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A NEW METHOD FOR INSPECTING THE STATUS OF SUBMARINE PIPELINE BASED ON A MULTI-BEAM BATHYMETRIC SYSTEM

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Key words: Multi-beam Bathymetric System (MBS), submarine pipeline inspection, 3D simulation, parameter optimization.

ABSTRACT

Conventional methods for inspecting submarine pipelines under certain complex conditions are inadequate. A new method for inspecting the status of submarine pipeline based on a Multi-beam Bathymetric System (MBS) that can function under these conditions is proposed to resolve these shortfalls. Dual sonar sensors are employed in this method and the optimization of system parameters is undertaken to allow inspection of the submarine pipeline status in real-time at the Shengli Oil Field in Dongying, Shandong Province. The inspection results are presented in both two- and three-dimensions. Compared with the traditional MBS with a single sonar sensor, our tests indicate that the stability and reliability of the pipeline status inspection data are greatly improved by employing an MBS with dual sonar sensors. The results of the dual sensors, which obtained high-density point cloud data of the submarine pipeline at great depths, are shown visually in 3D simulation and are presented in several ways. Combined with the optimized system parameters, the dual sonar system significantly improves the detection efficiency and allows the actual status of submarine pipe to be determined more precisely. This new method can be extended to practical engineering applications for pipeline status inspections under complex deep-sea conditions.

I. INTRODUCTION

With the increasing development of marine resources in the oil and gas industry, the number of submarine pipelines has increased dramatically. As a result, industry has placed a strong demand for improved submarine pipeline status inspections to monitor their conditions (Posakony and Hill, 1992; Kennedy, 1993; Zhao et al., 2012, Bao et al., 2013). Due to the challenges of the underwater environment including bottom turbulent currents, the submarine pipeline influenced by lateral currents can become exposed which can result in an unsupported state (Yang et al., 2013). If the unsupported span persists, the deformation and internal stress of pipelines can increase dramatically causing pipeline fractures associated with vibration fatigue induced by wave impact (Ronold, 1995; Zhao et al., 2012; Peng et al., 2013). The safety of offshore oil and gas industry are seriously threatened when this occurs. Thus, periodic external inspections are required to ascertain pipeline conditions to prevent risk or damage due to turbulent currents, tidal abrasion or sediment instability (Mousselli, 1981). Recently, an investigation concluded that the failure to conduct pipeline inspections properly was the major factor in the breakdown of an offshore transport pipeline (Tian, 2008). Therefore, there is an urgent need to conduct both a theoretical and an experimental investigation on the inspection of submarine pipelines.

Pipeline inspection surveys have been traditionally performed by a variety of available techniques, such as scuba diving, remotely operated vehicles (ROVs) and acoustic equipment such as the single-beam echo sounder, side-scan sonar and MBS, etc. Of these approaches, scuba diving and ROVs are most widely used for the evaluation of the conditions of submarine pipeline. However, effective light transmission under water is usually limited to a few meters even under the best of circumstances. ROVs connected to the mother ship by an umbilical cable are easily influenced by subsea flow velocity, water quality, and visibility. It is difficult to ascertain the status of a pipeline over a broad area under some environmental conditions (refer to Fig. 4). Similarly, scuba diving is not only limited by poor visibility, but also by limited diving depth and duration. Due to the narrow, low-resolution, and sampled volume across-track of the single-beam echo sounder, only the submarine pipelines directly beneath its transducer can be properly identified and the real conditions of pipeline are difficult to determine in detail. By employing side-scan sonar to completely cover the pipelines, a survey can be accomplished by placing two or more measuring lines on either side of the

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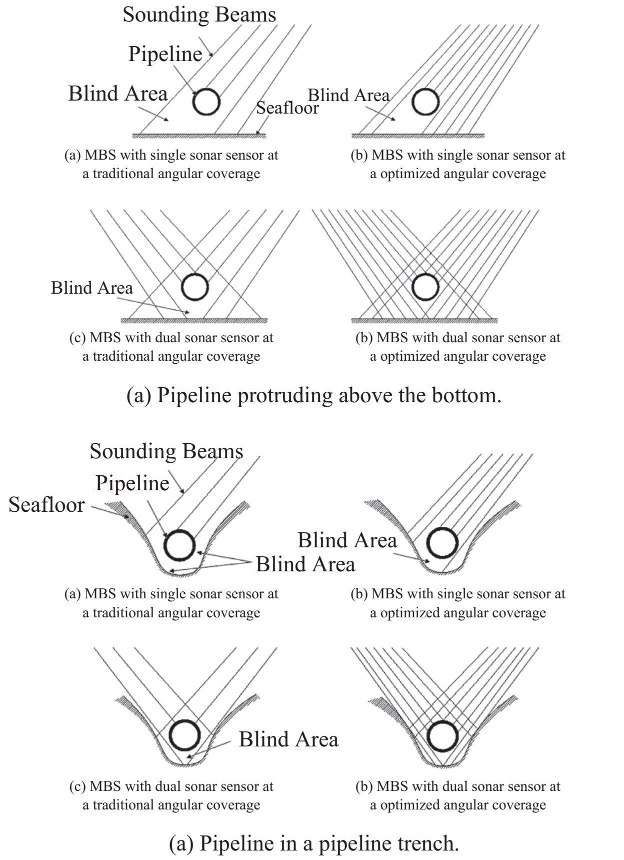


Fig. 4. Blind areas induced by pipeline protruding above the seabed or in a pipeline trench.

pipelines (Peng et al., 2013). As technology has evolved, alternative methods have begun to be utilized for inspecting pipelines. Multi-beam Bathymetric Systems (MBS) are becoming more widely used for pipeline inspection projects because of their ability to provide both a bathymetric map and a backscatter image of the surveyed area.

The MBS can achieve hundreds of beams in a single measurement and a swath by continuous single measurements with an orthogonal line array of hydrophones (Hellequin et al., 2003; Jakobsson et al., 2008; Michaud et al., 2011). Combined with auxiliary units like global positioning system (GPS), sound velocity profiler (SVP), gyrocompass, and motion reference unit (MRU), MBS could cover greater distances and survey seabed topography at high resolution, for improved submarine pipeline inspection (Li et al., 2013; Yang et al., 2013a; Zhao et al., 2014).

Although there are many advantages to using an MBS, given the complexity of the system and the difficulty in access to submarine pipelines and the considerable volume of data collected, there remain a few challenges and obstacles to the effective use of this technique (Wu et al., 2005; Yang et al., 2007; Yang et al., 2013a; Yang et al., 2013b; Zhao et al., 2014): First, there are many errors resulting from the sounding data in real-time survey, and overlapping data at great water depth

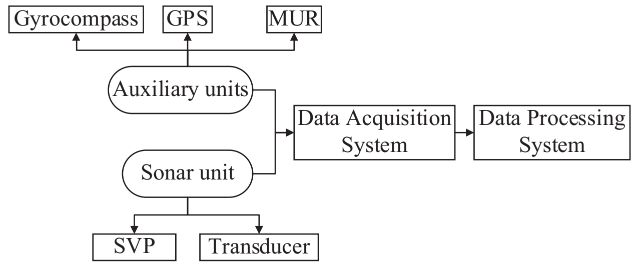


Fig. 1. Basic structure of multi-beam bathymetric system.

may be inconsistent between adjacent strips. Second, since marginal sounding beams diverge, the beam footprint increases with depth and the resolution and reliability of sounding data are strongly influenced by the angular coverage of transducer. This unfortunately restricts the application of MBS. Third, additional factors may alter detection results and can lead to inaccurate judgment of the real conditions in pipeline trenches, such as: water depth, angular coverage of transducer, beam angle, footprint, and vessel velocity. Fourth, considering the large volume of result data, a traditional digital elevation model constructed from scattered and rendered spot elevations cannot reveal the dynamic state of pipelines in real-time. Finally, for MBS application in pipeline inspection, less parameter optimization for different detection objectives compromises mission efficiency and the stability and reliability of detection results.

