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Method for Assessing Damage to Gas Distribution Network Pipelines based on Nonlinear Guided Wave

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ABSTRACT

Polyethylene pipeline is an essential infrastructure of gas distribution network, and there are some problems such as complex damage assessment and tedious assessment process. How to choose an effective damage assessment method for polyethylene pipelines is the focus of the implementation of the gas distribution network at present. In this paper, a nonlinear directional wave method is proposed to detect the damage of polyethylene pipeline by an acoustic wave, and the damage results of polyethylene pipeline are searched. The rationality of this method is verified by calculating the aerodynamic equation.The results show that the nonlinear fixed wave method can accurately determine the damage and crack propagation degree of the pipeline and simplify the damage assessment process, and the results are superior to the linear directional wave method. Therefore, the nonlinear directional wave can be used to assess the damage to ethylene pipelines in gas distribution networks, which has strong rationality and practicality and provides support for the actual pipeline damage assessment.

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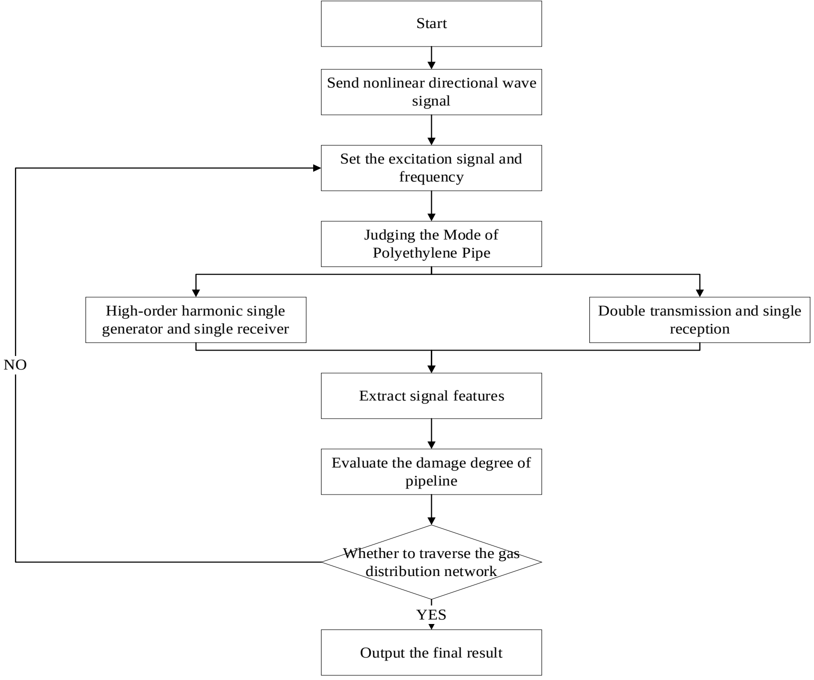
Graphical Abstract



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1. INTRODUCTION

Polyethylene as an important foundation of the natural gas network (1, 2), the gas distribution network plays a very important role in guaranteeing the supply of natural gas, and its material selection is directly proportional to network security (3, 4). Polyethylene pipeline belongs to a special composite process (5, 6), which has excellent transmission performance and corrosion resistance, and it is not easy to leave natural gas impurities on the inner wall of the pipeline (7-9). Compared with ordinary steel structure pipes, polyethylene pipes also have strong toughness and mechanical strength, which is suitable for long-distance foundation laying (10, 11). In addition, polyethylene pipes are suitable for harsh external environments and complex internal fluid pressure and have an extensive range of applications (12, 13). The survey results show that 34% of accidents in the natural gas field are caused by pipeline leakage, pipeline rupture, and cracks (14-16). Among them, the steel structure pipeline accident probability accounts for 70% (8), polyethylene pipeline accounts for 5.6%, and other types of pipeline account for 24.4% (17). Some scholars believe that the safety of polyethylene pipelines is high, but if it is laid for a long distance (18-21) or used for a long time, the polyethylene pipeline will have cracks, leaks, and other problems (22, 23). Moreover, the toughness and adhesion of the polyethylene pipeline itself will lead to cracks and other damages that are not easily detected (24, 25) and cannot even be identified by x-rays. Some scholars believe that the essence of polyethylene pipeline cracks is the aging of materials or the complete result of external culture, humidity, and internal stress. The previous methods, such as ray and light diffraction, cannot be effectively detected (26, 27). Some scholars believe that the previous testing methods for cracks in polyethylene pipes (28) have the problems of long testing time and complex testing process, which can not be continuously tested and affect the use of polyethylene pipes (29-32). Therefore, finding an effective detection method for polyethylene pipeline cracks is a problem that needs to be solved at present, and it is also to avoid major economic losses and casualties caused by polyethylene pipelines (33, 34). Based on this, this paper presents a nonlinear orientation-based assessment method of polyethylene pipeline damage in the gas distribution network, aiming at improving the identification effect of polyethylene pipeline damage.

