Analysis for Vibration Characteristics of Water Pump Piping System

Tiantian Liu and Zhiyong Liu

Abstract The vibration calculation model of the pipeline system is established by the finite element analysis method, and the calculation model is verified by experimental tests. The differences between calculation result and the actual measurement are controlled at about 10%. On this basis, the influence of the support bracket, tee, and elbow on the vibration of the pipeline system is calculated, which provides a reference for the vibration reduction measures of the pipeline system.

Keywords Pipe vibration · Bracket · Elbow · Tee

1 Introduction

The most intuitive manifestation of large stress in a pipe system is the deformation of the pipe, i.e., the generation of vibrational displacement. We can judge whether the force of each pipe section of the pipeline system is reasonable by observing whether the vibration displacement of the pipeline is within a reasonable range and whether it is necessary to modify the local pipe section of the pipeline system.

Long-term vibration beyond the safe range will cause uneven stress on the main equipment, affecting its performance and operation. Moreover, it also destroys the sealing property. If the pipeline contains explosive or toxic gases, it is easy to have a terrible accident [1–3].

Using software, it also can predict the vibration displacement and each mode shape under the operating conditions by vibration analysis, besides the severity of pipeline damage. The brackets and the linking methods can be adjusted according

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to the vibration displacement. Thus, it can avoid excessive vibration when the pipeline system is running, causing severe stress, which will damage the piping system equipment seriously [4].

2 Pipe Vibration Principle

2.1 Calculation of Reaction Force R_m Under Extreme Displacement

According to ASME Pressure Pipeline Specification B31.1, Sect. 319.3.1(b), the Extreme Displacement Conditions R_m is calculated by using the highest or lowest metal temperature, whichever produces greater reactive force [5].

The formulation of maximum force calculation is as follows:

$$R_m = R\left(1 - \frac{2C}{3}\right)\frac{E_m}{E_a} \quad (1)$$

where C is cold-spring factor varying from 0 to 1; E_a is reference elastic modulus at 21 °C (70 °F), Pa; E_m is elastic modulus at the highest or lowest metal temperature, Pa; R is E_a_based reaction force range corresponding to the full displacement stress range, N; R_m is instantaneous maximum reaction force calculated at the highest or lowest metal temperature, N.

2.2 Acceleration Calculation of the Ultimate Vibration

The formulation of acceleration calculation is as follows:

$$R_m = ma \quad (2)$$

where m is total unit mass of pipe and fluid, kg; a is acceleration of the pipe system vibration in the corresponding direction under operating conditions, m/s^2.

2.3 Calculation of the Ultimate Vibration Displacement

The formulation of calculating the ultimate vibration displacement is as follows:

$$X = \frac{1}{2}at^2 \quad (3)$$

where X is the vibration displacement of pipe system node in the corresponding direction, m; t the unit time of the node corresponding to the direction vibration under operating conditions, s.

2.4 Calculation of Natural Frequency

The formulation of natural frequency calculation is as follows [6]:

$$f = \alpha\sqrt{\frac{EI}{(M_{\mathrm{ef}} + M)l^3}} \tag{4}$$

where α is the frequency coefficient; f is natural frequency of pipe, Hz; l is the pipe length, m; E is elastic modulus of pipe section material at design temperature, Pa; I is inertial moment of section, m^4; M is concentrated mass, kg; M_{ef} is equivalent concentration mass, kg.

3 Brief Introduction of Pipeline System

The pipeline system includes mainly two pumps (the other with a backup.), a number of gate valves, safety valves, check valves, etc., as shown in Fig. 1. (Note: The black part in Fig. 1 is the pump piping system tested.)

4 Simulation Results and Discussion

4.1 Simulation Method

Modeling from the right suction side by software, where set the node number 10 at the origin coordinate. The coordinates of the remaining segment nodes are determined according to their positional relationship with the origin node.

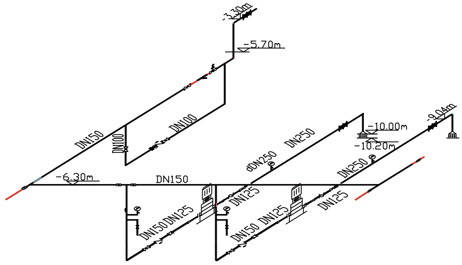


Fig. 1 Schematic diagram of pump piping system

4.2 Simulation Process

Since only one pump is in the starting state during the experiment process, the main pipe of the other pump does not enter the fluid due to the interception of the valve, but its vibration is affected by the side. Therefore, the part of the left side before node 1370 is ignored. The pipe wall thickness specification is set up SCH40, other parameters of the pipe were taken from measurement (the operating temperature $T = 5$ °C, the pump inlet pressure $P_{in} = 0.3$ MPa, and the pump outlet pressure $P_{out} = 1.1$ MPa).

