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Distributed detection of buckling for subsea pipelines with Brillouin fiber optic sensors

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ABSTRACT

The work presented in this article pertained to the development of a methodology for distributed detection of lateral buckling for subsea pipelines with Brillouin fiber optic sensors. Uncontrolled buckling may lead to serious consequences for the structural integrity of a pipeline. The cost-effective solution to this problem is to work with rather than against the pipeline by controlling the formation of lateral buckles among the pipeline. A simple solution to this problem is to control the formation of buckles among the pipeline. This firms the importance of monitoring the occurrence and evolution of pipeline buckling during the installation stage and long-term service cycle. The present work involved in using distributed sensor to monitor the evolution of lateral buckling for subsea pipelines. The primary advantage in using the Brillouin based fiber optics sensor is their distributed sensing capacity over the entire length of pipeline. This study included determination of sensing scheme and feasibility validation by a small-scale experiment. According to the theoretical formulations, the sensing scheme is proposed as that the longitudinal strains are monitored by mounting the Brillouin optical time domain analysis (BOTDA) distributed sensors on the outer surface of the pipeline. Then the bending-induced strain is extracted to detect the occurrence and evolution of lateral buckling. Feasibility of the method was validated by using an experimental program on a small scale model pipe. The lateral buckling was simulated by applying the axial compressive loads on a 5.47 m long model pipe. A BOTDA system was employed for distributed measurement of longitudinal strains and detection of lateral buckling. The distributions of bending-induced strains, derived from the measured longitudinal strains, were used to identify the occurrence and evolution of buckles. The results demonstrate that the proposed approach is able to detect, in a distributed manner, the onset and progress of buckling in pipelines. The methodology developed in this study provides a promising tool for assessing the structural integrity of subsea pipelines.

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1. INTRODUCTION

Most pipelines carry a longitudinal compressive force induced by the operating temperature and pressure. When hot oil pass through the line, the buckles sometimes occur suddenly because such compressive stress reaches a critical value. They can occasionally lead to a rupture when overstress the pipe wall (Talor 1996; Miles 1999; Karampour 2013). The oil leakage of subsea pipelines will cause ocean contamination and economic losses (Mirzaei 2013). Until recently, lateral buckling was less studied than upheaval, and little had been reported about the techniques for monitoring the lateral buckling. Therefore, it is urgently motivated to develop the effective approaches to monitor the lateral buckling of subsea pipelines.

One of the challenges for monitoring pipeline buckling is that the lateral buckle usually occurs over a substantial distance. The traditional discrete sensing techniques only monitor the pipeline in the limited locations, which cannot cover the whole range of the pipeline. It is difficult for them to detect the initial small buckling lobes at arbitrary locations and their developments. Recent emerging techniques based on Brillouin fiber optic sensors provide the promising tool for monitoring the long range structures in a real distributed manner, especially for pipelines. The Brillouin based sensing approaches have been used to monitor the civil, mechanical, and aerospace structures (Ansari 2007; Bao 2009; Mohamad 2012; Feng 2013; Feng 2014). Several studies were reported that the distributed optical fiber sensors were capable of detecting the pipeline leakage by distributed monitoring the abnormality of temperature (Eilser 2008; Nikles 2009; Glisic 2010). Glisic and Yao (2012) proposed a method to detect and localize the damage on pipeline due to earthquake-induced ground movement with distributed optical fiber sensor. Ravet et. al (2006) proposed a distributed Brillouin sensor based approach to detect the local buckling caused by the thinned wall of pipe. However, the distributed optical fiber sensing techniques have not been adopted to monitor the global lateral buckling of subsea pipelines. To detect the lateral buckling with distributed optical fiber sensor, the critical issues should be stressed as: (1) the monitoring scheme by using the distributed optical fiber sensors; (2) the identification strategy to detect the onset and revolution of lateral buckling with the distributed measurements.

In this study, we employ a Brillouin optical fiber time domain analysis (BOTDA) sensor system to monitor lateral buckling in the subsea pipeline. In Section 2 the monitoring scheme is proposed with the theoretic analysis. The design of the experimental program was described in Section 3, and the discussion of the experimental results is also presented in this part. Finally we draw the conclusions based on the experimental investigations.