2. DETECTION METHOD OF POLYETHYLENE PIPELINE DAMAGE IN THE GAS DISTRIBUTION NETWORK

2. 1. Damage Process of Polyethylene Pipeline

The damage to the polyethylene pipeline will change the density and shape of polyethylene. The damage process of polyethylene pipeline can be simplified as density calculation, which can be calculated by universal theory function and modified density function (35-37). Suppose A: The mass of polyethylene per unit area is M_{to}, the mass obtained by the universal theory function is M_a (38), and the mass obtained by the modified density function is , then the calculation process of polyethylene pipeline damage is shown in Equation 1:

$$f(\rho) = \sum \alpha \cdot \frac{\overline{M_a + M_b}}{B(M_{to}) \cdot V} + A(\zeta) \tag{1}$$

Among them, α is the density coefficient of polyethylene pipeline changes according to cracks, fatigue, creep, bonding degree, and so on; ρ is the pipe density; $f_{(\rho)}$ is the pipeline damage function; $A_{(\zeta)}$ is the density revision function; $B_{(M_{to})}$is a universal density function; V is the volume of the pipeline; ζ is the revised coefficient of the pipeline.

2. 2. Nonlinear Directional Wave Detection

Nonlinear directional waves can measure the lattice arrangement of polyethylene material, test irregular, and discontinuous damage, reduce the incidence of the linear excitation signal, and realize microscopic identification of the damage location. Compared with linear directional waves, nonlinear directional waves have fewer stress-strain hysteresis and nonlinear dissipation problems (18), and have a higher recognition rate for crack, fatigue, creep, and other characteristics, which can realize early recognition of polyethylene materials. Suppose B: The nonlinear ultrasonic test result function is $R_{(x)}$,the position vector of ultrasonic propagation in the pipeline is x (19), the amplitude is u, the wave number is k, the angular frequency is ω, the product thickness is $f_{(h)}$, the capacitance vector function is $\phi_{(x)}$, the expansion vector function is $\varphi_{(x)}$, and the test dimension is l, then the nonlinear directional wave detection process is shown in Equation 2.

$$R(x) = \sum_{l} \sum_{u} \sum_{t} A\cos(kx - \omega t) \cdot \mu \cdot \phi(x) \cdot fh + \frac{(\lambda + \mu) \cdot \varphi(x)}{\rho} \tag{2}$$

Among them λ is the Euler coefficient of the pipeline; t is the propagation time; μ is the Lagrange coefficient of damage, l test dimensions, including longitudinal, torsional, bending, etc.

There are two kinds of velocities for nonlinear directional wave propagation in polyethylene pipe, group velocity, and relative velocity. With the extension of propagation distance, directional waves with different frequencies will be separated (39), which will cause large-area dissipation of directional waves in a certain time domain and cause interference with the extraction of characteristic signals (40, 41). Therefore, when choosing non-directional waves, try to choose directional waves with slow speed changes (42). In addition, non-directional waves have multimodality.Under the same frequency, directional waves have many propagation modes, and each propagation mode presents different propagation velocities (43, 44). Therefore, the analysis of the directional wave's group velocity and relative velocity in different modes is the basis of polyethylene pipe damage detection (45).

