δf_3	10; 1000; 50000 MHz/min
Rayleigh amplitude	$\Delta I_s(\Delta f)$	Random number ∈ (0 1)
External vibrations	f_{vib}	∈ (0.1; 0.5; 1; 1000 Hz)
Sensing time	t	$n.T$; (n is an integer ≥1)
Length of FUT	L	1km

The evolution of LFD induced trace-to-trace intensity fluctuations plotted in Figure 1 showed that the extent of the signal fluctuations in the absence of external intrusion became severer with the increase of LFD. Therefore, we realized the critical condition of low LFD for the practicability of the φ-OTDR system. The LFD limitation is inherent to any φ-OTDR system because the actual technology cannot provide laser with null output frequency drift.

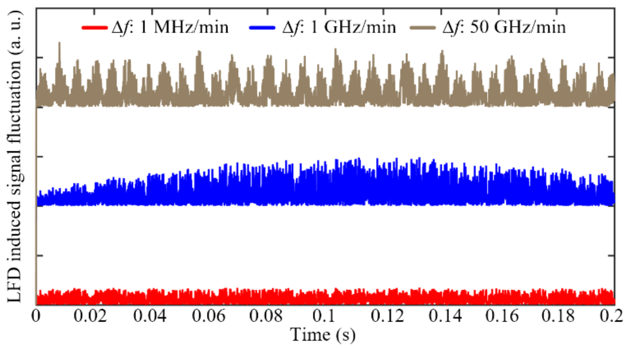

FIGURE 1. Influence of LFD on vibration measurement using φ-OTDR system.

B. PRINCIPLE OF THE ADAPTIVE PULSE PERIOD METHOD FOR DETECTION OF LOW-FREQUENCY VIBRATION

Generally, in φ-OTDR system when setting the pulse period of the optical modulator, only the length of the FUT is considered such that:

$$T \geq \frac{2L}{v_g}, \tag{4}$$

where T and L denote respectively for the pulse period and length of FUT and v_g represents the group velocity. The pulse period determines the maximum detectable vibration frequency in φ-OTDR system whereas the LFD sets the limits for the minimum measurable vibration frequency. In these conditions, there is a trade-off between the sensing distance and the frequency response bandwidth. To explore wide measurement response bandwidth, the pulse period is usually set in the vicinity of its minimum tolerable value in such a way to avoid pulse overlapping in φ-OTDR i.e. $T_{\min} = 2L/v_g$. However, at fast measurement speed, low-frequency vibration cannot induce important phase/intensity change from pulse to pulse compared to LFD induced change so that by using the ordinary intensity differential method, the sensing operation would fail. To see how the setting of the pulse period should influence on the detection of low-frequency vibration in the conditions of low LFD, we used the relation (2) to determine the change of the trace-to-trace fluctuation induced by the LFD compared to that induced by the intrusion, which we noted as δI. This value represents the Rayleigh intensity change measured in practical situations. The corresponding relation indicated in (5) provided the basis of the numerical simulations:

$$\begin{cases}\Delta I_{vib} = \Delta I_s\left(\Delta f\right).\{\cos\left[2\pi.\Delta f.t_{ij}\right.\\ \qquad\left.+2\pi\left({}^{c}/_{\lambda_0}\right)+\sin\left(2\pi.f_{vib}.t\right)\right]\\ \qquad-\cos\left[2\pi.\Delta f.t_{ij}+2\pi\left({}^{c}/_{\lambda_0}\right)\right]\}\\ \delta I = \Delta I_{vib}-\Delta I_{LFD},\end{cases} \tag{5}$$

where f_{vib} represents the frequency of external vibration with amplitude A equal to 1 and ΔI_{vib} is the intensity change caused by the simultaneous action of the LFD and external vibration. The frequency of the external vibration was changed four times to hold the values 1000; 1; 0.5 and 1 Hz. The time is following the variation $t = n.T$ (n is an integer ≥ 1, $T = 50\ \mu$s which implies that the pulse repetition rate is 20 kHz). The evolution of the change of LFD induced intensity fluctuation in comparison with that induced by the intrusion δI was recorded and plotted in Figure 2.

