Amplitude Vibration Measurement by Harmonic Frequency Analysis of a Distributed Acoustic Sensor

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Abstract: Distributed acoustic sensors (DAS) based in coherent optical time-domain reflectometry (C-OTDR) provide a cost-effective solution for intrusion monitoring of large civil infrastructures like pipelines, railways or motorways. Although detection of events is well demonstrated, an estimation of the amplitude of these events is difficult to achieve. We propose a new method to recover the amplitude of the vibration from the conventional C-OTDR backscattered power traces. It is based on the FFT analysis of the DAS signals. Using a discrete accelerometer as a reference, we have calibrated the response of an optical fiber DAS using known stimuli. A correlation between the amplitude of the vibration and the ratios of the amplitudes of harmonics to the fundamental of the DAS signals is demonstrated. This analysis overcomes the main issues of the amplitude measurement, related to the interaction between the stimulus and the interference pattern.

1 INTRODUCTION

Distributed acoustic sensing (DAS) optical fiber systems based on coherent optical time-domain reflectometry (C-OTDR) are currently used for the detection of events (vibrations) along large infrastructures for intrusion monitoring and surveillance purposes (J. Park, 2003), (R. Sifta, 2015), (Y. Lu, 2010).

These systems use the optical fiber as a distributed sensor, detecting variations in the interference of the backscattered signal. These variations are generated by shifts in the phase of the propagating pulse due to external disturbances.

One of the issues with this technique is the saturation of the phenomenon due to the nature of the interference. As the magnitude of the event increases, so do the phase shift and the amplitude of the interference. However, when the phase shift reaches a given point the periodic nature of the interference phenomenon shows, and the amplitude of the detected signal does not show a linear variation with the applied disturbances. The direct C-OTDR backscattered power analysis results in a non-linear response of the traces with the input stimulus. Therefore, true vibrations amplitudes cannot be directly measured (H. F. Martins, 2014).

To overcome this restriction, C-OTDR backscattered phase analysis can be used (G. Tu, 2015), (Z. Pan, 2011). By measuring the phase of the C-OTDR signal and using unwrapping phase methods to recover phase shifts over 2π, the dynamic measurement of strains has been demonstrated. Other authors use chirped pulses to measure strain and temperature values along an optical fiber (J. Pastor-Graells, 2016). In those cases however, systems are more complex and long term-stability is not sometimes clearly addressed.

This work proposes a new method to recover the amplitude of the vibrations from the C-OTDR backscattered power traces. It is based on the FFT analysis of consecutive traces and on the relation existing between the ratios of the amplitudes of the different harmonics and the amplitude of the vibration. The experimental setup used to validate the method is presented. It includes a C-OTDR with random polarization rotation between consecutive

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trains of optical pulses to achieve a statistical study of the interference. The stimulus was a vibration generator with 50 meters of fiber length strapped around it. Different frequencies and amplitudes were tested and discrete accelerometers included for reference and calibration purpose. The results open the way to overcome the non-linear response of a conventional C-OTDR and to provide amplitude vibration analysis in DAS systems.

2 DAS GENERAL CONCEPTS

Figure 1 shows the basic scheme of a DAS system based on direct C-OTDR backscattered power analysis. A pulsed high-coherence laser is amplified and injected into the sensing fiber. The optical power backscattered by the fiber produces a pattern of interferences due to the coherent sum of the M wavefronts generated by Rayleigh diffusion along the pulse width at each point k of the fiber. This pattern is a function of the phase Ω_i and amplitude a_i of the different wavefronts, according to expression (1),

$$r_k \exp(j\theta_k) = \sum_{i=0}^{M} a_i \exp(j\Omega_i) \qquad (1)$$

This backscattered signal is amplified and filtered to improve the signal-to-noise ratio prior to the optical detection. The electrical signal coming from the detector is then sampled and processed.

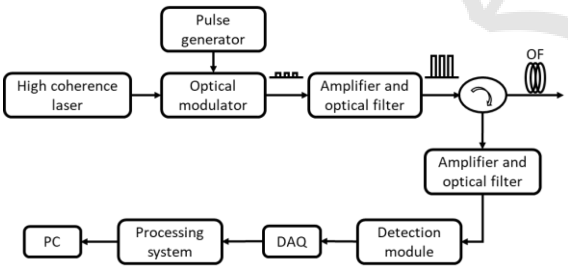

Figure 1: DAS scheme (direct).

If the phase of the backscattering produced by the light pulse does not change, the interference of the backscattered signals remains constant. However, any mechanical disturbance affects, via the stress-optic fiber coefficient, the phase of this signal and the resulting interference. Thus, the optical fiber becomes a distributed sensor that detects and locates pressure changes nearby.