2. 3. Propagation Modes of Nonlinear Directional Waves in Polyethylene Pipes

In order to realize the damage detection of polyethylene pipeline, the characteristic dispersion equation of non-directional wave in the pipeline should be calculated, and the displacement equation and stress expression equation of simultaneous directional wave in the pipeline should be established. Among them, the construction methods of the characteristic dispersion equation are divided into transfer matrix and global matrix methods (43). By calculating the boundary characteristics of non-directional waves, the transfer matrix method gradually eliminates the unknowns in the equation and obtains the dispersion characteristic solution. The global matrix method is to establish a large matrix, brings all the nonlinear directional wave values into the matrix, and combines the characteristics of each frequency directional wave to obtain the final calculation result. Because the global matrix method has a wider range of applications, can calculate the dispersion eigenvalues under different modes, and has higher robustness, this paper chooses the global matrix method to solve it. Assuming that the inner diameter of the polyethylene pipe is α, the propagation of nonlinear directional waves in the pipe should satisfy the Navier displacement equilibrium equation, and the results are shown in Equation 3.

$$\mu \cdot d^2 + (\lambda + \mu) d = \rho \frac{\partial^2 d}{\partial t^2} \tag{3}$$

Among them is the propagation displacement of nonlinear directional waves in the pipeline (note: it is not directional). In the actual test process, the nonlinear directional wave will be disturbed by external factors, so Helmholtz's law is introduced to decompose the nonlinear directional wave, and the calculation results are shown in Equation 4:

$$\begin{cases} F_{rm}(x) = [A_m \cdot \mu \cdot d^2 + \dfrac{B_m \cdot (\lambda + \mu) \cdot d}{r}] \cdot \cos n\theta \cdot \cos(\omega t + kz) \\ F_{\theta m}(x) = [\dfrac{C_m \cdot \mu \cdot d^2}{r} + D_m \cdot (\lambda + \mu) \cdot d] \cdot \sin n\theta \cdot \cos(\omega t + kz) \\ F_{zm}(x) = [\dfrac{E_m \cdot \mu \cdot d^2}{r} + F_m \cdot (\lambda + \mu) \cdot d \backslash \cdot \cos n\theta \cdot \cos(\omega t + kz) \end{cases} \tag{4}$$

Among them m is the number of layers of polyethylene pipes; when $F_{rm}(x)$, $F_{\theta m}(x)$ and $F_{zm}(x)$ are the radial, axial and circumferential components of the displacement of particles in the pipeline under directional waves, respectively. When $F_{rm}(x) \neq 0$, and are $F_{\theta m}(x)$ and $F_{zm}(x)$ equal to 0, it means that the guided wave is a longitudinal mode; When $F_{\theta m}(x) \neq 0$ and $F_{rm}(x)$, $F_{zm}(x)$ are equal to 0, the guided wave is a torsional mode; When $F_{zm}(x) \neq 0$ and $F_{rm}(x)$, $F_{\theta m}(x)$ are equal to 0, the guided wave is bending mode.According to Equation 4, the directional wave dispersion equation of a polyethylene pipeline can be constructed, and the result is shown in Equation 5.

$$[c_{ij}]_{6\times 6}[A, B, A_1, B_1, A_2, B_2]^T = [0,0,0,0,0,0]^T \tag{5}$$

Among them, the results in the matrix are related to wave number k and angular frequency , and the specific element coefficients are complex. Moreover, the coefficient is related to size, density, Young's modulus, and Poisson's ratio. In addition, the solution of the coefficient in Equation 5 depends on the wavelength, the thickness of the tube wall h, and the shear frequency of the tube wall, so only the approximate solution can be obtained when $\left[C_{1j}\right] = 0$ it shows that the longitudinal directional wave mode is in the pipeline when it shows that the transverse directional wave mode is in the pipeline when $[C_{1i}] = 0$ it shows that the bending directional wave mod is in the pipeline.

