Analysis of Vibration Characteristics of the Pig Launcher Based on Fluid-solid Coupling

Cheng Yu

Chengdu Technological University,

School of Intelligent Manufacturing,

Chengdu, China

Rui Xie

Sichuan University of Arts and Science,

School of Intelligent Manufacturing,

Dazhou, China

Abstract — In order to study the vibration characteristics of pig launcher of gas transmission pipeline, numerical simulation methods of natural frequencies and amplitudes are carried out based on the principle of fluid-solid coupling and finite element, and the vibration reason of the pig launcher of the gas transmission pipeline is analyzed. Furthermore, based on this, a comparative analysis of the optimized model was carried out. The results show that in the first six modes of the pig launcher, the vibration of the balance pipe and the vent pipe is severe, and the corresponding amplitudes of the first three and fifth modes are obviously larger. Under the same working conditions, the natural frequency of the optimized model significantly increases except that the frequency of the fifth mode is not much different. Besides, the amplitude decreases except that amplitude of the fourth mode is larger. It shows that the vibration of the launcher has been reduced effectively.

Keywords — Pig launcher; Gas-solid coupling; Natural frequency; Numerical simulation

I. INTRODUCTION

As a pipeline accessory, the pig launcher is an essential equipment for the construction and maintenance of long-distance pipeline projects [1]. The pig launcher is generally installed at the head of the main pipeline to launch the pig (ball). However, the pigging device vibrates severely when receiving and dispatching the ball, which may cause the damage and loosening of the connection between the pipe and the pipe and the connection between the pipe and the supports [2], and even result in a serious impact on pigging efficiency and operational safety. Consequently, the study on vibration characteristics of the pig launcher is of great significance.

Since the middle of the 20th century, foreign scholars have begun to study the pig pigging process, but most of them focused on the pigging model and pig [3]. Wang Shibin et al. [4] conducted research on the design of the pig receiving and launching pipe, and proposed that no matter whether the pressure vessel or the pressure piping engineering design specification is used to design the pig receiving and launching pipe, the personnel and management costs can be reduced. Han Chuanjun et al. [5] used Fluent software to study the flow field of receiving device of a gas transmission station, and analyzed the influence of pipe size on the flow field characteristics. Wu Zhendong [6] conducted a research on the optimization design of the foam pig and pig launcher. Wang Mengde[7] studied the requirements of the special equipment safety law and the regular inspection rules of pressure pipelines, and proposed the necessity of adding the pig launching and receiving device in the design of urban gas. Luan Xiaocong [8] focused on the pigging process of natural gas pipelines, and studied the structure, working principle and conditions of the pigs passing through the gas pipeline. However, most of the current domestic research focuses on the design standards of pig receiving and launching devices, tube structure design, pigging technology, flow field characteristics and practical engineering problems, and there is less research about the dynamic characteristics of pig receiving devices. Therefore, based on the previous study of the vibration characteristics of the pig launcher [9], the author further analyzed the vibration reasons of the pig launcher in the gas transmission station and established a gas-solid coupling model of the pig launcher through finite element software. Besides, the optimization analysis of vibration damping structure is carried out, which is of great significance to the optimization design of structural vibration damping.

II. REASON ANALYSIS OF VIBRATION OF PIG LAUNCHER

The pig launcher in the gas transmission station is taken as the research object in the paper. The device is mainly composed of a launcher, reducer, quick opening closure and locking mechanism, seals, by-pass pipe, pressure gauge, balance pipe, vent pipe, valve and other components, as shown in Fig. 1.

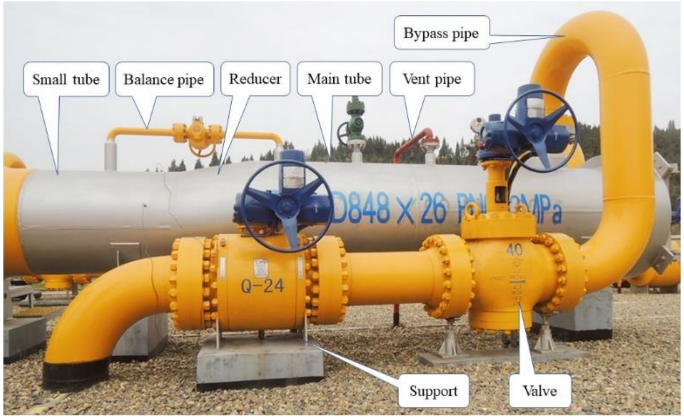

Fig. 1. The pig launcher

According to the pipeline vibration mechanism and causes, combined with the structural composition and working principle of the launcher, the vibration reasons of the launcher are analyzed under gas transportation condition.