2. MONITORING SCHEME

2.1 Theoretical Formulation

A pipeline containing hot oil or gas will expand longitudinally on account of the rise in temperature and operating pressures; and compressive axial stress will occur in the pipe-wall while such expansion is resisted. So there is a danger of buckling (Hobbs 1984). The compressive axial stress of the pipeline due to thermal expansion is determined as

$$P_1 = EA\alpha\Delta T \tag{1}$$

where p_1 is the compressive axial stress due to thermal expansion; E is the Young's modulus of the pipeline; A is the cross-sectional area of the pipe; α is the coefficient of linear thermal expansion and ΔT is the temperature change of the pipe. The axial compressive force carried by internal pressure in the pipe is

$$p_2 = \frac{Apr(0.5-\upsilon)}{t} \tag{2}$$

where P_2 is the axial compressive force carried by internal pressure; p is the pressure difference between the oil and the sea. υ is Poisson's ratio, t is the pipe wall thickness; and r is the radius of the pipe, respectively. It is found that the free axial strain occurs because of the pressure difference between the oil and the sea. If the free axial strain is completely restrained, the axial compressive force P due to the pressure and temperature of the pipeline is given by

$$p = p_1 + p_2 = EA\alpha\Delta T + \frac{Apr(0.5-\upsilon)}{t} \tag{3}$$

When the axial compressive force reaches the critical value, the Euler buckling will happen on the pipe. According to the classic beam theory, the governing equation of the pipeline under the axial compressive force can by expressed as

$$EI\,\frac{\mathrm{d}^2 w}{\mathrm{dx}^2} + Pw + \frac{\phi q(4x^2 - L)}{8} = 0 \tag{4}$$

where x is the axial position along the pipeline; w is the lateral displacement; I is the inertial moment of the cross section of the pipe; ϕ is the frictional coefficient between the pipeline and the seabed; q is the intensity of lateral frictional force; and L is the effective length of the buckle. The first buckling mode is schematically shown in Fig. 1. With the increase of axial compressive force, the higher modes of lateral buckling will occur. Within the buckle, the pipe is subjected to the combination of axial compressive force and lateral bending moment. Thus, any longitudinal strain on the outer surface can be rewritten in a compact form.

$$\varepsilon_L = \varepsilon_{comp} + \varepsilon_{bend} \tag{5}$$

where ε_{comp} and ε_{bend} correspond to the compression-induced strain and bending-induced strain, respectively. It is obvious that the appearance of the bending-induced strain indicates the onset of the buckling. Another feature is that the bending-induced strains are zero at both ends of the buckles. Hence the distribution of the bending-induced strain can be used to identify the buckling of the pipe.

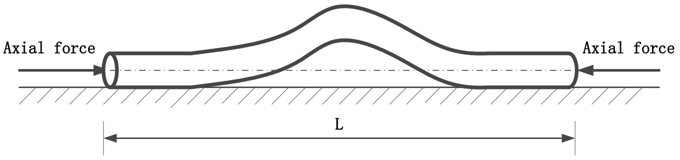
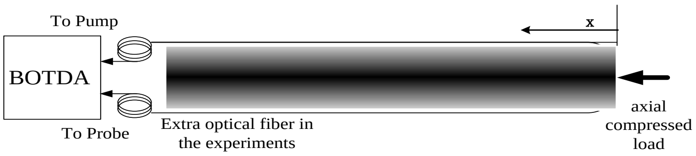


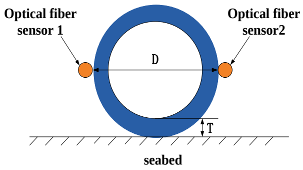
Fig. 1 first mode lateral buckling

2.2 Buckling Detection with Distributed Strain Measurements

In this work, we employ a Brillouin based distributed sensor to monitor the lateral buckling of the pipeline. A single-mode optical fiber was placed on the outer surface of pipe. Strain measurements were continuously and dynamically acquired along the pipe. The strain of the optical fiber can be detected by Brillouin scattering pump-probe techniques. Consider of the practical application of the optical fiber in subsea pipeline, we choose surface mounted configuration. Two optical fibers can be employed as buckling detection sensors. Figure 2(a) shows the attachment of two optical fiber sensors. The cross-sectional view of the optical fiber buckling detector sensor and the model pipe is shown in Figure 2(b). This sensor configuration can measure the maximum longitudinal strains along the pipeline. And then the compression-induced and bending-induced strains are discriminated from the distributed measurements according to Eq. (5).



