The feasibility study of a leak detection system for an underwater pipeline

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Abstract

When an underwater pipeline is damaged because of corrosion, a leakage is taken place. The high-pressure fluid inside the pipeline may leak out from the corroded orifice. This kind of leakage may cause direct loss of resource from the pipeline. Sometimes, it may induce more serious industrial damage and pollution. Hence, it is worthwhile to study the feasibility of designing a sensing system for the leak detection of an underwater pipeline. The characteristic of this acoustic field is a wideband noise field. Because the sound intensity of the leaky signal is very weak, we need an interferometer. Because the location of the leakage is uncertainty, it is not easy to detect this position. Also, because it is an underwater pipeline, the leakage may take place far away from the station on land. Hence, it may not proper to detect the position by some traditional sensors. Hence, a distributed sensing scheme is better for this kind of detection. In this paper, an in-line hybrid Sagnac and Mach-Zehnder interferometer is proposed to detect the location of the leaky point. In our experiment, the sensitivity of the sensing system is 3.3×10^{-4} rad /√Hz. Its dynamical range is 75 dB.

Text

When an underwater pipeline is damaged because of corrosion, a leakage is taken place. The high-pressure fluid inside the pipeline may leak out from the corroded orifice. The characteristics of this acoustic field are a wideband noise field. Because the position of leakage is uncertainty, it is not easy to detect this position. Also, because it is an underwater pipeline, the leakage may take place far away from the station. The sound intensity signal is very weak. Hence, it is worthwhile to study the feasibility of designing a sensing system for the leak detection of an underwater pipeline.

Fig.1. denotes the configuration of a hybrid Mach-Zehnder and Sagnac interferometer. In this figure, an ASE is used as a light source. Two optical path I & II, where path I start from the source, then, upper arm of coupler I to coupler II, passing through the leaky point and reflected from the FRM back to coupler II and from the lower arm to coupler I to the photo detector (PD). The path II start from the source, then lower arm of coupler I, to coupler II, to the leaky point and reflected from FRM to the coupler II, through the upper arm to coupler I and finally to the photo detector. Because these two optical paths are equal, it forms a Sagnac loop.

Assume that a high frequency carrier $\varphi_m \sin w_m t$ is feeded to the optical path through a PZT modulator. Here, φ_m is the amplitude of the carrier, w_m is the angular frequency of the carrier. If one of the leaky field can be denoted as $\varphi_s \sin w_s t$, where φ_s is the amplitude of the sound field, Ws is its angular frequency. Then, the optical field of these two paths can be represented as

Path I

$$\vec{E}_1 = E_1 \cdot \exp j \left\{ \begin{array}{l} \omega_c t + \phi_s \left[\sin \omega_s (t-\tau_1) + \sin \omega_s (t-\tau_2) \right] \\ + \phi_m \left[\sin \omega_m (t-\tau_{m1}) \right] + \psi_1 \end{array} \right\} \tag{1}$$

Path II

$$\vec{E}_2 = E_2 \cdot \exp j \left\{ \begin{array}{l} \omega_c t + \phi_s \left[\sin \omega_s (t-\tau_3) + \sin \omega_s (t-\tau_4) \right] \\ + \phi_m \left[\sin \omega_m (t-\tau_{m2}) \right] + \psi_2 \end{array} \right\} \tag{2}$$

Here, E_1 , E_2 are the electrical component of the guided light inside the optical fiber, respectively. Ψ_1, Ψ_2 are the phases of their carrier. Let C B n /) (1 = t be the time duration of the light passing through path I, while C L L D n m /) 2 2 (2 1 2 + + = t is that through path II. C L B n /) (1 1 + = t is the time which the guided light first passing through the leakage position, while C L L B n /) 2 (2 2 2 + + = t is the second time.