(1) The airflow pulsation excites the pipe to produce mechanical vibration.

The airflow pulsation will generate an impact force at the reducer or elbow, which cause mechanical vibration of the pipeline. As shown in Fig. 2, if the fluid in the pipe is pulsating and the pressure unevenness is δ , the pressure pulsation amplitude is presented as:

$$\Delta P = \frac{1}{2}\delta P_0 \qquad (1)$$

The amplitude of the impact force caused by the impact of the airflow on the elbow is as follows:

$$\Delta F = 2\Delta P A \sin\frac{\beta}{2} = \delta P_0 A \sin\frac{\beta}{2} \qquad (2)$$

Consequently, the pipeline vibrates under the impact of the exciting force.

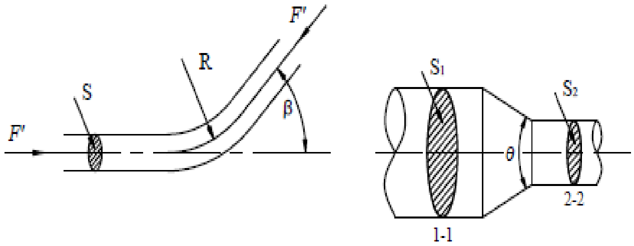

Fig. 2 The impact force caused at equal cross-section elbow and reducer

It can be seen from formula (2) that the impact force ΔF is proportional to the pressure unevenness δ, the average pressure P_0, the pipe cross-sectional area A and the elbow angle β. When the pressure unevenness is constant, the smaller the elbow angle, the smaller the impact force. Besides, when $\beta = 0$, the pipe is straight, that is to same, there is no impact force. Therefore, elbows should be reduced as much as possible, and there are no sharp elbows or adopt elbows with larger bending radius in the pipeline design.

Similarly, the reducer is shown in Fig. 2. There is airflow pulsation, the amplitude of the impact force caused by the impact of the airflow on the reducer is as follows[10].

$$\Delta F = \Delta P\left(A_1 - A_2\right) = \frac{1}{2}\delta P_0\left(A_1 - A_2\right) \qquad (3)$$

From the above analysis, as long as there is airflow pulsation in the pipeline, the impact force will be caused in these components, such as elbows, reducers, branch pipes and so on, which leads to the forced vibration of the pipeline. Consequently, reasonable design of the pipeline of the launcher can reduce the airflow pulsation and impact force, which can effectively reduce the vibration of the pipeline.

(2) The mechanical vibration system excites the launcher to vibrate.

The mechanical vibration system includes: 1) The main tube and components of launcher (quick opening closure, pressure gauge, balance valve, vent valve, bypass pipe and ball bracket, etc.), as shown in Fig. 3. 2) Improper basic design; When the impact force acts on the mechanical vibration system, which will cause mechanical vibration. In addition, the fluid with pressure pulsation will produce an unbalanced force at the elbow or the reducer, which will also cause the mechanical vibration of the launcher.

Fig. 3. Components of the pig launcher

III. CALCULATION MODEL

A. GEOMETRIC MODEL

When performing finite element model of the launcher, the flanges and valves that do not affect the analysis results are simplified. The outer diameter of the small tube is 718mm, the wall thickness is 18mm. The outer diameter of the main tube is 840mm, and the wall thickness is 20mm. The length of the small tube is 1500mm, the length of the main tube is 6600mm, the length of the reducer is 850mm, the nominal diameter of the bypass pipe is 400mm, and the nominal diameter of the balance pipe and the vent pipe is 50mm. The unstructured tetrahedral element is used to automatically divide the mesh, and the finite element model is shown in Fig. 4.

