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Effect of uneven thickness of adhesive layer on EMI method

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Abstract. The electromechanical impedance (EMI) method is utilized for monitoring corrosion damage in pipelines. However, the variable thickness of the adhesive layer at the planar and cylindrical interfaces presents a challenge. To investigate the impact of uneven adhesive layer thickness on the EMI method, a theoretical model has been developed. This model analyzes the distribution of shear stress in the adhesive layer and the root-mean-square deviation (RMSD) of the impedance of the PZT. It was observed that the energy conversion efficiency decreased with a thicker adhesive layer. In monitoring cylindrical surface structures using the EMI method, the thicker adhesive layer locations experienced concentrated shear stresses, exacerbating energy attenuation and reducing monitoring sensitivity. In an experimental corrosion monitoring study of an aluminum alloy pipeline, two groups of PZTs with different forms of pasting were compared. The analysis of the RMSD of the PZT impedance before and after corrosion revealed that the group with poorer homogeneity exhibited lower sensitivity. Additionally, the theory provides a permissible error range for the pasting process.

Keywords: corrosion monitoring; EMI method; uneven thickness of adhesive layer

1. Introduction

Corrosion of metal pipelines can have devastating effects in various fields such as energy engineering and marine engineering, leading to accidents caused by thinning and rupture of pipeline wall. For example, corrosion-induced pipeline ruptures made explosions and casualties in Illinois in 2009. Similarly, the sewage corrosion induced the leakage of natural gas pipeline, which result an explosion in Qingdao in 2013. And then rainwater corrosion of a natural gas pipeline caused leakage in Kaohsiung in 2014. And in 2016, the same situation led to evacuations and building damage in Pennsylvania. According to statistics, the global annual corrosion cost is about 2.5 trillion US dollars (Li *et al*. 2020), and the pipeline corrosion costs reaching as high as 276 billion US dollars (Thoriya *et al*. 2022). Besides, unlike cracks or deformations, corrosion often occurs in hidden areas, such as inner walls of pipelines or metal-coating interfaces. It progresses slowly and is hard to detect, especially in pipelines and marine engineering, where it can go unnoticed until causing major failures (Sun *et al*. 2021). Therefore, it is crucial to improve the reliability of pipeline corrosion damage monitoring methods.

Currently, the existing corrosion monitoring methods include the electrochemical polarization method (Xia *et al*. 2022), it provides real-time monitoring of corrosion rates with high sensitivity, particularly useful in wet corrosion environments but requires complex electrochemical equipment and is limited to monitoring localized areas. Electrochemical noise method (Obot *et al*. 2019) is sensitive to localized corrosion types, such as pitting, and can be automated but the technique is prone to noise interference from environmental factors, making it less straightforward compared to other methods. The advantage of acoustic emission method (Livadiotis *et al*. 2023) is effective for real-time monitoring of active corrosion processes, especially crack formation. However, only advanced equipment and can be sensitive to environmental noise. Magnetic induction intensity method (Zhang *et al*. 2017), it's effective for long-term monitoring and offers good coverage for large structures but the sensitivity is limited. Weight loss method (Kumar *et al*. 2023) is simple and cost-effective but It's slow and only provides cumulative data after significant corrosion has occurred. Radioactivity indicator method (Kalmykov *et al*. 2018) offers precise measurement in specialized environments (e.g., nuclear or high-radiation settings) but is expensive and complex. And corrosion monitoring sensors (Reddy *et al*. 2021) is effective for ongoing and automated corrosion tracking but the initial installation and maintenance costs are high, and sensor degradation over time can impact long-term reliability.

The electrochemical polarization method and electrochemical noise method are in the chemical category. Acoustic emission method, magnetic induction intensity method, weight loss method, radioactivity indicator method

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and corrosion monitoring sensors are in the physical category. Each method has its own advantages and disadvantages, the most suitable method should be chosen according to different situations. In order to achieve convincing results, a combination of multiple methods is needed. EMI technology is also an effective method for corrosion monitoring, with unique advantages. Firstly, it can monitor the corrosion of the inner wall of the pipe without penetrating the pipe wall (Reddy *et al.* 2021), secondly, the cost of piezoelectric sensors is very low, and it can locate the corrosion position in the complex pipe network, thirdly, EMI technology is more sensitive to the early pipe thinning because the thinning of the pipe wall directly affects the vibration characteristics of the thin-walled region, and the EMI technology for resonance frequency changes can be better recognized (Livadiotis *et al.* 2023).

