

The Method of Diagnosis for Corrosion Hydraulic Gate Based on Strain Mode and Frequency

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Abstract. The gate is important equipment of hydraulic structures. However, the special underwater working environment of the gate would cause corrosion of the in-service gate inevitably. The corrosion of steel would lead to the decrease of static bearing capacity and the instability of dynamic performance of gate structure. Therefore, in recent years, more and more studies on gate corrosion have been carried out. The hydrodynamic effect has an important influence on the dynamic performance of the gates under water operation, which include natural frequencies and modes. It is worth noting that the variation of the natural frequency and the mode have been used as the overall indexes of the steel gate in the structural inspection. These indexes are insensitivity to the detection of local pitting corrosion, and strain mode is better than these overall indexes. In this paper, the finite element dynamic analysis of the radial gate has been carried out by considering the fluid-solid coupling effect, and the arm has been taken for the corrosion simulation. It is found that under the condition of small area corrosion, the natural frequency of the steel gate did not change significantly. The local evaluation index of the strain mode (the change of the strain mode around the corrosion was obvious) could clearly determine the corrosion position of the steel gate.

1. Introduction
The steel gate of hydraulic structures is used to regulate upstream and downstream water levels and flows, so its main functions are flood control, irrigation, water diversion, navigation, and elimination effects of sediment, ice or other floating objects[1]. Due to the operational characteristics of the hydraulic engineering and the impact on the working conditions, it is necessary to carry out regular inspection and maintenance for the existing gates[2]. Although various anti-corrosion measures were taken, the corrosion phenomenon was still common in steel gate for washed by water for a long time. Corrosion of steel gate is an important factor affecting its service life[3,4].Damage identification of structural corrosion is usually based on the change of natural frequency and modal under different damage conditions to discriminate structural damage[5-7]. In the structural diagnosis, the natural frequency and mode shape are both the overall indicators, which could better evaluate the overall state of the structure. But in the complex structures, overall indicators are often insensitive to the diagnosis of local damage[8,9]. There are significant variations of the strain in and around corrosion areas, therefore, the strain mode index could better reflect the location and extent of the local damage of the structure. The advantage of the strain mode is that it can directly study the strain of some points when dealing with problems such as stress concentration and the effect of area change in variable region and

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the vicinity.

In this paper, the mainly corrosion identification method would be studied for the radial gate. The radial gate is a partial curved surface gate whose water retaining surface is a cylinder. The support hinge of the gate arm is located at the center of the circle, and the gate rotates around the support hinge when opening and closing. The main causes of the radial gate damage can be summarized as internal and external causes: the internal cause is the loss of stability of the gate arm, which causes the gate to be bent, twisted and deformed; the external cause is the damage of the gate under obvious hydrodynamic loading[10-13]. The damage of most radial gates occurs under strong vibration, the research at home and abroad shows that the main natural vibration frequency of the gate is basically the same as the natural vibration frequency of the gate arm[14,15]. This shows that the natural frequency of the gate arm has the greatest influence on the dynamic performance of the overall gate structure. In this paper, the natural frequency analysis method and the strain modal analysis method are used to study the radial gate arm in the case of the overall corrosion and local corrosion.

2. The method of strain modal analysis

The steps of establishing a strain mode by finite element method:

Let \{\delta_i\} represent the displacement array of all nodes of the i-th element, and \{\delta_i\} represents the displacement array of a point in the i-th element, then

\[
\{\delta_i\} = [N]\{\delta_i\}
\]  \hspace{1cm} (1)

Where \([N]\) is a shape function matrix, the strain array at a point of the i-th element is \{\varepsilon_i\}:

\[
\{\varepsilon_i\} = [D]\{\delta_i\} = [D][N]\{\delta_i\} = [B]\{\delta_i\}, \hspace{1cm} i=1,2,3\ldots p
\]  \hspace{1cm} (2)

Where\([D]\) is a differential operator, \([B]\) is a geometric matrix, and \(p\) is the number of elements. There are \(p\) equations in the equation (2), which can be integrated as follows:

\[
\begin{bmatrix}
\{\varepsilon_1\} \\
\{\varepsilon_2\} \\
\vdots \\
\{\varepsilon_p\}
\end{bmatrix} =
\begin{bmatrix}
[B]_1 \\
[B]_2 \\
\vdots \\
[B]_p
\end{bmatrix}
\begin{bmatrix}
\{\delta_1\} \\
\{\delta_2\} \\
\vdots \\
\{\delta_p\}
\end{bmatrix}
\]  \hspace{1cm} (3)

Where \{\varepsilon\} is the strain of \(p\) elements and \{\delta\} is the node displacement of \(p\) elements. Considering the displacement continuity of each element at the node, the equation (3) would be transformed into the global coordinate:

\[
\{\delta\} = [\beta]\{\delta_i\}
\]  \hspace{1cm} (4)

Where\([\beta]\) is coordinate transformation matrix, \{\delta_i\} is displacement vector of node in the global coordinate system.

