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Case Report

Study on vibration of reciprocating pump pipelines based on pressure pulsation theory

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Abstract: Due to the periodic movement of the piston in the reciprocating pump, the fluid will cause pressure pulsation, and the vibration of the pipeline will lead to instrument distortion, pipe failure and equipment damage. Therefore, it is necessary to study the vibration phenomena of the reciprocating pump pipeline based on the pressure pulsation theory. This paper starts from the reciprocating pump pipe pressure pulsation caused by fluid, pressure pulsation in the pipeline and the excited force is calculated under the action of the reciprocating pump. Then, the numerical simulation model is established based on the pipe beam model, and the rationality of the numerical simulation method is verified by the indoor experiment. Finally, a case study is taken as an example to analyze the vibration law of the pipeline system, and proposed the stress reduction and vibration reduction measures. The main conclusions are drawn from the analysis: (1) Excited force is produced in the bend or tee joint, and it can also influence the straight pipe in different levels; (2) In this pipeline system, the pump discharge pipe has a larger vibration amplitude and lower natural frequency; (3) The vibration amplitude increases with the pipe thermal stress, and when the oil temperature is higher than 85°C, it had a greater influence on the vertical vibration amplitude of the pipe.

Keywords: reciprocating pump; oil station; pipeline; vibration; pressure pulsation

1. Introduction

Strong vibration of the pipeline will not only make the structure of the pipeline and its pipe parts have fatigue damage, the connection parts loose and rupture, measuring instrument distortion or even damage, but also cause noise pollution, affect the staff's physical and mental health. Excessive vibration may even cause serious accidents and cause significant economic losses. According to a Canadian expert, in industrial developed America, the losses caused by pipe vibration in the past amounted to more than $10 billion annually. And in 100 cases of damage incidents, the factor of pipeline vibration occupied 19%. From the point of view of stress, uneven stress can lead to stress concentration of pipes. If stress exceeds allowable value, it will lead to more serious damage. Therefore, the stress and vibration analysis is necessary before the pipeline system with reciprocating pump is put into operation. The research has important engineering significance to ensure the safe and stable operation of pipelines in oil stations.

In 1974, a petrochemical plant's pipeline was destroyed by an explosion, resulting in a loss of $114 million. In March 2006, the export valve of a hydrogen compressor in a Chinese enterprise suddenly fell off due to vibration, resulting in a large number of flammable and explosive gas leakage, and eventually exploded. On the contrary, Benxi chemical fertilizer plant solved the problem of pipeline vibration of a compressor in 1984, the safety has been guaranteed. Besides, the increase of gas transmission and the reduction of power consumption have achieved [1-2].

Pipeline vibration research can be traced back to 1950s, the United States KBR company had studied pipeline vibration problem, and they failed to vigorously promote the development of this problem because the conditions and methods are immature [3]. Feadasev et al. used the beam model

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to derive the vibration equation of the straight pipe [4]. In 1975, Bickford et al. used the transfer matrix method to analyze the vibration problem of plane beam [5]. In 1980, Irie deduced the transfer matrix method for analyzing the vibration stability of pipelines [6]. In 1990, Lesmez et al. first used the separation of variables method in the derivation of the transfer matrix method of the space complex pipeline system. This method is more flexible and can solve the vibration problem of the complex space pipeline system [7].

In the aspect of pipeline modeling, the beam model or shell model is usually used. The beam model is mainly applied to the case where the pipe is much longer than the pipe diameter, and the shell model is more suitable for the local analysis of the pipeline. Researchers have studied the beam model more extensively. Ashley used the beam model to study the theory and experiment of pipeline vibration [8]. Paidousssi took the short pipe as the Timoshenko beam and studied the stability. It is found that the beam model is not suitable for the short pipe because pipe has both beam vibration mode and shell vibration mode [9]. Fuller and Fahy used single-frequency and axial single-point excitation to study the vibration of forced vibration straight pipe, and achieved much results [10]. Adachi et al. used a complete shell model to analyze the vibration of the straight pipe, and compared the results with other scholars' calculations. It was concluded that the shell model suitable for the pipe which is extremely short or the accurate results needed. After using the beam model, the Dunkerley method and the Ritz method can be used to calculate the natural frequency of the pipeline. For the complex pipe system, the finite element method and the transfer matrix method are always used [11].

