Electromagnetic ultrasonic guided wave long-term monitoring and data difference adaptive extraction method for buried oil-gas pipelines

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Abstract— An increasing number of buried oil-gas pipelines are generated in recent years and defects occur with higher probability in their long-running process. This work proposes an electromagnetic ultrasonic guided wave (EUGW) long-term monitoring scheme for buried oil-gas pipelines and a data difference adaptive extraction method for the monitoring data. The T (0,1) mode guided wave is selected because of its non-dispersive characteristic. For the electromagnetic acoustic transducer (EMAT), a circumferentially magnetized nickel strap is bonded on the pipe to provide the bias magnetic field and the excitation coils are winded on the nickel strap to provide the dynamic magnetic field. A detection stub is planted on the ground and the connector of buried coils is installed in the stub. The difference array is constructed and adaptive gain and attenuation are performed in the data difference adaptive extraction method. The EUGW long-term monitoring scheme is on-site applied for buried oil pipes in Jinan city, Shandong province, China. The EMAT is installed and buried with the pipe, and the periodical detection is conducted from December 2015 till now, once per month. A pit is found and verified by excavation at the distance 9.25 m from the buried EMAT on the flow direction. On-site detection results show that the data extraction method can dramatically improve the signal to noise ratio of the monitoring data and accurately extract the difference and variation of the pipe's structural health condition that occurred in the long-term service. The EUGW long-term monitoring scheme is proved to be a feasible method with prosperous prospect for the structural health monitoring of buried oil-gas pipelines.

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1. Introduction

Oil and gas are transported mainly through pipelines [1–3]. In recent years, quite a number of pipelines are laid under the ground of roads, houses, rivers, railways, et al, due to the accelerating construction of cities and public utilities [4]. And this leads to an increasing number of buried oil-gas pipelines [5,6]. Defects occur almost inevitably during the long-running process of oil-gas pipelines. Buried pipes could suffer quite higher probability of defects occurrence due to the complicated pressure and environmental stress above the ground [7–9]. However, traditional point to point non-destructive testing methods proved to be ineffective for the defects detection of buried pipelines because their service environments cannot be directly reached [10]. Electromagnetic ultrasonic guided wave testing (EUGW) can achieve long distance detection for pipelines by single-ended excitation, owning the advantages of 100% cross sectional detection and being free of couplant [11–14]. Therefore, EUGW testing is fairly suitable for inspecting and monitoring the structural health of buried oil-gas pipelines.

Buried oil-gas pipelines are usually on an extraordinarily long service period and their service environments are extremely harsh [15,16]. And guaranteeing the safe and stable operation of oil-gas pipelines is very important to avoid potential oil-gas leakages or even explosions [17,19]. Therefore, it is necessary to conduct long-term monitoring for buried oil-gas pipelines in order to achieve the timely and effective detection for potential defects. An active thermometry-based monitoring system is proposed in Zhao’s work for offshore pipeline scour [20]. Intelligent pigs are applied for inline inspection of buried pipelines to monitor their thorough health, but each time of inspection project costs lots of money and plenty of workload [21]. Wan proposes an automatic pipeline monitoring system to prevent accidental third-party damage [22]. However, for buried oil-gas pipelines, each time of detection corresponding to excavation wastes financial and manpower resources. One possible solution is to install the transducer on the pipe and bury it with the pipe for long-term monitoring. But most guided wave transducers are fairly expensive, which proves to be unrealistic in practical projects. Therefore, a feasible long-term installed and buried guided wave transducer is desiderated for the industrial monitoring of buried oil-gas pipelines.

However, the analysis for EUGW monitoring data of buried oil-gas pipelines is quite difficult and complex. One reason is that the transduction efficiency of electromagnetic acoustic transducers (EMAT) is relatively low, compared to piezoelectric or laser transducers [23]. And this leads to weak detection signals and lower signal to noise ratio (SNR) [24]. The defect reflection signals are submerged in the noise and it is nearly impossible to recognize the defect signals and the difference between each monitoring data. Another reason falls on the extrusion between pipe wall and its anticorrosive coating or its surrounding soil [25]. Part of the energy of guided waves will be lost in the pipe coating, surrounding soil and the transporting oil [26]. And this will also reduce the amplitude of detection signals. Consequently, it is necessary and practical to develop the difference extraction and analysis method for oil-gas pipeline EUGW monitoring data in order to obtain a reasonable and accurate monitoring result.

In this work, an electromagnetic ultrasonic guided wave long-term monitoring scheme for buried oil-gas pipelines and a data difference adaptive extraction method for the monitoring data are proposed. The theoretical foundation of the EUGW long-term monitoring for pipes will be analyzed. And the detailed procedures of the proposed data difference adaptive extraction method will be demonstrated. What's more, the on-site application of the EUGW long-term monitoring scheme and the data difference extraction method will be conducted.