2. 5. Steps for Evaluating the Damage of Polyethylene Pipeline Caused by Nonlinear Directional Waves

Because nonlinear ultrasound has a high sensitivity to polyethylene pipeline damage, Different excitation signals and frequencies should be selected according to the nonlinear ultrasonic modulation phenomenon inside the pipeline, and receiving sensors should be arranged on the surface of the pipeline, and signals should be received by using the single-generator and single-receiver method of higher harmonics and the double-generator and single-receiver method of sidelobe components. The specific evaluation steps are shown in Figure 1.

Step 1: Determine the network structure of the polyethylene pipeline, obtain the mode of the pipeline, record the characteristics of nonlinear waves, and determine the distribution of dispersion, excitation signal, and frequency.

Step 2: Set the threshold and weight of frequency, dispersion, angular frequency, and other indexes, and extract the relevant eigenvalues by Fourier series. At the same time, the iteration times of polyethylene pipeline damage are set.

Step 3: Determine the nonlinear directional wave signals under different modes, and calculate the damage situation of the polyethylene pipeline.

Step 4: Statistic evaluation results of polyethylene pipeline damage, compare and output the final evaluation results.

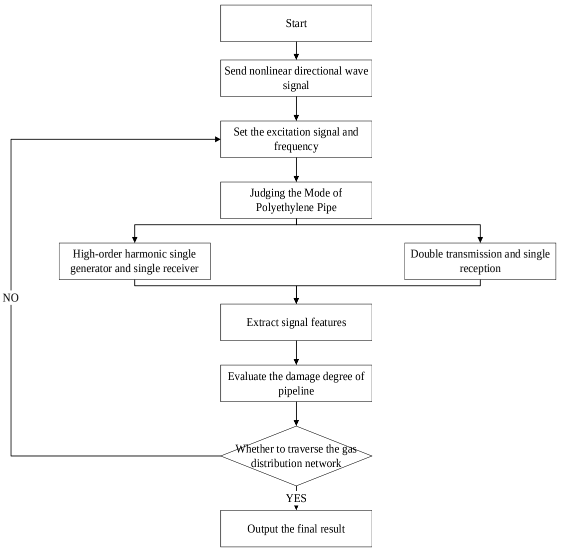

Figure 1. Damage assessment process of polyethylene pipeline caused by nonlinear directional wave

Step 5: Carry out iterative updating according to Equations 1-5, calculate the final damage of the polyethylene pipeline and output the final evaluation results under different modes.

Step 6: Whether the polyethylene pipeline in the gas distribution network is traversed, if not all traversed, repeat steps 1 to 5; otherwise, stop damage assessment.

3. CASE ANALYSIS OF DAMAGE ASSESSMENT OF POLYETHYLENE PIPELINE IN THE GAS DISTRIBUTION NETWORK

3. 1. Basic Condition of Polyethylene Pipeline in Gas Distribution Network

Taking the urban gas pipeline reconstruction project as a research case, the pipeline line is 10.32 kilometers long, with 15 straight-through pipes, 65 elbows, 72 reducers, 14 pipe caps, and 11 saddle-shaped bypass pipes. The basic information of specific pipelines is shown in Table 1.

It can be seen from Table 1 that the basic information of the polyethylene pipeline, the test frequency of the nonlinear directional wave, the calculated depth, and the error can be obtained. After obtaining the specific information aboutthe polyethylene pipeline, the parameters of the nonlinear directional wave transmitter should be determined, and the specific results are shown in Table 2.

According to the parameters in Tables 1 and 2, the amplitude and dispersion components are analyzed by using a nonlinear directional wave acquisition card and supporting software. At the same time, the judgment standard of polyethylene pipeline damage is set, and the results are shown in Table 3.