4.3 Boundary Conditions

As shown in Fig. 2, the five constraints of the water pump connection, the end of the pipe (i.e., the node numbers 725, 1370), and the branch part for the node between 1940 and 1990 are fixed brackets. Setting the guide bracket at the constraint of the pipe section passing through the wall (i.e., the part before the node number 2540 and 35). The constraint condition of the remaining pipe sections is the sliding support hanger, which only serves to support and limit the displacement of the support direction, and does not play a role of limiting displacement except the support direction.

4.4 Node Number

Numbering from the suction section of the side, and number the nodes where the vibration displacement such as valves, brackets, tees, pumps, and elbows may be significantly marvelous. Points of interest in the stress isometric are identified by node points. Increase the number as much as possible to ensure that the maximum stress of pipeline occurs at the node. Therefore, it can be accurately expressed, which makes the simulation more realistic [7].

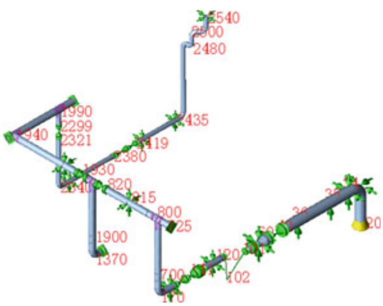


Fig. 2 The structure model of pump pipe

4.5 Mode Shape Analysis

The first-order and second-order modal shapes of the pump piping system are generated by software, thus it can be clearly seen which nodes are more deformed when the pipeline system resonates. Then vibration damping measures can be taken. (The first-order vibration mode shape is shown in Fig. 3, and the second-order vibration mode shape is shown in Fig. 4.)

From Figs. 3 and 4, we can find that:

The closer the spray pump is, the more serious the vibration deformation is. For example, the part between node 70 and 100.

The closer to the end equipment of the pipeline system, the more obvious the deformation of the joint position is. For example, the part between the node 2480 and 2520.

The vibration displacement of the elbow, nozzle, and valve is more significant. The deformation of tee, the valve, and the elbow are larger than connection of other pipe fittings; the deformation of the node 2300 is the most obvious. The more elbows there are, the more obvious the deformation is. For example, the node from 2480 to 2520.

Fig. 3 The 1st pipe mode shape

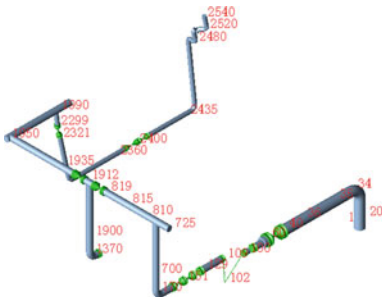
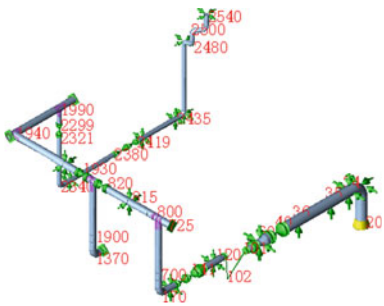


Fig. 4 The 2nd pipe mode shape



5 Test

The experiment measurement used a Pocket Vibrometer Measurement Instruments (type EMT220).

Measuring range: acceleration varying from 0.1 to 199.9, m/s^2; speed varying from 0.01 to 19.99, cm/s; displacement varying from 0.001 to 1.999, mm.

Frequency range: low frequency, 10–1000 Hz; high frequency, 1–15 kHz.

Error range: ±5%.

Using a Vibration meter to measure the vibration displacement of the node when the system was running. When measuring points, select the nodes near the elbow, tee, the water pump, valve, and the size head. The specific situation is shown in Fig. 2. The measurement nodes are 170, 2340, 2420, and 2460.

6 Analysis

6.1 Analysis Between Calculations and Measurements

The differences analysis of vibration displacement between the measurement and the calculation is shown in Table 1. (Note: When measuring data, the vibration displacement value displayed by the measuring instrument does not show the direction. Therefore, in order to facilitate the calculation during the analysis process, the obtained value when the model is subjected to the vibration analysis is also processed in no direction. Take its absolute value.)

As can be seen from Table 1, the maximum error between the calculated and experimental results is 15.38%, the minimum error is 0%; the average error is about 10%.

Table 1 Comparison between calculations and measurements

Node	Direction	Displacement (mm)	Simulation displacement (mm)	Error (%)
		Maximum	Maximum	
170	*X*	0.013	0.011	15.38
	Z	0.180	0.163	9.44
2340	*X*	0.009	0.008	11.11
	Z	0.760	0.838	10.26
2420	*X*	0.002	0.002	0.00
	Y	0.075	0.066	12.00
2460	*Y*	0.530	0.592	11.70
	Z	0.421	0.473	12.35

6.2 Analysis of Error

The main reasons for the vibration displacement error between the actual measurement and the model are as follows:

The error of vibration measuring instrument comes from itself.

When measuring data, the vibrometer probe is not completely perpendicular to the plane of the measurement point.

Although the pipeline system of spray pump is short, the scale is small as well, the pipeline system condition is a little complicated. There are two pumps, the other with a prepared, and some segments are shared with fire piping system. It is difficult to express accurately.

