Study on the effect of fluid-structure coupling on the outlet Piping of reciprocating compressor

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Abstract. The fluid-structure coupling has been one of the hot issues of academic research in recent years, the achievements in various fields of study also emerge in an endless stream, but on the current research status, The study of fluid structure interaction in the field of moving equipment, especially compressor, is not very common, With the development of industrial compressor, it is developing towards the direction of large scale and high parameter, Coupling analysis of fluid structure interaction can be used to evaluate the safety and stability of the system, and the evaluations are more close to the actual situation. Therefore, it has gradually been valued. Through the comparison and analysis of the vibration test system of the reciprocating compressor before and after the pipeline inflation, the vibration response caused by the coupling factor is obtained, for the correctness verification of the fluid-structure coupling simulation. the numerical model of the experimental system is established based on ANSYS, and the boundary conditions of the model are simulated by the experimental data, verified the feasibility of simulation program. the experimental and simulation results show that the fluid solid coupling characteristics are not obvious in the vicinity of the reciprocating compressor, and the effect is significant at the top of the buffer tank and the installation position of the orifice plate.

1. Introduction
Reciprocating compressors are widely used in many industrial fields such as petrochemical industry, aerospace, shipbuilding, and mining. However, the periodic pressure pulsation excitation in the pipeline caused by its working principle itself can cause severe vibrations in the pipeline system and serious affect the safe operation of the device. Vibration of reciprocating compressor pipelines in practical engineering applications is generally the result of multi-physics coupling, especially the fluid-solid coupling of the elastic air column in the tube and the pipeline structure.

In the 1950s and 1960s, Skalak solved an infinite number of piping wave modes considering the moment of inertia and bending stiffness of the pipeline, laying the foundation for the coupling theory of liquid-filled pipelines; Walker and Phillips considered The effects of Poisson coupling and connection coupling, as well as the influence of additional mass and radial inertia of the tube wall, have studied the law of short-wavelength fluid pressure fluctuations in straight tubes with low elastic modulus, and deduced the equation describing radial vibration [1]; Tentarelli, For the first time, the Poisson coupling vibration was measured by an experimental method, and the effect of Poisson coupling on the dynamic
characteristics of the pipeline system was clarified [2]; Tijssseling and Vardy studied the coupling vibration of branch pipes, valves and 90° curved pipes Problem [3-4]; S.Ziada conducted an experimental comparative study on the theory of fluid-solid coupling of T-shaped pipelines [5]; Duan conducted research on Y-tubes and obtained the gas-solid two-phase flow law of this type of pipeline [6].

In China, Wang Jian used the ALE method for pipeline fluid-solid coupling simulation calculations, and analyzed the influence of nonlinear dynamic characteristics [7]; Li Haifeng provided a new ideas for fluid-solid coupling problems based on the ANSYS parametric design language [8]; Tao Donglai conducted a two-way fluid-solid coupling numerical simulation study on the compressor lubricating oil pipeline system [9]; Zhao Jie based on the gas-solid coupling theory and the Galerkin method analyzed and calculated the coupled vibration characteristics of the empty pipe and inflation pipe [10]; Bai Changqing established a fluid-solid coupling three-dimensional dynamic finite element model and used the transient time history analysis method to analyze the compressor vent pipeline, the simulation analysis of dynamic response under impinging airflow is presented [11].

In recent years, the pipeline vibration of reciprocating compressors has attracted more and more attention from engineers in the industry. However, the current research on pipeline vibration mostly ignores the impact of gas column on pipelines. Although fluid-solid coupling is one of the hot issues in current research, but its research in the fields of dynamic equipment, especially compressors, has not been seen too much. With the continuous development of industrial compressors in the direction of large-scale and high-parameters, the coupling characteristic analysis represented by fluid-structure coupling can evaluate the safe and stable operation of the system closer to the actual situation, so it has gradually attracted the attention of the industry. The purpose of studying fluid-structure coupling vibration is to analyze the interaction between pipeline structure and fluid flow more comprehensively, and to explore the conditions under which fluid-structure coupling influence can be neglected. The research will provide guidance for solving the problem of pipeline vibration in reciprocating compressors, and also have important reference value and significance in similar fields.