As an example of the measured DAS signals, Figure 2 represents 21 consecutive acquired traces

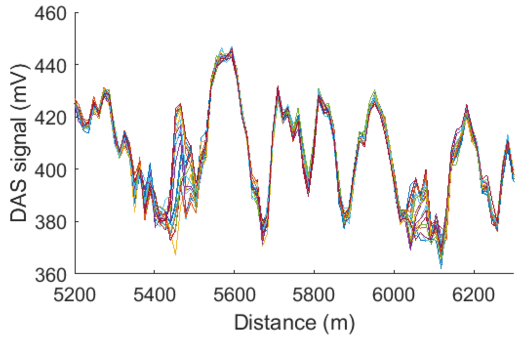

Figure 2: DAS signal.

with a constant stimulus at 5470 and 6070 meters. It is clearly seen that those points show much larger variability compared with the rest of the trace.

3 NON-LINEAR RESPONSE OF C-OTDR TRACES

The intensity resulting from the interference of several wavefronts depends on the phase relationships between them. These variations will always be within the range allowed by the destructive (minimum) and constructive (maximum) interference conditions.

In the case of a C-OTDR, when an external disturbance changes the relative phases of some of the components of the backscattered pulse, the intensity of the detected signal also varies. As the amplitude of the disturbance is greater, the induced phase variation is also greater. Since there is a maximum of the interference amplitude, there is a saturation phenomenon in the intensity variation of the C-OTDR trace. Once this saturation point has been reached, the amplitude increases of the external disturbance are not reflected as increases in the intensity variation detected in the DAS.

Figure 3 shows a simplified model of this phenomenon, with only two wavefronts interfering and a sinusoidal mechanical stimulus of frequency f_0. For small induced phase changes, variations of the traces are linear with the magnitude of the stimulus (same frequency and proportional amplitude). However, when there is a large phase shift, the

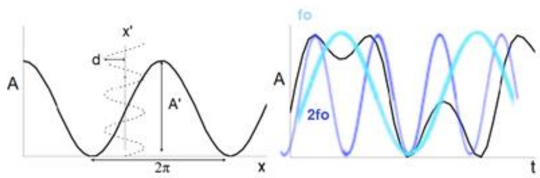

Figure 3: Interference pattern.

amplitude of the DAS signal cannot exceed its maximum value, A', non-linear response is given and harmonics of the fundamental frequency appear. The ratio of the amplitudes of these harmonics and the fundamental is related to the amplitude of the stimulus (M. Abramovitz, 1972).

Obviously in the case of a C-OTDR pulse, there is a large number of interfering wavefronts and it is not possible to obtain a simple analytical relation. Therefore, it is necessary to perform a large set of measurements under different intra-pulse interference conditions to determine experimentally these relations for DAS systems.

4 EXPERIMENTAL SET-UP

The experimental setup to determine the relationship between the stimulus amplitude and the amplitudes of the DAS signals (fundamental and harmonics) is shown in Figure 4.

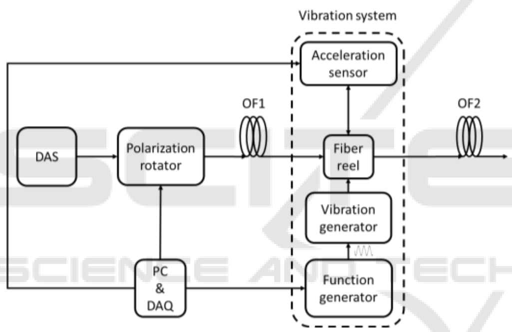

Figure 4: Basic scheme of the experimental setup.

The DAS system is based on a C-OTDR as described in Figure 1. The laser pulses are 600 ns long and are injected into the optical fiber in trains of 5000 pulses with a repetition rate of 1 kHz. In order to perform a statistical analysis for every possible interference condition, the polarization state is changed randomly from a pulse train to the next. Thus, each different pulse polarization accounts for a different intra-pulse interference condition at each point of the fiber. A controlled vibration system is placed between two single mode fiber reels of 5 km (OF1) and 40 km (OF2). It consists of a 50-meter-long fiber reel fixed to the rod of the vibration generator. A function generator controls the amplitude and frequency of the vibration. A commercial three-axis accelerometer (Analog Devices 16227) is attached on top of the fiber reel. This accelerometer provides the reference measurement of the real amplitude of the mechanical vibrations that are supported by the fiber. It allows the amplitude response calibration of the DAS system. Finally, a computer and a LabJack U3-HV data acquisition card (DAQ) provide control of the polarization rotator, the vibrator, the accelerometer and the DAS system.