The error between the actual construction and design drawings of the pipeline system cannot be predicted and considered.

7 Optimized Methodology

In order to ensure the piping system to operate more smoothly and safely, the following methodologies are determined to solve the problem. Different models are established by changing the number of brackets, the three-way, and elbow factors. Then the vibration displacement analysis is carried out to observe the damping effect of cases.

7.1 Adjusting the Numbers of Hangers

Hanger is an important part of the pipeline system's structural design. In this process, the purpose of reducing the vibration can be achieved by changing its position and number. This case changes the pipe system to establish model by adjusting the bracket. The vibration displacement analysis is performed to observe the vibration damping effect.

According to Figs. 3 and 4 obtained from the model, as well as the vibration displacement of the operating conditions (as shown in Table 1), The vibration displacement for the nodes from 2338 to 2480 is significantly large. Therefore, the bracket is added to the elbow of the pipe section, i.e., the bracket is added at the nodes from 2440 to 2460, and the detailed information is shown in Fig. 5. Then, the correlation result of the vibration displacement in the original pipeline system operating condition is compared with the optimism model, the calculation result analysis is shown in Table 2.

It can be seen from Table 2 that increasing the bracket in the maximum direction of the vibration displacement for the relevant node, the original vibration displacement can be reduced to 0, the reduction is 100%. Adding a bracket at a

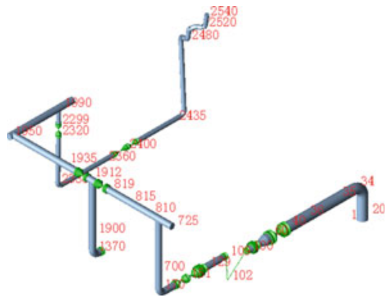


Fig. 5 Optimum pump piping system

Table 2 Case 1 vibration displacement change local part

Node	Direction	Prototype	Case 1	Reduction (%)
2440	*X*	−0.048	0	100
	Y	−0.199	0	100
	Z	1.429	0	100
2460	*X*	−0.376	0	100
	Z	0.473	0	100

certain node will also affect the vibration displacement of other nodes near the position. So adding a bracket is one of the most direct and effective methods.

7.2 Replacing Elbow with Tee

It can be obtained from Figs. 3 and 4, the vibration displacement at the node 2440 is most obvious during operation, therefore the elbow at the node 2440 is changed to a tee. The comparative analysis results between the case 2 and the original pipeline model are shown in Table 3.

It can be found in Table 3, after turning the elbow into a tee, the vibration displacement in the *Z* direction for the node 2440 is significantly reduced. The amplitude of the vibration in the *X* direction is reduced by 81.25%, the pipe coordinate *Y* direction is reduced by 73.77%, and the *Z* direction is reduced by 99.23%. Thus, the tee can effectively reduce vibration displacement.

Table 3 Case 2 vibration displacement change of local part

Type	*X*	*Y*	*Z*	*X*-reduction (%)	*Y*-reduction (%)	*Z*-reduction (%)
Elbow	−0.048	−0.199	1.429			
Tee	0.009	0.053	0.011	81.25	73.37	99.23

Table 4 Case 3 vibration displacement change of local part

Bends' number	2480 − *X*	2480 − *Z*	*X*-reduction (%)	*Z*-reduction (%)	2540 − *x*	2540 − *z*	*X*-reduction (%)	*Z*-reduction (%)
2	−0.332	0.403			0	0		
1	−0.162	0.394	51.2	2.23	0	0	0	0

7.3 Decreasing the Number of Elbows

Reducing the number of bends between the pipe sections for nodes from 2480 to 2540 and turn them into straight pipes. The comparative analysis of the vibration displacement results between the project 3 and the original pipeline model is shown in Table 4.

As indicated in Table 4, reducing the number of elbows can decrease the vibration displacement near nodes, but the amplitude over different coordinate is not same. The gap between them is quite significant. Displacement decreases dramatically. The pipe coordinate *X*, the decreased amplitude reaches to 51.20%; and the pipe coordinate *Z* decreases by 2.23%.

8 Conclusions

Throughout the calculation analysis and experimental tests, the following conclusions are as drawn:

First, it can be seen from Table 1 that the maximum error for the calculated and experimental results is 15.38%, the minimum error is 0%, and the average error is about 10%. It illustrates that the establishment and calculation of the model are feasible.

Second, as illustrated by Table 2, increasing the number of constraints can completely reduce the vibration displacement of the corresponding direction. Compared with other cases, adding the corresponding direction of bracket at the corresponding node, it's the most direct and effective methodology to decrease the vibration displacement.

Third, it can be observed in Table 3, turning the elbow into a tee, which can reduce dramatically the vibration displacement. The vibration displacement in different directions is reduced differently, and the maximum reduction reaches to 99.23%.

Fourth, as evident from Table 4 that reducing the number of elbows can reduce displacement at the nearby nodes. Compared with other cases, the reduction in the two directions is quite different, and the vibration displacement is larger in the *X*-direction. The decrease is by 51.20%.

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