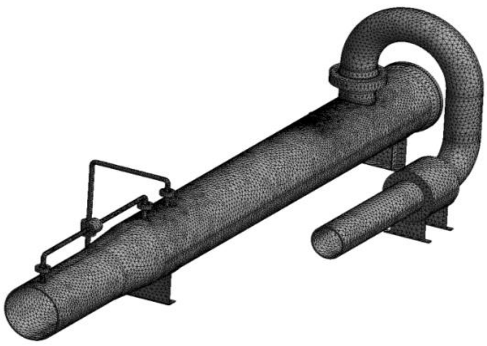

Fig. 4. The finite element model of the launcher

B. BOUNDARY CONDITIONS

Based on ANSYS-Fluent software, the fluid-solid coupling analysis of the pig launcher with natural gas is carried out. Set the coupling boundary conditions on the contact surface of the structure model and fluid domain model. When the transmission medium is natural gas, the methane whose density and dynamic viscosity is 0.6679kg/m^3 and 1.087×10^{-5} Kg·m^{-1}·s^{-1} respectively under standard conditions is used to approximately replace natural gas. The fluid inlet is set as a velocity inlet, and the inlet velocity is 12m/s. The outlet is set as outflow. For structural analysis, the inlet and outlet sections of launcher are zero-displacement constraints, the bypass pipe support and the tube support are fixed constraints. In addition, As the outlet section of the vent pipe is connected to the buried pipeline, it is set as a fixed constraint. The material properties of steel pipe are shown in Table 1 [11].

Table1. The material properties of the launcher

Name	Density/ kg·m^{-3}	Elastic Modulus / Pa	Poisson's ratio
Launcher	7850	2.09e11	0.28

3 Analysis of calculation results

In order to study the influence of fluid on the vibration characteristics of the launcher, the natural frequency and amplitude are calculated under the gas-solid coupling condition. The corresponding mode shapes of the first 6 modes of the launcher are shown in Figure 5. From the Fig. 5, the balance pipe of the first and second mode is offset, and the maximum amplitude appears at the middle of the valve of the balance pipe. The vent pipe of third mode is offset, and the maximum amplitude appears at the L-bend of the vent pipe. The vent tube is bent and the U-shaped pipe of the bypass pipe is offset in the fourth mode, and the maximum amplitude appears at the top of the U-shaped pipe. The vent pipe of the fifth mode is bent, and the maximum amplitude appears in the vent pipe valve and the upper pipe. The U-shaped pipe of the sixth mode is offset, and the maximum amplitude appears at the top of the U-shaped pipe of the bypass pipe.