EMI technique was first proposed by Simmers G E in 2005 and has since been validated through experiments. Subsequent research has focused on improving recognition accuracy and predicting corrosion evolution using various statistical methods and neural networks. Park *et al.* (2007) extended the EMI technique to wireless applications, using a miniaturized impedance measurement chip AD5933 and self-inductive piezoelectric fiber composite (MFC) to monitor the corrosion in aluminum beams. Raju *et al.* (2020) implemented corrosion monitoring of metal pipelines using a non-adhesive method. Talakokula *et al.* (2014) proposed an embedded method to overcome the difficulties in monitoring steel corrosion in concrete and obtained the equivalent parameters of the structure by analyzing the corrosion damage information. Yang *et al.* (2013) simulated corrosion process of steel beams in marine environments and conducted long-term corrosion monitoring experiments (167 days), and analyzing the relationship between admittance signals and resonant frequencies. After that, Zhu *et al.* (2016) proposed an algorithm to characterize corrosion damage using the structural mechanical impedance (SMI), and quantifying corrosion damage using root mean squared error (RMSD). RMSD as a more commonly used damage quantification index in EMI technology, is essentially a statistical result, and its accuracy often depends on the frequency of long-term observation. EMI technology is used to determine the damage of a PZT by exciting the PZT vibration within a specific frequency range, so that the PZT vibrates locally with the metal pipe wall, and then judge its damage. According to the monitoring principle of the EMI technique, increasing the vibration coupling between the PZT and the metal pipe wall (e.g., thinning the thickness of the adhesive layer, so that the vibration of the PZT is better transmitted to the metal pipe wall), searching for a suitable range of the vibration frequency of the PZT and other optimization algorithms and quantitative indexes of damage. For example, Zhu *et al.* (2021) uses a probability weighting function to improve the damage localization method, which belongs to a new damage indicator and Djemana *et al.* (2017) Used enhance damage detection and classification in structural Health Monitoring. In addition, increasing the frequency of observation is also a basic method of improving the accuracy of the statistical method. Subsequent research has focused on improving recognition accuracy. Luo *et al.* (2023) quantified and predicted point corrosion of metal structures using convolutional neural networks (CNN). CNN method to improve the progress of EMI technology is mainly through the observation data from the physical meaning is not very clear, but can obviously indicate the indicators of the damage, belongs to the optimization algorithm to get a new quantitative indicator of the damage, this method can be under the small observation data to improve the accuracy of the EMI technology of the high efficiency of the method. This method first divides the EMA (admittance) signals into multiple sub-range responses and calculates statistical indices and through processing the EMA signals with CNN, the method enables accurate quantification of concrete structural damage under various temperature conditions and is an important means to improve the accuracy of EMI monitoring in the future (Li *et al.* 2021). Achieving higher accuracy compared to the original method. Ai *et al.* (2022) numerically simulated corrosion damage identification, evaluating the relevant parameters and corrosion damage of concrete using three sets of piezoelectric sensors in the thickness, width, and length of the beam and proposing a new sensitivity indicator for evaluating corrosion evolution. Rao and Sasmal (2023) used functionalized multi-walled carbon nanotubes to create corrosion monitoring sensors for monitoring the corrosion process in concrete. Morwal *et al.* (2023) provides a comprehensive summary of the use of EMI technology for corrosion monitoring in concrete structures. In the future, corrosion monitoring methods should be interdisciplinary composite monitoring methods, including multi-sensor fusion monitoring methods (Sun *et al.* 2019), intelligent optimization algorithms (Guo *et al.* 2021), etc. In addition, using other new materials with piezoelectric properties to replace PZT is a research hotspot, and embedding PZT sensors into the structure processing process is also a good alternative to traditional bonding processes. Furthermore, new applications of EMI reported this year have also been added, as shown in Table 1.