To meet the needs to allow accurate search for and the inspection and recognition of submarine pipelines, a new method was adapted. This technique, which incorporates the knowledge and practices of underwater acoustical survey and image process, consists of an MBS (Sonic2024 MBS), a GPS, an MRU, a SVP and a sonar data acquisition and processing system. Dual sonar sensors were employed in this system and the system parameters, including angular coverage of transducer and vessel velocity, were optimized to allow a real-time inspection test on submarine pipeline status at the Shengli Oil Field in Dongying, Shandong Province. The main objectives of the present study were to determine the feasibility of using this new methodology for the inspection of submarine pipeline conditions. We compared inspections using an MBS with single sonar sensor or dual sensors to establish an effective and reliable procedure to conduct the inspection and recognition of pipeline conditions. Finally, the inspection results of pipeline status are given in two- and three-dimensions based on highly stable real-time data acquisition and processing system. The use of MBS with dual sonar sensors resulted in a more accurate condition report for submarine pipeline.

II. BASIC THEORY OF MBS

1. Principle of MBS

MBS is a complex and synthetic system which consists of a sonar unit, namely transducer and SVP, a data acquisition and processing system, and some auxiliary units including MRU, gyrocompass, and GPS (Kennett, 1982), as shown in Fig. 1.

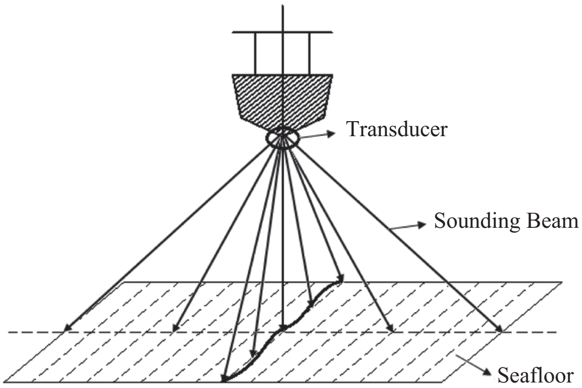


Fig. 2. Principle of multi-beam bathymetric system.

Usually installed on the port or starboard side of the survey vessel, MBS can achieve hundreds of beams in a single measurement and a swath by continuous single measurements with an orthogonal linear array of hydrophones. After bottom reflection and scattering, a beam forming process simultaneously creates numerous receiving narrow beams at different across-track directions (Fig. 2). The returning acoustic signal of each footprint delineated by the beam projection is captured and recorded by the transducer. This spatial filtering allows us to detect echoes coming from adjacent seafloor positions independently. One sounding is accurately calculated inside each beam by simultaneously measuring the beam arrival angle and the echo travel time, according to various estimation methods based on either amplitude or phase. According to the velocity of sound section data, the ability to calculate accurate angle of arrival and travel time translates to an accurate determination of both spatial position of the footprints and the water depth. A high density of sounding points is then generated along the survey swath, and new "pings" are transmitted as the ship moves. Taking into account the ship's navigation and attitude, the data from successive pings are finally gridded together in order to create an accurate geo-referenced digital terrain model (DTM). Complete coverage of precise measurements can be achieved by placing measurement lines on either side of the pipeline and optimizing their spacing.

2. Combined Uncertainty and Bathymetry Estimator (CUBE) Principle

The Combined Uncertainty and Bathymetry Estimator (CUBE) is an algorithm used to generate point-wise estimates of depth from dense soundings (CARIS, 2006a). By building a Dynamic Linear Model (DLM), the CUBE algorithm can determine the most probable depth at any point of the survey area and get as much as possible from the raw data. This process is realized by capturing the measured data, within the node point region and taking into account the distance from the sounding to the node and the base uncertainty of the sounding (i.e., Total Propagated Error (TPE), refer to Fig. 3). Horizontal and vertical uncertainty attached to each sounding were obtained running the TPE computation.

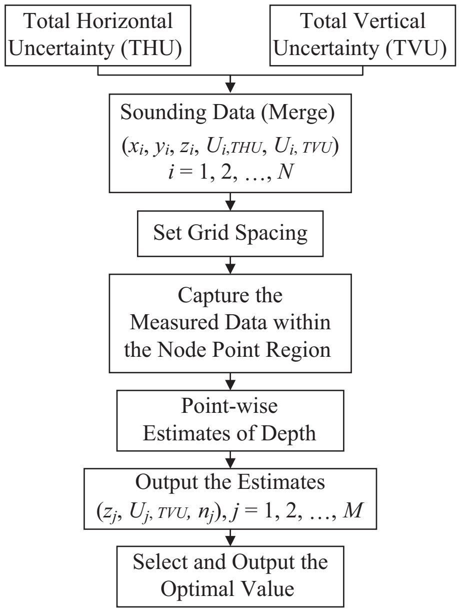


Fig. 3. Estimation model of MBS based on CUBE.

Here, let $\boldsymbol{s}_i = \left(\xi_i, \sigma_{H,i}^2, \sigma_{V,i}^2\right)^T$ be the depth, the vertical and horizontal uncertainty attributes associated with the input sounding (at its original location) and then the predictive information of the j-th node point of the grid can be given as: (Vásquez, 2007)

$$\boldsymbol{e}_j[i] = \left[d_{ij}, \sigma_{ij}^2\right]^T = \left[\xi_i, \sigma_{V,i}^2\left(1 + \left(\frac{\delta_{ij} + s_H\sigma_{H,i}}{\Delta_{\min}}\right)^{\alpha}\right)\right]^T \quad (1)$$

Where d_{ij} and σ_{ij} are the depth and measured variance of j-th node point predicted from the information of the i-th sounding point respectively. δ_{ij} is the distance from the sounding location to the node. s_H is the horizontal error scale. $\Delta_{\min}$ is the distance between nodes. α is the distance exponent.

Assuming that the estimation of the node's depth is $\zeta_j[n] = \left(\tilde{z}_j[n|n], \tilde{\sigma}_j[n|n]\right)^T$, where $\tilde{z}_j[n|n]$, $\tilde{\sigma}_j[n|n]$ are the estimation of the node's depth and the propagated error of the nth sounding point for the j-th node, respectively. The updating can be obtained by iteration. Thus, when a new sounding point is input, the updated estimated of the current node point can be obtained according to the depth and uncertainty attributes associated with the last node point and the precision of the depth and uncertainty attributes will be improved with more sounding data points.