From the study of vibration reduction of pipelines, in 2007, Yu Chenglong et al. analyzed the vibration and vibration reduction measures of reciprocating compressor pipeline. Moreover, some measures are put forwarded, such as to increase the buffer tank, change the diameter and so on [12]. In 2009, Ye Lyuhua used ANSYS software to analyze vibration of water injection pump pipeline in oil field [1]. Also in 2009, Chen Haifeng used the method of electro-acoustic analogy which regards pipe unit as circuit to analyze the vibration of pipelines in reciprocating compressor system, this method is convenient and fast, but it can only be used to calculate the frequency of the pipeline [13]. In 2013, Sui Kai and Wang Jie analyzed the water mains' pressure pulsation and used separation of variables method to deduce the expression of pressure pulsation [14].

From the literature in recent years, it can be seen that most of the research for the pipelines with reciprocating equipment are focus on the pipeline frequency. Moreover, vibration reduction research are mainly from the point of natural frequency enhancement and pressure pulsation control, the studies did not start with the amplitude of the pipeline. The calculation of pressure pulsation can be divided into analytical method and finite element method. Although the pressure pulsation can be calculated by the analytical method, the pressure nonuniformity can not reflect the real situation. The finite element method needs to use other professional software such as PRO/ENGINEER, its modeling process is more cumbersome.

One of this paper's authors, Hongfang Lu, did a similar study in 2016 [15], but that paper only from the point of view of pipeline stress and vibration frequency. Moreover, that paper did not compare the amplitude difference between the static condition and pressure pulsating condition. In this paper, numerical simulation combined with experimental methods for reciprocating pump pipeline vibration analysis. Firstly, the vibration analysis method of reciprocating pump is established based on the theory, a simple pipeline is designed, and the analytical method is verified by indoor experiment. Secondly, this verified method is used to analyze the vibration of the actual pipeline of an oil station and put forward the measures of vibration reduction.

2. Theory

The vibration analysis of the reciprocating pump pipeline is usually in accordance with the process shown in **Fig. 1**. Therefore, the basic theories involved include: the calculation of the pressure pulsation, the calculation of the imbalanced excited force, and the modeling of the pipeline.

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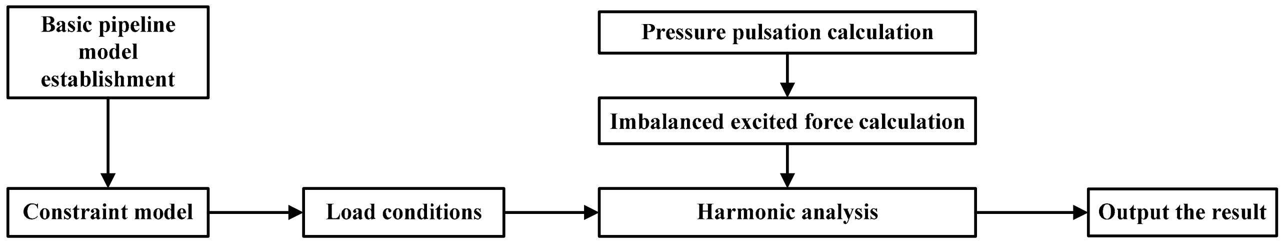

Figure 1: Vibration analysis process of the reciprocating pump pipeline

2.1 Pressure pulsation

Pressure pulsation refers to the maximum amplitude deviated from the average pressure, in the case of absence of pipeline pressure field data, it is difficult to calculate by shock-wave theory, in order to ensure the results' accuracy, separation of variables method is used to calculate.