2. Theoretical analysis

The EMAT for buried oil-gas pipeline long-term monitoring is based on magnetostriction. Figure 1(a) illustrates the structure of the EMAT. The nickel strap is circumferentially magnetized and bonded on the surface of the pipe by epoxy resin adhesive, to provide the circumferential static bias magnetic field. The coils winded on the surface of the nickel strap are excited by alternating currents and thus can provide the axial alternating magnetic field. In this configuration, circumferentially uniform torsional waves will be stimulated and the torsional waves will propagate along the axial direction of the pipe [27]. When the torsional waves encounter defects at a certain propagation distance, the waves will be reflected and then finally received by the EMAT.

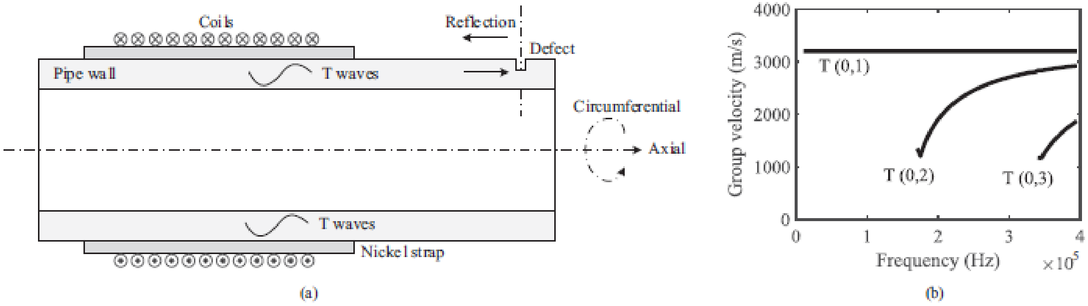

Fig. 1. (a) The structure of the magnetostriction EMAT and (b) group velocity dispersion curves of torsional waves.

The outer diameter of the pipe in this work is 325 mm, and the thickness of the pipe wall is 10 mm. The material of the pipe is steel, so the velocity of the longitudinal bulk wave is set as 5940 m/s, and the velocity of the transverse bulk wave is set as 3200 m/s. According to the dispersion equations of torsional waves and the above calculation parameters, the dispersion curves of torsional waves can be constructed, as shown in Fig. 1(b). It is indicated that the T (0,1) mode wave is non-dispersive, and its group velocity does not depend on the working frequency, which will simplify the interpretation of detection signals. Besides, the T (0,1) mode wave is not affected by the liquid in pipes [28], which makes the propagation more stable. In order to avoid the interference of multi-modes torsional waves, the working frequency can be confined less than 100 kHz, in which only T (0,1) mode wave exists. For the sake of longer propagation distance and smaller attenuation in buried pipes, lower frequency 32 kHz is selected as the working frequency of T (0,1) mode wave in this work.

The magnetostriction EMAT will be installed on the pipe permanently and buried underground. T (0,1) guided wave inspection will be conducted at regular periods to form the monitoring data. The monitoring data of the ith period is $Xi(xj)$, where $i = 1, 2, \dots, N$, $j = 1, 2, \dots, M$, N and M are positive integers. N is the total number of periods, so XN is the latest and present period of monitoring data. M is the total number of data points of the ith period monitoring data, and xj represents the specific detection signal voltage of the jth data point. The monitoring data difference adaptive extraction method for buried oil-gas pipelines is proposed as the following steps:

1. Construct the difference array $D(dj)$ of the present monitoring data and previous monitoring data

$$d_j = \sum_{i=1}^{N-1} |(|XN(xj)| - |Xi(xj)|)| \tag{1}$$

where $|Xi(xj)|$ is the absolute value of the detection signal voltage of the j^{th} data point in the i^{th} period monitoring data. The collection of dj (j = 1, 2, . . . , M) constructs the difference array $D(dj)$. The purpose of the absolute operation is to avoid unwelcome large difference amplitude caused by the situation where positive amplitude subtracts negative amplitude.

2. Determine the distance and transform origins. The distance origin ds of the difference array $D(dj)$ is determined by the present monitoring data

$$ds = \text{argmax}\ X_N(x_j) \tag{2}$$

The dead zone point dz of the difference array is determined by the array element that firstly reaches the average value of the latter half of the difference array

$$d_z = d_j\ \{\text{arg min}\ j\ s.t.\ \min(d_j - ave\ D(d_k))\} \tag{3}$$

where $ave\ D(d_k)$ is the average value of the latter half of the difference array, and k = M/2, M/2 + 1, . . . ,M.

The transform origin corresponds to the element position of the dead zone point

$$d_t = d_z \tag{4}$$

Therefore, the data to be transformed is $D_t\ (d_t, . . . , d_M)$.

3. Determine the transforming reference, gain threshold and attenuation threshold. The transforming reference r of $D_t\ (d_t, . . . , d_M)$ is

$$r = \text{arg max}\ Dt\ (dt, . . . , dM) \tag{5}$$

The gain threshold g_t is

$$g_t = g * r \tag{6}$$

where g is the gain threshold factor and satisfies $0.5 < g \leq 1$.