Due to the influence of the angular coverage of transducer, the returning acoustic signal intensity of marginal sounding beams is affected by attenuation due to sound absorption through the water column. The returning acoustic signals consist of reflected waves in the central beam and gradually transform into scattering waves in marginal beams. Thus, the returning acoustic signal intensity decays quickly so that it cannot provide sufficient backscattered acoustic energy to the receiving transducers to allow detection of the object. This subsequently results in large errors and numerous detection blind spots and even some blind areas in the sonar images. Because of this, the conventional method cannot provide the high resolution needed for imaging seafloor backscatter with a sufficient amount of detail. Compared with traditional inspection, the dual-sensor system proposed here enhances beams echo signal density to significantly improve the quality of beams and enhance the resolution and the ability of small target recognition.

III. THE OPTIMIZATION PROCEDURE

Optimization to determine the real conditions of objects on the seafloor such as pipelines using an MBS involves four interdependent components: object dimensions, inspection hardware, field operation and environmental factors. An effective and optimized MBS should incorporate these conditions and must additionally take into consideration the following three requirements (Simons and Snellen, 2009; Tian, 2011): the detectability of the objects, the resolution of the MBS, and the quality of the inspection results.

The status of a pipeline (either exposed, unsupported, buried or partially-buried) are recognized by obtaining the pipe diameter and determining the difference in water depth between the top of the pipe and the seafloor. However, marginal sounding beams diverge with water depth and incident angle. In situations where the pipeline protrudes above the bottom or is located in a pipeline trench, sounds may be prevented from reaching the sea floor (Fig. 4). This will produce some acoustic blind spots and zones which appear on the record as a blank area. Due to these blind spots, a target's dimensions and the accurate distance that the pipeline is unsupported beyond the seabed cannot be identified visually. Therefore, optimization methods are needed to overcome these problems.

Parameters affecting the inspection on pipelines include swath scale (i.e., angular coverage of transducer), vessel speed, and beam angle (system performance). Other parameters over which the operator exercises control include angular coverage of transducer and vessel speed.

1. Optimization of Angular Coverage of Transducer

Factors that can influence the performance of MBS include water depth, angular coverage of transducer (incidence angle), and vessel velocity (Simons and Snellen, 2009; Zhao et al., 2014). Resolution of the MBS has a large influence on the quality of the inspection results. Operational factors which control the resolution of MBS include frequency, size of footprint, pulse width, ambient noise, sweeping width, and vessel speed (Zhuet al., 2010). With increasing depth, marginal sounding beams become divergent and the spacing of adjacent beams increases unevenly. Because the beam footprint increases with depth and incident angle, footprint size plays an important role in spatial resolution of MBS. Although the width of the measurement becomes positive with a bigger angular coverage, the spatial resolution decreases. The spatial resolution of MBS is given by (Wu et al., 2011):

$$\begin{cases} \sigma_x = H\left(\beta\pi/180\right) \\ \sigma_y = \dfrac{H\left(\alpha\pi/180\right)}{\cos^2\theta} \\ \sigma_z = \dfrac{ct}{2\cos\theta} \end{cases} \tag{2}$$

Where α and β are the beam angles in lateral and longitudinal respectively; H is the water depth directly under the transducer; θ is the incident angle; c is the velocity of sound; and t is time difference between edge pulses of a beam in the horizontal direction for submarine pipeline inspection with MBS, angular coverage of transducer optimization problem is neglected for most inspections. Due to lateral resolution, σ_y, the determination of pipe diameter is controlled by factors such as water depth, incident angle, and lateral beam angle. The resolution is inversely proportional to the angular coverage (i.e., swath width to depth ratio). There is a trade-off between spatial resolution and swath width that can be correlated to produce detailed information for inspection efficiency and results. A smaller angular coverage provides a negative width of measurement and causes low efficiency inspection. With a larger angular coverage, MBS can scan a larger area of the seafloor and have a satisfactory inspection efficiency but compromises both the resolution and the results of inspection. An ideal condition would possess the advantages of both approaches. Hence, the swath width used in MBS surveys is very important and should be selected with forethought during the operational planning stage. With a proper width to depth ratio of survey measurement, angular coverage optimization should be required to meet the high efficiency inspection and the stability and reliability of inspection results. Taking the lateral resolution of MBS as the footprint width of edge beam whose incident angle is, in order to make the edge beam recognize target compound, should be less than the pipe diameter as follows:

$$\sigma_y \le D \tag{3}$$

With Eq. (1):

$$\cos\theta_{\max} \ge \sqrt{\frac{H\left(\alpha\pi/180\right)}{D}} \tag{4}$$

The relationship between critical angular coverage and pipe

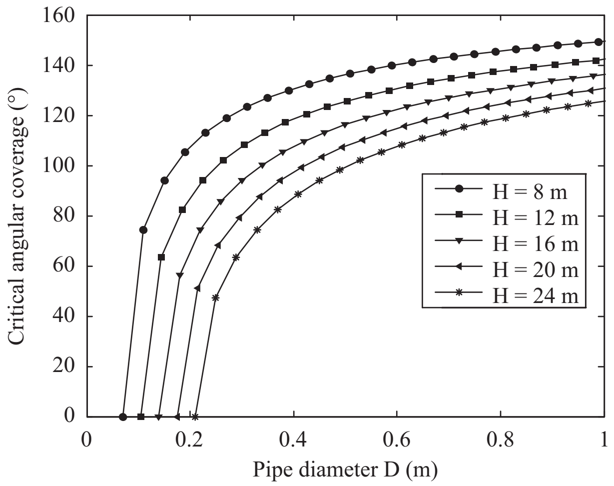


Fig. 5. Critical angular coverage vs. pipe diameter at different water depth.

diameter is shown in Eq. (3). There is a trade-off in increasing the separation of the factors as shown in Fig. 5. With a fixed fine spatial resolution, critical angular coverage is inversely proportional to depth and directly proportional to pipe diameter. Thus, according to the detection efficiency and width depth ratio of survey measurement, the range of optimal angular coverage can be determined such that both the wide coverage and increased number of echo signals can be obtained.

2. Optimization of Vessel Velocity

In order to ensure the adjacent beam bands, real-time survey should be connected along the ship track and the time interval between them must be sufficient to allow the transducer to receive the echo signal of edge beam (Wu et al., 2011). Echo time t is given by:

$$t = \frac{2H}{c\cos\theta_{\max}} \quad (5)$$

According to the longitudinal resolution of MBS, the vessel velocity can be described as:

$$v \leq \frac{\sigma_x}{t} = \frac{\beta\pi c\cos\theta_{\max}}{360} \quad (6)$$

Results from the parametric study can be summarized as follows. First, the critical angular coverage can be inversed according to the size of detecting objective and water depth. In addition, the inspection efficiency can be used to determine the range of optimal angular coverage and the optimal detection effect can be obtained by adjusting the angular coverage. Second, according to the optimal angular coverage, the optimal vessel speed can be set in order to capture more echo signals. Based on these parameters, the quality of marginal sounding beam will be improved. Furthermore, by reducing the influence of angular coverage, the efficiency of the inspection and the quality of the results will be maximized.

Table 1. Results of parameters calibration.

