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Steel Structure Corrosion Inspection Using Impedance Spectrum of Piezoelectric Plate

Yiming Wang

Changsha University of Science & Technology, Changsha, China
1774212246@qq.com

Abstract. Steel structures are widely used in the engineering field because they have really excellent mechanical features, but corrosion brings a very big threat to their safety and the length of their service life. So it is quite essential to carry out effective checking of the corrosion condition for the health management of steel structures. Traditional inspection ways, like looking at the steel structures directly and doing ultrasonic check on them, have many obvious limitations in practical use. For example, these ways are subjective in judgment, not efficient enough when applied to large-scale engineering projects, and some even have the problem of being invasive to the structures. In recent years, impedance analysis has become a promising non-destructive way to monitor the health of various structures. This method has a high level of sensitivity to the early damage of steel structures, and it can realize this by detecting the tiny subtle changes in the electromechanical impedance reaction of piezoelectric sensing devices that are stuck on the surface of the steel structures. This particular research puts forward the impedance analysis method and applies it to the corrosion checking of steel structures in detail. It focuses on making a deep investigation into the correlation between two key points, which are the loss of thickness caused by corrosion and the corresponding changes of impedance signals, and the loss of thickness caused by corrosion is an important sign of structural damage. The main purpose of this research is to build a dependable and real-time way of monitoring the corrosion of steel structures in actual engineering use. The final findings and results of this research are expected to provide a new technical solution for the work of assessing the whole condition of steel structures. And with this new solution, we can better improve the safety performance, the durability and the management of the whole service life of steel structures in different engineering projects.

Keywords: corrosion, impedance analysis method, piezoelectric sensor, structural health monitoring

1. Introduction

Steel structures are often used in engineering work. They have very good mechanical qualities. But corrosion (rust) is very bad for their safety and how long they can be used. So it is very important to check corrosion well to keep steel structures healthy. Traditional ways to check, like looking carefully and using ultrasonic tests, have many problems. For example, people's opinions may be different, they are not good for large areas, or they may hurt the structure. Recently, impedance analysis has become a good new way to check structures without hurting them. It can find small early damage. It does this by checking tiny changes in the electromechanical impedance of piezoelectric sensors stuck

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on the structure. This study talks about using impedance analysis to check corrosion on steel structures. It focuses on finding the link between corrosion-caused thickness loss—a key sign of damage—and changes in impedance signals. The research wants to make a reliable way to check in real time. The results may bring a new technical method to check if structures are good. This helps make steel structures safer, more durable, and better to manage during their whole use time.

Given how bad corrosion is for steel structures, checking corrosion has become a must-do part of keeping structures healthy [1-4]. Checking corrosion in time and correctly lets engineers know if structures are safe, guess how long they can still be used, and do the right maintenance work. This stops terrible accidents from happening and cuts down the cost of using structures for their whole life. For example, on sea platforms or long bridges that stay in bad, rust-causing places, checking corrosion nonstop can stop unexpected work pauses and keep things running safely [5,6]. What's more, as we need more eco-friendly buildings and roads, checking corrosion helps make steel structures last longer and work better. This fits with the goals of green engineering and saving resources.

To meet the need of checking corrosion, many different ways have been created and used in real work [7-10]. Old ways include looking carefully at structures, using ultrasonic tests, doing magnetic particle tests, and using electrochemical techniques (like linear polarization resistance and electrochemical impedance spectroscopy to check corrosion on small pieces of material). Although these ways give useful information, they often have problems: looking carefully depends on people's own opinions and can't find corrosion inside structures or at an early stage; ultrasonic tests need skilled workers and are not efficient for big structures; electrochemical techniques are usually only used in labs or small outdoor areas, so they are hard to use to check whole structures. Besides, some ways damage structures or need to stop structures from working, which makes costs go up and breaks normal work.