The expression of pressure pulsation is:

$$p_{\Delta}\left(x,t\right)=\left[\frac{-2p}{n\pi}\left(\cos n\pi l-1\right)\cos\omega_n t+\frac{-2u}{n^2\pi^2 cl}\left(\cos n\pi l-1\right)\sin\omega_n t\right]\sin\frac{n\pi}{l}x \tag{1}$$

where $p_{\Delta}(x,t)$ is pressure pulsation at x position and t time, Pa; n is order number; c is sound velocity, m/s; l is total pipe length, m; x is distance from the starting point, m; ω_n is excitation circular frequency, rad/s; p is initial pressure, Pa; u is initial velocity, m/s.

2.2 Imbalanced excited force

The reciprocating pump produces a pressure wave in the pipe in a regular time interval. The pressure wave propagates through the fluid and produces harmonic loads at each elbow in the pipe system, as shown in **Fig. 2**. It is assumed that the inner diameter of the pipe is d_i, the angle of elbow is β, the inlet and outlet pressures are p, then the resultant force of elbow is [14]:

$$R=2F_1\sin\left(\frac{\beta}{2}\right)=2F_2\sin\left(\frac{\beta}{2}\right)=2\left(\frac{\pi d_i^2 p}{4}\right)\sin\left(\frac{\beta}{2}\right) \tag{2}$$

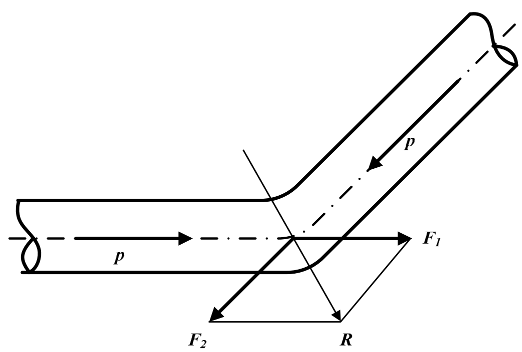

Figure 2: Elbow force diagram

If p is constant, then R is constant and the bend deformation and stress are static. If the pressure is pulsating, then $p=p_0+\Delta p$ and the resultant force of elbow is:

$$R=2\left(\frac{\pi d_i^2}{4}\right)\left(p_0+\Delta p\right)\sin\left(\frac{\beta}{2}\right)=2\left(\frac{\pi d_i^2}{4}\right)p_0\sin\left(\frac{\beta}{2}\right)+2\left(\frac{\pi d_i^2}{4}\right)\Delta p\sin\left(\frac{\beta}{2}\right) \tag{3}$$

where p_0 is average pressure, Pa; Δp is amplitude of pressure pulsation, Pa.

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In Eq. (3), the first term is the force produced by static pressure on the elbow, the second term is the alternating force--ΔR produced by pressure pulsation.

$$\Delta R = 2\left(\frac{\pi d_i^2}{4}\right)\Delta p \sin\left(\frac{\beta}{2}\right) = 2S\Delta p \sin\left(\frac{\beta}{2}\right) \tag{4}$$

where Δp is pressure pulsation, Pa; S is cross sectional area of pipe, m^2.

From Eq. (4), it can be seen that the excited force of the pipe increases with the increase of the elbow angle when the pulsating pressure is constant within the 0~180 degree of the elbow angle.

2.3 Pipeline model

In pipeline model section, it mainly includes the mechanical model of the pipeline, the finite element mesh and the finite element method of the pipeline structure. These contents are available in two additional papers published by the author [15, 16].

3. Numerical simulation method and experimental verification

3.1 Numerical simulation

Because the pipeline of reciprocating pump is more complex, the pipe beam model is usually used. According to the basic pipeline model, CAESAR II software was selected to analyze the vibration of pipelines. The following assumptions are made for the calculation of the vibrations of the reciprocating pump pipelines using the CAESAR II software:

(1) The small deformation assumption is that the local deformation of the cross section of the element under load is negligible; (2) The pipe material is in the elastic range without considering the plastic deformation and large deformation, that is, the nonlinear problem of the pipe structure is not considered; (3) The plane stays flat during loading; (4) Only consider the elastic changes of the pipe and the load, that Hooke's law applies to the full load range of the tubular section; (5) The forces and moments acting on the structure are assumed to be the points acting on their central axes; (6) The amount of rotational deformation of the system is assumed to be small; (7) The force is not affected by structural deformation; (8) Ignore the friction between the liquid and the pipe wall; (9) There is no vacuolization in the liquid filled pipeline [16, 17].

