Coherent Rayleigh Backscattering-Based AE Sensing for Crack Detection in Steel Pipeline

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Abstract: Our theoretical model and derived formula predict that the intensity-based DAS can accurately detect acoustic emissions from pipeline cracks. Preliminary experimental results validated the theoretical prediction for crack-induced AE waveform detection.

1. Introduction

The acoustic emission (AE) technique offers the distinct advantages of being a passive and non-invasive approach to observe the progression of defects in pipeline systems [1]. The AE sensors are attached to the pipeline surface to detect transient mechanical waves generated from defect sources, such as fatigue crack and stress corrosion crack. These crack-induced stress waves may be weak in amplitude (< 1 nm in displacement), encompassing high frequency (up to 1 MHz), and having burst waveform (a few wave cycles) [2]. The commonly used AE sensors are point-type sensors that are made from piezoelectric materials, optical microphone, or fiber interferometer [3-5]. As the pipeline system is often deployed over long distance and has no vicinity site power supply and data transmitting module, the point-type AE sensors are difficult to be deployed in real-world environments. Therefore, the distributed acoustic sensor (DAS) had also been tested to detect the crack induced AE signal [6]. Unfortunately, the capability of the DAS system to detect AE signals generated by crack growth has not been demonstrated successfully [6].

In this paper, firstly, we derive that the intensity variation of coherent Rayleigh backscattering (RB) in DAS is just proportional to the AE waveform. Secondly, we demonstrate that AE waveform can be detected by using coherent RB light in DAS.

2. Theory

To monitor the pipeline thinning, an optical fiber cable is usually wrapped helically around the pipe surface to measure the strain distribution using optical frequency domain reflectometer (OFDR) or Brillouin optical time domain analyzer (BOTDA), as shown in the left figure of Fig. 1 [7]. When a crack happens, the generated AE wave is attenuated quickly along the pipe so that it only affects the optical fiber in the vicinity of the position where the crack happens. Typically, the affected fiber length is less than 1 m. Hence if the fiber length is far longer than 1 m, for example 50 m or 100 m, a simplified model, as plotted in the right figure of Fig. 1, can be adopted. In this model, the affected fiber length is neglected, and the AE wave is assumed to change the optical phase between the nth and the (n+1)th Rayleigh scatterers with the function of $\delta(t)$. Any other Rayleigh scatterers are not affected by the AE wave.

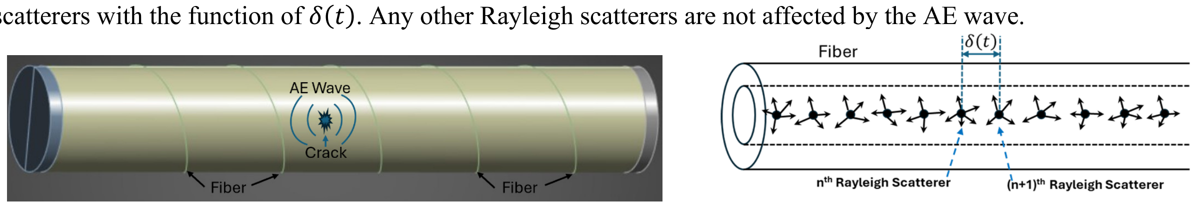

Fig.1 A pipe with optical fiber helically wrapped on the surface (Left). A phase variation $\delta(t)$ generated by AE wave between the nth and the (n+1)th Rayleigh scatterers in an optical fiber (Right).

If there are totally N Rayleigh scatterers in the fiber, the intensity of the coherent RB light can be expressed as [8]

$$P(t) = S_0 \sum_{k,l=1}^{N} c_k c_l \left[(\hat{m}_k \cdot \hat{m}_l) \cos 2\Delta\varphi_{kl} + \hat{S} \cdot (\hat{m}_k \times \hat{m}_l) \sin 2\Delta\varphi_{kl} \right] \tag{1}$$

where the subscript k stands for the kth Rayleigh scatterer in the fiber; $c_k = \sqrt{\gamma_k} e^{-\rho_k}$, ρ_k is the fiber attenuation, and γ_k is the RB coefficient; φ_k is the optical phase and $\Delta\varphi_{kl} = \varphi_k - \varphi_l$. The items $m_{jk}, j = 7,8,9$ are the matrix elements of the forward Mueller matrix at the fourth row and the second, third and fourth column, respectively. $\hat{m}_k = [m_{7k}, m_{8k}, m_{9k}]$ is a unit vector. S_0 is the input optical power. $\hat{S}$ stands for the input polarization state [8]. When the fiber is perturbed by the AE wave and the above-mentioned can be adopted, it can be calculated that the intensity variation of the coherent RB light is

$$\Delta P(t) = A\delta(t) = \left\{4S_0 \sum_{\substack{k=1 \\ l=n+1}}^{\substack{k=n \\ l=N}} c_k c_l \left[-(\hat{m}_k \cdot \hat{m}_l)\, sin\, 2\Delta\varphi_{kl}(0) + \hat{S} \cdot (\hat{m}_k \times \hat{m}_l)\, cos\, 2\Delta\varphi_{kl}(0)\right]\right\} \delta(t) \qquad (2)$$

Based on Eq. (2), it is evident that the intensity variation $\Delta P(t)$ is just proportional to the AE wave induced optical phase variation $\delta(t)$. It means that we can use the intensity-based DAS to measure the AE waveform in pipeline monitoring, rather than the more complex phase-based DAS [9]. As the coefficient A is determined by the distributions of the fiber phase and birefringence, fading effect may occur to make $A \approx 0$. In principle, the fading effect can be eliminated by using a frequency comb [10].