(a) Attachment of optical fiber sensors



(b) Cross-sectional view
Fig. 2 Sensor locations for distributed fiber optical sensors

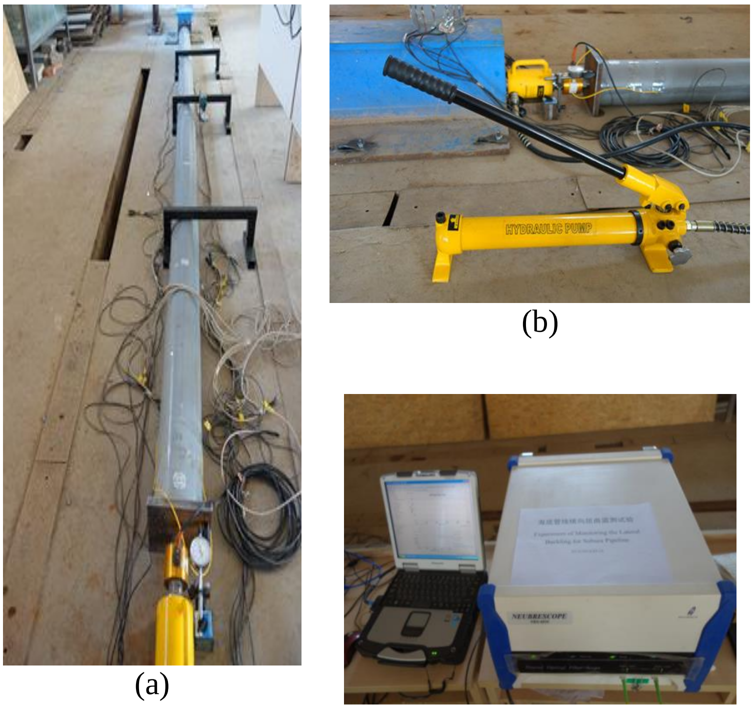
3. EXPERIMENTAL INVESTIGATIONS

We conducted a series of model tests to evaluate the feasibility of the proposed methodology. We used the BOTDA sensor system to monitor the distributed strain and detect the lateral buckling of the model pipe. In this study, we aim to investigate the performance of the detection method, instead of the structural behavior of the prototype pipeline. Hence the similitude between model and prototype was not considered in the experiments.

3.1Experimental Setup

In order to monitor the buckling phenomenon in the effective length as small as possible, we carried out the experiment with a polyvinyl chloride (PVC) pipe with smaller elastic modulus. A 5.47m long pipe with 110mm outer diameter was employed for the experiments. The wall thickness and the Young's modulus of the model pipe are 2.70 mm and 13.77 GPa respectively. The model pipe was fixed with the steel frame disposed along the vertical direction, so as to ensure he pipe's movement in the horizontal lateral direction. Measurements were carried out along the model pipe.

The experimental setup for monitoring lateral buckling of the mode pipe is show in Fig. 3(a). It mainly consists of three units: loading unit, constrain unit, and instrumentation unit. In order to simulate the resistance at the end of subsea pipeline, in addition to the end fixed, two steel boxes were used as end constrains units. A 5 mm deep circle groove, is dug out of each steel plates. Thus the model pipe was inserted into the steel plates at both ends.



(a)

(b)

(c)

Fig. 3 Experimental setup: (a) Model pipe; (b) Hand-controlled hydraulic jack and load cell; (c) Data acquisition instruments based on BOTDA

An axial load is applied at one end of the pipe in the experimental, and the other end of the pipe is fixed. The axial compressive load was applied by a hand-controlled hydraulic jack. Fig. 3(b) shows the hand-controlled hydraulic jack. And thus the axial force applied by the hydraulic jack should be monitored. The test uses a load cell to measure the axial force. The load cell is the full bridge transducer. The measurements were collected by NI compact DAQ.

The axial compressive forces performed on model pipe correspond to five different load cases: 3.6kN, 6.2kN, 7.7kN, 8.8kN, and 13.3kN. A BOTDA interrogation NBX-6050A (Neubrex, Japan) was employed for the tests (Fig. 3(c)). The minimal spatial resolution of BOTDA is 5cm and its measuring accuracy is 20με. In order to obtain more sample points from the uniform bending section, 10cm spatial resolution and 5cm distance resolution were set up. For each loading step, the load was held constantly for 10 minutes before acquiring data. The strains were measured three times automatically by BOTDA at each load level, and the average values were used for the final analysis.

The lateral and axial displacement of the pipe was measured by a laser total station RTS 311L, manufactured by FOIF Inc., China. The laser total station possesses high accuracy of deformation measurement with 0.01mm. Seven targets are set on the pipe in the experiment. The locations are 0.07m, 0.97m, 1.87m, 2.77m, 3.67m, 4.57m, and 5.27m, respectively.