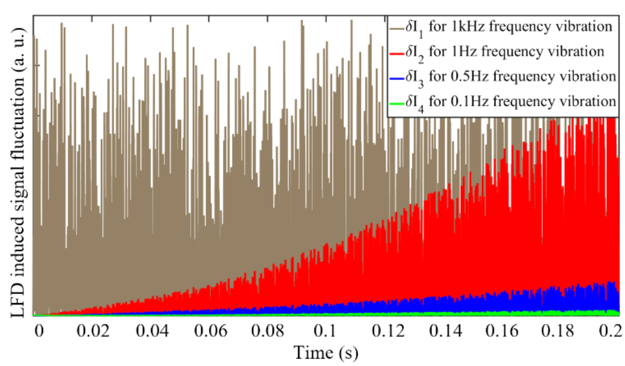

FIGURE 2. Illustration of adaptive pulse period method for detection of low-frequency vibrations.

The simulation results analysis presented below intimated that:

(1) the intensity fluctuation in the conditions of low LFD with a 1000 Hz vibration frequency together is always

high enough to allow the intrusion detection. Also, it is observable that in the case of high external vibration frequency, the Rayleigh intensity has a nonlinear relationship with time. This nonlinear response of φ-OTDR causes obstacle to using the system for detection of the amplitude of external vibration unless processing further signal demodulation [27]–[31],

(2) the additional fluctuation caused by the intrusion was nearly imperceptible for low-frequency vibrations with shorter pulse period. This is the reason for the success of using the φ-OTDR system to sense the higher frequency vibration signal and the failure of detection of low frequency vibration,

(3) in the case of low frequency vibration, the additional intensity change caused by the external vibration varies proportionately with time and frequency of the external vibration.

Then, we concluded that by setting the optical modulator with longer pulse period, the intrusion induced trace-to-trace fluctuations would increase significantly and allow for the detection of low-frequency vibration.

C. LOW-FREQUENCY VIBRATION MEASUREMENT

Another focal point of this paper is the measurement of low-frequency vibration. For this purpose, we developed a method similar to the approach proposed by Ren M. and co-workers to quantify a 500 Hz frequency vibration [32]. Their proposed approach (6), as shown at the bottom of the next page, used the Bessel function analysis to interpret the intensity signal of the φ-OTDR system in the conditions of external sinusoidal vibrations, with $\varphi_0 = 2\pi.\Delta f.t_{ij}+\varphi_{ij}$. With this method, they achieved that the output intensity signal includes sinusoidal components with frequencies multiple of that of the external sinusoidal vibration with amplitude proportional to $J_n(A)$ (J_n is the n^{th} order Bessel function). The vibration measurement was procured through monitoring the amplitude of the fundamental of the FFT spectrum. In the particular cases of low-frequency vibration $\cos(x-x_0)$ and $\cos(x+x_0)$ terms could be approximated and the relation (6) for low-frequency vibration (7) could be simplified is shown at the bottom of the next page.

Consequently, we realized that the Rayleigh intensity output from the φ-OTDR system in the particular case of low-frequency vibration is a composition of sinusoidal signals with amplitude given by the $2n^{\text{th}}$ order Bessel function $J_{2\text{n}}(A)$ and frequencies of $2n$ times the frequency of the external vibration (n being an integer).

III. EXPERIMENTAL RESULTS AND ANALYSIS

Our experimental procedure included two steps, (1): the measurement of LFD; (2): location and measurement of low-frequency vibration in both coherent and direct-detection φ-OTDR.

