Influence of FSI on the Natural Frequencies and Mode Shapes of Tubing

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Abstract. Numerical simulation method was adopted to analyze the influence of fluid-solid interaction (FSI) on the vibration characteristics of tubing. The natural frequencies and mode shapes of tubing were analyzed for the cases of no FSI, gas-solid interaction, and liquid-solid interaction in the modal module of ANSYS Workbench software. It shows that natural frequencies of tubing decreased when considering FSI. The decrease is greatest for the case of liquid-solid interaction, which is more than 13% compared with gas-solid interaction. The mode shapes are almost unchanged even considering FSI. The results show that the effect of FSI can not be ignored, especially when the internal fluid density is large.

1. Introduction
Tubing is filled with gas or liquid when working. Due to variable production, pressure, tubing diameter, the tubing is subject to complex vibration loads. Vibration of the tubing affects its stability and fatigue life. Resonance will also be induced when the external excitation frequency is close to the natural frequency of the tubing. Knowing the vibration characteristics of the tubing such as natural frequency and vibration mode can effectively prevent resonance and provide reference for structural optimization design [1]. Because tubing in oil and gas well contains fluids during operation, the additional mass can not be neglected [2]. Also, the complex liquid-solid interaction or gas-solid interaction occur when the internal fluid flows through the tubing. If neglecting the interaction between fluid and structure, the dynamic characteristics of the structure can not be truly reflected [3]. Due to the dynamic load acting on the tubing in oil and gas wells, it is not enough to evaluate its safety if only considering its static characteristics [4-7].

2. Establishment of Vibration Equation of Tubing

2.1. Establishment of Vibration Equation of FSI Tubing
Due to the structural damping of oil and gas well tubing is small, its influence on natural frequency and vibration mode can be neglected. Considering the interaction effect of internal fluid on oil and gas well tubing, the free vibration equation of the tubing can be obtained by the virtual mass method [8]:

\[(M + M_f)y'' + (K + K_f)y = 0\]  

(1)
Where, \( M \) is the mass matrix. \( M_j \) is the additional mass matrix. \( K \) is the stiffness matrix. \( K_j \) is the additional stiffness matrix.

2.2. Analysis of Vibration Characteristic of Tubing

The tubing is considered as an Euler-Bernoulli beam and the influence of shear deformation on the moment of inertia is neglected for low frequency vibration. The differential equation for transverse free vibration is:

\[
EI \frac{\partial^4 y}{\partial x^4} + \rho A \frac{\partial^2 y}{\partial t^2} = 0
\]  

(2)

Where, \( EI \) is bending stiffness, \( \rho \) is density, \( A \) is the area of cross section.

The solution of equation (2) meets the following form:

\[
Y(x) = B_1 \cos \beta x + B_2 \sin \beta x + B_3 \cosh \beta x + B_4 \sinh \beta x
\]  

(3)

The corresponding boundary conditions are:

\[
Y(0) = 0, \quad Y'(0) = 0, \\
Y'(l) = 0, \quad Y''(l) = 0
\]  

(4)

Substituting equation (3) into equation (4), the natural frequency of the tubing can be obtained.

3. Numerical simulation of vibration characteristics of FSI tubing

Considering that the fluid filled in the oil and gas well tubing will affect the mass matrix and stiffness matrix of the system, the vibration characteristics of tubing considering FSI or not were analyzed.

3.1. Establishment of Finite Element Model for FSI Tubing

To accurately evaluate the influence of internal fluid on the natural frequency of tubing, the natural frequency of the tubing considering gas-solid interaction and liquid-solid interaction is analyzed in ANSYS Workbench. The fluid in the tubing is obtained by Fill command. The fluid-solid interaction model of the tubing is shown in Figure 1. The length of the tubing is 5m. The density of the tubing is 7800 kg/m\(^3\). The density of water is 1000 kg/m\(^3\).

![Figure 1. Model of FSI Tubing](image)
3.2. Results of vibration characteristics of FSI tubing

The results of natural frequencies of tubings with no FSI, gas-solid interaction and liquid-solid interaction were listed in Table 1 and shown in Figure 2. Some modal shapes were shown in Figure 7.

| Order number | No interaction | Gas-solid interaction of Tubing | Liquid-solid interaction of Tubing |
|--------------|----------------|---------------------------------|-----------------------------------|
|              | frequency/Hz   | frequency/Hz                    | Reduction rate                    |
| 1            | 3.3845         | 3.3841                          | 0.0118                            |
| 2            | 21.154         | 21.150                          | 0.0189                            |
| 3            | 58.978         | 58.966                          | 0.0203                            |
| 4            | 114.84         | 114.84                          | 0                                 |
| 5            | 188.36         | 188.35                          | 0.0053                            |
| 6            | 278.77         | 278.71                          | 0.0215                            |

Table 1. Natural Frequencies of Tubing with and without FSI

As can be seen from Table 1 and Figure 2, when considering FSI, the natural frequency of the tubing is less. Compared with gas-solid interaction, the natural frequency of the tubing with liquid-solid interaction decreases by more than 13%. That’s because the density of the liquid is greater than that of the gas, resulting in a larger additional mass. The analysis shows that fluid-solid interaction can affect the natural frequency of oil and gas well tubing, especially when the internal fluid density is high.
The vibration modes of tubing remain unchanged even considering FSI. The fluid-solid interaction has little effect on the vibration mode of the tubing, but the maximum displacement of the modal shape decreases.

The results were compared with reference [9], which was listed in Table 2. We can see that the results match very well.

**Table 2. Natural Frequencies of Pipeline with and without FSI**

| Order number | without FSI | with FSI |
|--------------|-------------|----------|
|              | literature [9] | This paper | error/% | literature [9] | This paper | error/% |
| 1            | 20.44       | 21.20     | 3.718   | 20.36       | 21.19     | 4.077   |
| 2            | 126.06      | 130.60    | 3.601   | 125.85      | 130.53    | 3.719   |
| 3            | 344.63      | 356.38    | 3.409   | 344.34      | 356.21    | 3.447   |
| 4            | 402.52      | 400.96    | 0.388   | 402.58      | 400.87    | 0.425   |

4. Conclusion

The vibration characteristics of tubing considering FSI or not were analyzed and some conclusions were drawn. Compared with the gas-solid interaction, the natural frequency of tubing with liquid-solid interaction decreases by more than 13%. The fluid-solid interaction has little influence on the vibration shape of the tubing. The maximum displacement of the mode shape decreases.

Acknowledgments

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