At the same time, the frequency standard of the receiver is three levels, which are 1~2Hz, 2~3Hz, and 3~4Hz, respectively. Under different frequency standards, there are three modes: longitudinal mode, bending mode, and torsion mode.

TABLE 1. Parameters of polyethylene pipe

Pipe shape	Inner diameter (mm)	Outer Diameter (mm)	Thickness (mm)	Test frequency (Hz)	Depth of focus (mm)
Lining	74.29±1.23	89.59±4.32	3.86±0.56	6.5~7.6	7~9
Through	78.78±2.42	86.73±4.32	3.67±0.23	5.6~7.3	17~21
Elbows	83.27±2.37	82.86±3.62	4.69±0.71	6.1~7.4	22~25
Reducer	89.82±3.56	80.82±4.35	5.86±0.35	6.3~7.2	10~12
Tube cap	85.33±4.23	82.41±5.36	6.90±0.23	6.6~7.8	30~33
Saddle bypass	90.62±6.23	82.55±6.32	7.24±0.37	6.8~7.9	24~28

TABLE 2. Parameters of nonlinear directional waves

Device type	Emission frequency (Hz)	Magnification (times)	Accepted frequency (Hz)	Test accuracy(%)	Scanning angle (°)	Wave velocity (m/s)
Agilent	6~14	5.32	5~16	1	20~70	(-2341,+2457)
HFVA-41 power amplifier	8~19	6.25	10~28	1	30~80	(-3121,+3417)
REKHF piezoelectric amplifier	11~19	5.62	12~19	10	20~75	(-2611,+2737)

Note: + stands for shear wave, andstands for longitudinal wave

TABLE 3. Parameters corresponding to the damage state

Damage parameters	Injury status					
	1	2	3	4	5	6
Degree of damage (grade)	I	III	IV	VI	IV	VV
Depth of damage (mm)	0~0.5	0.5~1	1~1.5	1.5~2	2~2.5	2.5~3

3. 2. Harmonic Assessment of Polyethylene Pipeline Damage in the Gas Distribution Network

The damage assessment of polyethylene pipelines is mainly based on the amplitude and dispersion of directional waves, so it is necessary to analyze the damage location above and get the response results. According to the criteria in Table 3, the amplitude change of polyethylene pipeline damage is obtained, and the results are shown in Figure 2 of the tough-brittle transformation of the internal structure of the pipe.

By amplifying the spectrum, it is found that the nonlinear directional wave has a concentrated peak value, and the amplitude of the third harmonic is higher than that of the second harmonic. There are many reasons for the above phenomenon. One possibility is that the attenuation speed of the third harmonic in the gas distribution network is slower than that of the second harmonic. Another possibility is that the reception effect of the third harmonic is better, and the amplitude changes more. The third possibility is that the third harmonic is more sensitive to polyethylene pipeline structure. After the signal in Figure 2 is transformed by Equation 4, the amplitude changes under different damage states are obtained, and the results are shown in Figure 3.

According to the results shown in Figure 3, it can be seen that the harmonic amplitude changes with the increase of the width under different damage states. The transmitted signal fluctuates irregularly in the amplitude of the second harmonic wave, and there is no obvious law. The reason why the second harmonic amplitude does not appear obvious regularity with the increase of damage state may be that the second harmonic is less sensitive to the damage of the polyethylene pipeline. The third harmonic amplitude increases with the increase of the damage state due to the increase in dispersion rate caused by damage to the polyethylene pipeline. Moreover, the scattering rate of the nonlinear directional wave at the damage location is higher, which leads to more received harmonics, which verifies the effectiveness of nonlinear directional waves in the damage assessment of polyethylene pipelines. However, the rising trend of the third harmonic amplitude lacks regularity and presents fluctuating changes, mainly because the gas flow in the gas distribution network will affect the wave conductivity of the medium under different damages. In addition, the angular frequency, wave number of the nonlinear directional wave, and pipeline mode will affect the conductivity of the directional wave, and then affect the excitation signal received every time, and cause a different degree of amplitude change.