2. Experimental research

In order to provide boundary conditions for the finite element analysis of the coupled field and verify the accuracy of the software simulation analysis, it is necessary to measure the pressure unevenness of the coupled field and the dynamic response values of different measuring points. For this purpose, a comprehensive experimental platform for reciprocating compressor pipeline vibration characteristics analysis was designed and built. The experimental flow chart is shown in Figure 1.

![Fig. 1 Experiment system flow chart](image)

The aperture ratio of the orifice plate used in the experiment is recommended in the literature [12]-[14], and the optimal aperture ratio range that has been verified by this experimental system is taken as 0.5. The initial pressure is set to 0.1MPa, but the internal pressure of the pipeline will increase with the increase of air temperature during actual operation, and the flow rate is 5m³/h, and the motor
operating frequency is 50Hz. During the experiment, one of the pressure fluctuation curves at the position of the pressure sensor in front of the buffer tank is shown in Figure 2.

![Figure 2](image)

**Fig. 2** Changes of pressure diagram of pressure sensor

According to the pressure fluctuation data, the maximum pressure is 111432.6Pa, the minimum pressure is 100446.7Pa, the average pressure is 101745.2Pa, and the pressure unevenness is 2.912048%. This value will be used in the pulsation setting of the pressure fluctuation curve in the finite element simulation calculation [15]. In addition to the pulsating pressure, the vibration displacement of the inflation pipeline of the experimental system under this pressure was also measured. A total of 7 measuring points were arranged. Each measuring point will test the displacement and vibration intensity in three directions: east-west, north-south, up and down. The gas flow direction and the distribution of measuring points in the experimental pipeline are shown in Figure 3.

![Figure 3](image)

**Fig. 3** The chart of measuring points on pipeline

The tests on the 7 measuring points in the figure were carried out in two experimental states: inflatable tube and empty tube, once the valve above measuring point 2 was opened, and the fluid-structure coupling vibration displacement occurred under the condition of current carrying in the experimental pipeline; and the other was closed the vibration displacement of the valve above the measurement point 2 when the gas is discharged through the other two vent pipes, that is, the pure mechanical vibration displacement without fluid-solid coupling when the experimental pipe is empty.

Vibration displacement data was collected with a portable vibration tester. A total of 7 measuring points were collected in 21 directions. As shown in Table 1, the name of measuring point 1-E corresponds to the east-west direction of measuring point 1, which is also Z direction in the cloud chart. Measurement point 1-N corresponds to the north-south direction of measurement point 1, which is also the X direction in the cloud diagram; measurement point 1-U corresponds to the vertical direction of measurement point 1, which is also the Y direction in the cloud diagram. Other measurement points are expressed in similar ways. TL is the sum of the displacements of each column in the table.
Table 1. Comparison of test results

| Test point name | Inflatable tube displacement (µm) | Empty pipe displacement (µm) | Total displacement of inflatable pipe (µm) | Total displacement of empty pipe (µm) | Total displacement difference (µm) |
|----------------|----------------------------------|------------------------------|------------------------------------------|-------------------------------------|----------------------------------|
| 1-E            | 265                              | 259                          | 511                                      | 493                                 | 18                               |
| 1-N            | 405                              | 376                          | 613                                      | 729                                 | -115                             |
| 1-U            | 164                              | 187                          | 286                                      | 307                                 | 21                               |
| 2-E            | 254                              | 237                          | 892                                      | 753                                 | 137                              |
| 2-N            | 740                              | 672                          | 962                                      | 905                                 | 57                               |
| 2-U            | 428                              | 244                          | 670                                      | 670                                 | 0                                |
| 3-E            | 255                              | 486                          | 711                                      | 711                                 | 0                                |
| 3-N            | 413                              | 391                          | 804                                      | 798                                 | 6                                |
| 3-U            | 375                              | 377                          | 752                                      | 752                                 | 0                                |
| 4-E            | 407                              | 142                          | 553                                      | 553                                 | 0                                |
| 4-N            | 422                              | 388                          | 800                                      | 798                                 | 2                                |
| 4-U            | 42                               | 21                           | 63                                       | 63                                  | 0                                |
| 5-E            | 583                              | 270                          | 853                                      | 853                                 | 0                                |
| 5-N            | 400                              | 399                          | 799                                      | 796                                 | -3                               |
| 5-U            | 23                               | 13                           | 36                                       | 36                                  | 0                                |
| 6-E            | 371                              | 180                          | 551                                      | 551                                 | 0                                |
| 6-N            | 26                               | 242                          | 368                                      | 368                                 | 0                                |
| 6-U            | 59                               | 61                           | 120                                      | 120                                 | 0                                |
| 7-E            | 206                              | 202                          | 408                                      | 408                                 | 0                                |
| 7-N            | 233                              | 216                          | 449                                      | 449                                 | 0                                |
| 7-U            | 101                              | 113                          | 214                                      | 214                                 | 0                                |
| TL             | 6172                             | 5476                         | 4014                                     | 3497                                | 746                              |