The attenuation threshold at is

$$at = a * r \tag{7}$$

where a is the attenuation threshold factor and satisfies $0 \leq a < 0.5$.

4. Considering a certain discrete data point d_j in $D_t(d_t, . . . , d_M)$, where j = t, t + 1, . . . ,M, judge if d_j is greater than the gain threshold g_t, if it is, then step Eq. (5) is performed; otherwise, judge if d_j is less than the attenuation threshold a_t, if it is, then step Eq. (6) is performed; otherwise, step Eq. (7) is performed.

5. Conduct adaptive gain for the data point d_j , and replace d_j with d_{jg}

$$d_{jg} = \frac{d_j - g_t}{g_t} * G * d_j \tag{8}$$

where G is the gain coefficient and satisfies $G > 1$.

6. Conduct adaptive attenuation for the data point d_j , and replace d_j with d_{ja}

$$d_{ja} = \frac{d_j}{a_t} * A * d_j \tag{9}$$

where A is the attenuation coefficient and satisfies $0 < A < 1$.

7. If all the data points in D_t (d_t, . . . , d_M) are analyzed, then the transformed difference array turns out to be D_n (d_j), where $j = 1, 2, \ldots$,M, and step Eq. (8) is performed; otherwise, data point d_{j+1} is taken into consideration and the procedure returns to step Eq. (4).

8. The difference curve is constructed based on the transformed difference arrayDn(dj), and the peaks of the difference curve are

$$d_p = \arg\max D_n(d_j) \tag{10}$$

where $p = 1, 2, \ldots$, P, and P is the total number of peaks in the difference curve.

The distances of the extracted differences are

$$l_p = l(d_p) - l(d_s) \tag{11}$$

where $l(dp)$ is the distance position of peaks in the difference curve, and $l(ds)$ is the distance position of the distance origin.

Figure 2 illustrates the procedures of the monitoring data difference adaptive extraction method. The proposed data difference adaptive extraction method will be applied in the monitoring data of buried oil-gas pipelines to improve the SNR of the original data acquired from EMAT. This method does not rely on any other function except for the data itself and owns relatively high adaptability.

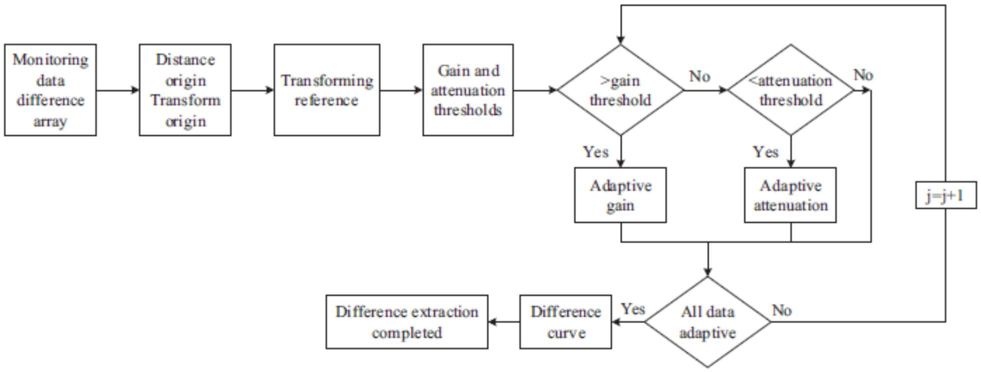

Fig. 2. Theoretical procedures of the monitoring data difference adaptive extraction method.

3. EUGW long-term monitoring for buried pipes

A low-cost and feasible solution for the long-term monitoring of buried oil-gas pipelines is proposed in this part. Firstly, excavation is conducted around the detection area on the pipe for enough space to install the EMAT. And the external surface of the detection area on the pipe is cleaned. Secondly, the nickel strap is circumferentially magnetized and boned on the external surface of the pipe circumferentially by epoxy resin adhesive. Thirdly, coils are winded circumferentially on the nickel strap, and the width of coils should be less than that of the nickel strap. Fourthly, the connector of the coils is installed in the detection stub planted in the ground and the connector is linked with coils by the cable. Fifthly, the detection area of the pipe is covered with its original anticorrosive coating or the thermal insulation layer, and is recovered just as the same as the environment and situation before excavation. Finally, the excavation pit is filled with soil and both the EMAT and the cable are buried in the ground. Figure 3 illustrates the schematic of the EUGW long-term monitoring for buried oil-gas pipelines.