5 EXPERIMENTAL RESULTS

The signals from the DAS system and the accelerometer are captured simultaneously. To establish the relationship between the amplitude of the vibration and the DAS signals at a given frequency, an amplitude sweep of the vibrator is performed. At each point of the sweep there are 50 iterations using random polarizations, and 5000 DAS traces are captured for an FFT analysis. As an example, we present tests carried out for an excitation frequency of 100 Hz. More frequencies have been proved in the following range, [50, 110] Hz at several distances as 5 and 10 km, although the results presented were at 5 km and 100 Hz.

The acceleration measured by the accelerometer versus the amplitude of the function generator is used as calibration of the real mechanical vibrations supported by the fiber. In addition, it assures that no harmonics of the applied fundamental frequency are mechanically generated in the vibration setup. Figure 5 shows an example of the signal captured by the accelerometer for the maximum tension applied by the function generator in the test, 2 V, and the corresponding FFT. It shows the 100 Hz fundamental frequency without evidence of any harmonic. Figure 6 shows the mechanical amplitude displacement measured in function of the applied tension. The acceleration has been converted to displacement for a better understanding of the magnitude of the test vibrations. The response of the system is clearly linear, and the curve is used for a direct calibration of the DAS signal.

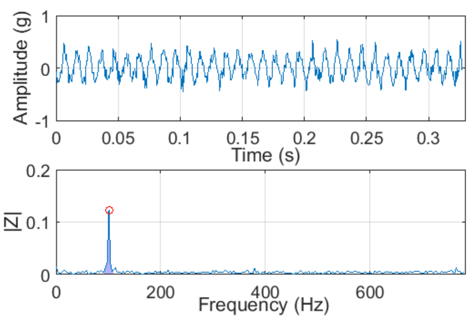

Figure 5: Accelerometer signals: time (top) and FFT (botton).

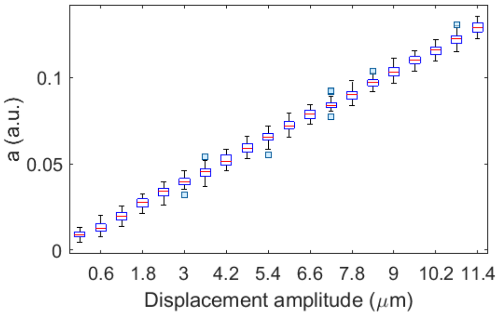

Figure 6: Mechanical amplitude calibration curve of the vibration setup.

Figure 7 shows a 2D representation of the signal captured by the DAS system during 5 seconds, with a constant stimulus of 100 Hz located at 5.6 km. The trace remains stable within the 5 seconds, except for the vibration area. When the acquisition is complete, we search for the stimulus in the frequency domain, at the excitation frequency and its harmonics (up to $4f_o$). The location in frequency and distance of each of the harmonics is shown in Figure 8. The search area is shaded in frequency and a marker (circle) is placed in the position of the maximum.

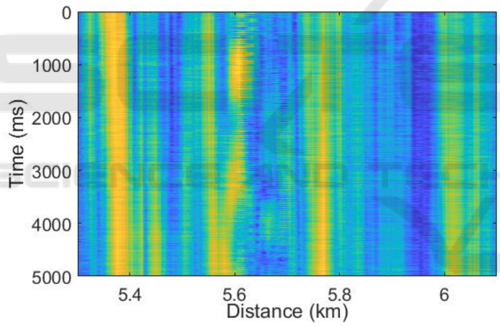

Figure 7: Representation of 5 seconds DAS signal around the 50 m fiber reel.

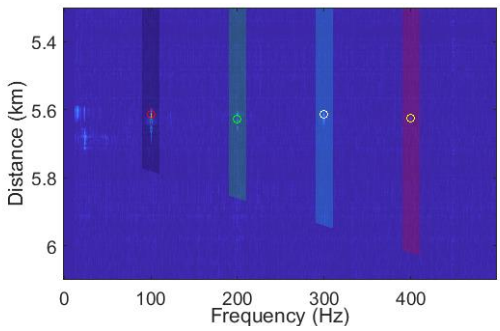

Figure 8: Location of the fundamental frequency and its harmonics in the DAS signal at 5,6 km.

The amplitude of the DAS signal at 100 Hz versus the displacement amplitude of the vibration at the same frequency is shown in Figure 9. The central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively, with 50 data points for each amplitude. For small displacements, the dependence is approximately linear but, contrary to the results of the accelerometer in Figure 6, it soon reaches a saturation level due to the non-linear response of the DAS signal, as predicted in section 3.

The signal missing from the 100 Hz tone is distributed between its harmonics, as shown in Figures 9-12. These harmonics are not generated by the vibrating structure but by the saturation effect of the DAS, as evidenced by the frequency response of the accelerometer in Figure 5.