Through the comparison experiment of the inflatable tube and the empty tube of the experimental system, the vibration displacement, total displacement and total displacement difference of 7 measuring points in each direction under the two conditions are obtained. The total displacement difference is the additional displacement of the pipeline caused by the fluid-solid coupling effect. It can provide comparative data for the verification of the correctness of the finite element numerical simulation method below.

From the data in Table 1, it can also be seen that the overall displacement of each measuring point of the pipeline after inflation is 0.746µm higher than that of the empty pipe, indicating that the fluid-solid coupling effect will increase the dynamic response value of the pipeline system under the experimental conditions.

The total displacement difference of the 7 measuring points in the experimental system, 6 of them rose after inflation, and the maximum difference was 225µm. This position is the top of the buffer tank, indicating that the fluid-solid coupling effect is the most obvious here, and measuring point 1 The total displacement difference with measuring point 7 is below 20µm, indicating that the fluid-structure coupling effect at the two measuring points is not significant. At the same time, the displacement value at measuring point 3 corresponding to the second elbow of the compressor outlet in the figure does not rise but drops by 115µm after inflation, indicating that the fluid-solid coupling after inflation has transferred the energy of the pipeline system. The energy at the original elbow is redistributed elsewhere in the pipeline.

3. Numerical simulation

Due to the limitations of its own conditions, the reciprocating compressor pipeline system built in the laboratory can only complete some specific experiments when the experimental conditions are met. If the finite element analysis software is used and the reasonable coupling field analysis method is adopted,
the fluid solid coupling simulation of pipeline under various complex working conditions can be completed, which has important research value and engineering practice significance [16-17].

Use the finite element multiphysics simulation software ANSYS Workbench to model and simulate the experimental piping system to study the influence of the fluid-structure coupling effect on the pipeline vibration under the experimental conditions. If the influence is obvious, it is not advisable to ignore the fluid structure coupling effect and solve the system vibration alone under the experimental conditions. If the influence is limited, the influence of coupling factors can be ignored in the subsequent structural vibration characteristic analysis. The main simulation process and parameter settings are as follows:

The experimental system pipe material is 20# carbon steel, density is 7820 kg/m³, Poisson's ratio is 0.3, elastic modulus is $2.16 \times 10^{11}$ Pa. The experimental pipeline model established is shown in Figure 4.

![Fig. 4 The model of experimental pipeline system](image)

There are two entities in the figure: pipeline model and fluid model. The pipeline model unit type is set to Solid187, and the fluid model unit type is set to mesh200. The structure domain is finally divided into 36756 nodes and 9712 units, and the grid diagram is shown in Figure 5. The divided fluid domain has a total of 120246 nodes and 130576 units. The fluid grid diagram is shown in Figure 6.