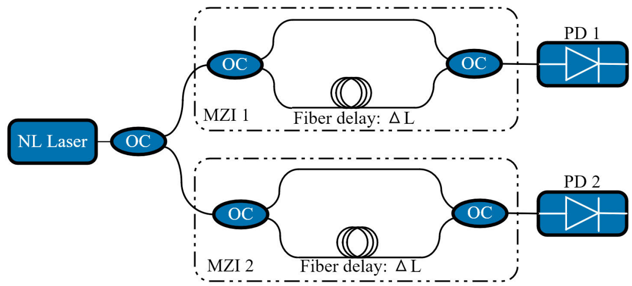

FIGURE 3. Experimental setup for the LFD measurement. Optical coupler (OC); photo-detector (PD).

A. MEASUREMENT OF LASER FREQUENCY DRIFT

To measure the LFD, a pair of unbalanced Mach-Zehnder interferometer with a fiber delay $\Delta L = 500$ m was used to produce corresponding phase signal that is recorded through the temporal fringes in the interferometer and showed in the intensity signal captured by the PDs (see Figure 3). The laser source is that of narrow linewidth used further in φ-OTDR system to demonstrate the efficiency of APP method for low-frequency vibration sensing. Both MZIs were insulated from thermal and environmental disturbance. The intensity signal detected by the PDs is of pseudo-periodic sinusoidal waveform whose period is related to the LFD [33]. Relation (8) gives the mathematical expression for the LFD measurement.

$$\alpha = \frac{c}{n.\Delta L.\tau_f}, \tag{8}$$

where α is the LFD rate; τ_f represents the pseudo-period of the intensity signal output from the PDs; c and n count respectively for the celerity of light in free-space and refractive index of the fiber core. The LFD measured here was the superimposition of the frequency drift induced by laser and the MZI which is characteristic of our experimental conditions. Even though the use of one MZI interferometer should be sufficient to perform the LFD measurement, we used two MZIs to allow us to contrast the phase change of the different fringes and minimize measurement errors. The relatively constant phase of the different fringes proved that the frequency drift measurements were effectively induced by the laser source.

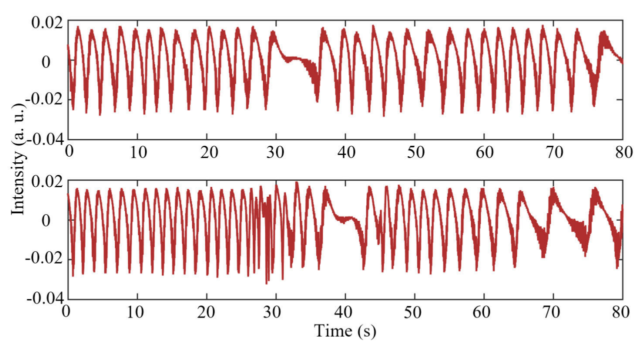

FIGURE 4. LFD measurement results.

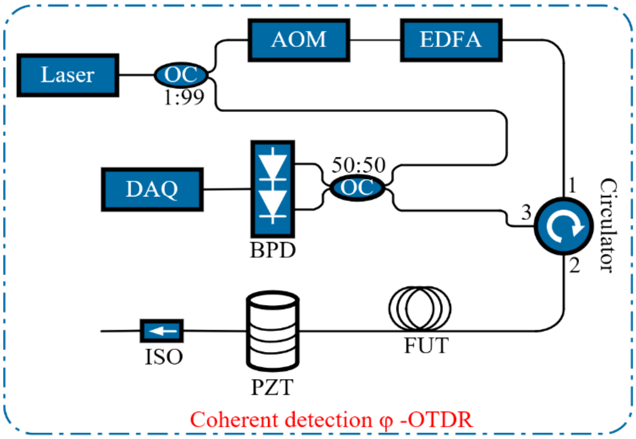

FIGURE 5. Coherent φ-OTDR system: acousto-optic modulator (AOM); Erbium doped fiber amplifier (EDFA); balanced photo-detector (BPD); data acquisition card (DAQ); fiber under test (FUT); PZT: Piezo-transducer.