3. Experimental Results

To verify the theoretical prediction, the experiment is performed using the setup illustrated in the left figure of Fig. 2. The narrow linewidth laser (NLL) has a linewidth of less than 100 Hz and an output optical power of 1 mW at 1550 nm. The CW coherent light is coupled into a 110 m-long single-mode fiber (SMF) with 0.9 mm tight buffer jacket. Approximately 2 m-long SMF segment in middle is helically wrapped and glued on the surface of a 0.5 m-long 3-inch stainless steel pipe. A PZT is used to generate the simulated AE waveform, which is stimulated by the signal generator with 200 kHz frequency, 10 V peak-to-peak voltage and 10 cycles. The on-pipe SMF segment is 18 cm far away from the PZT, and the AE induced displacement at SMF segment is measured to be 0.43 nm by using a laser vibrometer. The coherent RB light is detected by using a balanced photodetector (BPD) to reduce the DC component. After digitized by a data acquisition card (DAQ) with a 5 MHz sampling rate and processed by a 100 kHz~800 kHz digital filter, the detected AE waveform is plotted in the right figure of Fig. 2. The profile of the detected waveform is introduced by the transit response of the PZT. The smaller waveform after 0.1845 s is induced by the reflection of the pipe boundary.

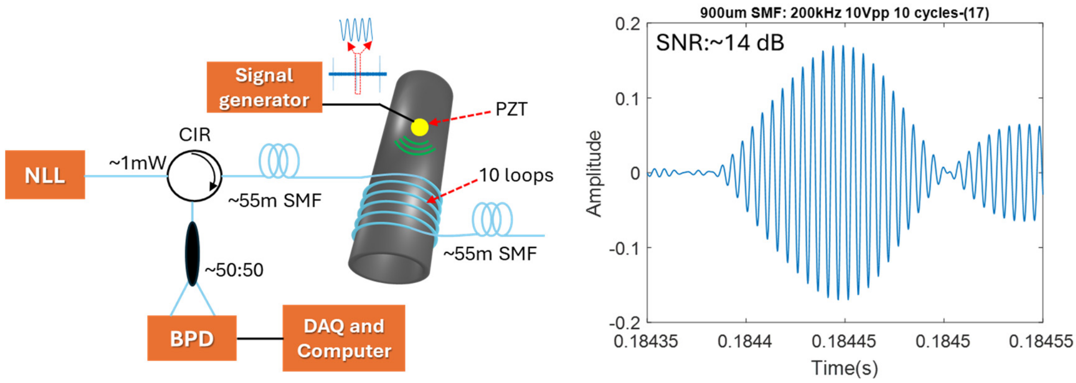

Fig.2 The experimental setup for pipeline AE detection using coherent RB (Left). The detected AE waveform using coherent RB (Right).

4. Conclusions

We demonstrate that intensity variation of the coherent RB light in DAS is just proportional to the AE induced optical phase variation in the pipeline crack monitoring application. Preliminary experimental results confirm that the high-frequency, short-duration and weak AE waveform can be correctly detected by intensity-based DAS, paving the way to achieve a fully passive distributed fiber-optic based solution for pipeline crack monitoring in harsh environment.

5. Acknowledgements

This work was supported by the "In-Service Structural Health Monitoring (IS-SHM) for Predictive Maintenance" project funded by NRF and hosted by A*STAR under the LCER Phase 2 Programme HETFI Directed Hydrogen Programme (Grant No: U2307D4002).

6. References

[1] H. A. Kishawy, *et al.*, INT J PRES VES PIP. **87**, 373-380 (2010).
[2] A. Terchi, *et al.*, Meas. Control. **34**, 240-244 (2001).
[3] A. A. Pollock, Acoustic Emission Inspection. Nondestructive Evaluation of Materials. ASM International. 360-379 (2018).
[4] B. Fischer, Nat. Photonics **10**, 356-358 (2016).
[5] J. A. Garcia-Souto, *et al.*, Opt. Express **14**, 9679-9686 (2006).
[6] F. Baensch, *et al.*, Feasibility study: Continous monitoring of pipes using distributed acoustic and fibre optic sensors. International Symposium on Structural Health Monitoring and Nondestructive Testing, Saarbrücken, Germay (2018).
[7] J. Tao, *et al.*, Struct Control Health Monit. **24**:e2016 (2017).
[8] H. Dong, *et al.*, Sensors, **24**, 1760 (2024).
[9] Z. Y. He, *et al.*, IEEE J. Light. Technol.39, 3671-3686 (2021).
[10] B. Redding, *et al.*, Opt. Express **27**, 34952-34960 (2019).