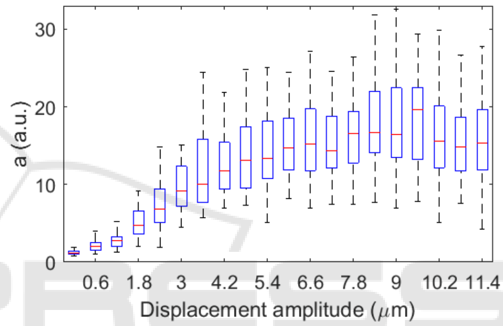

Figure 9: DAS signal at the fundamental frequency f_0=100 Hz.

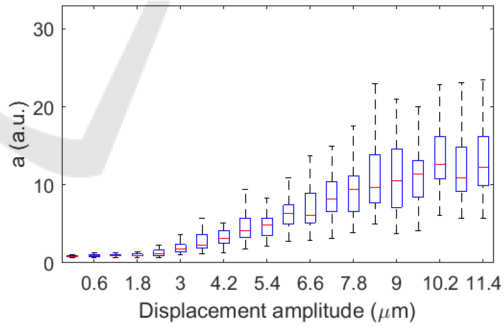

Figure 10: DAS signal at the first harmonic of the excitation frequency (f_1=200 Hz).

These graphs represent the non-linear dependence of the DAS signal with the displacement amplitude of the vibrations, and can be used to estimate the real magnitude of unknown excitations despite the saturation effect. Figure 13 shows the calibration curves obtained from these measurements. It shows, in function of the vibration amplitude, the normalized variation of the fundamental to its maximum and the ratio of harmonics to the fundamental. From this

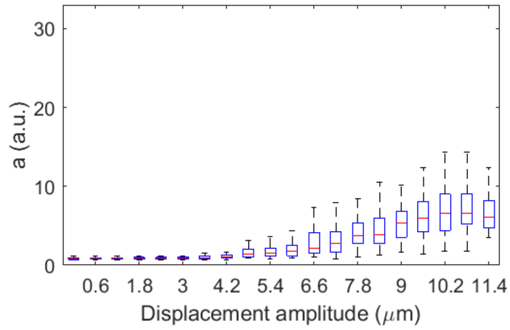

Figure 11: DAS signal at the second harmonic of the excitation frequency (f_2=300 Hz).

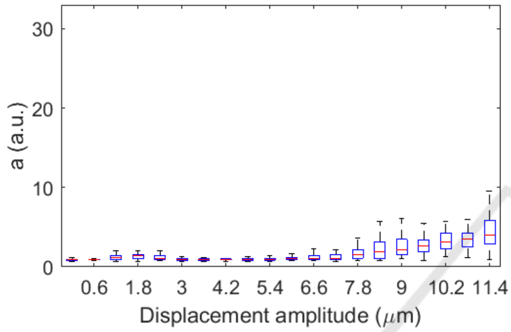

Figure 12: DAS signal at the third harmonic of the excitation frequency (f_3=400 Hz).

Figure 13, given a stimulus of unknown amplitude, after FFT analysis of the C-OTDR traces, the harmonic to fundamental amplitude ratios will allow the estimation of the magnitude of the excitation.

The distribution of the measured values for a given vibration condition accounts for the statistical behavior of the interference phenomenon. Thus, it is clear that the accuracy of the method is strongly related to the use of random polarization states for the launched pulses, in order to ensure a large enough sample.

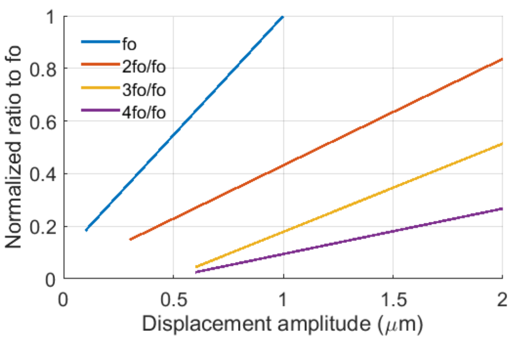

Figure 13: Calibration curves of the non-linear behavior of DAS signals.

6 CONCLUSIONS

A new method to recover the magnitude of the stimulus from DAS signals has been described. It is based on the FFT analysis of C-OTDR traces using random polarization states in consecutive trains of pulses and on the relation existing between the magnitude of the vibration and the ratios of the amplitudes of the harmonics to the amplitude of the fundamental tone.

The experimental setup used to validate the method has also been presented. It uses discrete accelerometers for reference and calibration. The results demonstrate the viability of the method, which overcomes some of the issues in the magnitude measurement. It opens the way to work through the non-linear response of conventional C-OTDR to provide not only detection of events in DAS systems, but also vibration amplitude analysis.

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