Experimental results for LFD measurement were shown in Figure 4. The output of both MZIs were quite similar and indicated the measured LFD as $\alpha = 0.8 \sim 1.2$ MHz/min.

B. ADAPTIVE PULSE PERIOD METHOD IN COHERENT φ-OTDR FOR LOW-FREQUENCY VIBRATION DETECTION

To investigate experimentally the capability of the APP method to sense low-frequency vibration with intensity-based φ-OTDR system, an experiment was firstly carried out with a coherent φ-OTDR system whose setup is drawn in Figure 5. A 100 Hz linewidth laser operating at 1550 nm was used as coherent light source. An optical coupler splits the laser output light into the signal and reference lights. Then, the signal light went through an AOM with high extinction-ratio and EDFA for respectively pulse modulation and signal amplification to prevent the fiber loss. Later, the amplified signal was launched into a 1 km long FUT via the port 2 of the circulator. The probe pulse-width and pulse period were set respectively to 200 ns and 50 μs. A PZT was used to produce the low-frequency vibration. Another optical coupler recombined the Rayleigh back-scattered signal with the reference light. The interference signal detected by a BPD was acquired with a 1GSamples/s DAQ. In the experiment, the probe pulse period was not directly changed to have higher value. An efficient way to implement longer probe pulse period was to keep its initial value and extract an optical intensity signal after the propagation of every N number of pulse signals inside the FUT for signal processing. This way preserved the energy distribution along the FUT. Different vibration frequencies of respectively 0.1 Hz, 0.5 Hz, 1 Hz and 5 Hz were applied to the PZT under a driving voltage of 3 V. The signal processing was conducted offline with a personal computer.

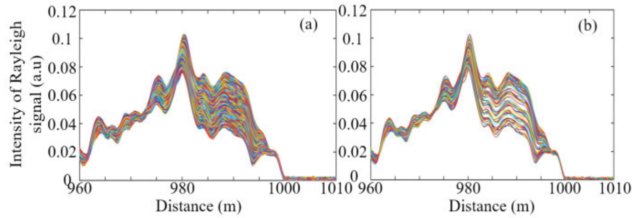

FIGURE 6. Intensity of the Rayleigh back-scattered signal in coherent φ-OTDR system acquired (a): with a pulse period of 50 μs; (b): with a corresponding pulse period of 5 ms.

To illustrate the APP method for low-frequency vibrations sensing with intensity-based φ-OTDR system, N was chosen to hold respectively the values 1, and 100, with the corresponding pulse periods of 50 μs, and 5 ms. The detected intensity signal was acquired during 0.5 s. The acquired signals were processed with I/Q demodulation to retrieve the Rayleigh intensity signal. Figure 6 (a) shows the superimposition of the 10000 plots of the intensity signal with a pulse period of 50 μs, and Figure 6 (b) presents the corresponding 100 traces obtainable with a pulse period of 5 ms in the last 50m of the FUT that includes the disturbance region. The first thing observable is that the 100 traces of the Figure 6 (b) could represent the 10000 traces in Figure 6 (a) without loss of information as stipulates the Nyquist sampling criterion. From both Figure 6 (a) & (b), it could be readily suspected the intrusion location that is position at which an obvious envelope was formed. However, the intrusion detection would be problematic in case (a) for two reasons (1): the volume of the data to be processed is massive; (2): the non-significant intrusion-induced change in the intensity signal from pulse to pulse (unnecessary data) that causes consequent high computational cost for denoising.