In recent years, impedance analysis has become a good new way to check if structures are healthy [11-15]. It is a way that doesn't damage or invade structures. It can find tiny changes in a structure's properties (like stiffness, weight, and damping) that are caused by corrosion—even at the very start. By measuring the electrical impedance response of piezoelectric sensors stuck on the structure, this way can clearly link changes in impedance to the structure getting worse. This method makes it possible to check steel structures nonstop and in real time all the time. Also, impedance analysis is really sensitive to the small local damage that appears on steel structures. It does not require people to prepare too many testing tools for the related check work. It can also be used together with wireless sensor networks to check those large steel structures or the steel structures that are far away from the testing place. These good characteristics make this method especially suitable for checking the corrosion problem on steel structures that are in complex and harsh working environments. And it can well solve all those practical problems that the traditional old testing methods have in actual use.

Because of these above challenges and the good features of impedance analysis, the research study at present puts the impedance analysis method into the corrosion check and analysis of steel structures. By looking into the close correlation between the thickness loss caused by corrosion (a main sign of steel corrosion) and the impedance response of steel structures, this study tries to build a reliable and efficient way to monitor steel corrosion based on the impedance analysis method. The final findings and results of this study are expected to give a new technical solution for the real-time monitoring and assessment of corrosion on steel structures, and this solution can further help to improve the safety of steel structures, their durability in practical use and the overall management of their whole service life as well.

2. Methods-impedance analysis model of piezoelectric plate embedded in steel component

We don't consider the force of the body and the electric charge of the body. We can write the basic equations for the piezoelectric thin layer in this way [16,17]

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$$T_z = c_{33}^E S_z - e_{33} E_z \tag{1}$$

$$D_z = e_{33} S_z + \varepsilon_{33}^S E_z \tag{2}$$

Sz is the strain of the piezoelectric thin layer in the z direction. Tz is the stress of the piezoelectric thin layer in the z direction. These two are different physical quantities for the z direction of the piezoelectric thin layer. Ez is the strength of the electric field in the z direction. Dz is the electric displacement in the z direction. These two are different electric physical quantities for the z direction. c_{33}^E is the elastic constant of the piezoelectric thin layer. e33 is the piezoelectric constant of the piezoelectric thin layer. ε_{33}^S is the dielectric constant of the piezoelectric thin layer. These three are all important constants of the piezoelectric thin layer. The superscripts E and S mean written at the top of the constants have special meanings. The superscript E means we measure this parameter when the electric field does not change at all. The superscript S means we measure this parameter when the strain does not change at all. For simplicity, we will not write these superscripts in the following parts.

We can write the equations that show the shape and position relations of the piezoelectric thin layer like this

$$S_z = \frac{\partial w}{\partial z} \tag{3}$$

$$E_z = -\frac{\partial \phi}{\partial z} \tag{4}$$

w is the distance that the piezoelectric thin layer moves along the z direction (this is called displacement). ϕ is the electric potential of the piezoelectric thin layer.

We can write the equations that show the dynamic balance and electric displacement balance of the piezoelectric thin layer like this

$$\rho \frac{\partial^2 w}{\partial t^2} = \frac{\partial T_z}{\partial z} \tag{5}$$

$$\frac{\partial D_z}{\partial z} = 0 \tag{6}$$

where ρ is the density of the piezoelectric thin layer — density means how much mass the piezoelectric thin layer has in a certain volume.

If the voltage we put into the system (it's called input voltage, written as $V(t)$) is a harmonic signal, and this signal has the following form

$$V(t) = V_{in} e^{j\omega t} \tag{7}$$

V_{in} is the maximum value of the input voltage (this is called voltage amplitude). $\mathrm{j} = \sqrt{-1}$, $\omega = 2\pi f$ is the circular frequency, and f is the frequency of the input signal — frequency means how many times the signal changes in one second. With this input voltage, we can write the steady state expressions of four things of the piezoelectric thin layer: stress, electric displacement, electric potential and displacement. Steady state means the state where these physical quantities don't change in a regular changing way anymore. The expressions are written as

$$(T_z, D_z, \phi, w) = [T_z(z), D_z(z), \phi(z), w(z)] e^{j\omega t} \tag{8}$$

When we put Equation (3) and Equation (4) into Equation (1), we can get a new equation

$$\frac{\partial T_z(z)}{\partial z} = \frac{c_{33} \partial^2 w(z)}{\partial z^2} + \frac{e_{33} \partial^2 \phi(z)}{\partial z^2} \tag{9}$$

