Evaluation Method of Pipe Corrosion Based on the Natural Frequency II: Corrosion of internal surface of pipe

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Abstract. Corrosion of internal surface of pipe is serious because it is difficult to observe. So it is very important to put forward a new method to evaluate the average corrosion rate of pipe which corrosion occurred in internal surface of pipe. Based on the damage of corrosion to the mechanical properties of materials, the mass loss factor of corroded pipe is defined, and the elastic modulus of pipe materials is equivalent. According to the modal analysis theory of elastic materials, a modal analysis model of corroded pipe was established, and the relationship between the modal of the corroded pipe and the mass loss factor was analyzed. The results indicate that it is effective and feasible to equivalence the elastic modulus of corroded pipe, and external surface corrosion is more destructive to the pipe than internal surface in the case of the same corrosion rate. At the same time, the model can be used to evaluate the corrosion rate of corroded pipe by monitoring and analyzing the modal..

1. Introduction
Pipe is often used as the transmission channel of fluid medium [1]. Because these fluid medium itself has certain corrosiveness, the inner surface of the pipeline is easy to produce corrosion, and this corrosion phenomenon is difficult to be observed by naked eyes, and the damage to the pipe is more hidden, which is the hidden danger of safe and reliable operation of the pipeline. Because the corrosion environment is complex and changeable, it is difficult to build a model from the mechanism to evaluate it. At present, the main method to evaluate the corrosion of the inner surface of pipeline is to build a mathematical empirical model between various corrosion environmental factors and corrosion rate based on the time monitoring data. Such as grey theory [2], neural network [3] Projection pursuit regression (PPR) [4], extension analytic hierarchy process [5], support vector machine [6], and the combination of various methods [7].

In the paper, by introducing the mass loss factor, the Young's modulus of the pipe with external surface corrosion is equivalent. On this basis, the natural frequency analysis model of the pipe with internal surface corrosion is established, and the relationship between the natural frequency and mass loss factor is analyzed, so that the corroded pipe can be evaluated through the natural frequency analysis. In addition, the effects of corrosion on cross-sectional area, cross-sectional moment of inertia and natural frequency are analyzed when the corrosion rate is the same.
2. Natural frequency method of pipe

2.1. Equivalent Young's modulus of pipe
S.X.[8] performed equivalent calculations on the elastic modulus and yield strength of corroded steel, and verified it through experiments. The corrosion mass loss rate $f$ is defined as[8]:

$$f = \frac{m}{m_0}$$

(1)

And the equivalent Young's modulus of pipe can be expressed as:

$$E = \frac{2(1-2\nu)(1-f)}{2(1-2\nu)+f(1+\nu)} E_0$$

(2)

Where $\nu$ is Poisson's ratio, $E_0$ is the Young's modulus when the pipe without corrosion, and the $E$ is the equivalent Young's modulus of corroded pipe.

2.2. Equivalent cross-sectional area and area moment of inertia of pipe cross section

The calculation of mass is:

$$m = \rho A_0$$

(3)

Assumed that the density $\rho$ remains unchanged before and after corrosion, the equivalent cross-sectional area $A$ is:

$$A = (1-f)A_0$$

(4)

In the calculation process, corrosion mainly occurs on the internal surface of the pipe, and the external surface is slightly corroded. This kind of situation is more common. For example, in Alberta transportation pipeline, the internal corrosion is more obvious. At this time, effect of external surface corrosion can be ignored.

When the internal surfaces of pipe corroded, the internal diameter of pipe change to $d$, the external diameter has no changed.

The cross-sectional area of pipe can be expressed as:

$$A = \pi \left( \frac{d_0^2}{4} - \frac{d^2}{4} \right)$$

(5)

Substituting equation (4) into equation (5), the changed internal diameter $d$ is:

$$d = \sqrt{\left(1-f\right)d_0^2 + fD_0^2}$$

(6)

The expression of area moment of inertia of pipe cross section is:

$$I = \frac{\pi}{64} (D^4 - d_0^4)$$

(7)

Substituting equation (6) into equation (7), so when internal surfaces of pipe corroded, the equivalent area moment of inertia of pipe cross section is:

$$I = \frac{\pi}{64} (1-f)[(1+f)D_0^4 - 2fD_0^2d_0^2 - (1-f)d_0^4]$$

(8)

2.3. Calculation of natural frequency of corroded pipe

In the calculation of the natural frequency, it is generally calculated according to the cantilever beam. The first three natural frequencies are [9]:

$$\omega_i = \frac{15.4}{L^2} \sqrt{\frac{E_0 I_0}{\rho A_0}}$$

(9)

$$\omega_2 = \frac{50}{L^2} \sqrt{\frac{E_0 I_0}{\rho A_0}}$$

$$\omega_3 = \frac{104}{L^2} \sqrt{\frac{E_0 I_0}{\rho A_0}}$$
Defined:

\[ \xi_n = \sqrt{\frac{EI}{\rho l_n^2}} \quad (10) \]