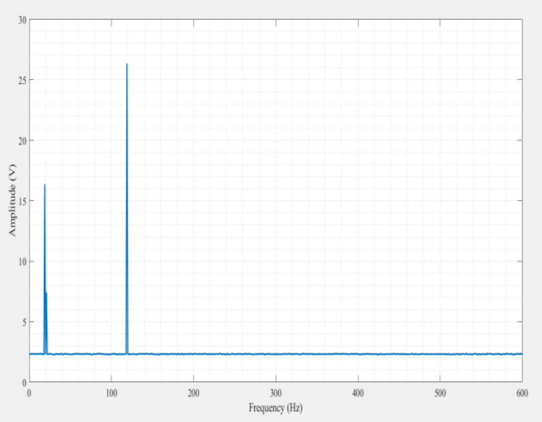

Figure 2. Receiving spectrum of damage signal

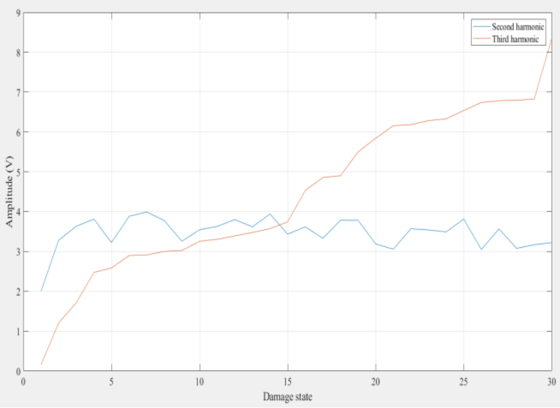

Figure 3. Amplitude variation of second and third harmonics

3. 3. Energy Assessment of Polyethylene Pipeline Damage in the Gas Distribution Network

According to the spectrum information in Figure 2, the difference frequency component, sum frequency component, energy value, and energy coefficient of nonlinear directional wave are extracted. Among them, the reference standards are shown in Table 4.

The frequency reference values in Table 4 allow better signal response, and sum frequency and difference frequency components can be obtained, as shown in Figure 4.

From the signal results shown in Figure 4, it can be seen that the signals of *Groups 2* and *3* have little change in difference frequency amplitude and sum frequency amplitude under the same damage, and the whole show a

TABLE 4. Parameters corresponding to the damage state

Stimulus signal group	**1**	**2**	**3**
High-frequency excitation signals	120	220	320
Low-frequency excitation signal	100	200	300
Sum frequency signal	80	180	280
Difference frequency signal	140	240	340

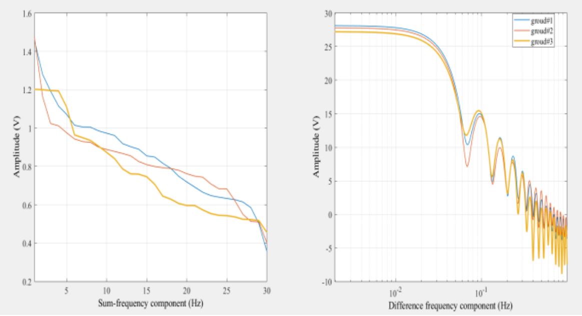

Figure 4. Amplitude variation of sum frequency component and difference frequency component

downward trend of ups and downs. It can be seen from the difference frequency component that the frequencies of high frequency and low frequency are close, and the difference frequencies produced in polyethylene pipeline are similar, so different frequencies have different evaluation results on polyethylene pipeline damage, and high and low frequencies can be selected according to pipeline damage. At the same time, in different groups of excitation signals, the difference frequency component and sum frequency component fluctuations tend to be consistent, and later fluctuations are gentler, mainly because the nonlinear directional wave energy values of each group show consistent attenuation in the later period. Therefore, the damage to the polyethylene pipeline can be well evaluated using different excitation signals, sum frequency, and difference frequency components.