$$I = I_s(\Delta f).\cos(\varphi_0 + A.\sin(2\pi.f_{vib}.t)) = I_s(\Delta f).\begin{bmatrix} J_0(A).\cos(\varphi_0) + \\ J_1(A).\cos(\varphi_0 + 2\pi.f_{vib}.t) - J_1(A).\cos(\varphi_0 - 2\pi.f_{vib}.t) + \\ J_2(A).\cos(\varphi_0 + 2\pi.2f_{vib}.t) + J_2(A).\cos(\varphi_0 - 2\pi.2f_{vib}.t) + \\ J_3(A).\cos(\varphi_0 + 2\pi.3f_{vib}.t) - J_3(A).\cos(\varphi_0 - 2\pi.3f_{vib}.t) + \\ J_4(A).\cos(\varphi_0 + 2\pi.4f_{vib}.t) + J_4(A).\cos(\varphi_0 - 2\pi.4f_{vib}.t) + \ldots \end{bmatrix} \tag{6}$$

$$I_{low} = I_s(\Delta f).\begin{bmatrix} J_0(A).\cos(\varphi_0) + \\ J_2(A).\cos(\varphi_0 + 2\pi.2f_{vib}.t) + J_2(A).\cos(\varphi_0 - 2\pi.2f_{vib}.t) + \\ J_4(A).\cos(\varphi_0 + 2\pi.4f_{vib}.t) + J_4(A).\cos(\varphi_0 - 2\pi.4f_{vib}.t) + \\ J_6(A).\cos(\varphi_0 + 2\pi.6f_{vib}.t) + J_6(A).\cos(\varphi_0 - 2\pi.6f_{vib}.t) + \ldots \end{bmatrix} \tag{7}$$

Later, we extracted the intensity signal in the disturbance region that we subtracted from that in non-disturbed region to record experimentally the intensity fluctuation δI as we did in the previous numerical simulations. The intensity fluctuation δI under different vibration frequencies acquired for 0.04 s were set at the same origin to enable us for comparison. The experimental results plotted in Figure 7 indicated that the trace-to-trace fluctuation grows in respect with time and frequency of the external vibration. The experimental result was consistent with theoretical analysis.

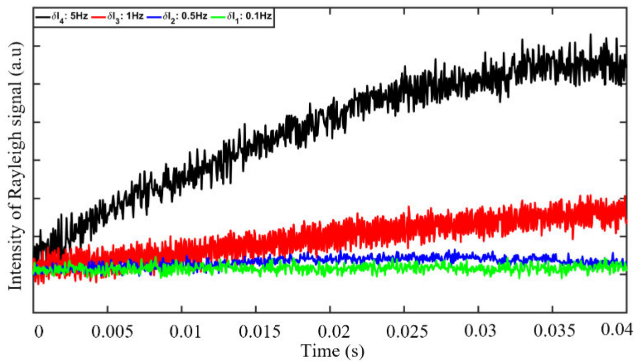

FIGURE 7. **Experimental illustration of the adaptive pulse period method δI_1, δI_2, δI_3, and δI_4 respectively for 5, 1, 0.5, and 0.1 Hz.**

Thereafter, we performed the intrusion detection using the APP method and moving variance of the intensity signal. As it could be seen from Figure 8, the APP method successfully detected the intrusion location for the different low-frequency vibrations with good signal-to-noise ratio.

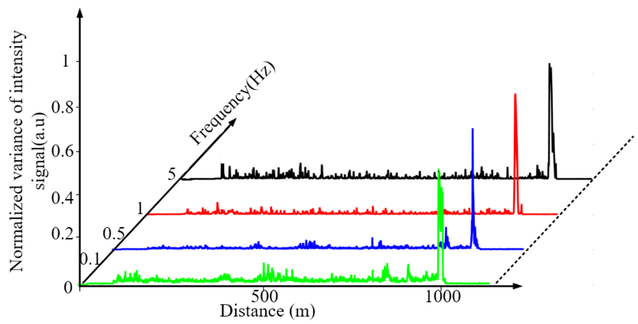

FIGURE 8. **Intrusion detection with adaptive pulse period method in coherent φ-OTDR system.**

After verifying experimentally the effectiveness of APP method for location of low-frequency vibration in coherent φ-OTDR system, we further extracted the evolution of Rayleigh intensity in the disturbance region acquired for 0.5 s. The results obtained were plotted in Figure 9. The output intensity signal showed approximately a sinusoidal waveform signal whose frequency is the double of that of the external intrusion. These observations could be well suspected with Figure 9. (c) & (d). The rigorous frequency components of the signal in Figure 9 (d) is given by its spectrum plotted in Figure 14.