When we put Equation (4) and Equation (6) into Equation (2), we can get another new equation

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$$\frac{\varepsilon_{33}\partial^2\phi(z)}{\partial z^2} = \frac{e_{33}\partial^2 w(z)}{\partial z^2} \tag{10}$$

When we put these two new equations (Equation (9) and Equation (10)) together and combine them, we can get a new equation

$$\frac{\partial T_z(z)}{\partial z} = \frac{\left(e_{33}{}^2 + c_{33}\varepsilon_{33}\right)}{e_{33}} \frac{\partial^2\phi(z)}{\partial z^2} \tag{11}$$

When we put Equation (11) into Equation (5), we can get a new equation

$$-\rho\omega^2 w(z) = \frac{\left(e_{33}{}^2 + c_{33}\varepsilon_{33}\right)}{e_{33}} \frac{\partial^2\phi(z)}{\partial z^2} \tag{12}$$

When we put Equation (10) into Equation (12), we can get a new equation

$$\frac{\partial^2 w(z)}{\partial z^2} + \alpha^2 w(z) = 0 \tag{13}$$

where $\alpha^2 = \frac{\varepsilon_{33}\rho\omega^2}{e_{33}{}^2 + c_{33}\varepsilon_{33}}$

When we solve Equation (13), we can get the result

$$w(z) = A\,sin(\alpha z) + B\,cos(\alpha z) \tag{14}$$

In this result, A and B are coefficients that we don't know their values yet (they are called unknown coefficients).

When we put Equation (14) and Equation (10) together and combine them, we can get a new equation

$$\phi(z) = \beta\left[A\,sin(\alpha z) + B\,cos(\alpha z) + C_1 z + C_0\right] \tag{15}$$

where $\beta = \frac{e_{33}}{\varepsilon_{33}}$, C1 and C0 — we don't know their values yet.

So now, we can write the expression of the stress part of the piezoelectric thin layer

$$T_z(z) = \alpha\eta[A\,cos(\alpha z) - B\,sin(\alpha z)] + \delta C_1 \tag{16}$$

where $\eta = \frac{e_{33}{}^2 + c_{33}\varepsilon_{33}}{\varepsilon_{33}}$ $\delta = \frac{e_{33}{}^2}{\varepsilon_{33}}$

We can also write the expression of the electric displacement of the piezoelectric thin layer

$$D_z(z) = -e_{33}C_1 \tag{17}$$

Until now, we have found the expressions of four key things of the piezoelectric thin layer: stress, electric displacement, electric potential and displacement. In these expressions, there are four unknown constants that we don't know the values of yet: A, B, C0, and C1.

For the elastic thin layer (it's different from the piezoelectric thin layer), we can get the corresponding expressions of its stress and displacement. We just need to set the piezoelectric constant e33 to 0 (that means let e33=0) when calculating. In these expressions of the elastic thin layer, the only unknown constants are A and B.

In this study, we want to tell the material parameters and unknown coefficients of different thin layers apart (so we won't mix them up). So we use a subscript for all these parameters and coefficients — a subscript is a small number or letter written at the bottom right of a symbol. Now let's look at a structure: it has one piezoelectric thin layer and two elastic thin layers (this structure is shown in

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Figure 1). In total, there are eight unknown constants in this structure. We can list all these eight unknown constants like this

$$\left[A_1, A_2, A_3, B_1, B_2, B_3, C_{02}, C_{12}\right] \tag{18}$$

The last number in the subscript is the number of the thin layer (it tells us which layer the constant belongs to). We can find the exact values of all these unknown coefficients by using the boundary conditions and continuous conditions of the structure.