The vibration analysis of pipes is usually done according to the process shown in Fig. 1, and the corresponding numerical simulation steps are as follows: (1) Establish a pipeline foundation model: input the basic parameters of the pipeline such as inner pressure, thickness, pipe material, not including pipeline constraints; (2) Establish the constraint model according to the actual engineering loads or constraints; (3) Set the load condition: combine the load according to the actual pipe load, such as pressure, temperature; (4) Harmonic analysis: call harmonic analysis module in CAESAR II software and enter the imbalanced excited force calculated from Eq. (4).

In order to verify the correctness of the numerical simulation method, this method is used to simulate a simple pipeline and is verified by indoor experiments. As shown in **Fig. 3**, the simple pipe models is divided into straight pipe section and elbow section, wherein the straight pipe section is 4.4 m long, and the angle of the elbow is set at 90 degree, 60 degree and 45 degree. The direction of fluid flow in the pipeline is from right to left. There are three clamped supported constraints in the pipeline, the specific parameters of the pipeline are shown in **Table 1**. The pump delivery pressure is 0.9 MPa, the transmission medium is water, the temperature is 15 degrees centigrade, the flow rate is 1283 L/h. Pipeline foundation model and constraint model can be seen in **Fig. 4**.

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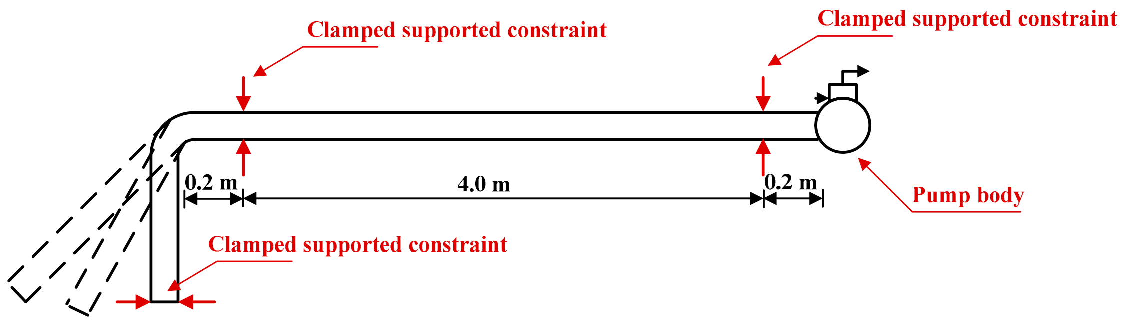
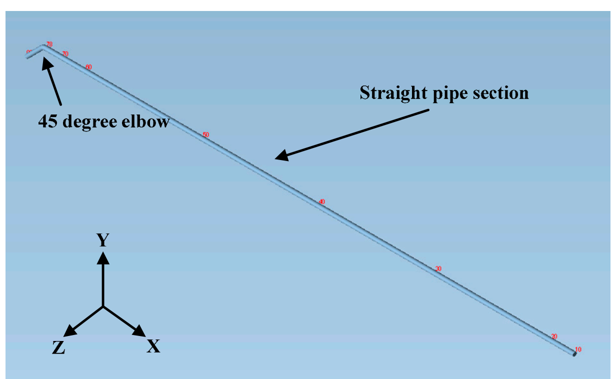
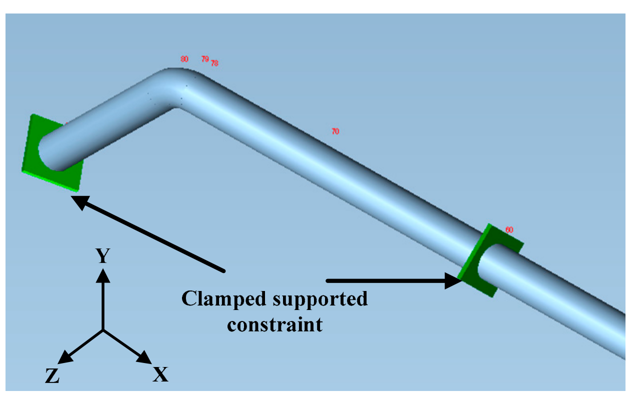