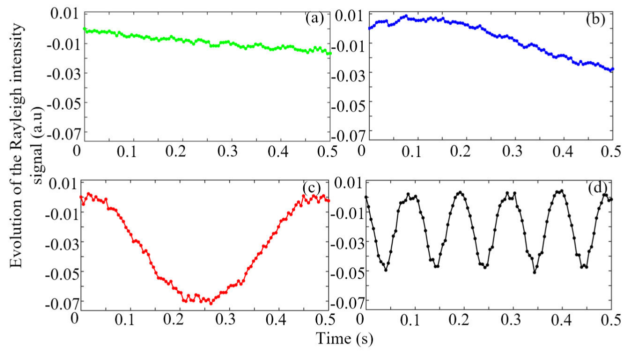

FIGURE 9. **Evolution of the Rayleigh intensity in the disturbance region for 0.5 s under vibration frequencies of (a): 0.1 Hz; (b): 0.5 Hz; (c): 1 Hz; and (d): 5 Hz.**

C. ADAPTIVE PULSE PERIOD METHOD IN DIRECT DETECTION φ-OTDR FOR LOW-FREQUENCY VIBRATION DETECTION

In a second experiment, we processed to the same experimental investigations as previously but in a direct detection φ-OTDR system for this time. The experimental setup is shown in Figure 10. It is the simplest configuration for φ-OTDR system. Light from the narrow-linewidth laser (100 Hz) went successively through pulse modulation and amplification with high extinction-ratio AOM and EDFA; then launched after into the FUT. The Rayleigh-backscattered intensity signal was received with a PD and acquired with same DAQ as in previous experiment.

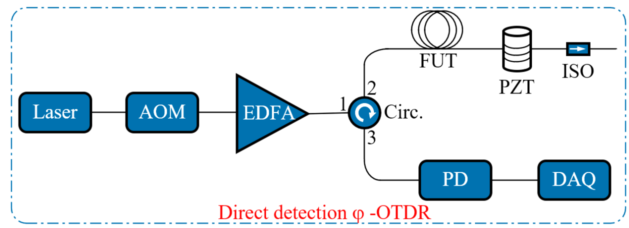

FIGURE 10. **Direct-detection φ-OTDR system.**

The Rayleigh back-scattered intensity signal in the conditions of intrusion of low-frequency vibration using the direct-detection shown in Figure 11 exhibited the formation of an obvious envelope in the disturbance region.

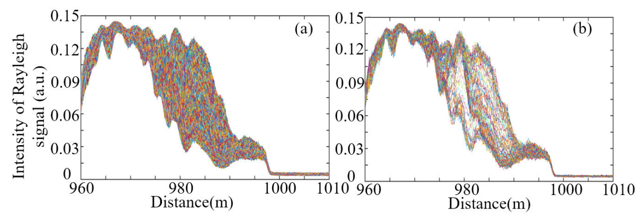

FIGURE 11. **Intensity of the Rayleigh back-scattered signal in direct-detection φ-OTDR system acquired (a): with a pulse period of 50 μs; (b): with a corresponding pulse period of 5 ms.**

Next, we performed the intrusion detection using the APP in direct-detection φ-OTDR system. The APP method conveniently detected the intrusion location for the different low-frequency vibrations with good signal-to-noise ratio (see Figure 12).