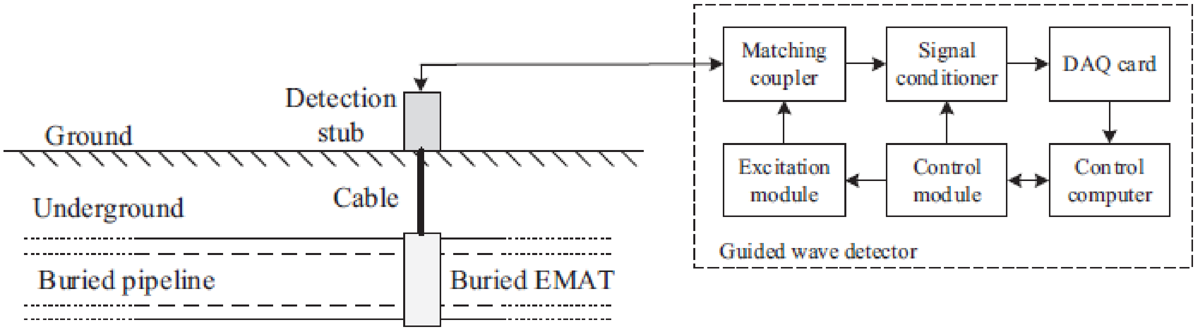

Fig. 3. The schematic diagram of the EUGW long-term monitoring for buried oil-gas pipelines.

After the installation of the buried EMAT and the detection stub, the guided wave inspection on the buried pipe can be implemented at regular periods by the guided wave detector. The connector of coils in the detection stub is linked with the matching coupler of the guided wave detector. Then the detection signals are amplified and narrow-band filtered by the signal conditioner and transferred to the data acquisition card to form the digital detection data. The detection data is sent to the control computer for further analysis and process. The instructions from the control computer are sent to the control module to achieve parameter configuration for the signal conditioner and the excitation module, such as the amplification factor, the center frequency of the filter, the excitation voltage, the excitation frequency, the number of excitation cycles, et al. The excitation module can generate high excitation voltage to stimulate the coils of the EMAT, through the matching coupler. The matching coupler has two main functions:

It connects the excitation module and the EMAT to maximize the excitation power in order to achieve a longer T mode wave propagation distance, and it protect and insulate the signal conditioner form the high voltage of the excitation module.

The cost of the buried EMAT is fairly low because it only contains the pre-magnetized nickel strap and some coils. Only some excavation and landfill works are needed, which are also necessary for other kinds of buried pipe inspection methods. And once the EMAT is installed and buried with the pipe, no other extra work is needed afterwards. The only thing to do is to connect the detection stub with the guided wave detector, and collect the detection data at regular periods. Therefore, this proposed scheme is a low-cost and feasible solution for long-term monitoring of buried oil-gas pipelines.

4. On-site monitoring for buried oil pipelines

The EUGW on-site monitoring for buried oil pipelines is conducted in Jinan city, Shandong province, China. The periodical detection is carried out from December 2015 till now, once per month. The outer diameter of the oil pipe is 325 mm, and the thickness of the oil pipe wall is 10 mm. The width of nickel strap is 60 mm, and the width of the EMAT coil is 50 mm. Two separate groups of coils and nickel straps are applied to achieve the propagation direction control. And the distance between the two coils is 125 mm. Figure 4(a) illustrates the on-site photo of the buried monitoring EMAT.

The EMAT is then buried with the pipe and the connector of coils is leaded out to the detection stub, which is plated on the ground. Figure 4(b) illustrates the on-site photo of detection and data collection process on a certain period. The connector in the detection stub is linked to the guided wave detector and the detection data is collected and stored in the computer to form the monitoring data of the specific period. The excitation voltage is 500 V, the excitation frequency is 32 kHz, and the number of excitation cycles is 10. The center frequency of the filter in the signal conditioner is 32 kHz.