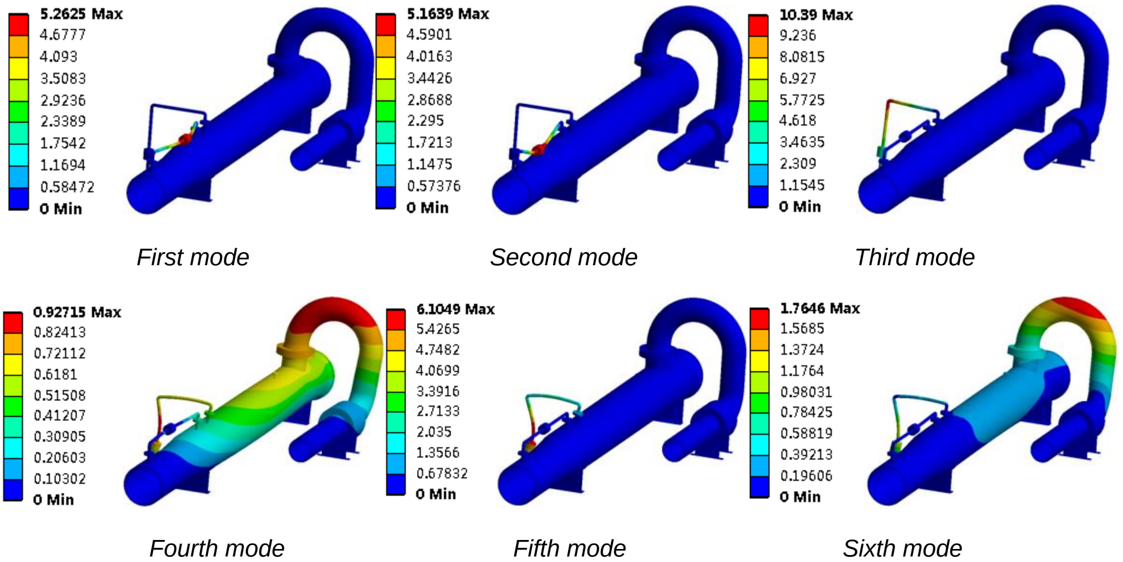

Fig. 5. Mode shape of the launcher under gas-solid coupling

Table 2 shows the natural frequencies and amplitudes of first 6 modes of the launcher under gas-solid coupling conditions. From the Table 2, the amplitudes corresponding to the first, second, third and fifth modes are obviously larger.

Table 2. The natural frequencies and amplitudes of the launcher

Mode	1	2	3	4	5	6
Natural frequencies / Hz	20.258	23.482	26.262	42.496	48.777	49.955
Amplitudes / mm	5.2625	5.164	10.390	0.927	6.105	1.765

IV. STRUCTURAL OPTIMIZATION OF THE LAUNCHER

The main reason of pipeline vibration is that the airflow generates impact force when passing through elbows, reducers, valves and other components. From the vibration analysis of the original launcher, the vibration of the balance pipe and the vent pipe in the launcher system is severe under the gas-solid coupling condition. This is mainly because the nominal diameter of these two pipes is significantly less than the diameter of the main tube. Therefore, on the premise of meeting the technological requirements of the launcher, the structure of the launcher is optimized to change the natural frequency to avoid the resonance frequency region and to reduce the vibration amplitude of the pipe system. The nominal diameter of the balance pipe and the vent pipe of the optimized launcher is 100mm, and the diameter of the elbow is 100mm, as shown in Fig. 6.

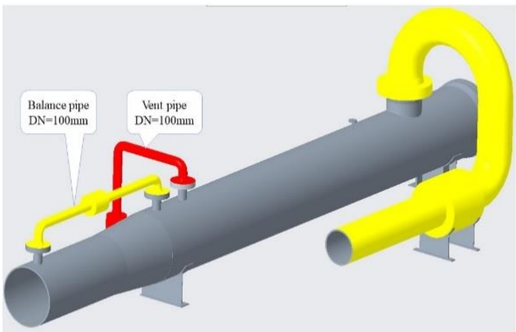

Figure 6 The optimized launcher

V. COMPARATIVE ANALYSIS

The vibration shape of the first 6 modes of the optimized launcher is shown in Fig. 7. From the Fig. 7, the balance pipe of the first and third mode is offset, and the maximum amplitude appears at the middle of the valve of the balance pipe. The U-shaped pipe of the second and fifth mode is offset, and the maximum amplitude appears at the top of the U-shaped pipe of the bypass pipe. The vent pipe of fourth mode is offset, and the maximum amplitude appears at the L-bend of the vent pipe. The main tube of sixth mode is offset, and the maximum amplitude appears at the junction of the bypass pipe and the main tube.