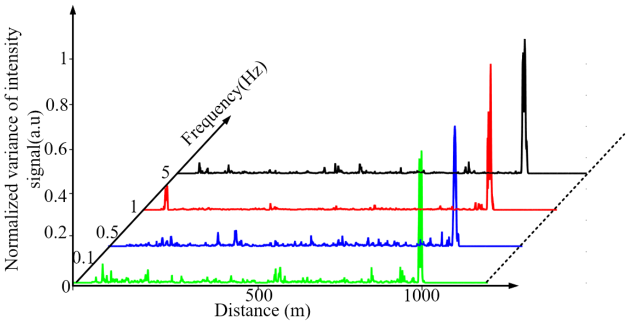

FIGURE 12. **Intrusion detection of low-frequency events with adaptive pulse period method in direct-detection φ-OTDR system. The traces have been scaled for clear visibility.**

Analogously to the previous results, the output intensity signal from the φ-OTDR system is the composition of sinusoidal signals with $2n \times f_{vib}$ as it was the case in coherent detection (see Figure 13). These results could be well observed from the spectrum corresponding to the signal in Figure 13. (d) plotted in Figure 14.

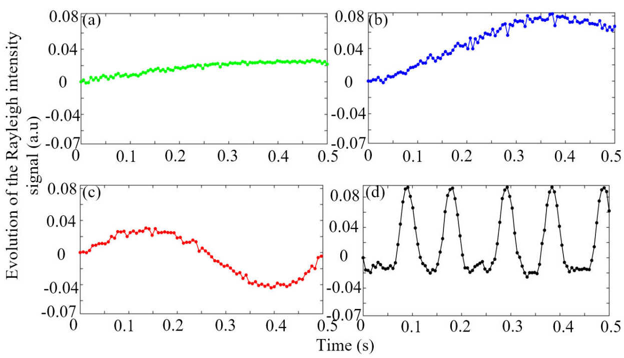

FIGURE 13. **Evolution of the intensity of the Rayleigh back-scattered signal in the cases of external vibrations of frequencies of (a): 0.1 Hz; (b): 0.5 Hz; (c): 1 Hz and (d): 5 Hz with direct-detection φ-OTDR system.**

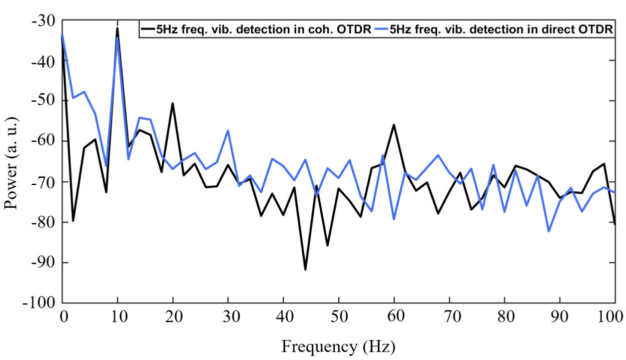

FIGURE 14. **Spectrum of the intensity signal in the case of an external vibration of 5 Hz in both coherent and direct-detection φ-OTDR system.**

Figure 14 is the spectrum of the intensity signal in the case of 5 Hz for both coherent and direct detection. This spectrum gave a clear pattern with peaks synchronized with 10Hz that is the double of the frequency of the external

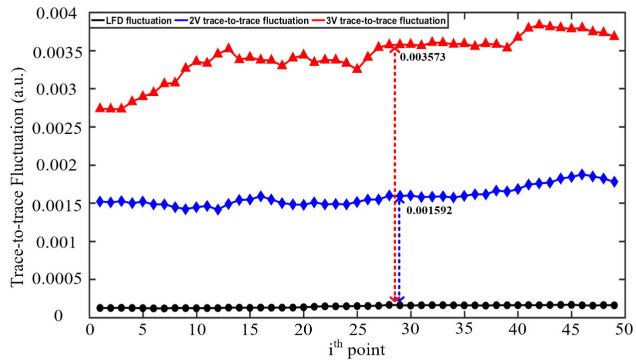

FIGURE 15. **Amplitude response of the low-frequency vibration measurement.**

vibration. Also, one could readily notice the harmonics of frequencies 4×5 Hz, 6×5 Hz etc. This is the confirmation of the composition of the intensity signal with sinusoidal signals with frequencies of $2n \times f_{vib}$.