	Latency (s)	Roll (°)	Pitch (°)	Yaw (°)
Calibration	0.00	-0.37	0.49	0.00

IV. EXPERIMENTS AND ANALYSIS

For the purpose of effective inspection and determination of the real conditions of the pipeline at the Shengli Oil Field in Dongying, two phases of field MBS inspecting operations were conducted, calibration surveys and detailed surveys.

In an ideal situation, the coordinates of the ship hull, transducers and MRU should be coincident and the heading for ship and gyrocompass should be parallel. In practice, these conditions cannot be easily achieved. Therefore, the purpose of the calibration surveys is to modify the parameters such as latency, roll, pitch, and yaw in order to reduce errors during installation. In addition, calibration must ensure that the proper MBS settings are obtained. In this way, an operator may exercise control and ensure that the search for and identification of the pipeline status for the subsequent surveying operations is achievable (i.e., detailed surveys).

Detailed surveys are conducted to detect and recognize the pipelines, tag their locations with GPS coordinates individually, and evaluate their real status in the defined area. Therefore, the priority at this phase is to produce detailed information with proper feature resolution of MBS for the detection and recognition of the objects. In addition, information such as water depth and submarine topography can also be collected by the MBS system.

1. Calibration Surveys

To meet the necessity of inspecting, recognizing and detecting the real conditions of pipeline, a series of MBS calibration surveys were conducted at a specific site near the Shengli Oil Field. The average water depth of the test site was 20 m. Two coincident survey lines were chosen to calculate latency. The errors of roll were measured with the same survey line where the survey vessel travelled in the opposite direction at a same speed (8 knots). The test site was a flat seabed area. The same method was adopted to measure the errors of pitch at an area where the water depth was changing greatly and the errors of yaw were measured with two survey lines with a spacing of about two-thirds of the swath width.

Several sets of survey data were obtained. The velocity of sound section and tide data were recorded. The results of the calibration are shown in Table 1.

2. Parameter Analysis

In the case study presented here, the pipeline at the Shengli Oil Field in Dongying, Shandong Province was inspected. The pipe diameter D is 245 mm and pipeline length is 619.15 m.

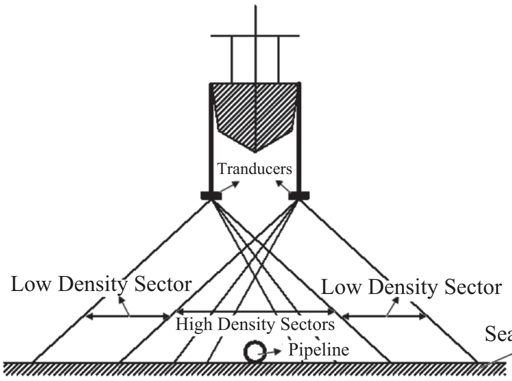


Fig. 6. MBS with dual sonar sensors.

The study area is a shallow area at a depth ranging between 12.4 m and 14.8 m and averaging 13 m. The survey ship is 18 m long and 4 m width, draft 1.0 m.

As spatial resolution of MBS has great influence on the inspection efficiency and quality, one of the early steps in inspecting the pipeline is the calculation of the design angular coverage of transducer and vessel velocity. Typically in pipeline inspections, the angular coverage of transducer and ship velocity are set by experience. For submarine pipe under different environment conditions, the parameters remain constant, making the stability and reliability of the pipeline status detection data poor. In light of these, according to the pipe size, water depth of inspection region and spatial resolution of MBS, parameter optimization was undertaken before the inspection tests. In these tests, an MBS with dual Sonic2024 sonar sensors as illustrated in Fig. 6 was employed for the inspection. Two sets of tests were carried out as follows:

(1) by controlling the working states of the sonar sensors, single and dual sonar sensors system could be activated. These systems were used for pipeline inspection tests at the same angular coverage.
(2) By adjusting the angular coverage, MBS with single and dual sonar sensors were used respectively at two different angular coverage and the results obtained were analyzed based upon how the angular coverage can affect the observed results.

According to the pipe diameter and average water depth, the critical angular coverage calculated by Eq. (3) is 105°. In order to ensure the edge of the beam reaches the pipe, the angular coverage optimal value should be less than 105°. Because a too small angular coverage will compromise the inspection efficiency, the set value is reduced by about 20%. Sonic2024 sonar sensor has a maximum swath of 160°, 10°~160° online continuously adjustable and the angular coverage is usually set at 130° for pipeline inspection. Based on these parameters, the angular coverage was set at 130° and 80° in this study. The corresponding vessel velocity was calculated at 13.2 knots and 20.6 knots. Ideally, the survey ship should be moving perfectly straight at constant speed. However, in practice this can never be achieved. Since vessel velocity is not considered in this study, the ship velocity was set at about 5 knots, providing acceptable data density and quality.

3. Data Acquisition and Data Processing

Based on the detailed surveys, both sonar data and the coordinates were integrated using a data acquisition system and a data processing system to form a three-dimensional flight simulation, geocoded sonar imagery, and point cloud data. The flight simulation allows us to recognize the condition of the pipeline intuitively in real time. The geocoding sonar imagery and point cloud data allow us to assign the absolute geographical locations and accurately determine the real condition of pipeline.

In the case study presented here, two Sonic2024 sonar sensors were simultaneously used for pipeline inspection. The Sonic2024 can operate with multiple working frequencies of 200 kHz, 300 kHz, and 400 kHz, and has a maximum depth of 500 m. It has a maximum number of soundings of 256 and a maximum swath of 160°, 10°~160° online continuously adjustable, vertical resolution of 12.5 mm and acoustic beam width of 1.0° by 0.5°. The latter has a major influence on the area of the seafloor surveyed by each beam (beam footprint), and it meets the IHO international hydrographic sounding precision premium standards. In order to avoid mutual interference between two sensor signals, the two Sonic2024 sonar sensors must operate with different working frequencies so we used 200 kHz and 400 kHz. Because the target of the new method presented herein is the status of submarine pipelines, different frequencies of the dual sensor system have little impact on the test.

Survey positioning was provided by the onboard differential global positioning system (DGPS), with precision of ±1 m at 95% probability. The attitude and heading for the ship were measured by the MRU and Octants. The absolute geographical coordinates of the ship were then provided by incorporating both datasets through an integrated positioning system. Combining the SVP and tide data, the footprints of each beam could be calculated exactly by real-time data acquisition system EIVA and data processing system CARIS.

The GPS signal was received and collected by the measuring software HYPACK and then input into the data acquisition system of MBS after transformation. Integrating the transducer and some auxiliary units such as the MRU, the SVP and the gyrocompass, real-time data acquisition was realized by EIVA.