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Similarly, *C L D n* /) (1 3 + = *t* is the first time, *C L L D n* /) 2 (2 1 4 + + = *t* is the second time passing through the leakage position of the light of path II. Here, C is the light speed in vacuum; n is the refractivity index of the fiber. The output of those two light beams form an interferometric signal with an intensity as.

$$I_o = 1 + \cos\left\{ \begin{aligned} & 4\phi_s \cos \omega_s\left(t - \frac{\tau_T}{2}\right)\sin \omega_s\left(\frac{\tau_D}{2}\right)\sin \omega_s(\tau_x) \\ & + 2\phi_m \cos \omega_m\left(t - \frac{\tau_T}{2}\right)\sin \omega_m\left(\frac{\tau_T}{2}\right) \end{aligned} \right\} \qquad (3)$$

where τ_T is the time duration that a light beam finish a whole cycle. τ_D is the time duration that the light beam passing through the delay fiber. τ_X is the time that light flies from FRM to the leaky point. From the analysis of Eq. (3), we can get the relation between ω_S and the interferometric signal. According to [2]. [3], we recognize that when a pipeline is leaky, a wideband sound noise is generated. From Eq. (3), by mean of Bessel function expansion, and with PGC demodulation scheme [4], we can get the output signal Y like.

$$\int Ydt = \int PQ \cdot J_1(\phi_m)J_2(\phi_m)\phi_s'(t)dt = PQ \cdot J_1(\phi_m)J_2(\phi_m)\phi_s(t) \qquad (4)$$

where P. Q are constants. From the above equation, we can get the phase φ_S as

$$\phi_s(t) = 4\phi_s \cos\omega_s\left(t - \frac{\tau_T}{2}\right)\sin\omega_s\left(\frac{\tau_D}{2}\right)\cos\omega_s(\tau_x) \qquad (5)$$

Fig. (2) denotes the configuration of this experiment. In this figure, we can find that the system can be separated into two parts. One of them is the leaky system and the other is the sensing system. The leaky system including a high-pressure air compressor or high-pressure nitrogen tank, the high-pressure tube, a simulator, fixtures and some isolation facilities for acoustic and vibration insulation.

Fig.3 is an experimented results which shows that when different length of delay fiber are used, the variation of the signal. From our experiment, we found that the maximum signal we get is 40 volts while the minimum signal is 0.007 V. Hence, the dynamic range is 75 dB. At the same time, we find that the sensitivity of this sensing system is 3.3×10^{-4} rad / √Hz.

In conclusion, a distributed in-line hybrid Mach-Zehnder and Sagnac interferometric type sensing system is designed for the leak detection of an underwater pipeline. This sensing system has zero optical paths to allow the use of low coherent light source. The single mode fiber is used to avoid the modal dispersion problem. The advantage of the PGC demodulation system is that this system has very good signal to noise ratio and large dynamic range. The dynamic range is about 75 dB with sensitivity 3.3×10^{-4} rad / √Hz.

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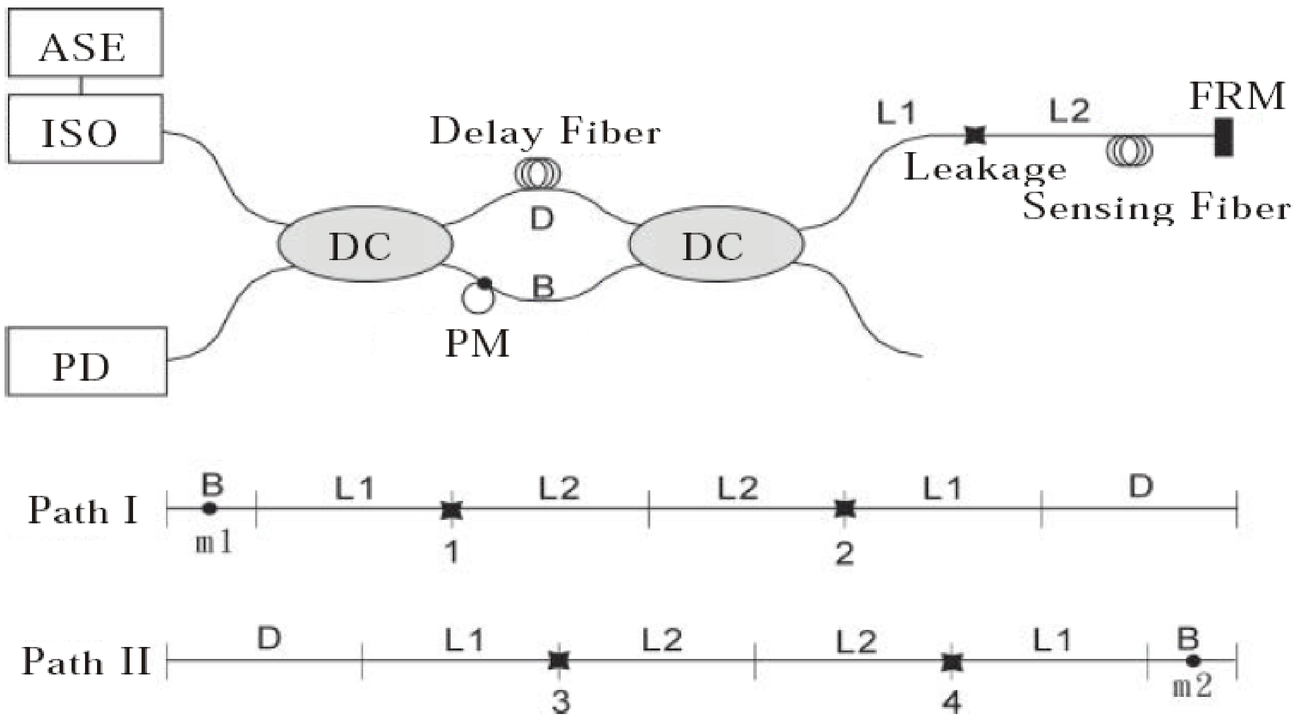