3.1Experimental Results

In this study, for each load cases, the longitudinal strains were measured by the distributed fiber optic sensors. The experimental results are shown in Fig.4 and Fig.5 for the two fiber sensors, respectively. Measurement results for five load cases are aligned together in Fig.4 and Fig.5, in order to provide for a qualitative assessment. The measured results here have been corrected for temperature compensation using the loose optical fiber. We can note that the strain of the pipe grows with a small increment for loads of 3.6kN, 6.2kN, 7.7kN, 8.8kN, and13.3kN in the Fig.4. Meanwhile, the longitudinal strains of Sensor 1 tend to tensile strains with increasing amplitude, whereas the measurements of Sensor 2 approach to the larger and larger negative values. It can be observed that the lateral displacements of model pipe become larger and larger, and the bending behavior appears more and more obvious. The sudden jump of measured strains at the load of13.3KN is contributed to a small fracture in the model pipe. On the whole, the measured longitudinal strains by the distributed sensors can reveal the bending behavior of the model pipe; however, they cannot be used to detect the occurrence and evolution of the lateral buckling. Therefore, the further analysis should be performed on the measured data.

The calculated compression-induced strain and bending-induce ones of five different load cases are plotted in Figs. 6. It clearly demonstrates the progress on lateral buckling of model pipe. Within the buckling lobe, the bending-induced strains measured by Sensor 1 are the tensile strains, whereas those measured by Sensor 2 are the compressive strains. This phenomenon is caused by the lateral deformation of buckling lobe is towards to the negative direction (defined in Fig. 1).

In the case1 and case 2, the axial compressive force becomes larger and provides the driven force to form the lateral buckling. Up to load case 3, the drive force is large enough to create a global lateral buckling on the model pipe. In the load case 4, two zero-crossing points can be clearly found. In a result, the global lateral buckling can be detected by this phenomenon. Based on buckling theory of pipe, we know that this buckle is the first global mode of lateral buckling.

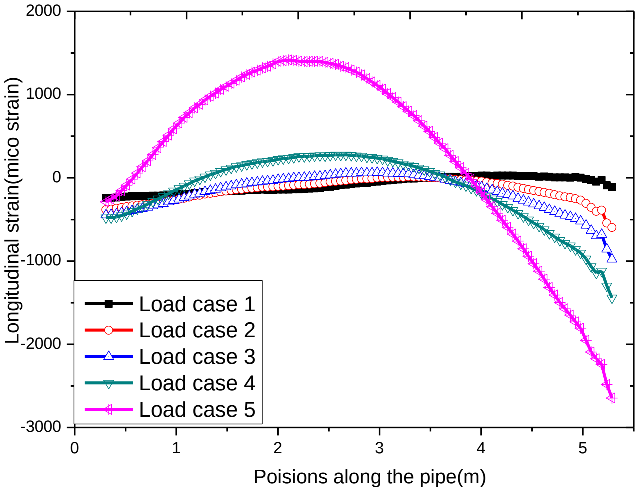


Fig. 4 Distributed measurements of longitudinal strains monitoring by sensor 1 for five different load cases.