4. DISCUSSION

According to the parameters in Table 1, the damage to the polyethylene pipeline in the gas distribution network is evaluated, and the following evaluation results are obtained, as shown in Table 5.

As can be seen from Table 5, there is no significant difference between nonlinear directional wave and linear directional wave in calculation time, but the nonlinear directional wave is higher in accuracy. The reason is that when the directional wave passes through the damage position, the amplitude of dispersion and angular frequency is small, which leads to no significant amplitude difference of the received signals, especially crack, fatigue, creep, and bonding degree. In addition, because the attenuation speed of the directional wave is slow, the energy and energy coefficient of the conduction wave change little after passing through the damaged position, so it is impossible to identify at the receiving point. The energy attenuation of nonlinear directional waves is faster, and the difference between different and sum frequencies is more prominent.

TABLE 5. Evaluation results of polyethylene pipeline damage by different methods

Scope	Component	Nonlinear directional waves		Linear directional waves	
		Accuracy (%)	**Time (min)**	**Accuracy (%)**	**Time (min)**
Pipeline	Lining	93.34	4.41	88.33	4.32
	Through	94.37	5.23	88.39	5.36
	Elbows	92.33	6.24	85.34	6.42
Annex	Reducer	92.14	11.34	88.33	10.23
	Tube cap	91.27	8.25	88.32	9.25
	Saddle bypass	90.23	4.32	84.32	4.63
	Different modalities	99.31	5.23	85.34	5.12

5. CONCLUSION

In this paper, a nonlinear directional wave method is proposed to evaluate the damage to a polyethylene pipeline in a gas distribution network, and the rationality of the evaluation method is verified. The damage to the polyethylene pipeline was analyzed by taking the amplitude, sum frequency component, and difference frequency component of the nonlinear directional wave as the main observation indices. The results show that the amplitude of the third harmonic wave of the nonlinear directional wave changes regularly and is proportional to the damage to the pipeline. At the same time, the sum frequency and difference frequency components are inversely proportional to the damage to the pipeline. All three indexes can reflect the damage of the polyethylene pipeline, which verifies the rationality of the damage evaluation of the nonlinear directional wave. Compared with the linear directional wave, the nonlinear directional wave is more accurate in evaluating the damage to polyethylene pipeline. There is no difference in the evaluation time, so the nonlinear directional wave can better evaluate the damage of polyethylene pipeline and has better rationality. However, in the study of nonlinear directional waves, there are few studies on the influence of propagation medium and the error in artificial measurement, so we will focus on optimizing the above contents in the future.

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Persian Abstract

چکیده

خط لوله پلی اتیلن زیرساخت ضروری شبکه توزیع گاز است و مشکلاتی از جمله ارزیابی پیچیده خسارت و فرآیند خسته کننده ارزیابی وجود دارد. نحوه انتخاب روش موثر ارزیابی خسارت برای خطوط لوله پلی اتیلن در حال حاضر محور اجرای شبکه توزیع گاز است. در این مقاله، یک روش موج جهت دار غیر خطی برای تشخیص آسیب خط لوله پلی اتیلن توسط موج صوتی پیشنهاد شده است و نتایج آسیب خط لوله پلی اتیلن جستجو می شود. منطقی بودن این روش با محاسبه معادله آیرودینامیکی تأیید می‌شود. نتایج نشان می‌دهد که روش موج ثابت غیرخطی می‌تواند به طور دقیق میزان آسیب و انتشار ترک خط لوله را تعیین کند و فرآیند ارزیابی آسیب را ساده کند و نتایج نسبت به جهت خطی برتری دارد. روش موج بنابراین، موج غیر خطی جهت دار را می توان برای ارزیابی آسیب به خطوط لوله اتیلن در شبکه های توزیع گاز استفاده کرد که از عقلانیت و عملی قوی برخوردار است و از ارزیابی واقعی آسیب خط لوله پشتیبانی می کند.