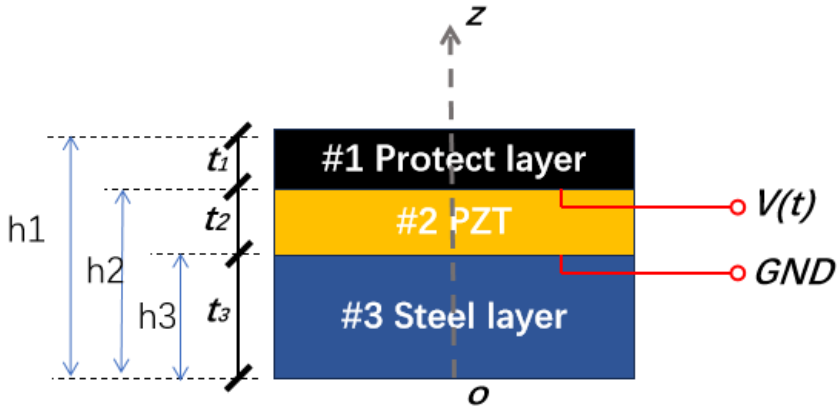


Figure 1. One-dimensional model of PZT patch embedded in steel component

We list the electrical boundary conditions, the mechanical boundary conditions and the mechanical continuous conditions one by one below. Please remember this rule clearly: the last number in the small subscript of each physical quantity stands for which layer the physical quantity belongs to.

Electrical boundary conditions. These conditions are only for the piezoelectric layer — and this piezoelectric layer is layer 2.

$$\begin{cases} \phi_2(z)\Big|_{z=h_2} = V_{in} \\ \phi_2(z)\Big|_{z=h_3} = 0 \end{cases} \tag{19}$$

Mechanical boundary conditions: These are the mechanical boundary conditions for the layers.

$$\begin{cases} w_3(z)\Big|_{z=0} = 0 \\ T_{z1}(z)\Big|_{z=h_1} = 0 \end{cases} \tag{20}$$

Mechanical continuous conditions: These are the mechanical continuous conditions for the layers.

$$\begin{cases} w_1(z)\Big|_{z=h_2} = w_2(z)\Big|_{z=h_2} \\ T_{z1}(z)\Big|_{z=h_2} = T_{z2}(z)\Big|_{z=h_2} \\ w_2(z)\Big|_{z=h_3} = w_3(z)\Big|_{z=h_3} \\ T_{z2}(z)\Big|_{z=h_3} = T_{z3}(z)\Big|_{z=h_3} \end{cases} \tag{21}$$

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The eight math equations that come from the boundary and continuous conditions can be put together as

$$\begin{cases} \beta_2\left[A_2\,sin\left(\alpha_2 h_2\right)+B_2\,cos\left(\alpha_2 h_2\right)+C_{1_2}h_2+C_{02}\right]=V_{in} \\ \beta_2\left[A_2\,sin\left(\alpha_2 h_3\right)+B_2\,cos\left(\alpha_2 h_3\right)+C_{1_2}h_3+C_{02}\right]=0 \\ B_3=0 \\ \alpha_1\eta_1\left[A_1\,cos\left(\alpha_1 h_1\right)-B_1\,sin\left(\alpha_1 h_1\right)\right]=0 \\ A_1\,sin\left(\alpha_1 h_2\right)+B_1\,cos\left(\alpha_1 h_2\right)=A_2\,sin\left(\alpha_2 h_2\right)+B_2\,cos\left(\alpha_2 h_2\right) \\ \alpha_1\eta_1\left[A_1\,cos\left(\alpha_1 h_2\right)-B_1\,sin\left(\alpha_1 h_2\right)\right]=\alpha_2\eta_2\left[A_2\,cos\left(\alpha_2 h_2\right)-B_2\,sin\left(\alpha_2 h_2\right)\right]+\delta_2 C_{12} \\ A_2\,sin\left(\alpha_2 h_3\right)+B_2\,cos\left(\alpha_2 h_3\right)=A_3\,sin\left(\alpha_3 h_3\right)+B_3\,cos\left(\alpha_3 h_3\right) \\ \alpha_2\eta_2\left[A_2\,cos\left(\alpha_2 h_3\right)-B_2\,sin\left(\alpha_2 h_3\right)\right]+\delta_2 C_{12}=\alpha_3\eta_3\left[A_3\,cos\left(\alpha_3 h_3\right)-B_3\,sin\left(\alpha_3 h_3\right)\right] \end{cases} \tag{22}$$