Complex ocean conditions can complicate the MBS survey, resulting in noisy data. Thus, before processing the measured data, the data gathered by these sensors was pre-processed to remove errors and improve the accuracy. The data processing system CARIS/HIPS was used here and the details of the procedure for the processing of dual sensor system data can be summarized in three steps: (CARIS, 2011) (1) Data pre-processing; (2) Data post-processing; (3) Build the digital geographic model (DTM). (Fig. 7):

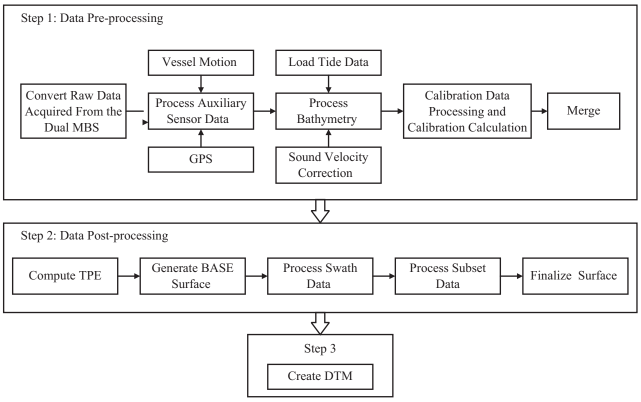


Fig. 7. Data processing flow of MBS with CARIS/HIPS.

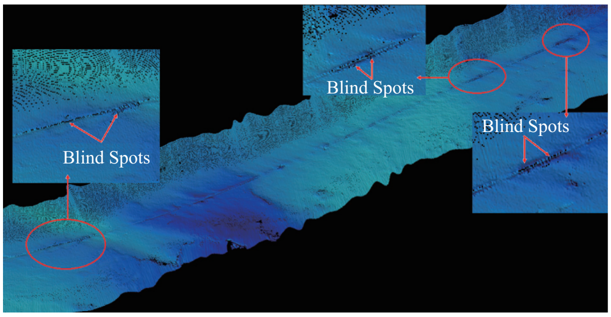


Fig. 8a. Inspection result of MBS with single sonar sensor at 130° angular coverage.

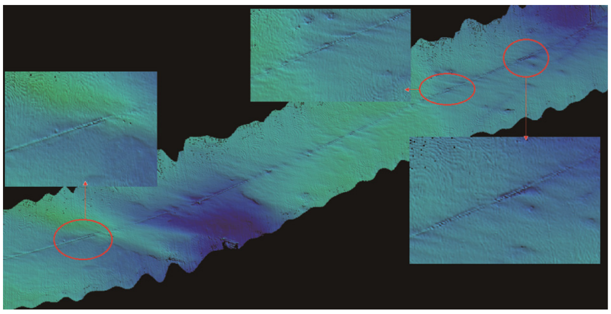


Fig. 8b. Inspection result of MBS with dual sonar sensors at 130° angular coverage.

Step 1: Data Pre-Processing

First, raw data files were converted to data processing system format and we calculated the deviations of the MBS transducer in the heading, roll and pitch directions according to the calibration data. Next, we removed the noise and errors in the massive data with both interaction platform and automatic clearance technology, such as auxiliary sensor data, tide measurement, sound speed measurement, bathymetry data, and data merge to reduce errors and improve the reliability of the data. To avoid incompatibility of the raw data, we processed the data and calculated the calibration which is critical to merge the data using the specialized software CARIS/HIPS.

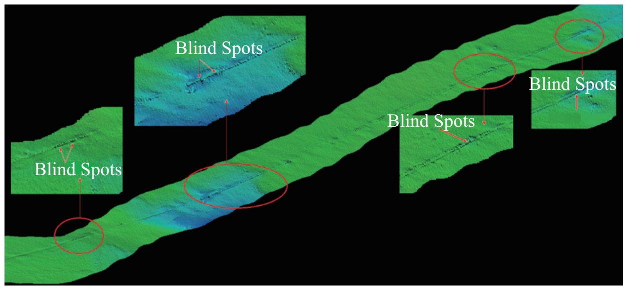


Fig. 9a. Inspection result of MBS with single sonar sensor at 80° angular coverage.

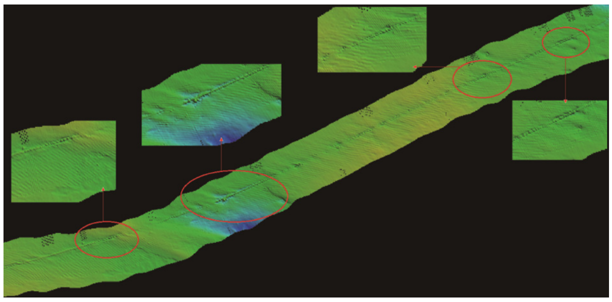


Fig. 9b. Inspection result of MBS with dual sonar sensors at 80° angular coverage.

Step 2: Data Post-Processing

We next computed the TPE values according to the vessel configuration. TPE values are necessary to run CUBE. Finally, the results are stored and presented in a CARIS BASE (Bathymetry with Associated Statistical Error) surface which is a geo-referenced image of a multi-attributed, weighted-mean surface. (Vásquez, 2007).

Step 3:

We then created the digital geographic model (DTM) and exported the finished soundings to a CARIS map or other format.

4. Inspection Results and Discussion

The quality of the sonar results plays an important role in the accurate detection and recognition of objects on the seafloor. Based on the data acquisition system of MBS and the auxiliary units, the status of submarine pipeline and the seabed were inspected in real-time and dynamically rendered. The results were displayed in a three-dimensional flight simulation with accompanying digital video, which revealed directly and in real-time the condition of the pipeline. As shown in Figs. 8a, 8b, 9a and 9b, the inspection results were interpreted in 2D using the data processing system CARIS/HIPS. Additionally, the point cloud data (Figs. 10~17) provided subtle information such as whether the pipeline was exposed, buried, or unsupported and its corresponding value.

Comparison of the inspection results of the MBS with dual sonar sensors (Fig. 8b), Fig. 8a indicated that the quality of

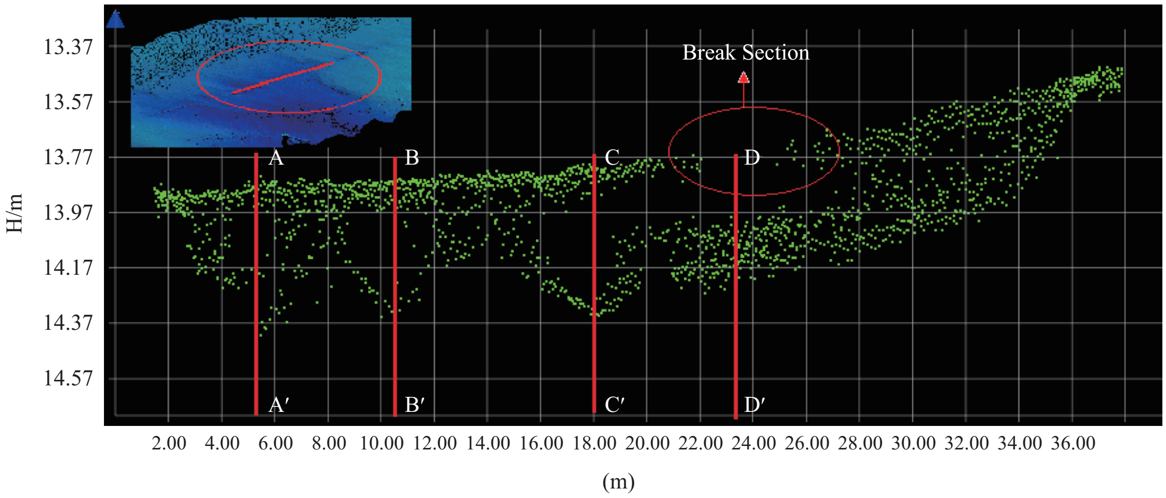
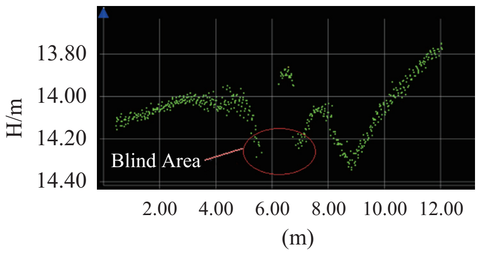
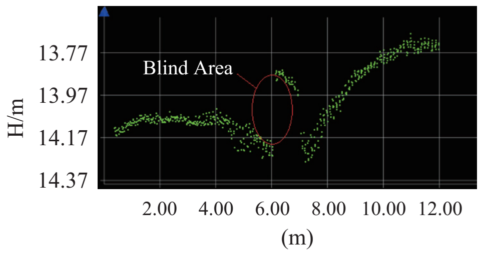