Substituting equation (2), (8) and (10) into equation (9):

\[ \xi_n^2 = \frac{3f}{2(1-2\mu)+f(1+\mu)} E_0 \times \frac{\pi}{64} \left[ (1-f)(1+f)D_1^4 - 2D_1^4 d_n^4 - (1-f)d_n^4 \right] \]

\[ (1-f)\rho l_n \quad (11) \]

So when internal surfaces of pipe corroded, the first three natural frequency can be expressed as:

\[
\begin{align*}
\omega_{1_{\text{in}}} &= \frac{15.4}{l^2} \xi_n \\
\omega_{2_{\text{in}}} &= \frac{50}{l^2} \xi_n \\
\omega_{3_{\text{in}}} &= \frac{104}{l^2} \xi_n
\end{align*}
\]

\[ (12) \]

3. Results & Discussion

Values of parameters of pipe and corrosion mass loss rate are listed in table 1 and 2. All calculation results are in international units.

| Parameters | External diameter(m) | Internal diameter(m) | Length(m) | Young’s modulus(Pa) | Poisson’s ratio | Density (kg/m³) |
|------------|----------------------|----------------------|-----------|---------------------|----------------|-----------------|
| Value      | 0.06                 | 0.054                | 2         | 206                 | 0.3            | 7850            |

According to equation (1) and (20), the first three natural frequencies of corroded pipe can be calculated and the results is shown in table 3.

| No. | 1 | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9 |
|-----|---|----|----|----|----|----|----|----|---|
| Value | 0.1 | 0.2 | 0.25 | 0.3 | 0.35 | 0.4 | 0.5 | 0.6 | 0.7 |

Table 3. Results of the first three natural frequency of corroded pipe under different corrosion mass loss rates during internal corrosion of pipe.

| Mass loss rates | 0 | 0.10 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 | 0.50 | 0.60 | 0.70 |
|-----------------|---|------|------|------|------|------|------|------|------|------|
| The first order natural frequency | 398.97 | 352.89 | 313.25 | 295.17 | 277.97 | 261.49 | 245.59 | 214.98 | 185.12 | 154.86 |
| The second order natural frequency | 1295.40 | 1145.70 | 1017.00 | 958.30 | 902.50 | 849.00 | 797.40 | 698.00 | 601.00 | 502.80 |
| The third order natural frequency | 2694.40 | 2383.10 | 2115.50 | 1993.30 | 1877.20 | 1765.90 | 1658.50 | 1451.80 | 1250.20 | 1045.80 |

When corrosion was occur in internal surfaces of pipe, the change of the first three natural frequencies with the corrosion mass loss rate is shown in figure 1.
Figure 1. The change of first three natural frequencies with the mass lost rates in internal surfaces of pipe corroded. (a) The first order natural frequency, (b) The second order natural frequency, (c) The third order natural frequency.

Quadratic fitting of the first three natural frequencies and corrosion mass loss rate, the numerical model of first three natural frequencies and corrosion mass loss rate can be obtain:

\[
\begin{align*}
\omega_{1,in} &= 128.64 \times f^2 - 431.95 \times f + 396.50 \\
\omega_{2,in} &= 417.60 \times f^2 - 1402.40 \times f + 1287.30 \\
\omega_{3,in} &= 868.70 \times f^2 - 2917.10 \times f + 2677.70
\end{align*}
\]  

When the first three natural frequencies of corroded pipeline are measured, according to equation (13), the mass loss factor can be predicted, and the final quality loss factor can be the average of the three quality loss factors. The average corrosion rate can be evaluated as follows:

In the case of uniform corrosion on the internal surface of the pipe, the internal diameter of the pipe will be reduced, which is:

\[ d = d_0 + 2vt \]  

Which \( v \) is the average corrosion rate, \( t \) is the time.

Substituting equation (18) into equation (5), the reduced volume is:

\[ A = \frac{\pi}{4} (D_0^2 - (d_0 + 2vt)^2) \]  

According to the equation (6) and (17), we can obtain that:

\[ \frac{\pi}{4} (D_0^2 - (d_0 + 2vt)^2) \rho = f m_0 \]  

So the average corrosion rate can be evaluated like is:

\[ v = \frac{1}{2t} \sqrt{D_0^2 - m_0 \frac{4}{\rho}} - d_0 \]  

When we have know the time which the corrosion have be occurred, the average corrosion rate can be evaluated with equation (17).
According to the calculation results, the cross sectional area of pipe, area moment of inertia of pipe cross section and the first order natural frequency with the change of mass loss rate of external and internal surfaces of pipe corroded can be compared as shown in figure 2.

See figure 2 above, we can obtain that:

- When the pipeline is corroded internally or externally, the change of cross-sectional area with mass loss factor is the same;
- When the external surface is corroded, the change of the moment of inertia with the mass loss factor is greater than that of the internal surface, the change of natural frequency is the same;
- It indicated that the external surface corrosion is more destructive to the pipeline than internal surface in the case of the same corrosion rate.

4. Conclusion
The equivalent elastic modulus of external corroded pipeline is analyzed, and the relationship between natural frequency and mass loss factor is found. The mathematical model between natural frequency and mass loss factor is established, through which the average corrosion of pipeline internal surface can be evaluated. It provides a new method for the average rate of internal corrosion of pipeline and a reference for the practical application of pipeline corrosion assessment.

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