This can be changed into the form of a coefficient matrix, like this

$$\begin{bmatrix} 0 & \beta_2 sin(\alpha_2 h_2) & 0 & 0 & \beta_2 cos(\alpha_2 h_2) & 0 & \beta_2 & \beta_2 h_2 \\ 0 & \beta_2 sin(\alpha_2 h_3) & 0 & 0 & \beta_2 cos(\alpha_2 h_3) & 0 & \beta_2 & \beta_2 h_3 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \alpha_1\eta_1 cos(\alpha_1 h_1) & 0 & 0 & -\alpha_1\eta_1 sin(\alpha_1 h_1) & 0 & 0 & 0 & 0 \\ sin(\alpha_1 h_2) & -sin(\alpha_2 h_2) & 0 & cos(\alpha_1 h_2) & -cos(\alpha_2 h_2) & 0 & 0 & 0 \\ \alpha_1\eta_1 cos(\alpha_1 h_2) & -\alpha_2\eta_2 cos(\alpha_2 h_2) & 0 & -\alpha_1\eta_1 sin(\alpha_1 h_2) & \alpha_2\eta_2 sin(\alpha_2 h_2) & 0 & 0 & -\delta_2 \\ 0 & sin(\alpha_2 h_3) & -sin(\alpha_3 h_3) & 0 & cos(\alpha_2 h_3) & -cos(\alpha_3 h_3) & 0 & 0 \\ 0 & \alpha_2\eta_2 cos(\alpha_2 h_3) & -\alpha_3\eta_3 cos(\alpha_3 h_3) & 0 & -\alpha_2\eta_2 sin(\alpha_2 h_3) & \alpha_3\eta_3 sin(\alpha_3 h_3) & 0 & \delta_2 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \\ B_1 \\ B_2 \\ B_3 \\ C_{02} \\ C_{12} \end{bmatrix} = \begin{bmatrix} V_{in} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{23}$$

We can find the eight unknown coefficients by using these eight math equations. These eight math equations are made from the electrical boundary conditions and the mechanical boundary conditions.

We can say what the size (value) of the input electric current is with this equation:

$$I_{in}=\int_a \frac{dD_{z2}\big|_{z=h_1}}{dt}da=-\omega a e_{332}C_{12}j \tag{24}$$

We can find the input impedance and the input admittance one by one with these equations:

$$\begin{cases} Z=\frac{V_{in}}{I_{in}} \\ Y=\frac{1}{Z} \end{cases} \tag{25}$$

3. Results and discussion

In this part, we talk about how three things affect the impedance spectrum of the stuck-on PZT patch. These three things are the thickness of the piezoelectric layer, the thickness of the protective layer, and the original thickness of the steel structure layer. The material parameters (the special numbers that describe the materials) of the piezoelectric layer, the protective layer and the steel structure layer are shown in Table 1.