However, maintaining uniformity in the thickness of the adhesive layer on the cylindrical surface of pipelines poses a challenge. The thickness of the adhesive layer significantly affects the results of structural health monitoring. Several studies have investigated the impact of the adhesive layer on the EMI technology and proposed methods to prevent detachment of the adhesive layer (Moharana and Bhalla 2014a and Huang *et al.* 2010).

Table 1 Applications of EMI method

Han *et al.* 2020	Monitoring the corrosion of wooden materials.
Ferreira *et al.* 2020	Measuring the characteristics of the grinding process
Lan *et al.* 2024	Monitoring crack damage in concrete
Silva *et al.* 2020	Monitoring σ-phase embrittlement in duplex stainless steels
Le *et al.* 2023	Detection of cracks in prestressed anchored bearing plates

Xu and Liu (2002) studied the vibration coupling properties among PZT, adhesive layer and the structure. Moharana (2021) investigated the adhesive layer as an elastomer, which was considered to be transferring the energy through the successive tangential stresses, and also investigated the effect of the adhesive layer on the energy conversion efficiency (Moharana and Bhalla 2014b). Ai and Zhu (2023) incorporated the theory of curing effect into the shear mechanism of the adhesive layer and developed a one-dimensional PZT structural impedance model, and analyzed the impact of structural health monitoring methods by electromechanical conductance as an indicator of damage monitoring. Qing *et al.* (2006) investigated the influence of the thickness and elastic modulus of the adhesive layer on the EMI technology, and pointed out that the thickness of the adhesive layer has an influence on the electromechanical impedance and resonant frequency of the PZT as well as the amplitude of the sensor signal. Parpe and Saravanan (2021) investigated the damage miscalculation due to the detachment of the adhesive layer, and proposed a method to prevent the detachment of the adhesive layer by adding a protective layer. Nonetheless, there is a need for further research on the effects of non-uniform pasting conditions on EMI technology. Understanding these effects is crucial for the advancement of corrosion monitoring methods.

2. Modeling

Monitoring the corrosion damage to the pipeline involves pasting PZT to the pipeline wall, which exist in two forms of non-uniform pasting, as shown in Fig. 1. In the first situation, the thin adhesive layer is positioned in the center with a thickness of h_0, and the thicker adhesive layer positioned at the edges with a thickness of h_1. The second situation is that one side of the adhesive layer is thinnest at h_0, while the other side is thickest at h_1. The second situation can be considered as the right half plane of the first situation, the derivation is similar, only analyzing the first one.

The length of the PZT is $2a$, the outer diameter of the metal pipeline is $2r$, the schematic diagram for calculating the thickness of the adhesive layer in Fig. 2, and the thickness of the adhesive layer can be represented as $h(y)$:

$$h(y) = h_0 + \frac{\sqrt{r^2+y^2}-r}{\cos(\theta)} = h_0 + \frac{1}{r}\left(\sqrt{r^2+y^2}-r\right)\sqrt{r^2+y^2} \tag{1}$$

Modeling the actuator. The side length of the PZT is much larger than its thickness, and the deformation in the thickness direction can be neglected. The axial deformation of PZT is related to the electric field applied in the thickness direction and the axial force it receives. Its force balance equation is

$$\frac{d\sigma(y)}{dy} + \frac{\tau(y)}{h^p} = 0 \tag{2}$$

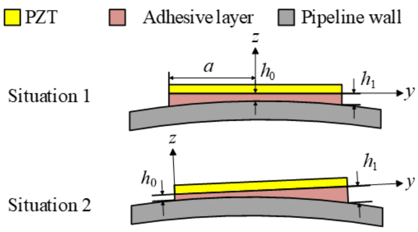


Fig. 1 Non-uniform pasted forms of pipeline corrosion monitoring using EMI method