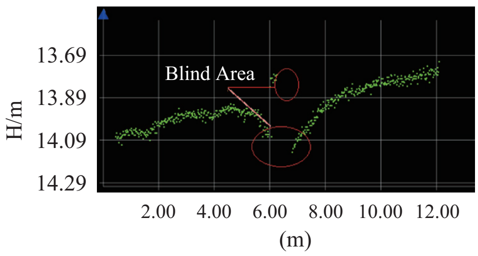
Fig. 10. Point cloud data of MBS with single sonar sensor along the direction of pipeline at 130° angular coverage.



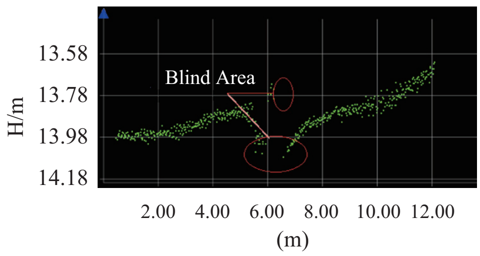
(a) Point cloud data of A-A′ cross section of pipeline.



(b) Point cloud data of B-B′ cross section of pipeline.



(c) Point cloud data of C-C′ cross section of pipeline.



(d) Point cloud data of D-D′ cross section of pipeline.

Fig. 11. Point cloud data of different cross section of pipeline in Fig. 10.

marginal sounding beams by MBS with single sonar sensor was poor at the angular coverage of 130°. Typically, the measuring lines cannot be arrayed compatibly with the trace of pipeline. Therefore, MBS with single sonar sensor can only sweep the side of the pipeline which faces the incident beams. The opposite side of the pipeline is missed and appears on the record as blind spots and blind areas. As shown in Fig. 8a, the target pipeline shows a clear deviation from the region of high density beams leading to numerous detection blind spots including in the pipeline trench, which results in poor quality of data and unstable inspection results. In addition, it is difficult to recognize whether the small diameter pipeline is exposed or unsupported. Hence usually two or even more measuring lines need to be placed on either side of the pipelines and several inspections need to be taken on one pipeline. Unfortunately, the inspection efficiency is decreased as errors are increased in this case.

However, the inspection using an MBS with dual sonar sensors at the angular coverage of 130° produced a high-quality accurate high-resolution result. As shown in Fig. 8b, a higher density of beams obtained by dual sonar sensors improves the quality of marginal sounding beams. Due to the elimination of areas with blind spots, more subtle information of pipeline condition (buried, exposed or unsupported) was obtained. Furthermore, the results were achieved with a lower number of measuring lines and higher efficiency and the data

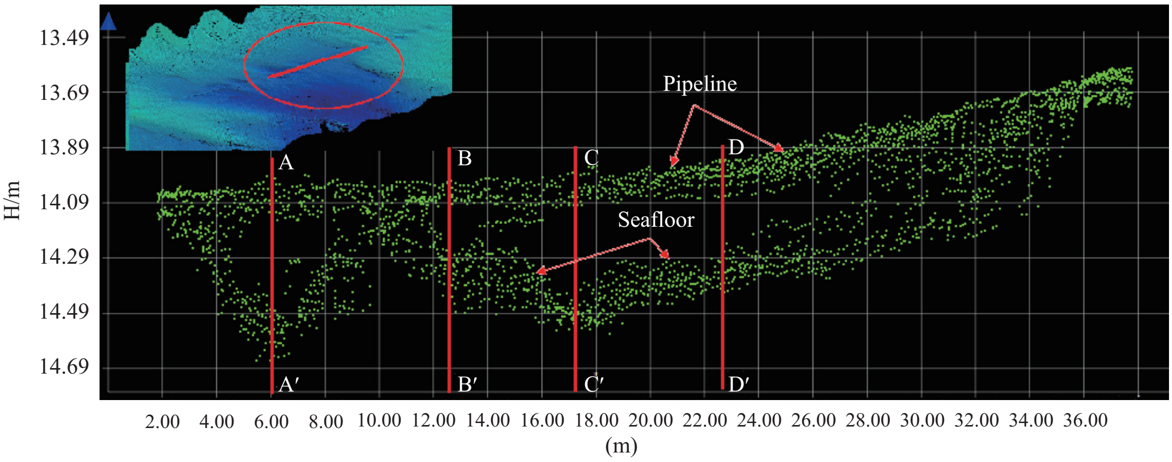
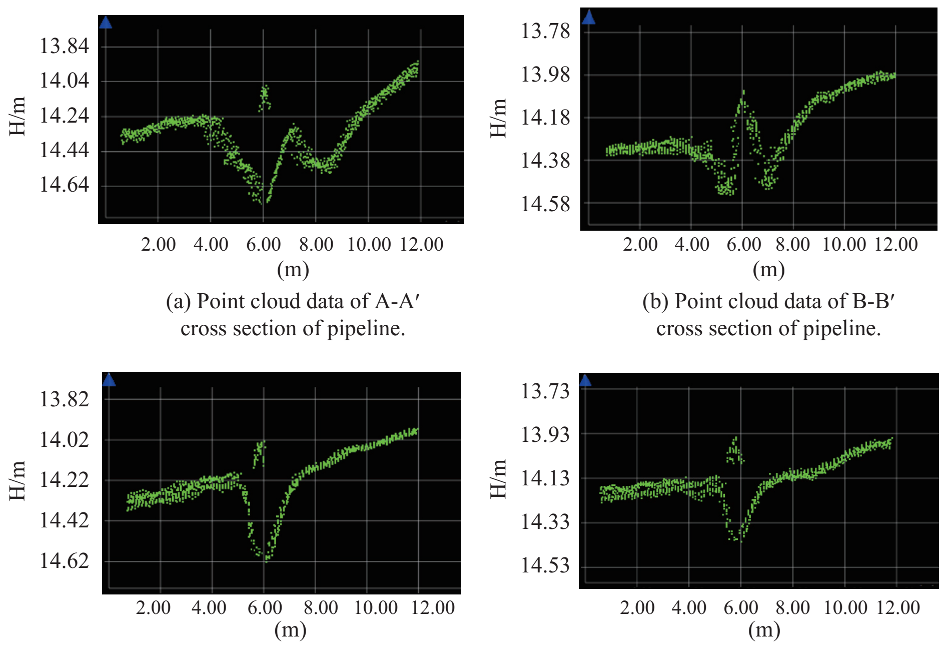


Fig. 12. Point cloud data of MBS with dual sonar sensors along the direction of pipeline at 130° angular coverage.