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Table 1. Material parameters of the piezoelectric layer, the protective layer and the steel structure layer [16,17]

	Density ρ	Stiffness constant c_{33}^{E}	Piezoelectric constant e_{33}	Dielectric constant ε_{33}^{S}
PZT layer	$7.5\times10^{3}\,kgm^{-3}$	$11.7\times10^{10}\,Nm^{2}$	$22.3Cm^{-2}$	$1470\varepsilon_{0}$
Protect layer	$7.5\times10^{3}\,kgm^{-3}$	$11.7\times10^{10}\,Nm^{2}$	----	----
Steel layer	$7.85\times10^{3}\,kgm^{3}$	$2\times10^{11}\,Nm^{2}$	----	----

Note: ε_{0} =8.854× 10^{-12} farads m^{-1}

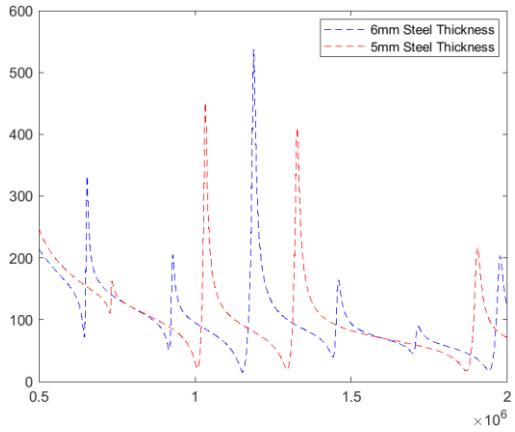


Figure 2. Influence of steel thickness loss on impedance spectrum of a 1mm thick piezoelectric plate covered by 2mm thick protect layer

We take the electromechanical model from Section 2 for the research, and the impedance spectrum of the fixed PZT patch that takes steel layer loss into account is shown clearly in Figure 2. We base our analysis on the impedance spectrum curves in Figure 2, and we study the exact effect on the piezoelectric sensor's response when the steel structure's thickness is cut from 6 mm to 5 mm. This thickness change is used to simulate the loss of steel thickness that is caused by corrosion in real engineering situations.

First of all, the value of the resonance peak goes down obviously. In detail, the impedance peak stands at about 550 when the steel structure has a thickness of 6 mm. But this peak falls down to around 450 when the steel structure's thickness is reduced to 5 mm. This kind of phenomenon tells us that the drop in steel thickness will bring about several key changes to the system. It will make the mechanical load of the system become smaller, make the energy dissipation of the system get stronger, or make the electromechanical coupling effect of the system become weaker. All these changes together lead to a noticeable fall in the resonance amplitude of the system in the end.

Second, the resonance frequency shifts to the left side on the spectrum. The resonance frequency is about 1.5×10^{6} Hz when the steel structure is 6 mm thick. When the steel structure's thickness is lowered to 5 mm, the resonance frequency moves towards the low-frequency area of the spectrum. This change clearly shows that making the steel structure thinner will reduce the equivalent stiffness of the whole system. And the drop of the system's equivalent stiffness will then cause the resonance frequency of the system to become lower as a direct result.

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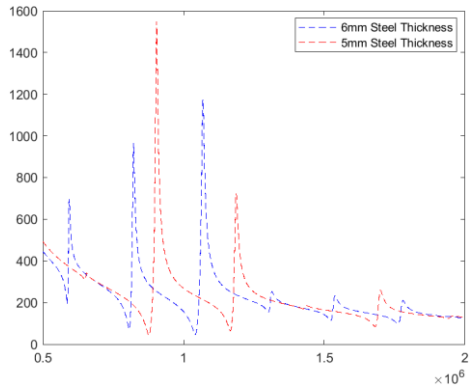


Figure 3. Influence of steel thickness loss on impedance spectrum of a 2mm thick piezoelectric plate covered by 2mm thick protect layer

We use the electromechanical model that is gained from Section 2, and the impedance spectrum of the fixed PZT patch which takes steel layer loss into consideration is shown clearly in Figure 3. Based on the impedance spectrum curves that can be seen in Figure 3, we analyze the specific effect on the response of the piezoelectric sensor that comes from cutting the thickness of the steel structure from 6 mm down to 5 mm, and this change is used to simulate the thickness loss that is caused by corrosion in actual situations.