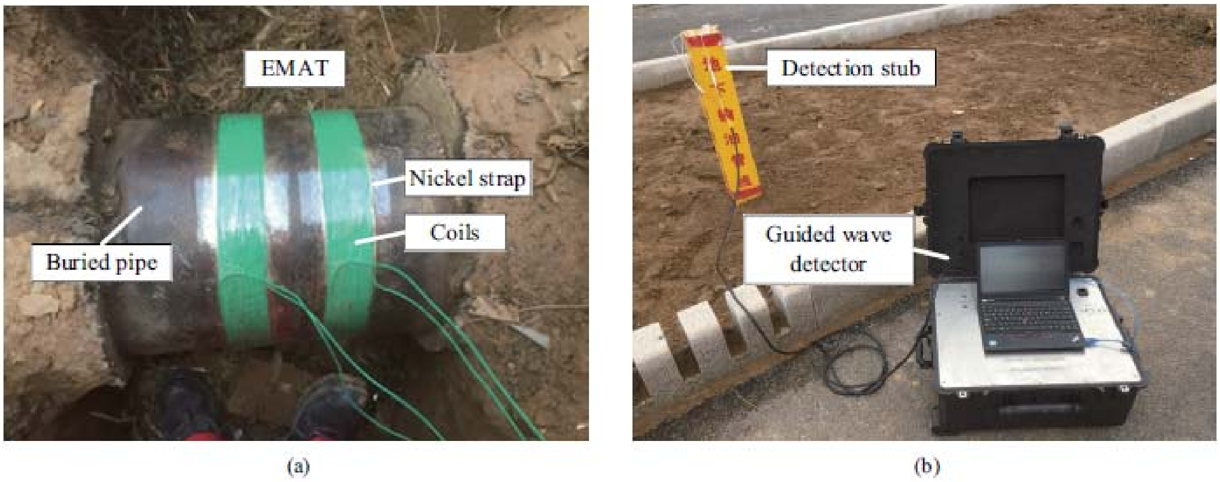

Fig. 4. On-site monitoring photos for buried oil pipelines. (a) On-site photo of the monitoring EMAT and (b) on-site photo of detection and data collection on a certain period.

Totally four groups of monitoring data, from December 2015 to March 2016, will be analyzed by the data difference adaptive extraction method to find out possible changes in the monitoring data and the structural health condition of the buried oil pipeline. The gain threshold factor is 0.73, the attenuation threshold factor is 0.4, the gain coefficient is 20 and the attenuation coefficient is 0.05. Figure 5 shows the data difference extraction result of the four groups of monitoring data.

In the data difference extraction result, an obvious waveform stands up at the distance 9.25 m from the buried EMAT on the flow direction. The corresponding position was excavated for verification, and a pit on the surface of the pipe was found, as shown in Fig. 6(a). It is confirmed that this pit was caused by the building construction on the ground above the pipe in March, 2016. And some prevention and strengthening measures were conducted on the local area of the pipe after the finding of the pit. The anticorrosive coating was firstly coated on the pit area circumferentially and a piece of anti-pressure steel ring was fixed on the anticorrosive coating to protect the pit area, as shown in Fig. 6(b). Finally, the thermal insulation layer was coated outside. Rather than reparation, protection and prevention on the pit area were conducted by circumferential reinforcement, in order to keep the continuity and the correspondence of all the monitoring data from each period.