(a) Point cloud data of A-A′ cross section of pipeline.

(b) Point cloud data of B-B′ cross section of pipeline.

(c) Point cloud data of C-C′ cross section of pipeline.

(d) Point cloud data of D-D′ cross section of pipeline.

Fig. 13. Point cloud data of different cross section of pipeline in Fig. 12.

combination problem between adjacent strips were resolved.

After optimizing the angular coverage of transducer, the inspections using MBS with single and dual sonar sensors at the angular coverage of 80° (Figs. 9a and 9b) are characterized by stable and accurate data. Thus, the results for both were evidently improved. In comparison, the results of the inspection using MBS with single sonar sensor resulted in blind spots as indicated as black areas in the image. Thus, MBS with dual sonar sensor could detect conditions of submarine pipeline more accurately with no blind spots.

Inspection results using MBS with single and dual sonar sensors at 80° and 130° angular coverage were also compared. As shown in Figs. 8a and 9a, the comparison reveals that the angular coverage of transducer has a great influence on MBS with single sonar sensor and allows better detection and more reliable data using a smaller angular coverage. For MBS with dual sonar sensors, the influence of angular coverage is not significant, however, a smaller angle can improve results.

In contrast to the data shown in Figs. 8a, 8b, 9a and 9b, a region which is 36.5 m along the direction of pipeline and 1 m width was chosen to cover the pipeline (the sample at left corner in the Figs. 10, 13, 14 and 16). The point cloud data of part of the pipeline for each situation in this region are shown in Figs. 10, 12, 14 and 16. In order to reveal the feature of each method, four typical cross sections (11.5 m and 1 m) at the same locations were chosen as shown in Figs. 11, 13, 15, 17.

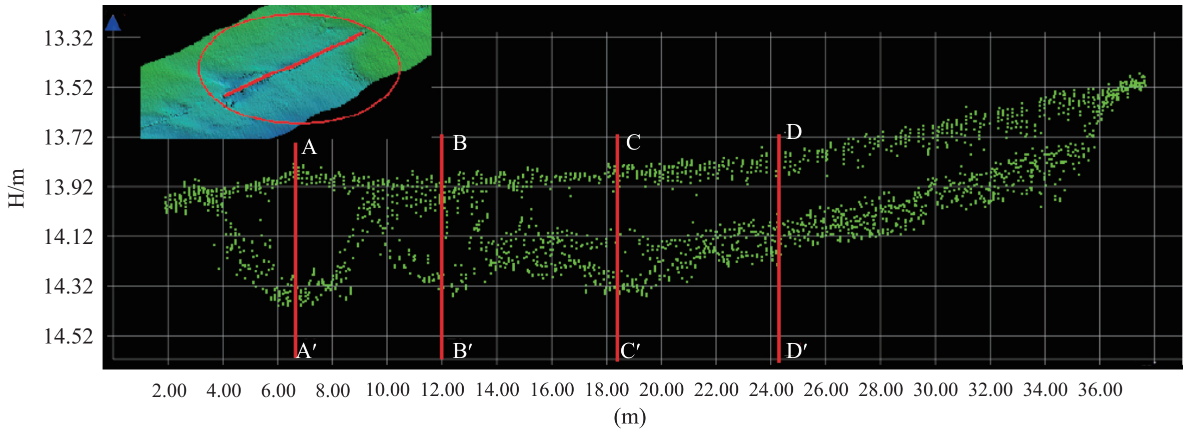


Fig. 14. Point cloud data of MBS with single sonar sensor along the direction of pipeline at 80° angular coverage.

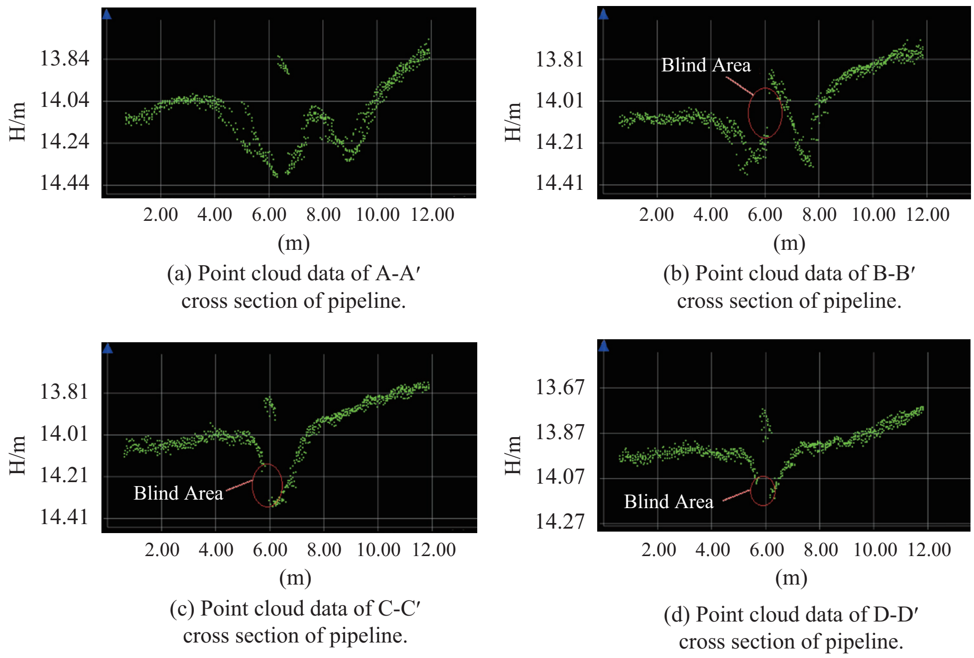


Fig. 15. Point cloud data of different cross section of pipeline in Fig. 14.

Each point cloud dataset was compared, namely cross sections A-A′, B-B′, C-C′, D-D′.

As shown in Fig. 10, due to the deviation from the region of high-density beams and 130° angular coverage, sparse point cloud data were obtained, resulting in many blind spots and areas. This negative result is clearly indicated in Fig. 11. Each cross section point cloud data indicates this part of the pipeline is unsupported or exposed in the pipeline trench. Because the marginal sounding beams diverge, the bottom of the trench cannot be seen (indicated as a blind area in Fig. 11) and the depth of the pipeline trench cannot be determined. Based on this, it is only possible to determine if the pipeline is buried or not. The more subtle information, such as whether the pipeline is exposed or unsupported and the exact value it was unsupported, cannot be determined accurately. By optimizing the angular coverage of transducer, the problem is only partially resolved, as shown in Figs. 14 and 15. Although the stability and reliability of the pipeline status inspection data were greatly improved, it is still difficult to extract accurate information in all situations. In some cases, such as section D-D’ in Figs. 11 and 15, the real condition of pipeline is not completely obvious. In conclusion, the traditional method for determining pipeline condition falls short.