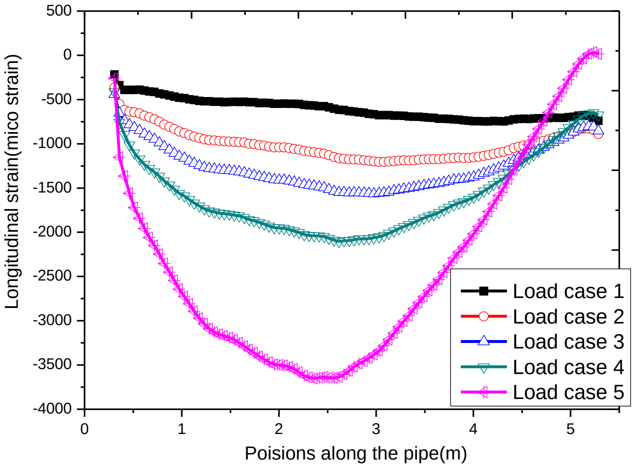
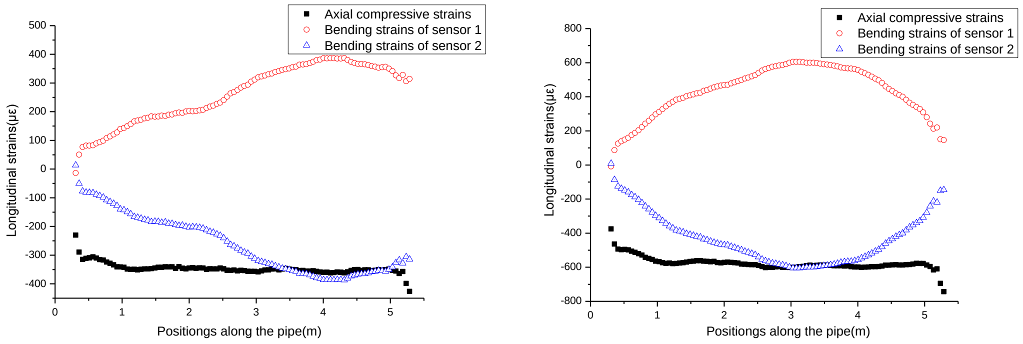
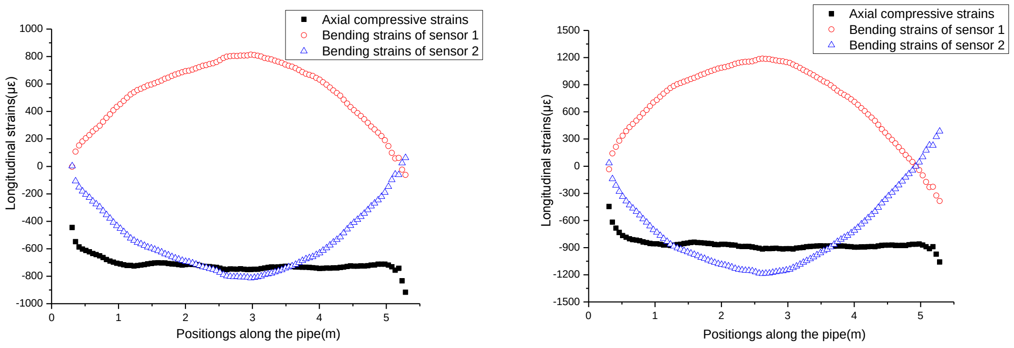


Fig. 5 Distributed measurements of longitudinal strains monitoring by sensor 2 for five different load cases.

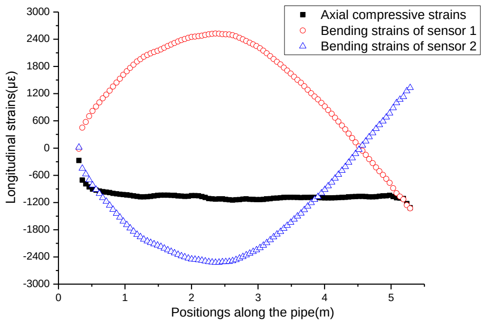
For load case 4, the length of the first mode buckling narrows with the growing of axial force. For the last load case, the bending-induced strains increase further, and the buckling length become narrower. The increase of the axial force tends to form the higher buckling modes, such as the second mode and so on. And hence the buckle length of first mode decreases for these two load cases. From a comparison between the results obtained on the two sensors, the increase of compression-induced strain significantly falls behind the growing of bending-induced strains during the first three load cases. It appears that the bending effect resulted to be much more active to form a new buckle. In the last two load cases, the bending deformation close to the right end of model pipe has the opposite direction to the other parts. If the axial force is larger enough, the second mode of lateral buckling will occur. The fracture observed in load case 5. For this reason, it was not possible to continuously apply the load. However, by comparing compression-induced strains with bending-induce ones, both the pre-buckling and post-buckling behavior of the pipelines can be obtained. Therefore the proposed method can detect the evolution of lateral buckling for pipe structures.



(a) Load case 1 (b) Load case 2



(c) Load case 3 (d) Load case 4



(e) Load case 5

Fig. 6 Calculated compression-induced strains and bending-induce strains

4. CONCLUSIONS

A novel method based on distributed fiber optic sensors was proposed to detect the lateral buckling for subsea pipelines in this study. A set of experimental tests demonstrated the capability of the methodology to identify the occurrence and evolution of buckles. We used the BOTDA system to measure the mode shape of the first lateral buckling mode for the pipe. The distributions of compression-induced strains and bending-induce strains derived from the measured longitudinal strains were reported. The experimental results show that the proposed approach can effectively monitor the lateral buckling for subsea pipelines.

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