Figure 3: Schematic diagram of simple pipe model

Table 1: Pipeline material parameters and structural parameters

Items	Parameters	Straight pipeline	Elbow
Structural parameters	Outside diameter *D*	33.5 mm	33.5 mm
	Pipeline thickness *ξ*	2.5 mm	2.5 mm
	Curved radius of elbow *R*	/	120 mm
	Straight pipe length at both ends of the elbow *l*	/	340 mm
	Straight pipe length *L*	4000 mm	/
Material parameters	Pipeline material	Q235 galvanized pipe	
	Minimum yield strength	235 MPa	
	Modulus of elasticity *E*	206 GPa	
	Density *ρ*	7860 kg/m^3	
	Poisson ratio *ε*	0.3	





(a) (b)

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Figure 4: Pipeline foundation model and constraint model of the simple pipe established by CAESAR II software

The imbalanced excited force of the elbow is calculated as follows:

(1) Calculation of pressure pulsation

The pump revolution speed is 170 r/min, it belongs to single cylinder single-action equipment, and then the excited frequency is:

$$f = nNP/60 = 170 \div 60 = 2.83\text{Hz}$$

Circular frequency is: $\omega = 2\pi f = 2\times 3.14\times 2.83 = 17.77\text{rad}/s$

Sound velocity is: $c = \sqrt{\frac{E_{water}}{\rho}} = \sqrt{\frac{2.1\times 10^9}{1000}} \approx 1449.14\text{m}/\text{s}$

The distance from the starting point to the elbow is 4.4 m, and the total length of the pipe is 5 m. The pressure pulsation at different times of the elbow can be calculated based on **Eq. (3)**:

Make x=4.4 m, $t\in[0,200]$, n=1, then Eq. (3) can be written as:

$$p_\Delta(4.4,t) = \left[\frac{-2\times 0.9\times 10^6}{\pi}(\cos 5\pi l - 1)\cos 5.66\pi t + \frac{-2\times 0.56}{7245.7\pi^2}(\cos 5\pi - 1)\sin 5.66\pi t\right]\sin\frac{4.4\pi}{5}$$

The calculated pressure pulsation of the first 200 seconds can be seen in **Fig. 5**, it can be obtained that the maximum value of the pressure pulsation is 1031.00 Pa, and the minimum value of the pressure pulsation is -1030.71 Pa.

Then ΔP is:

$$\Delta P = 0.5(P_{\max} - P_{\min}) = 0.5\times(1031.00 + 1031.71) = 1031.36\text{Pa}$$

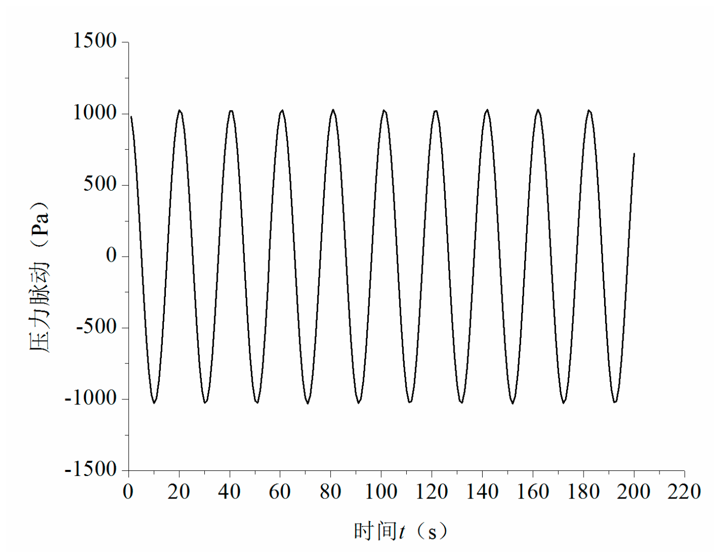


Figure 5: Pressure pulsation at the first 200 seconds of the elbow

According to **Eq. (4)**, imbalanced excited forces of 45 degree elbow, 60 degree elbow and 90 degree elbow are calculated:

45 degree elbow:

$$F = 2\times\Delta P\times S\times\sin\left(\frac{45}{2}\right) = 2\times 1031.95\times\frac{3.14\times 0.0285^2}{4}\times 0.3827 \approx 0.50\text{N}$$

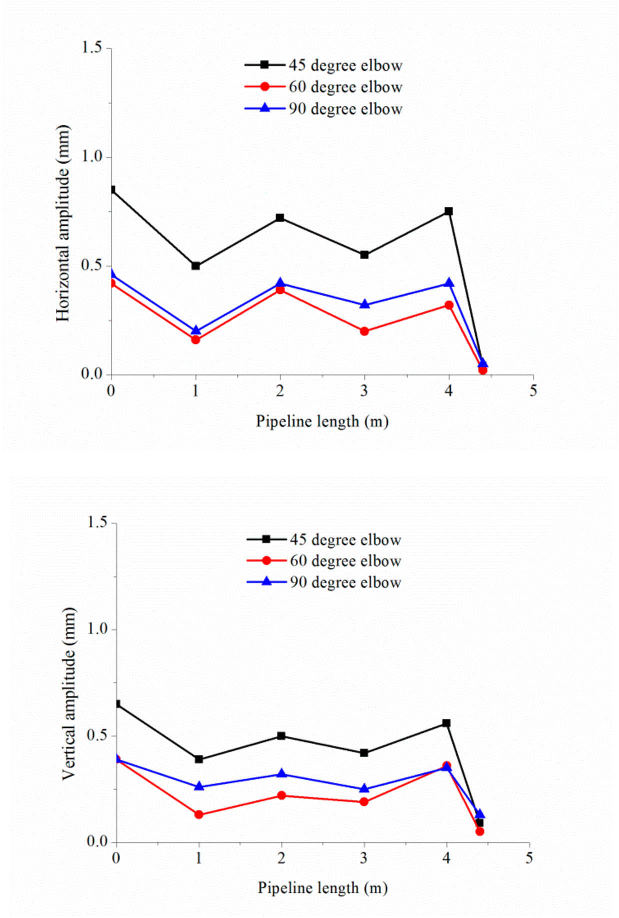
60 degree elbow:

$$F = 2\times\Delta P\times S\times\sin\left(\frac{60}{2}\right) = 2\times 1031.95\times\frac{3.14\times 0.0285^2}{4}\times 0.5 \approx 0.66\text{N}$$

90 degree elbow:

$$F = 2\times\Delta P\times S\times\sin\left(\frac{90}{2}\right)=2\times1031.95\times\frac{3.14\times0.0285^2}{4}\times0.707\approx0.93\text{N}$$

The calculated imbalanced excited force is loaded onto the pipe, and the horizontal and vertical amplitudes are computed by CAESAR II software. The results are shown in **Fig. 6**.



(a) (b)

Figure 6: Horizontal and vertical amplitudes of pipelines with different elbow degrees (a) Horizontal amplitude (b) Vertical amplitude

3.2 Experimental verification of numerical simulation method

In order to verify the correctness of the numerical simulation method, an indoor experimental system is established according to the simple pipeline model used in numerical simulation. The experimental system is mainly composed of four subsystems, such as power unit, loop circuit, experimental platform and signal acquisition and analysis system. The main structure and composition are shown in **Fig. 7**.

As shown in **Fig. 7**, the straight pipe is connected with the elbow, and the axis of the straight pipe and the elbow are in the Z-Y plane. The piston pump provides pulsating flow at different flow rates and pressures for the entire experimental system, the signal acquisition and analysis system (including strain gauges, acceleration and displacement sensors) measures the different test points of the test section under each operating condition.

