Evaluation Method of Pipe Corrosion Based on the Natural Frequency I: Corrosion of external surface of pipe

Yonghong Chen 1, Tingtao Ming2, Bin Shen 3*, Wengye Luo1, Han Wang1 and Yiting Zheng4

1College of Mechanical and Electrical Engineering, Wuhan Donghu University, Wuhan 430212, China
2Equipment support room of Donghai, Shanghai, 201318, China
3Wuchang Shouyi University, Wuhan 430033, China
4Corresponding author’s e-mail: tcaixs@163.com

Abstract. All Corrosion destroys the continuity of the pipe and has an impact on the mechanical properties of the material. It is very important to evaluate the corrosion state 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, 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

Corrosion is a common phenomenon for metal or non-metal materials, which is also one of the main reasons for material failure. It not only affects the safety of materials, but also causes huge losses to the national economy[1]. Corrosion is the main factor affecting the reliable operation of pipe, and corrosion rate is generally used as the evaluation index of pipe corrosion. Due to the working environment, there are many factors affecting the corrosion of pipes in each system, and the factors interact with each other to form an extremely complex and random corrosion system. It is difficult to directly establish a clear functional expression between the corrosion rate and the influencing factors. In addition, the measurement of some corrosion influencing factors also has certain uncertainty and fuzziness. For the problem of corrosion rate prediction with fuzziness and complexity, the classical prediction method is difficult to play a role [1]. The prediction method based on machine learning is widely used in the actual corrosion rate, 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 this 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 external 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.
2. Natural frequency method of pipe corrosion evaluation

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 main calculation process is:

The initial shear modulus of the material is $G_0$, the initial bulk modulus is $K_0$, the initial cross-sectional area is $A_0$, the initial external diameter is $D_0$, the initial internal diameter is $d_0$, the Poisson's ratio is $\nu$, the density and length are $\rho$ and $l$, the density and length before and after corrosion remain unchanged, then the corrosion mass loss rate $f$ can be expressed as[8]:

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

$$E^f = (1-2\nu)\frac{12G_0K_0(1-f)}{4G_0 + 3K_0f}$$

Where $m$ is mass loss caused by corrosion, $m_0$ is initial mass of steel. Because the material is not corroded or completely corroded, no equivalent calculation is required, so the value of $f$ can’t be 0 or 1. Then the equivalent elastic modulus (Young's modulus) of the corroded material is[8]:

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

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

In the calculation process, corrosion mainly occurs on the external surface of the pipe, and the internal surface is slightly corroded. At this time, the effect of the internal surface corrosion is ignored. The calculation of mass is:

$$m = \rho A_0$$

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

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

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

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

$$A_0 = \frac{\pi}{4}(D_0^2 - d_0^2)$$

$$A = \frac{\pi}{4}(D^2 - d_0^2)$$

Substituting equation (7) into equation (8), the changed external diameter $D$ is:

$$D = \sqrt{(1-f)D_0^2 + fd_0^2}$$

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

$$I = \frac{\pi}{64}(D^4 - d_0^4)$$
Substituting equation (9) into equation (10), so when external surfaces of pipe corroded, the equivalent area moment of inertia of pipe cross section is:

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

(11)

2.3. Calculation of natural frequency of corroded pipe

The installation and connection of pipe is shown in figure 1. In the calculation of the natural frequency, it is generally calculated according to the cantilever beam. The first three natural frequencies are [9]:

\[
\begin{align*}
\omega_1 &= \frac{15.4}{l^2} \frac{E_0 I_0}{\rho A_0} \\
\omega_2 &= \frac{50}{l^3} \frac{E_0 I_0}{\rho A_0} \\
\omega_3 &= \frac{104}{l^4} \frac{E_0 I_0}{\rho A_0}
\end{align*}
\]

(12)

Where \( l \) and \( \rho \) are the length and density of pipe, \( A_0 \) and \( I_0 \) are cross-sectional area of pipe and area moment of inertia of pipe cross section; and \( E_0 \) is the Young’s modulus.

For corroded pipe, Young's modulus, cross-section area and area moment of inertia cross section will change due to corrosion, and its natural frequency will inevitably change. For uniform corroded pipe, the outer and inner diameter are uniformly reduced. Natural frequency can be calculated like equation (12). Because the corrosion of most pipe is not uniform corrosion, or other corrosion cases, the diameter changes irregularly, and it is difficult to directly use the above equation (12) for calculation. In this paper, the calculation is mainly carried out by equivalent treatment.