As shown in Figs. 12 and 16, the MBS with dual sonar sensors can achieve high-density beams at both 130° and 80° angular coverage, allowing more stable and reliable pipeline status detection data. According to the four cross sections point cloud data in Fig. 13, the pipeline condition could be classified as unsupported, partial buried, unsupported, or exposed (cannot be recognized accurately) and exposed with the exact value of

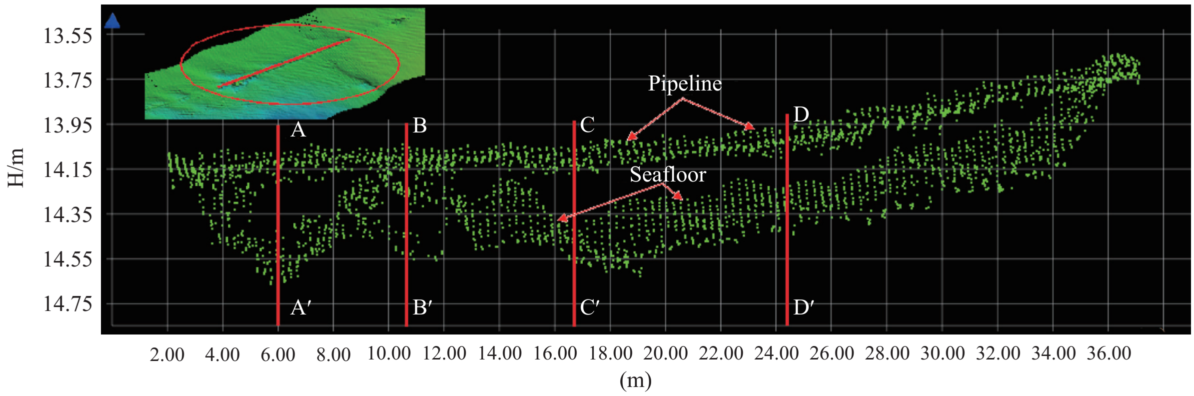
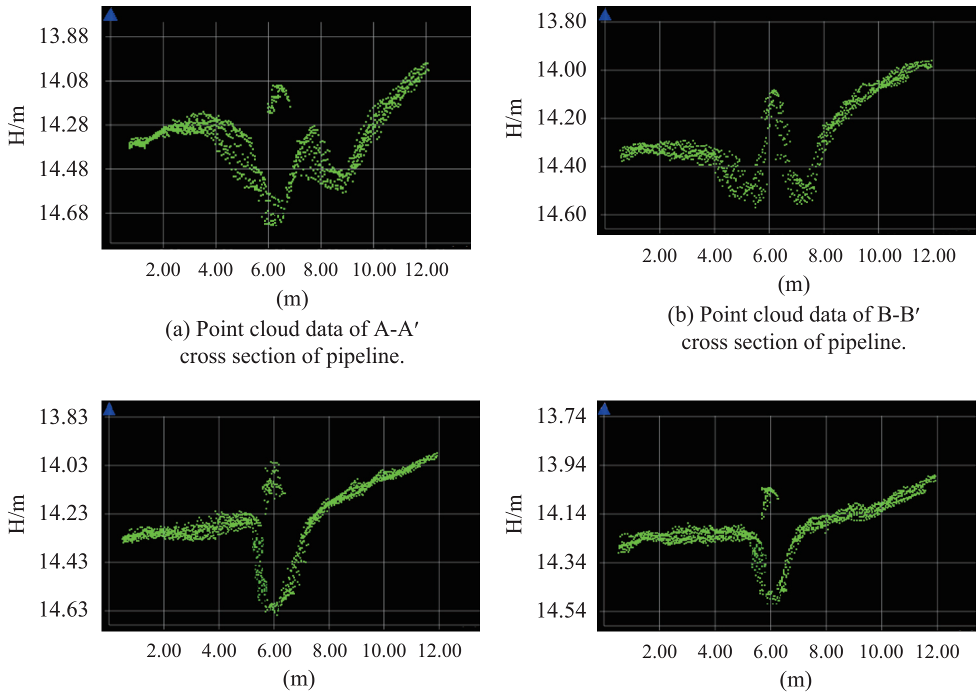


Fig. 16. Point cloud data of MBS with dual sonar sensors along the direction of pipeline at 80° angular coverage.



(a) Point cloud data of A-A′ cross section of pipeline.

(b) Point cloud data of B-B′ cross section of pipeline.

(c) Point cloud data of C-C′ cross section of pipeline.

(d) Point cloud data of D-D′ cross section of pipeline.

Fig. 17. Point cloud data of different cross section of pipeline in Fig. 16.

the unsupported at section A-A' length being 0.2 m. However, by optimizing the angular coverage, the pipeline condition can be determined to be unsupported, partial buried, exposed and unsupported accurately as shown in Fig. 17 and the exact value of the unsupported at cross section A-A′ and D-D′ was determined to be 0.13 m and 0.05 m, respectively. By employing dual sonar sensors in the new method, the high-density sounding beams reach at the pipeline from more incident angles. In addition, even the bottom of pipeline trench appears on the record as continuous point cloud data, and the exposed and unsupported pipeline can be seen completely with the accurate value of unsupported length accurately determined.

Compared with the traditional MBS with single sonar sensor, the MBS with dual sensors can provide high-density point cloud data and more detailed information of submarine pipeline. Parameter optimization based on the target pipe, water depth and inspection efficiency should be considered for future modifications and improvements of this technique.

V. CONCLUSIONS

In this paper, a method for submarine pipeline status inspection based on an MBS with dual sensors is proposed. A real-time inspection test on submarine pipeline status was conducted with the new method and compared with traditional methods. By optimizing system parameters, the results of inspection were compared visually. Compared with traditional MBS with single sonar sensor, the proposed method exhibits many potential advantages as follows:

(1) By employing MBS with dual sonar sensors, the errors resulting from overlapping water depth data were reduced making it is easier to splice the data between adjacent strips and significantly improving the efficiency of inspection and data processing. In addition, high-point cloud data provides high resolution and reliability of sounding data, especially for the marginal sounding beams. Blind spots and areas as well as break sections typically associated with traditional MBS inspection methods are obviously resolved by this new method.
(2) Analysis of the results of the two sets of inspection tests indicates that the angular coverage of transducer has a large influence on the inspection results compared with those of traditional MBS with single sonar sensor. By optimization of the angular coverage of the transducer, the stability and reliability of the pipeline status detection data can be greatly improved.
(3) Considering the large volume of data, the inspection results of submarine pipeline status are described in 2D and 3D. The submarine pipeline status are described visually in 3D simulation and expressed simultaneously in several ways. These allow the submarine pipeline status to be inspected in real-time and dynamically rendered, allowing effective visualization in real time.
(4) Considering the size of the objective and water depth, the quality of the inspection using an MBS with dual sonar sensors can be additionally improved. The quality of marginal sounding beams can be improved to allow collection of more stable and reliable detection data. Although high-density point cloud data can be obtained with a smaller angular coverage by an MBS with single senor sensor, the inspection efficiency will inevitably be decreased. By employing an MBS with dual sonar sensors and optimizing the system parameters, both inspection efficiency and high-density point cloud data are obtained simultaneously. As a direct result of the improved system presented herein, the real-time condition of deep sea pipeline can be accurately determined, thereby providing improved value for practical engineering applications.

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