There are three different elbow structures in the experiment: the elbow angles are 45 °, 60 °, and 90 °, respectively. The inlet end of straight pipe and outlet end of elbow are connected by flexible hose with inner diameter 25 mm, and fastened through the clamp. The fixed straight pipe section is

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connected with the two ends of the elbow through rigid band joints, so as to replace the elbow with different angles (As a result of the use of flexible hose, metering pump water flow will lead to flexible hose vibration, this vibration is inevitably passed to the test straight pipe, which belongs to the external excitation load, bring certain influence for the straight section of the test data).

The experimental principle as shown in **Fig. 7**, the elbow of test section is connected to a JD-1350/1.6-type plunger metering pump (pump maximum flow rate is 1350 L/h, the measurement accuracy is ±1%); the maximum pumping pressure is 1.6 MPa (Accuracy is ±3%); the metering valve range is 1-100 mm (Adjustment accuracy is 95%). The water flow through the metering pump from the water tank, through the LWGY-32 type turbine flow sensor (Accuracy is ±0.5%R), YB-2088 type pressure transmitter (Accuracy is ±0.5%FS), transitional straight pipe with a length of 4 m (The material is the same as the elbow), elbow of test section, throttle valve and DN32 type rubber pressure-resistant steel pipe, then the water back to the water tank.

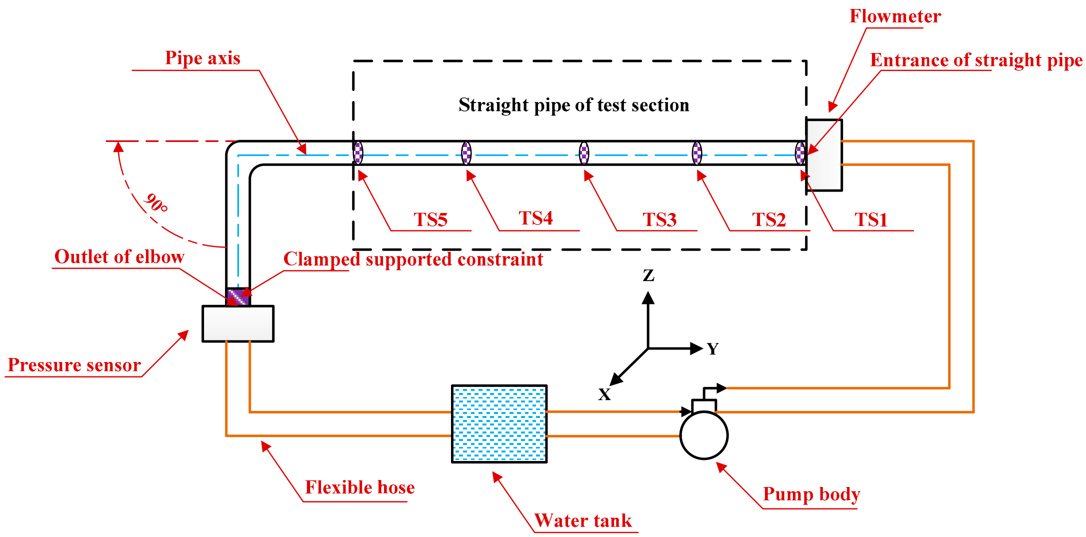

Figure 7: Schematic diagram of experiment

A flat steel plate with a format of 40 mm×40 mm×1 mm was mounted on the upper side of the pipe. Obtaining acceleration and displacement of elbow from measuring the steel plate's acceleration and displacement using the piezoelectric three-way acceleration sensor (Measuring accuracy is ±1%, frequency response is 1-5 kHz) which fixed to two test surfaces and the non-contact eddy current displacement sensor (Measuring accuracy is ±1%, frequency response is 0-10 kHz) which parallel to the two test surfaces.