Substituting equation (4) into (3) and let \([B']=[B][\beta]\)

\[
\{\varepsilon\} = [B][\beta]\{\delta_i\} = [B']\{\delta_i\}
\]  \hspace{1cm} (5)

According to the finite element analysis model, the node displacement should satisfy the following differential equation in the global coordinates:

\[
[M_i]\{\ddot{\delta}_i\} + [C_i]\{\dot{\delta}_i\} + [K_i]\{\delta_i\} = \{f_i\}
\]  \hspace{1cm} (6)

Let \{\delta_i\} = \{F_i\} e^{jm\theta} and \{\delta_i\} = \{U_i\} e^{jm\theta}, then equation(6) is:
\[
\left( -\omega^2 [M] + j\omega [C] + [K] \right) \{U\} = \{F\} \tag{7}
\]

By means of modal superposition method, the solution of the above formula can be expressed as:

\[
\{U\} = [\phi] \{Y\} [\phi]^T \{F\} = [H] \{F\} \tag{8}
\]

\[
[H] = [\phi] \{Y\} [\phi]^T = \sum_{r=1}^{m} Y_{r} \{\varphi_{r}\} \{\varphi_{r}\}^T \tag{9}
\]

Where \([Y] = \text{diag}[Y_1 Y_2 \cdots Y_m] \), \([\phi] = \left[ \{\varphi_1\} \{\varphi_2\} \cdots \{\varphi_m\} \right] \), \(Y_{i} = \left( K_{i} - \omega^2 m_{i} + jo_{i} \right)^{-1} \)

Substituting equation (8) into equation (5):

\[
\{e\} = E \{e\} e^{\text{im}} = [B] \{[B]\} \{Y\} [\phi]^T \{F\} e^{\text{im}} = \left[ [\psi^{e}] \right] \{Y\} [\phi]^T \{F\} e^{\text{im}}
\]

\[
\left[ [\psi^{e}] \right] \{q\} = \sum_{r=1}^{m} q_{r} \left[ \psi^{e}_{r} \right] = \sum_{r=1}^{m} \left[ \psi^{e}_{r} \right] \{\varphi_{r}\} \{\varphi_{r}\}^T \{F\} \tag{10}
\]

Let \([B]\} = \left[ [\psi^{e}] \right] \), where \([\psi^{e}] \) is strain modal matrix, \([\psi^{e}_{r}] \) is the vibration mode of \(r\)-th strain mode corresponding to the displacement mode \(\{\varphi_{r}\} \).

3. Finite element model of radial gate

The radial gate is composed by the main horizontal beam, the secondary horizontal beam, the panel, the side longitudinal beam, the main longitudinal beam, and the longitudinal clapboard. The curvature radius of the gate panel is 18500 mm. The side longitudinal beam, the main longitudinal beam and the top and bottom beams are all solid I-shaped, and the longitudinal partitions are T-shaped. The main beam is a solid box section with a height of 1800 mm. The hinge is a spherical hinge with a pitch of 18200 mm and a hinge diameter of 530 mm. Gate sealing water adopts \(L_{60}-A\) specification rubber. The gate adopts a pull-back swing hydraulic hoist, double lifting points, and the lifting point spacing is 18800 mm. The gate adopts a double inclined arm support structure, and the opening point of the gate is located at the intersection of the lower main beam and the side longitudinal beam. The main frame of the gate is connected by high-strength bolts, and a shear plate is arranged at the intersection of the main horizontal beam and the gate arm.

The model was built by ANSYS finite element software. The element type included space beam element beam188, shell element shell63 and spring unit Combin14. Considering the fluid-solid coupling effect of water on the gate, the coupling field element Fluid30 has been used. The gate model is shown in Figure 1(a,b).

![Figure 1. radial gate model(a,b)](image)

Through the study and analysis of the fluid-structure coupling of the gate, it has found that the effect of the fluid-structure coupling was more serious when the gate was only subjected to the
upstream load. According to the actual local water level, the fluid-solid coupling analysis of the radial gate only considered the upstream water level of 8.82m, model with a water body length of 10 times water depth. Table 1 is the first ten-order natural frequency of radial gate under ten times water body.

| Order | Frequency (Hz) |
|-------|----------------|
| 1     | 4.1740         |
| 2     | 5.7437         |
| 3     | 5.7485         |
| 4     | 5.7485         |
| 5     | 5.8301         |
| 6     | 5.8301         |
| 7     | 7.3189         |
| 8     | 7.3189         |
| 9     | 8.3797         |
| 10    | 9.7712         |

Take the ten-order array from modal analysis. The first order: the whole gate vibration, the panel vibration along the radial direction, and the gate arm vibration around the hinge. The second order: the oblique web of the gate vibrates along the vertical axis of the bar with torsion. The third and the fourth order: the oblique web of the gate vibrates along the vertical axis of the bar. The fifth order: the longest straight web of the gate arm vibrates along the vertical bar axis with torsion. The sixth order: the longest straight web of the gate arm vibrates along the vertical bar axis. The seventh and the eighth order: the shortest straight web of the gate arm vibrates along the vertical axis. The ninth order: the straight web of the gate arm vibrates along the vertical bar axis with torsion. The tenth order: the vibration of the gate as a whole, the panel vibrates along the radial direction, the gate arm vibrates around the hinge, and the arm web vibrates along the vertical axis with torsion.