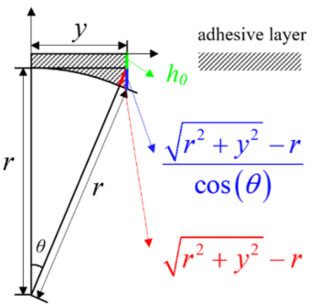


Fig. 2 Schematic diagram for calculating the thickness of the adhesive layer

where h^p represents the thickness of PZT, $\tau(y)$ represents the shear stress at the interface between the piezoelectric actuator and the adhesive layer. Duo to the PZT is not subjected to external forces at both ends, it can be determined

$$\sigma(y) = 0, \quad |y| = a \tag{3}$$

$$\sigma(y) = \int_{-a}^{y} \frac{\tau(\xi)}{h^p} d\xi \tag{4}$$

$$\int_{-a}^{a} \tau(\xi)\, d\xi = 0 \tag{5}$$

According to the constitutive equation of PZT, the axial stress of PZT can also be expressed as the axial strain and the applied electric field (Jin and Wang 2011)

$$\sigma(y) = E^p \epsilon_y^p(y) - e^p E_z \tag{6}$$

where E_z represents the electric field intensity equal to V/h_p. E^p and e^p determined by the properties of the PZT. The mechanical and electrical properties of PZT can be described fully by Wang and Meguid (2000)

$$\sigma_{ji,j} + f_i = \rho \ddot{u}_i \tag{7}$$

Gauss' law

$$D_{ij} = 0 \tag{8}$$

The constitutive equations

$$\{\sigma\} = [c]\{\epsilon\} - [e]\{E\}, \quad \{D\} = [e]\{\epsilon\} - [\epsilon]\{E\} \tag{9}$$

where

$$\epsilon_{ij} = \frac{1}{2}\left(u_{i,j} + u_{j,i}\right), \qquad E_i = -V_i \tag{10}$$

In these equations, $\{\sigma\}$ and {Ò} are the stress and the strain fields, f_i and ρ are the body force and the mass density, while $\{D\}$, $\{E\}$ and V represent the electric displacement, the electric field intensity and the potential, respectively. $[c]$ is a matrix containing the elastic stiffness parameters for a constant electric potential, $[e]$ represents a tensor containing the piezoelectric constants and [Ò] represents the dielectric constants for zero strains. According to the electroelastic line actuator model, the effective material constants of the actuator model are given by

$$E^p = c_{11} - \frac{c_{13}^2}{c_{33}} \tag{11}$$

$$e^p = e_{13} - e_{33}\frac{c_{13}}{c_{33}} \tag{12}$$

Eqs. (1) and (6) can be combined to express the axial strain and deformation of PZT by $\tau(y)$

$$\epsilon_y^p(y) = -\frac{1}{E^p h^p}\int_{-a}^{y} \tau(\xi)\, d\xi + \frac{e^p E_z}{E^p} \tag{13}$$

$$u_y^p(y) = \frac{-1}{E^p h^p}\int_{-a}^{y} (y-\xi)\tau(\xi)\, d\xi + \frac{e^p E_z y}{E^p} \tag{14}$$

Modeling the adhesive layer. The mechanical energy generated by PZT is transmitted through the adhesive layer, and the force exerted on the pipeline wall is related to the shear stress. Its force diagram was shown in Fig. 3.

The displacements on the upper and lower surfaces of the adhesive layer are denoted as μ^+ and μ^- respectively. Due to the cylindrical surface of the bottom of the adhesive layer, the displacement needs to be converted to obtain the shear stress $\tau(y)$

$$\tau(y) = -\mu^b \frac{u^+(y) - u^-(y)\frac{r}{\sqrt{r^2+y^2}}}{h(y)} \tag{15}$$

$$\tau(y) = -\mu^b \frac{u^+(y) - u^-(y)\frac{r}{\sqrt{r^2+y^2}}}{h(y)} \tag{16}$$

where μ^b is the shear modulus of the adhesive layer.

Modeling the structure, the pipeline is only subjected to circumferential shear stress, and when the side length of PZT is much smaller than the outer diameter of the pipeline, the shear stress on the pipeline along the y-axis can be represented by circumferential shear stress $\tau(\theta)$