Fig.1.The configuration of the sensing system

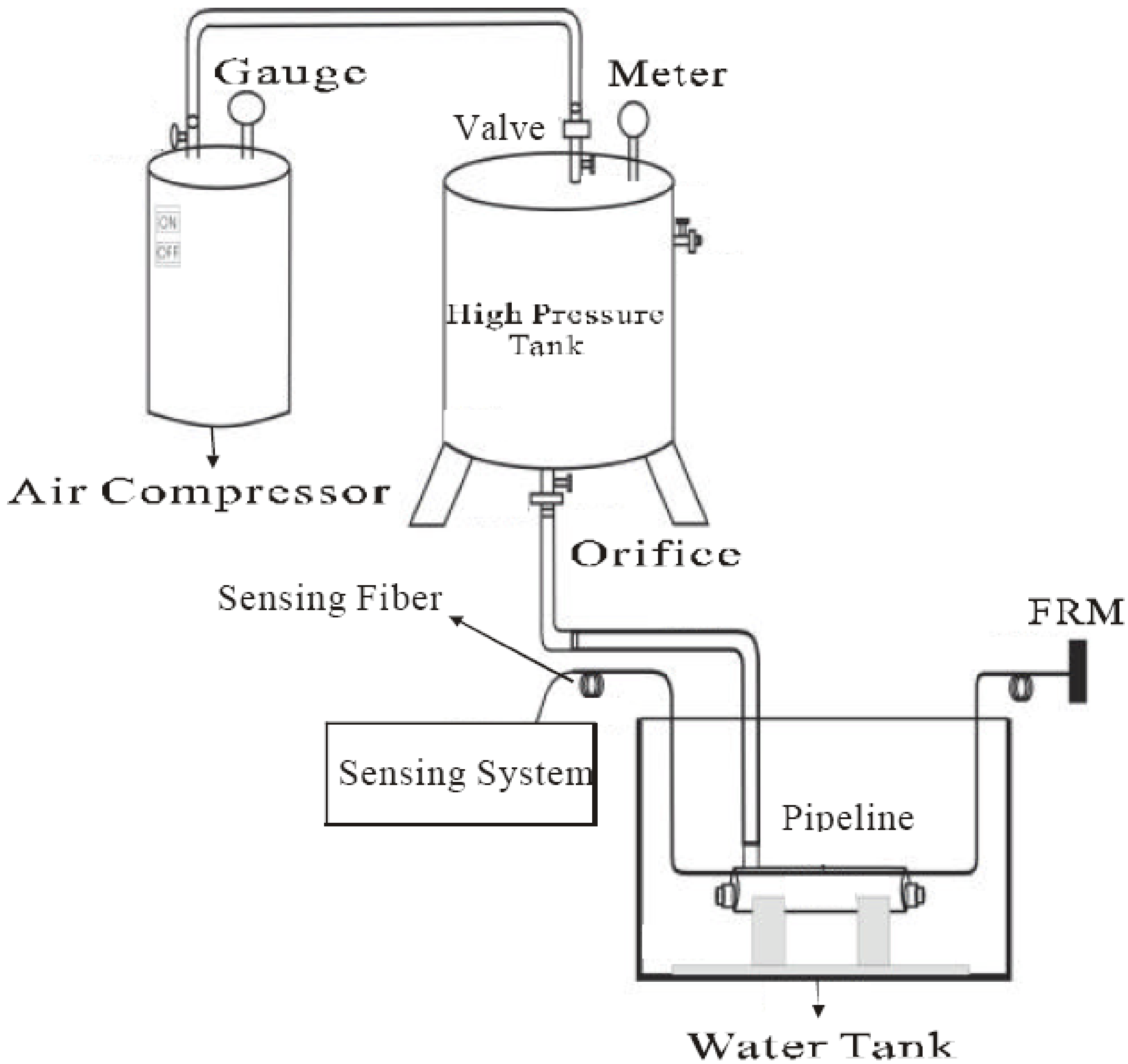
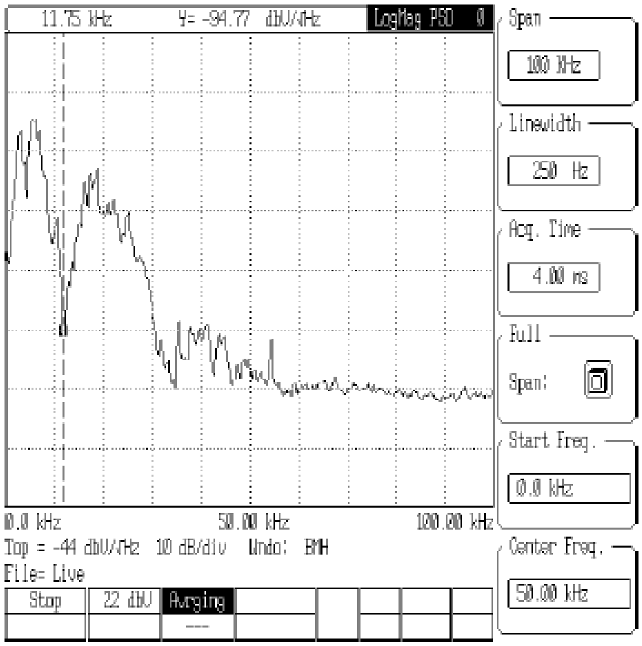
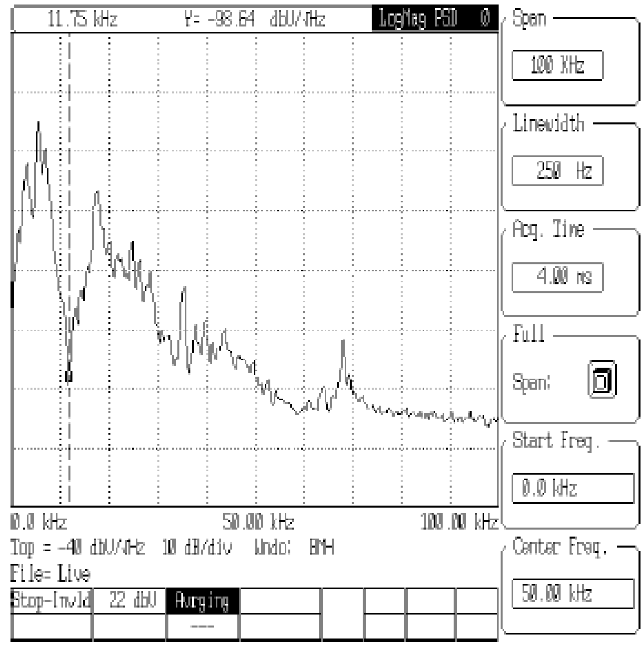


Fig.2.The leak detection system





Delay fiber =3 km

Delay fiber =2 km

Fig.3.The spectra of the sensing system with different length of delay fiber