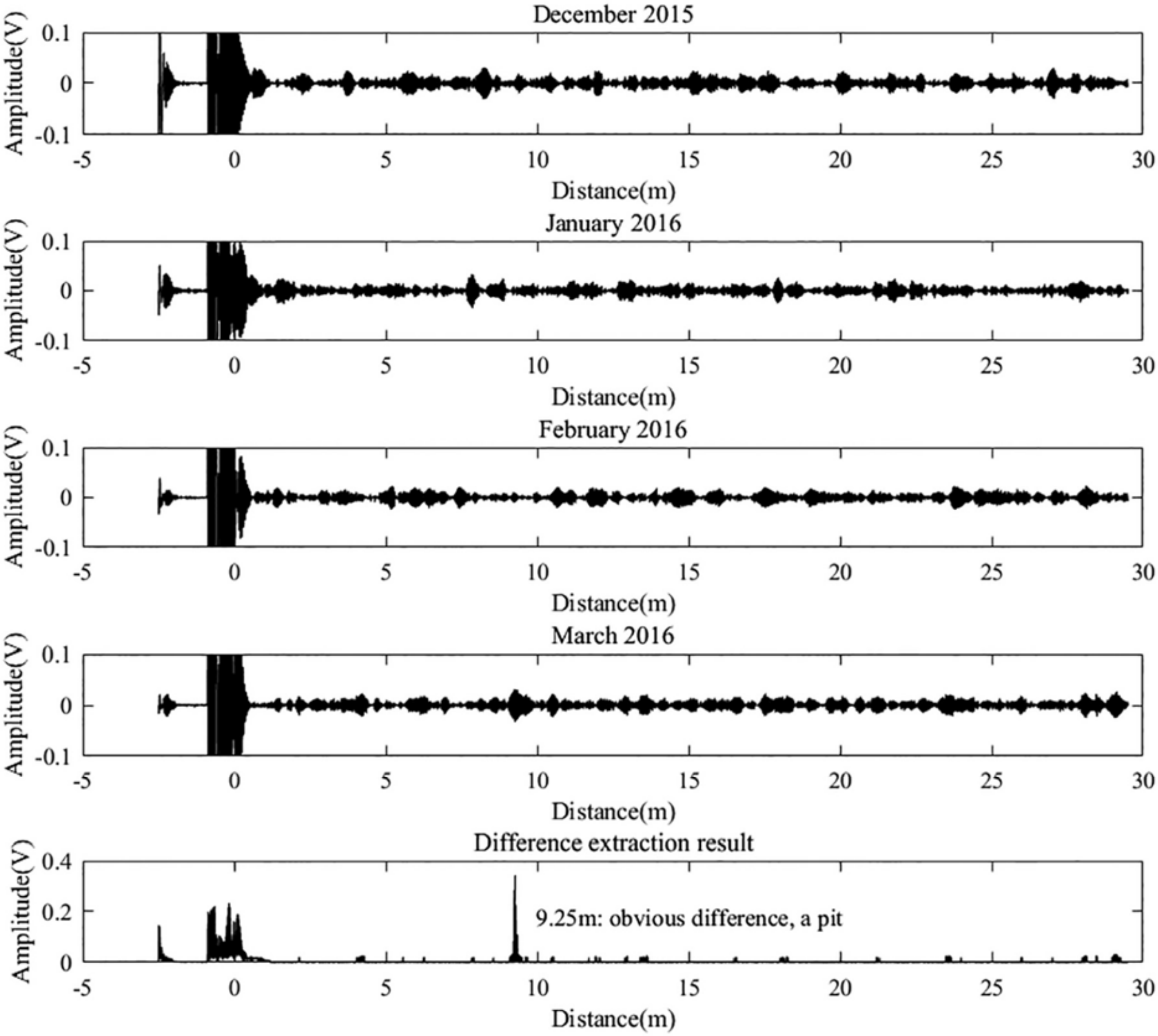

Fig. 5. Four groups of monitoring data and the data difference extraction result.

(a)

(b)

Fig. 6. (a) The found pit based on the data difference extraction result and (b) the protection for the pit area before the thermal insulation layer.

After the protection for the pit area, the monitoring data of April 2016 and May 2016 were collected. Then three groups of monitoring data, from March 2016 to May 2016, are analyzed by the proposed data difference adaptive extraction method, and the related method factors and coefficients are the same as those in Fig. 5. The data difference extraction result for the three groups of monitoring data is shown in Fig. 7.

The extraction result in Fig. 7 illustrates that no waveform stands up and no obvious difference is found among the monitoring data of three months. Therefore, the protection for the pit area is properly installed and the reinforcement works to prevent any further destruction for the pit area.

The SNR of the four groups of monitoring data in Fig. 5 and the difference extraction result are calculated in Table 1. Due to the relatively low transduction efficiency of buried EMAT and the energy attenuation in the coatings or transporting medium, the SNR of the monitoring data are relatively low and the detection signals are submerged in the noise. The SNR of the difference extraction result is much higher than those of the monitoring data and the difference is accurately extracted.

The baseline drift of the difference extraction result in Fig. 5 is caused by the theoretical principle of the data difference extraction method, in which the absolute value of the detection signal voltage is applied, as calculated in Eq. (1). As a consequence, there are only positive numbers in the difference extraction result, which seems like the baseline drift. But this does not influence the extraction result, because it is the data difference that actually matters. Besides, the SNR analysis between the original monitoring data and the extraction result has proven that the difference can be effectively extracted with much higher SNR than the original data.

Table 1

The SNR of the monitoring data and the difference extraction result

Data	Dec 2015	Jan 2016	Feb 2016	Mar 2016	Difference extraction
SNR (dB)	6	8	7	7	18

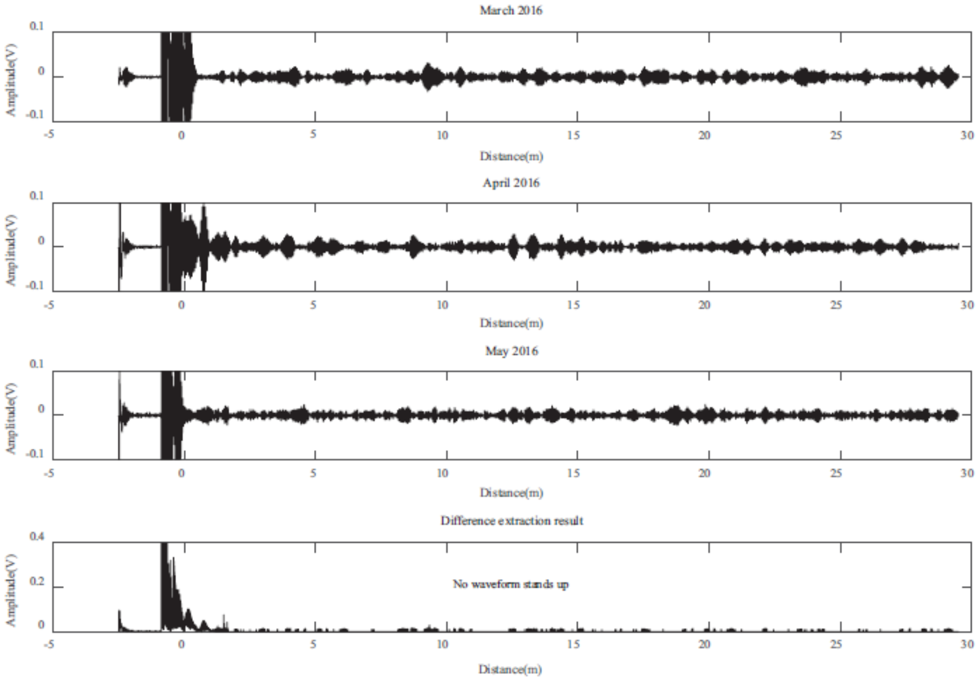

Fig. 7. Monitoring data after the protection and the data difference extraction result.