4. The analysis of the gate arm corrosion
The finite element model analysis was carried out on the whole of the radial gate arm (except for the straight web and the inclined web) with the corrosion rate of 20%, 40%, 60% and 80% respectively. The thickness of gate arm before corrosion was 20 mm. The ten-order natural frequencies of the radial gate were obtained. The corrosion location is shown in Figure 2, and the dark parts indicate the damage location.

The first ten-order natural frequencies of the gate under different corrosion degrees were obtained by finite model analysis, as shown in Table 2. The selected corrosion arm with a large area which could be seen from Figure 2. The natural frequency of the gate was less affected by corrosion when the corrosion rate of the arm is less than 40%, the variation of natural frequency is obvious when the corrosion rate is more than 60%. When the corrosion rate is 80%, the natural frequency of first order and tenth order are 2.9608 Hz and 6.2226 Hz separately, about 29.06% and 36.32% less than the uncorroded. From Table 2, there is a strong influence on the dynamic performance of the gate by this corrosion section.

![Corrosion model diagram of gate arm(a,b)](image-url)
Table 2. Natural frequency of radial gate (Hz)

| Order | 0     | 20%   | 40%   | 60%   | 80%   |
|-------|-------|-------|-------|-------|-------|
| 1     | 4.1740| 3.8648| 3.7493| 2.9608| 1.5284|
| 2     | 5.7473| 5.6694| 5.6692| 3.9179| 1.5290|
| 3     | 5.7485| 5.6694| 5.6694| 3.9180| 1.5328|
| 4     | 5.7485| 5.7320| 5.7300| 4.1988| 1.5328|
| 5     | 5.8301| 5.7890| 5.7639| 4.2064| 2.0783|
| 6     | 5.8301| 5.7890| 5.7639| 4.9482| 2.5212|
| 7     | 7.3189| 7.2486| 7.2420| 5.0881| 2.5474|
| 8     | 7.3189| 7.2489| 7.1047| 5.9691| 2.8447|
| 9     | 8.3797| 8.0964| 7.4408| 6.0018| 2.8454|
| 10    | 9.7712| 9.2182| 7.6371| 6.2226| 3.2186|

5. Strain modal analysis

The steel plate on the upper surface of the arm was taken as the research object of strain mode as shown in Figure 3, and the selected element was weakened along the thickness direction. In Figure 4, the number is the node number, and the dark element is the corrosion section, the node numbers corresponding to the rust element are 6, 7, 10, 11. The thickness after corrosion are 16 mm, 12 mm, 8 mm and 4 mm respectively (corresponding to corrosion rate of 20%, 40%, 60% and 80%). Modal analysis using Lanczos method. In the modal analysis, the strain values of the first five-order of the corrosion element and the adjacent nodes were extracted and analyzed, as shown in Figures 5 to 9.

Figure 3. Partial corrosion diagram of the gate arm

Figure 4. the detail of gate arm corrosion

Figure 5. First-order mode strain

Figure 6. Second-order mode strain

Figure 7. Third-order mode strain
In Figures 5 to 9, the abscissa is the node number, the ordinate is the strain value, and the different broken lines indicate the strain values of the nodes at different thicknesses in corrosion. Through the analysis of the first five-order strain modes of the gate as shown in Figure 5 to 9, the strain of the corrosion element node changes obviously, and the strain of the nodes around the corrosion element also changes. The strain of the nodes far away from the corrosion element changes slightly. The location of the corrosion could be clearly identified from the diagram. The higher the corrosion rate, the greater the variation range of the node strain at the corresponding location.

The frequency of the first ten-order modes was extracted based on the corrosion condition of this section. The chart is shown in Figure 10, the abscissa is the modal order, the ordinate is the frequency value, and the fold lines are the first ten-order frequency by the thickness of the different corrosion. From Figure 10, it can be seen that the natural frequencies of structures have almost no variation under five different corrosion rates of the same element.

6. Conclusion
The radial gate is widely used in hydraulic structures for its unique advantages: simple operation, low opening and closing force and good flow condition. The steel material is highly susceptible to electrochemical corrosion and accompanied by bio-corrosion due to the working environment which are dark and humid, alternating wet and dry, high-speed water flow and water bio-corrosion. The corrosion of the gate is the main content of the detection, and it is also the main factor threatening the life of the gate. The influence of corrosion on steel could not be ignored. Through this study, the natural vibration frequency and vibration mode of the structure would change significantly by the relatively large corrosion area simulated in the section 4. The degree and location of corrosion could only be approximated in a few typical cases. If the simulation of corrosion is a small area, the overall index of the structure would change weakly, the identification of corrosion using the overall indicator often fails to clearly determine the location and the degree of corrosion. Frequency modes are insensitive to the location and degree of local corrosion, and the corrosion at different locations and degrees may cause the same change in frequency of structures. The strain mode performs well in the study of local corrosion, and it can accurately identify the corrosion area. The more variation of strain mode, the greater degree of corrosion.

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