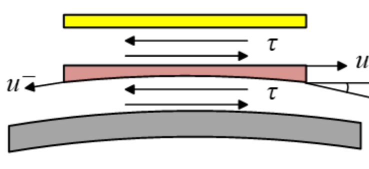


Fig. 3 Force diagram of the adhesive layer

$$\tau(y) = \tau(\theta)\cos(\theta) \tag{17}$$

Then the strain $Ò_y^h$ and displacement $\boldsymbol{u_y^h}$ of pipeline can be expressed by the shear stress (Muskhelishvili 1953)

$$\epsilon_y^h(\theta, 0) = \frac{1-\nu^h}{\pi\mu^h}\int_{-\theta_0}^{\theta_0} \frac{\tau(\xi)\cos(\xi)}{\theta_0 - \xi} d\xi \tag{18}$$

$$u_y^h(\theta, 0) = \frac{1-\nu^h}{\pi\mu^h}\int_{-\theta_0}^{\theta}\int_{-\theta_0}^{\theta_0} \frac{\tau(\xi)\cos(\xi)}{\theta_0 - \xi} d\xi\, d\theta \tag{19}$$

where ν^h and μ^h are the Poisson's ratio and shear modulus of the pipeline wall. Combine Eqs. (13) to (19), and differentiating $\tau(y)$ with respect to y

$$\begin{aligned} -\frac{d\tau(y)}{\mu^b dy} = {} & f_1(y)\int_{-a}^{y}\int_{-a}^{a} \frac{\tau(\xi)}{y-\xi} d\xi \\ & + f_2(y)\int_{-a}^{y} (y-\xi)\tau(\xi)\, d\xi \\ & + f_3(y)\int_{-a}^{a} \frac{\tau(\xi)}{y-\xi} d\xi \\ & + f_4(y)\int_{-a}^{y} \tau(\xi)\, d\xi + f_5(y)\frac{e^p E_z}{E^p} \end{aligned} \tag{20}$$

where the functions from $f_1(y)$ to $f_5(y)$ are

$$\begin{aligned} f_1(y) = {} & \frac{ry(1-\nu^h)}{\pi\mu^h\sqrt{(r^2+y^2)^3}h(y)} \\ & + \frac{r^2 y(1-\nu^h)}{\pi\mu^h(r^2+y^2)^2\left(h(y)\right)^2} \end{aligned} \tag{21}$$

$$f_2(y) = \frac{r^2 y}{E^p h^p\sqrt{(r^2+y^2)^3}\left(h(y)\right)^2} \tag{22}$$

$$f_3(y) = -\frac{1-\nu^h}{\pi\mu^h}\frac{r}{\sqrt{(r^2+y^2)^3}h(y)} \tag{23}$$

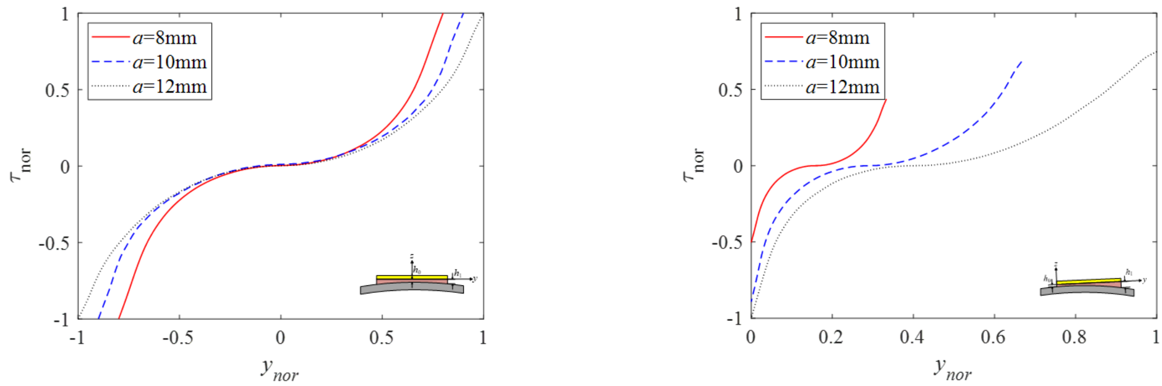
$$f_4(y) = -\frac{1}{E^p h^p h(y)} \tag{24}$$

$$f_5(y) = \frac{1}{h(y)} - \frac{r^2 y^2}{\sqrt{(r^2+y^2)^3}\left(h(y)\right)^2} \tag{25}$$

Eq. (20) is a first-order singular integral equation, which can be expanded using Chebyshev polynomials, and taking the first n terms, the normalized expression for shear stress τ_{nor} (Wang and Meguid 2000) can be represented as

$$\tau_{nor}(\eta) = \frac{1}{\sqrt{1-\eta^2}}\sum_{j=0}^{\infty} d_j T_j(\eta) \tag{26}$$

where $\eta = y/a(-a < y\ a)$. According to the derivation of EMI (Bhalla *et al.* 2009), the force transferred to the pipeline wall is obtained by the shear stress at the interface between the structure and the adhesive layer.