In order to achieve long-range monitoring for the buried oil pipelines in Jinan city, totally fifteen EMATs were installed along the flow direction of the pipeline. Several kinds of defects and structures were found on the pipeline based on the long-term monitoring and the data difference extraction method. Some of the related monitoring results till July, 2016 are illustrated in Table 2.

Table 2

Some related monitoring results till July, 2016 in Jinan city

Monitoring point number	Outer diameter * thickness (mm *mm)	Found detects or structures	Position accuracy (mm, relative error %)	Loss of sectional area (%)	Verification method
567	325*10.04	Corrosion	20(5.2)	5	Excavation
1560	325*9.96	Pit	30 (3)	15	Excavation
2225	325*10.27	Weld seam	30(5.7)	_	Excavation
2461	325*9.85	Pit	20 (5.7)	7	Excavation
	325*9.85	Mechanical scratches	10 (2)	10	Excavation
5170	325*9.98	Corrosion	10 (2.4)	3	Excavation
6650	325*11.42	Corrosion	10 (3)	4	Excavation
9500	325*11.65	Welded casing	20 (2.2)	_	Excavation
12805	325*10.13	Mechanical scratches	50 (8.6)	8	Excavation
13325	325*9.9	Corrosion	30 (6.4)	4	Excavation

According to the monitoring results in Table 2, the positioning accuracy of the proposed EUGW long-term monitoring method for possible defects or structures is relatively high, and the minimum positioning relative error is only 2%. The detection sensitivity, which is represented by the loss of sectional area for the defect in this work, is shown to reach the minimum value of 3%, which announces the relatively high detection sensitivity of the proposed EUGW long-term monitoring and data difference extraction method.

The proposed data difference adaptive extraction method is proved to be able to dramatically increase the SNR of the monitoring result and accurately extract the difference and variation of the pipe's structural health condition that occurred in the long-term service. And the proposed EUGW long-term monitoring can act as a feasible and practical method for the structural health monitoring of buried oil-gas pipelines.

5. Conclusions

This work proposes an electromagnetic ultrasonic guided wave long-term monitoring scheme for buried oil-gas pipelines and a data difference adaptive extraction method for the monitoring data. The theoretical foundation of the EUGW long-term monitoring for pipes is analyzed and the detailed procedures of the proposed data difference adaptive extraction method are demonstrated. A circumferentially magnetized nickel strap is bonded on the pipe to provide the bias magnetic field and the excitation coils are winded on the nickel strap to provide the dynamic magnetic field. A detection stub is planted on the ground and the connector of buried coils is installed in the stub. The cost of the buried EMAT is fairly low and the only thing to do for monitoring is to connect the detection stub with the guided wave detector and collect detection data at regular periods. The difference array is constructed and adaptive gain and attenuation are performed in the data difference adaptive extraction method. This proposed method does not rely on any other function except for the data itself and is entitled to relatively high adaptability.

The EUGW long-term monitoring scheme is on-site applied for buried oil pipes in Jinan city, Shandong province, China. The EMAT is installed and buried with the pipe, and the periodical detection is conducted from December 2015 till now, once per month. Four groups of monitoring data are analyzed by the data difference adaptive extraction method. A pit is found and verified by excavation at the distance 9.25 m from the buried EMAT on the flow direction. On-site detection results show that the data extraction method can dramatically improve the SNR of the monitoring data and accurately extract the difference and variation in the data. The EUGW long-term monitoring scheme is proved to be a feasible method with prosperous prospect for the structural health monitoring of buried oil-gas pipelines.

Acknowledgments

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References

[1] E. Al Hosani, M. Meribout, A. Al-Durra, K. Al-Wahedi and S. Teniou, A new optical-based device for online black powder detection in gas pipelines, *IEEE Transactions on Instrumentation and Measurement* 63 (2014), 2238–2252.

[2] A. Nazari, P. Rajeev and J.G. Sanjayan, Offshore pipeline performance evaluation by different artificial neural networks approaches, Measurement 76 (2015), 117–128.

[3] S.L. Huang, Y. Tong, W. Zhao and S. Wang, An adaptive compression algorithm for pipeline EMAT inspection data, International Journal of Applied Electromagnetics and Mechanics 33 (2010), 1095–1100.

[4] B. Han, J.B. Hao, H.Y. Jing, J.P. Liu and Z.Z. Wu, Analysis of stresses on buried pipeline subjected to landslide based on numerical simulation and regression analysis, Proceedings of the Asme International Pipeline Conference 1 (2010), 83–88.

[5] M. Ruiz, L.E.Mujica,M. Quintero, S. Quintero and J. Florez, In-line inspection of pipelines by using a smart pig (ITION) and multivariate statistical analysis, Structural Health Monitoring 1–2 (2015), 2342–2349.