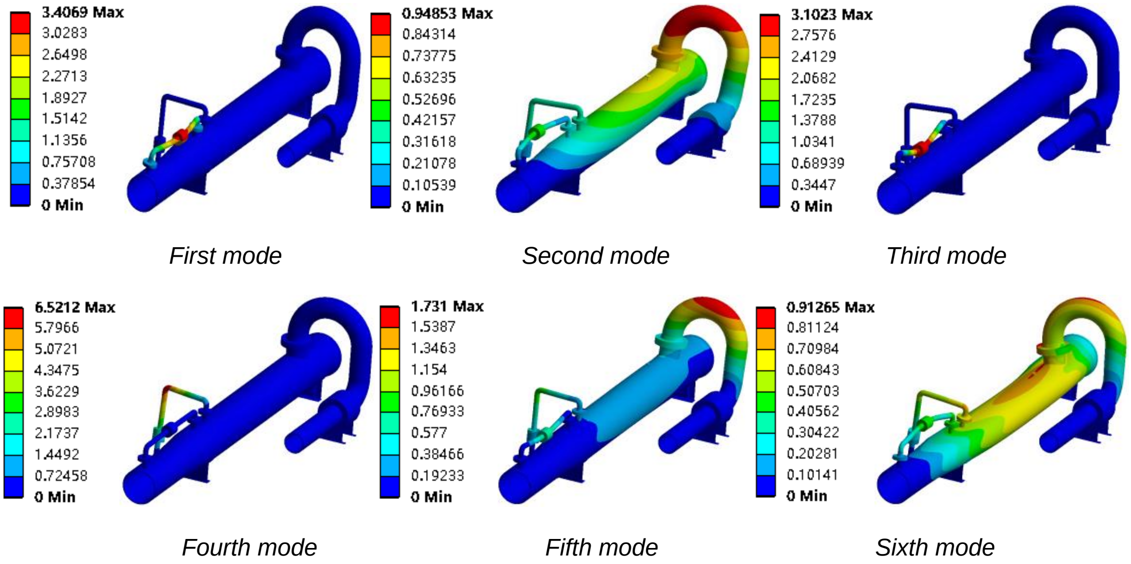

Fig. 7. Mode shape of launcher in gas-solid coupling

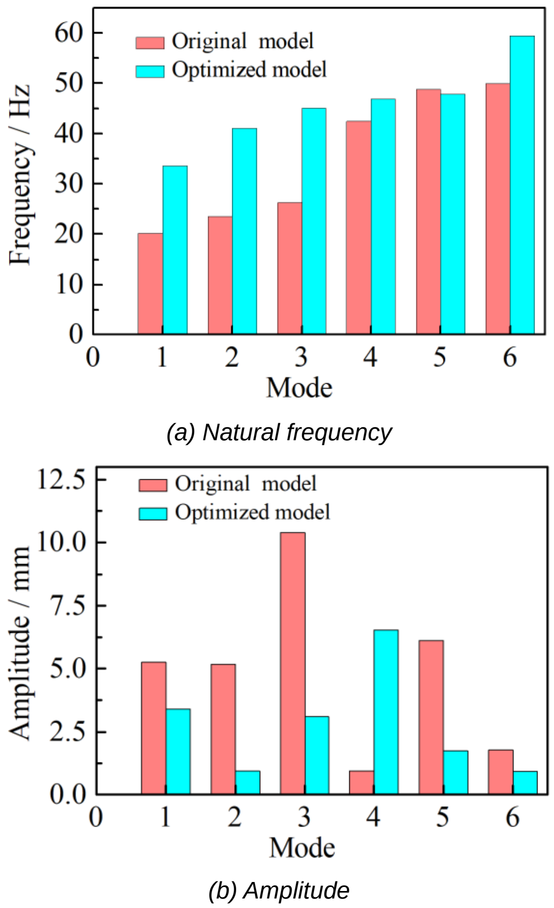

Fig. 8. The comparative analysis of natural frequency and amplitude of two launchers

The comparative analysis of natural frequency and amplitude of two launchers are shown in Fig. 8. From the Fig. 8, except that the natural frequency of fifth mode is not much different, the natural frequency of the optimized model significantly increases. Besides, except that the amplitude of the fourth mode is larger, the amplitude values of the other modes are significantly reduced, indicating that the vibration of the launcher has been reduced effectively.

VI. CONCLUSION

The gas-solid coupling model of the pig launcher is established, and the natural frequency and amplitude are solved. Besides, combined with the analysis of vibration reasons, the structure is optimized. The following conclusions are obtained:

(1) Under the gas-solid coupling condition of the original structure model, the maximum amplitude of the first six modes mainly appears in the balance pipe and the vent pipe, and the amplitude of the first, second, third and fifth modes is significantly larger.

(2) Under the same working conditions, compared with the optimized model, it is found that except for the natural frequency of fifth mode, the natural frequency of the optimized model increases significantly. Besides, except that the amplitude of the fourth mode is larger,

the amplitude value of the other modes significantly reduces, indicating that the vibration of the launcher has been reduced effectively.

ACKNOWLEDGMENT

This work is supported by the school-level research project of Chengdu Technological University (NO. 2018ZR003).

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