(a) Situation 1 (b) Situation 2

Fig. 4 The distribution of shear stress between the adhesive layer and the pipeline

$$F = -Z_s(\dot{u}^p - \dot{u}^h) = -Z_s j\omega \frac{h_{nor}}{\mu^b_{nor}\sqrt{1-\eta^2}} \sum_{j=0}^{\infty} d_j T_j(\eta) \tag{27}$$

The equivalent mechanical impedance of a pipeline can be expressed as

$$Z_{s\_eff} = Z_s\left(\frac{h_{nor}(\eta)}{\mu^b_{nor}\sqrt{1-\eta^2}} \sum_{j=0}^{\infty} d_j T_j(\eta)\right) \tag{28}$$

The modified result of the admittance for PZT is obtained by substituting Z_{s_eff} into the PZT-adhesive layer-structure model (Bhalla *et al*. 2009).

$$\bar{Y} = 2\omega j \frac{wl}{h_0}(\bar{\varepsilon}^T_{33} - d^2_{31}\bar{Y}^E) + 2\omega j \frac{wl}{h_0}\left(\frac{Z_a}{Z_{s\_eff} - Z_a}\right) d^2_{31}\bar{Y}^E \frac{\tan kl}{kl} \tag{29}$$

3. Numerical calculation

Numerical calculation uses PZT-5 and aluminium alloy 6063 pipeline as an example, and the adhesive layer adopt epoxy resin after curing at 25°C. The distribution of shear stress at the interface between the adhesive layer and the pipeline is shown in Fig. 4. The shear stress in situation 1 is mainly distributed at the edge of the interface. The thicker edge of the adhesive layer reduces the efficiency of energy transfer. In situation 2, the decrease in energy transfer efficiency is more pronounced because the distribution of shear stress is asymmetrical. The RMSD under different τ values resulted in two different scenarios as shown in Fig. 5. The thickness ratio h_0/h_1 is considered to be adhesion uniformity index, the RMSD decreases as the h_1 increases for both non-uniform pasting situations. The decrease in sensitivity is more significant for the second non-uniform situation. According to the calculation results, when h_1 is not greater than twice h_0 for both non-uniform pasting situations, the impact on sensitivity for corrosion damage is minimal. However, when h_1 exceeds twice h_0, the decrease

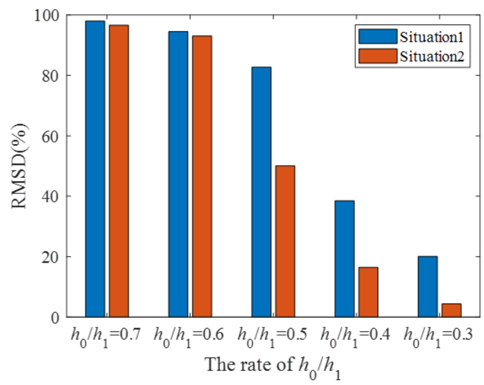


Fig. 5 RMSD of impedance under different situation

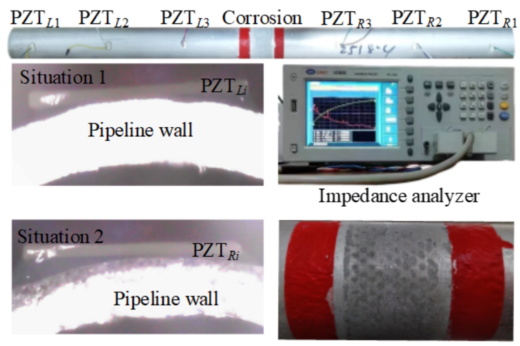


Fig. 6 Corrosion monitoring experimental platform

in sensitivity for corrosion damage monitoring becomes more apparent.