First of all, the specific value of the resonance peak goes down in a very significant way. When the thickness of the steel structure is 6 mm, the peak value of the impedance can reach about 1400 in total. But on the other hand, this impedance peak falls down to around 1200 when the steel structure's thickness is reduced to 5 mm. This special phenomenon takes place because the loss of steel thickness brings about three main changes: it makes the mechanical load become smaller, lets the piezoelectric coupling efficiency go down, and causes the energy dissipation to increase a lot. All these three changes work together, and they all lead to the obvious drop in the peak value of the impedance. This research result is in line with the changing trend that is presented in Figure 1 completely.

Second, the resonance frequency has a slight shift to the left side. The resonance peaks of these two different curves are both found around the position of 1.5×10^6 Hz. But the peak frequency that corresponds to the steel structure with 5 mm thickness moves a little bit towards the low-frequency range, when we compare this frequency with the one that corresponds to the steel structure with 6 mm thickness. What we observe from this change tells us that the reduction in the thickness of the steel structure makes the equivalent stiffness of the whole system become lower than before.

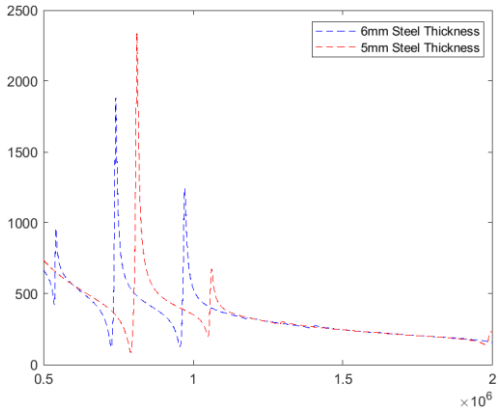


Figure 4. Influence of steel thickness loss on impedance spectrum of a 3mm thick piezoelectric plate covered by 2mm thick protect layer

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Using the electromechanical model obtained in Section 2, the impedance spectrum of the attached PZT patch considering steel layer loss is presented in Figure 4. Based on the impedance spectrum curves shown in Figure 4, the effect of reducing the steel structure thickness from 6 mm to 5 mm (simulating thickness loss caused by corrosion) on the response of the piezoelectric sensor is analyzed.

Firstly, the resonance peak value undergoes a significant decrease. At a steel thickness of 6 mm, the impedance peak is approximately 2200, which is close to the 2500 scale mark; when the thickness is reduced to 5 mm, the peak falls to about 1700 (ranging between 1500 and 2000). This represents a reduction of around 500 units. This phenomenon indicates that the thickness loss of the steel structure cuts down the mechanical load and piezoelectric coupling efficiency of the system, thereby resulting in an increase in energy dissipation.

Secondly, the resonance frequency presents a slight leftward shift. The resonance frequencies of the two curves are both around 1.5×10^{6} Hz. In comparison with the curve corresponding to the 6 mm thickness, the one for the 5 mm thickness shifts slightly toward the low-frequency range. This suggests that thickness loss brings about a slight reduction in the equivalent stiffness of the system.

4. Conclusions

Based on the results from this study (the piezoelectric plates are 1mm, 2mm, and 3mm thick respectively), we fully summarize how steel structure corrosion (when its thickness goes down from 6mm to 5mm) affects the piezoelectric impedance spectrum in Table 2:

Table 2. The impact of steel structure corrosion on the piezoelectric impedance spectrum

Piezoelectric Plate Thickness	Steel Structure Thickness	Impedance Peak (Estimated)	Peak Reduction Value
1mm	6mm	≈550	≈200
	5mm	≈450	
2mm	6mm	≈1400	≈400
	5mm	≈1200	
3mm	6mm	≈2400	≈500
	5mm	≈1700	

And the key Trends and Analysis of Physical Mechanisms are concluded in the following

Firstly, the relationship between Impedance Peak and Piezoelectric Plate Thickness is revealed

It is found that the thicker the piezoelectric plate, the higher the system's impedance peak.