![Fig. 5 The solid domain grid map](image) ![Fig. 6 The fluid domain grid map](image)

In the fluid material option, 25°C air is selected as the medium. The inlet boundary of the coupling analysis can be applied with periodic pulsating pressure according to the results of the experimental part. The outlet boundary condition is normal pressure. In the transient result option, set the output selection items as pressure and total displacement. Analyze and monitor the pressure changes at the front and back positions of the buffer tank and the total displacement changes of the 7 measuring points on the experimental system. The pressure distribution cloud diagram at 0.02s after the solution convergence is shown in Figure 7, and the total displacement distribution cloud diagram at the corresponding time is shown in Figure 8.
From the pressure distribution cloud chart, it can be obtained that the pressure value of the pipeline at the pressure sensor position in front of the buffer tank is 110700Pa, which is 732.6Pa smaller than the measured maximum pressure, and the error value is 0.66%. The pressure value at the position of the pressure sensor behind the buffer tank is 83127.8Pa, which is 17758.6Pa and 18369Pa different from the measured average pressure and maximum pressure respectively. There are two main reasons for the large error: One is the V-cone flowmeter installed on the outlet pipeline of the buffer tank, the pipeline has abrupt cross-section reduction and expansion, but the obstructive effect of the flowmeter on the fluid is ignored when modeling; the second is that the outlet pipe is equipped with a ball valve at the elbow, and the valve only uses a characteristic orifice instead of simulation, there is a gap with the real situation. The error analysis of the pressure behind the tank and the simulation pressure before the tank are highly consistent with the actual measured results, indicating that the simulation results of the fluid part in the above fluid-solid coupling analysis are credible.

It can be seen from the cloud diagram of the total displacement distribution that the most obvious part of the vibration effect of the experimental system is on the top of the buffer tank, corresponding to measuring point 5 on the experimental pipeline, and the secondary vibration part is the position of the installation orifice, corresponding to the actual measuring point 4. The total displacement result of the test is compared with the simulation result. The data list is shown in Table 2, and the comparison line chart is shown in Figure 9.

| Test | Measured total displacement | Simulated total displacement | deviation |
|------|-----------------------------|----------------------------|-----------|
| 1    | 18                          | 79                         | 77.2      |
| 2    | 137                         | 62                         | -54.7     |
| 3    | 115                         | 134                        | 14.2      |
| 4    | 174                         | 167                        | -4        |
| 5    | 225                         | 208                        | -7.6      |
| 6    | 67                          | 55                         | -17.9     |
| 7    | 10                          | 10                         | 0         |

![Fig. 7 Stress distribution nephogram](image1) ![Fig. 8 The total displacement distribution nephogram](image2)

Fig. 9 Comparison of test results
It can be seen from Table 2 and Figure 9 that the error of measuring point 1 and measuring point 2 is relatively large. This is because the two measuring points are located close to the compressor body, and the vibration of the body will affect the measuring point 1 and 2. For the amplitude at point 2, the fluid-structure coupling effect is not obvious. In the actual engineering pipeline, the part near the compressor body is often vibrated severely and often requires special treatment. This part is most obviously affected by the vibration of the body, and it is also the pipe section that is least affected by gas. The two measuring points close to the compressor have huge errors in the experimental total displacement considering the forced vibration of the air frame and the coupled simulation total displacement without considering the forced vibration of the air frame. It just confirms that the fluid effect in this part is not obvious, and the correctness of the simulation process can be explained in combination with the actual engineering situation. At the same time, it can be seen that the error between the measured displacement and the simulated displacement at the remote end of the compressor is relatively small, indicating that the simulated fluid-structure coupling value at the remote end of the compressor is basically consistent with the real situation. In addition, the maximum value of the simulation is 208µm at the measurement point 5. The measured data shows that this position is also the most obvious part of the fluid-structure coupling vibration characteristics, which further demonstrates the reliability of the fluid-structure coupling analysis in this paper.

4. Conclusion

(1) The numerical simulation of fluid structure coupling characteristics of reciprocating compressor pipeline system can provide relevant parameter conditions through experimental test, so it is different from the research method of simulation before experiment verification for general problems, which can be studied by the method of experiment before simulation or by experiment and simulation at the same time.

(2) The fluid-solid coupling characteristic of the reciprocating compressor pipeline system has no obvious effect on the pipeline near the compressor body, but has a significant effect on the top of the buffer tank and the installation position of the orifice plate.

(3) The reciprocating compressor pipeline vibration model established based on ANSYS and experimental data can be used for fluid-solid coupling vibration characteristics analysis, and the simulation effect at the pipeline away from the compressor body is highly consistent with the actual situation.

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