4. Experiment

Experiment sets two groups of PZT_{Li} and PZT_{Ri}. The PZT_{Li} applied the first pasting form, and the PZT_{Ri} applied the second pasting form. And the aluminum pipeline is corroded with hydrochloric acid (20% HCl) at the middle part. The experimental platform is shown in Fig. 6.

The amplitude of the impedance of the left group is higher than the right group, which may indicate that the uniformity of pasting not only affects the RMSD, but also

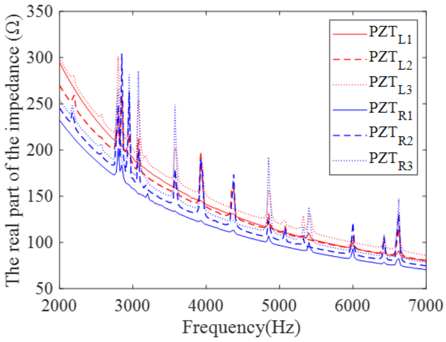


Fig. 7 Impedance original signals of each PZT

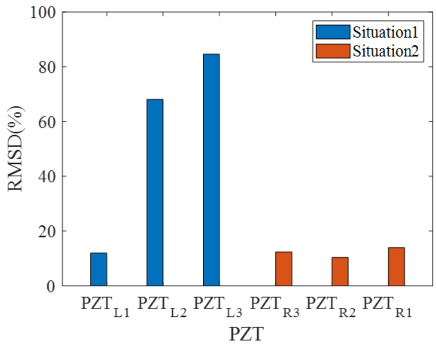


Fig. 8 RMSD of each PZT for two non-uniform paste situation

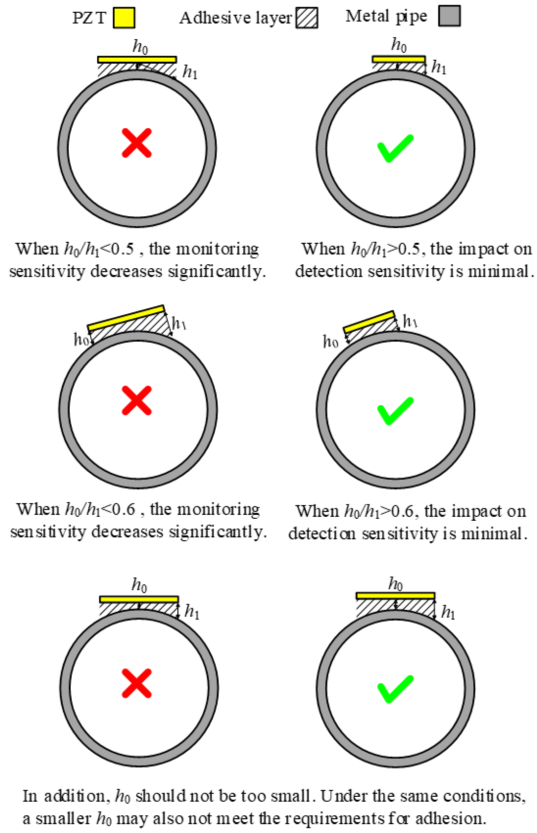


Fig. 9 Paste effect comparison

affects the impedance original signal, as shown in Fig. 7.

The RMSD results reflect that the sensitivity of the first pasting situation is better than the second one.

5. Conclusions

Corrosion in pipelines often occurs at the bottom and sides of the pipelines, and it is more conducive to monitoring when the PZT is positioned close to the corrosion site. Due to factors such as gravity, the flowability of the adhesive, and the curved surface of the pipeline, it is difficult to ensure the effectiveness of the pasting. The use of special fixtures and pasting equipment can solve these problems, but in practical engineering, manual pasting is still the most effective method due to the narrow gaps between pipelines. Therefore, it is of great significance to study the evaluation criteria for pasting effectiveness in Fig. 9.

According to theory and experimental results, the ratio between the thinnest thickness h_0 and the thickest thickness h_1 of the adhesive layer in the first case can be ignored for the sensitivity of PZT monitoring, ranging from 0.5~1. In the second case, this ratio is between 0.6~1. Furthermore, the article summarizes several principles of the adhesive process.

- During the PZT pasting process, measures should be taken to ensure consistent 5 ratio h_0/h_1 should be between 1 and 0.6.

Acknowledgments

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