Secondly, the mechanism of this phenomenon is proposed. Increasing the thickness of the piezoelectric plate means a larger volume and a more active piezoelectric vibrator, resulting in stronger inherent electromechanical coupling capability. This enables the generation and reception of more intense mechanical vibration signals, manifesting as higher resonance peaks in the impedance spectrum.

Then the Corrosion on Impedance Peak (Detection Sensitivity) is effected.

It is seen that the thicker the piezoelectric plate, the greater the reduction in impedance peak caused by steel structure corrosion (thickness loss) (increasing from 200 to 500).

Also, a thicker piezoelectric plate couples more deeply with the structure, making it more sensitive to changes in the mechanical state (such as stiffness, mass loading) of the underlying substrate. When the steel structure thins due to corrosion, its "loading effect" diminishes, altering the energy transfer and dissipation pathways of the entire vibrating system. This change is amplified in the more strongly coupled system with a thicker piezoelectric plate, resulting in a more pronounced peak reduction. This indicates that using a thicker piezoelectric plate can achieve higher sensitivity for corrosion detection.

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Thirdly, Corrosion on Resonant Frequency is effected.

We find that corrosion makes the resonant frequency of all systems move left, toward lower frequencies. This movement is the clearest in the system with the thin 1mm piezoelectric plate. It becomes slowly smaller as the piezoelectric plate gets thicker.

And the thinning of the steel structure directly leads to a local reduction in its stiffness, thereby decreasing the equivalent stiffness of the entire composite structure. According to vibration theory, the system's resonant frequency is proportional to the square root of its stiffness; a decrease in stiffness inevitably causes a frequency drop. For thicker piezoelectric plates, their own stiffness takes up a much larger part of the total stiffness of the whole system. This situation may cover up the influence of the stiffness change of the steel structure below to some degree on the system's overall frequency. And this will finally lead to a relatively smaller shift of the frequency in the end.

Finally, the overall research conclusions and the possible implications for practical application are presented in the following parts one by one.

1. Detection Effectiveness: The piezoelectric impedance method can effectively monitor the thickness loss of steel structures in a reliable way. The main characteristic signals that reflect such thickness loss are the reduction of the impedance peak value and the left shift of the resonant frequency. Among these two key signals, the change of the peak value is a more stable and prominent indicator for judging steel structure corrosion and thickness loss.

2. Sensor Optimization: From the angle of raising the strength and sensitivity of the detection signal, thicker piezoelectric plates (for example, the ones with 2mm or 3mm thickness) have obvious and distinct advantages. They can provide a much stronger initial detection signal, which means a high signal-to-noise ratio for the monitoring work, and they can also produce a greater response amplitude to corrosion. Such good performance is very beneficial for people to identify the early-stage and minor corrosion problems on steel structures in time.

3. Parameter Selection: When people design practical monitoring systems for steel structures, the thickness of the piezoelectric plate should be selected with full consideration of various trade-offs between different factors.

If the design aims to pursue high detection sensitivity and strong detection signals, a thicker piezoelectric plate should be chosen for the monitoring system.

If the design focuses on the indicative role of frequency change or the system needs to operate in a certain specific high-frequency range, a thinner piezoelectric plate might show higher sensitivity to the stiffness changes of the steel structure.

Besides the plate thickness, other important factors also need to be taken into full account in the design process, such as the available installation space for the sensors, the overall cost of the monitoring system, and the compatibility between the piezoelectric plates and the protective layer on steel structures.

In short, this whole series of experiments clearly shows a key research result for structural health monitoring. The thickness of the piezoelectric plate, as a core parameter in sensor design, has a systematic influence on the working effect of impedance-based structural health monitoring systems. If people can select a proper and suitable thickness for the piezoelectric plate, it can greatly optimize the system's monitoring capability for various damages on steel structures, and this is particularly true for the corrosion damage that is common on steel structures.

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