[6] D.T. Zeitvogel, K.H. Matlack, J.Y. Kim, L.J. Jacobs, P.M. Singh and J.M. Qu, Characterization of stress corrosion cracking in carbon steel using nonlinear Rayleigh surface waves, NDT & E International 62 (2014), 144–152.

[7] P. Vazouras, S.A. Karamanos and P. Dakoulas,Mechanical behavior of buried steel pipes crossing active strike-slip faults, Soil Dynamics and Earthquake Engineering 41 (2012), 164–180.

[8] G.F. Xu, J.L. Qi and H.J. Jin, Model test study on influence of freezing and thawing on the crude oil pipeline in cold regions, Cold Regions Science and Technology 64 (2010), 262–270.

[9] S. Saha, S. Mukhopadhyay, U. Mahapatra, S. Bhattacharya and G.P. Srivastava, Empirical structure for characterizing metal loss defects from radial magnetic flux leakage signal, NDT & E International 43 (2010), 507–512.

[10] J.M. Muggleton, M. Kalkowski, Y. Gao and E. Rustighi, A theoretical study of the fundamental torsional wave in buried pipes for pipeline condition assessment and monitoring, Journal of Sound and Vibration 374 (2016), 155–171.

[11] J. Lee, J. Park and Y. Cho, A novel ultrasonic NDE for shrink fit welded structures using interface waves, Ultrasonics 68 (2016), 1–7.

[12] Y. Zhang, S.L. Huang, S. Wang and W. Zhao, Time-frequency energy density precipitation method for time-of-flight extraction of narrowband lamb wave detection signals, Review of Scientific Instruments 87 (2016), 054702.

[13] P. Khalili and P. Cawley, Excitation of single-mode lamb waves at high-frequency-thickness products, IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control 63 (2016), 303–312.

[14] P. Belanger and G. Boivin, Development of a low frequency omnidirectional piezoelectric shear horizontal wave transducer, Smart Materials and Structures 25 (2016), 045024.

[15] C.C. Chiu and C.H. Huang, Time domain inverse scattering for a buried homogeneous cylinder in a slab medium using NU-SSGA, International Journal of Applied Electromagnetics and Mechanics 40 (2012), 195–204.

[16] Z. Liu and Y. Kleiner, State-of-the-art review of technologies for pipe structural health monitoring, IEEE Sensors Journal 12 (2012), 1–6.

[17] D. Sun, Y. Yan, R.M. Carter, L.J. Gao, G. Lu, G. Riley and M. Wood, On-line nonintrusive detection of wood pellets in pneumatic conveying pipelines using vibration and acoustic sensors, IEEE Transactions on Instrumentation and Measurement 63 (2014), 993–1001.

[18] O.M. Aamo, Leak detection, size estimation and localization in pipe flows, IEEE Transactions on Automatic Control 61 (2016), 246–251.

[19] P. Belanger and G. Boivin, Development of a low frequency omnidirectional piezoelectric shear horizontal wave transducer, Smart Materials and Structures 25 (2016), 045024.

[20] X.F. Zhao, W.J. Li, L. Zhou, G.B. Song, Q. Ba, S.C.M. Ho and J.P. Ou, Application of support vector machine for pattern classification of active thermometry-based pipeline scour monitoring, Structural Control & Health Monitoring 22 (2015), 903–918.

[21] S. Vats, Health monitoring of new and aging pipelines-development and application of instrumented pigs, Materials Science and Information Technology 433–440 (2012), 6121–6127.

[22] C.F. Wan, A. Mita and T. Kume, An automatic pipeline monitoring system using sound information, Structural Control & Health Monitoring 17 (2010), 83–97.

[23] S. Dixon, M.P. Fletcher and G. Rowlands, The accuracy of acoustic birefringence shear wave measurements in sheet metal, Journal of Applied Physics 104 (2008), 114901.

[24] M. Kubinyi, O. Kreibich, J. Neuzil and R. Smid, EMAT noise suppression using information fusion in stationary wavelet packets, IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control 58 (2011), 1027–1036.

[25] Y. Gao, F.S. Sui, J.M. Muggleton and J. Yang, Simplified dispersion relationships for fluid-dominated axisymmetric wave motion in buried fluid-filled pipes, Journal of Sound and Vibration 375 (2016), 386–402.

[26] E. Leinov, M.J.S. Lowe and P. Cawley, Investigation of guided wave propagation and attenuation in pipe buried in sand, Journal of Sound and Vibration 347 (2015), 96–114.

[27] R. Ribichini, F. Cegla, P.B. Nagy and P. Cawley, Study and comparison of different EMAT configurations for SH wave inspection, IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control 58 (2011), 2571–2581.

[28] A. Demma, P. Cawley, M. Lowe and A.G. Roosenbrand, The reflection of the fundamental torsional mode from cracks and notches in pipes, Journal of the Acoustical Society of America 114 (2003), 611–625.