IV. DISCUSSION

Indeed, the APP method used in this paper to detect low-frequency vibration acts as the reciprocal of the Nyquist's sampling theorem that requires the maximum detectable vibration frequency in φ-OTDR system to be less than or equal to the half of probe pulse repetition rate. Reciprocally, a detection of low-frequency vibration can be performed using any probe pulse repetition rate greater than or equal to the double of the frequency of the vibration to be measured. However, by choosing adequate pule period/pulse repetition rate, subsequent Rayleigh intensity fluctuation should be realized and allow for the detection of low-frequency vibration because the phase change induced by the intrusion follows monotonic time variation whereas the phase change induced by the LFD varies randomly.

It is apparent that the output intensity signal allowed for the recovery of waveform of the external vibration without further signal processing. The amplitude of the vibration signal output from the PZT is dependent on its sensitivity coefficient and the amplitude of the driving voltage [32]. From the spectrum plotted in Figure 14, we could conjecture that amplitude of the vibration output from PZT is low. In the cases of low values input, the higher order Bessel function are negligible compared to $J_2(x)$ as shown in Figure 16 (a). The signal output from the φ-OTDR system could be approximated as $I_{low} = a.\ J_0(A) + b.\ J_2(A).\cos(2f_{vib}.t)$ where a and b are two constants. This explains the reason for the direct recovery of the external vibration. Thereafter, we investigated the amplitude response of the low-frequency vibration measurement using our method. For this purpose, we used the coherent φ-OTDR system because of its higher signal-to-noise. To do so, we changed the driving voltage of the PZT to 2 V in the case of 1 Hz vibration frequency and processed to the calculation of the trace-to-trace fluctuation for all the points included in the disturbance region in both

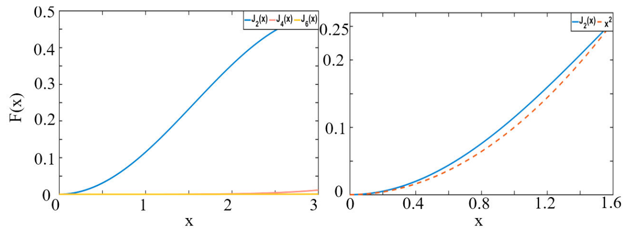

FIGURE 16. **(a): Plot of Bessel functions $J_2(x)$, $J_4(x)$ and $J_6(x)$; (b): plot of second order Bessel function $J_2(x)$ and x^2 for low x.**

cases of driving voltages. The results obtained were denoised using the moving averaging (see Figure 15). The amplitude response of the vibration measurement method showed the results in the proportion $2^2/3^2$ where the amplitude of the driving voltage was in the ratio 2/3. To be acquainted with these results, we plotted simultaneously the second order Bessel function $J_2(x)$ and x^2 as could be seen in Figure 16. (b). We could deduce that $J_2(x)$ and x^2 are closely approximate for low input values. This confirmed the amplitude response of the proposed vibration measurement.

V. CONCLUSION

In this paper, we proposed theoretically and demonstrated experimentally the APP to consistently detect an external intrusion in φ-OTDR system no matter its frequency without need to remove the LFD influence using wavelength scanning or any other additional component that could reduce the degree of freedom of the system while increasing the system cost. This method that expands the applications of the φ-OTDR system to the fields where there is need of detection of low-frequency vibration. Afterwards, low-frequency vibrations were measured through direct acquisition of the intensity signal in the disturbance region with good signal-to-noise ratio. The proposed vibration measurement method is insensitive to the Rayleigh fading phenomenon that is common limitation in φ-OTDR system. With this method, the reinforcement of the system stability would allow for the precise temperature/strain measurement using direct-detection OTDR.

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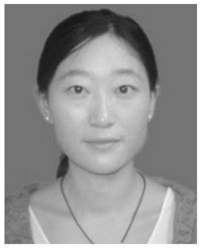

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