Defined:

\[ \xi_{es} = \sqrt{\frac{E}{\rho M}} \]

(13)

Substituting equation (5), (7) and (11) into equation (13):

\[ \xi_{es} = \frac{3f}{2(1-2\nu)+f(1+\nu)} \frac{E_0}{64} \frac{\pi}{(1-f)[(1-f)D_0^4 + 2fD_0^2d_0^2 - (1+f)d_0^4]} \]

(14)

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

\[
\begin{align*}
\omega_{1_{es}} &= \frac{15.4}{l^2} \xi_{es} \\
\omega_{2_{es}} &= \frac{50}{l^3} \xi_{es} \\
\omega_{3_{es}} &= \frac{104}{l^4} \xi_{es}
\end{align*}
\]

(15)

2.4. Evaluation of corrosion pipe

The specific steps for evaluating the corrosion of pipe are as follows:

- Determining the connection model of pipe. Because the natural frequency related to the connection model;
• Determining the main locations of pipe corrosion, external surface corrosion or internal surface corrosion mainly occurs;
• Collecting the initial parameters of the pipe, such as: size parameters, material parameters, etc., and calculate the natural frequency of the pipe like equation (12);
• Calculating the equivalent elastic modulus, equivalent cross sectional area and equivalent area moment of inertia of corroded pipe cross section;
• Calculating the natural frequency of the corroded pipe under different corrosion mass loss rate \( f \), it can choose any values except 0 and 1, and more than five values must be chosen;
• A diagram can be draw with the mass loss rate values and calculated natural frequency, also a numerical model can be constructed by fit them;
• Measuring the actual natural frequency of corroded pipes;
• Comparing the position of measured natural frequency value in the diagram, or substitute it into the numerical model, then the evaluation value of mass loss rate can be obtained. Then according to equation (15), the mass loss of corroded pipe can also be obtained;
• Using the evaluated mass loss divided by the service time of corroded pipe, we can calculate the average corrosion rate of the pipe, and according to the classification table of corrosion level, the corrosion evaluation of pipe was realized.

3. Results & Discussion

Values of parameters of pipe and corrosion mass loss rate are listed in table 1 and table 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            |

Table 2. Value of corrosion mass loss rate

| 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 external 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 |
|-----------------|------|------|------|------|------|------|------|------|------|------|
| First order natural frequency | 398.97 | 349.20 | 306.74 | 287.52 | 269.35 | 252.05 | 235.48 | 203.98 | 173.80 | 143.87 |
| Second order natural frequency | 1295.40 | 1133.80 | 995.91 | 933.50 | 874.51 | 818.36 | 764.56 | 662.26 | 564.30 | 467.12 |
| Third order natural frequency | 2694.4 | 2358.20 | 2071.50 | 1941.70 | 1819.00 | 1702.20 | 1590.30 | 1377.50 | 1173.70 | 971.60 |

According to equation (1) and (15), the first three natural frequencies of corroded pipe can be calculated and the results is shown in table 3.

When corrosion was occur in external surfaces of pipe, the change of the first three natural frequencies with the corrosion mass loss rate is shown in figure 2.
Figure 2. The change of first three natural frequencies with the mass lost rates in external surfaces of pipe corroded.

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:

\[
\begin{align*}
    w_{1,ex} &= 160.90 \times f^2 - 470.01 \times f + 396.40 \\
    w_{2,ex} &= 522.40 \times f^2 - 1526.00 \times f + 1287.00 \\
    w_{3,ex} &= 1086.70 \times f^2 - 3174.10 \times f + 2677.00
\end{align*}
\]

According to equation (16), when the first three natural frequencies of corroded pipeline are measured, the mass loss factor can be predicted, the mass loss of corroded pipe is:

\[
m = f m_0
\]

In the case of uniform corrosion on the external surface of the pipe, the outer 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 (8), the reduced volume is:

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

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

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

So the average corrosion rate can be evaluated like is:

\[
v = \frac{1}{2t} \left( D_0 - \frac{4f m_0}{\pi \rho} + d_0 \right)
\]

When we have know the time which the corrosion have be occurred, the average corrosion rate can be evaluated with equation (21).

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 external surface can be evaluated. It provides a new method for the average rate of external corrosion of pipeline and a reference for the practical application of pipeline corrosion assessment.
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References
[1] R.W. Revie. (2005)Uhlig’s corrosion handbook. John.Wiley &Sons Inc. New York.
[2] Y.H Chen,D.F Zhang. (2009)Prediction method of pipeline corrosion rate based on Grey Markov combination model. Nuclear power engineering, 30:95-98.
[3] L.T Ma, H.F Dong, G Zhu. (2018)Application and research of neural network to predict metal corrosion rate in marine environment. Material protection,51:35-39.
[4] Z.S Luo, M.Y Yao, J.H Luo. (2019)Prediction model of external corrosion rate of submarine pipeline based on PCA-BAS-PPR. Material protection, 52:64-6974.
[5] J.Y Du, J Han, S.C Kou. (2014)Prediction of corrosion rate of grounding grid based on fuzzy extension analytic hierarchy process. Computer application and software, 31:170-173+197.
[6] X Yin, Y Huang, Y.Q Li. (2020)Grey dynamic model for corrosion prediction based on particle swarm optimization. Corrosion and protection, 41:18-22.
[7] S.X Li, G.Q Ji, Hui Kang. (2019)Support vector machine modeling and forecasting of annual maximum load in northern Hebei Province. Science, technology and engineering, 36:179-183.
[8] A.P. (2010)T.P.Harris’ shock and vibration handbook. The McGraw-Hill Companies, Inc, New York.
[9] S.H Xu, S.B Ren. (2015)Calculation model of elastic modulus and yield strength of corroded steel. Mechanical engineering materials, 39:74-78.