The output flow of piston pump has obvious regular pulsation, in order to avoid the non-real-time synchronization acquisition of the data, the TST5912 dynamic signal test and analysis system and the TST3826F dynamic and static strain test system were used to simulate the acceleration, displacement, stress and strain of different measuring points. Piston metering pump in the supply of pulsating flow will produce a certain degree of fluctuations due to pressure, flow changes. In the meantime, there will be varying degrees of air in the test pipe section, which will also affect the experimental results. Therefore, in each case, when the working condition is stable, the continuous data collection is carried out for a certain period of time, and the data collected in each working cycle are compared and screened to ensure that the data is true and effective.

The test pipe is equipped with acceleration sensors, and there are six measuring points. The measuring points 1, 2, 3, 4 and 5 (Denoted as TS1, TS2, TS3, TS4 and TS5) are on the straight pipe, and the measuring point 3 is the middle measuring point on the straight pipe. Clamped supported constraints of straight pipe section and elbow section (Take 60 degree elbow for instance) can be seen in **Fig. 8**. As shown in **Fig. 9**, the test straight pipe section is 4 m, and a measuring point is added every 1 m. There is only one measuring point at the bend, as shown in **Fig. 10**.

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(a)

(b)

Figure 8: Physical map of clamped supported constraints (a) Straight pipe section (b) Elbow pipe section

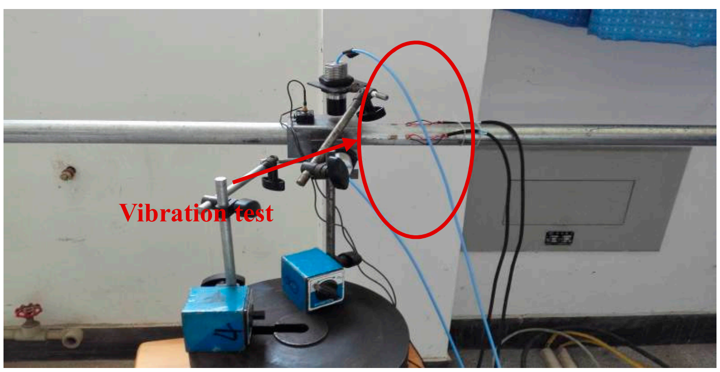

Figure 9: Physical map of pipe vibration test device in straight pipe section

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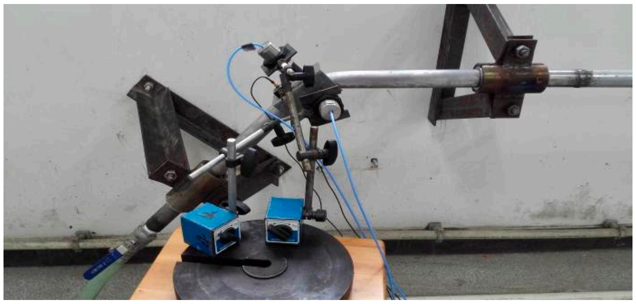

Figure 10: Physical map of pipe vibration test device in elbow section

The experimental conditions are shown in **Table 2**, before the experiment, the acceleration, displacement sensors, flowmeter and pressure sensors should be corrected. Mark the straight pipe measuring points and stick the strain gauges (Its quality is small and light, it will not affect the actual movement of the pipe). Before starting the pump test, adjust the flow and pressure corresponding to each condition (Flow control through the flow meter, control valve to achieve the required pressure value).

Table 2: Experiment conditions

Maximum outlet pressure *P* (MPa; ±5%)	Elbow angle (Degree)	Average flow rate *Q* (L/h; ±2%)	
0.9	45	1080	1283
	60	1080	1283
	90	1080	1283
1.2	45	1080	1283
	60	1080	1283
	90	1080	1283
1.4	45	1080	1283
	60	1080	1283
	90	1080	1283

The horizontal and vertical amplitudes test results of the pipeline are shown in **Fig. 11**. The relative error of the experimental and numerical simulation results are shown in **Fig. 12**. From **Fig. 12**, it can be concluded that the relative error of the horizontal amplitude range is -13.04%~8.70%, and the relative error range of the vertical amplitude is -13.33%~8.33%. Based on the above results, the relative error is within the acceptable range, indicating that the numerical simulation method described in section 3.1 is more feasible.

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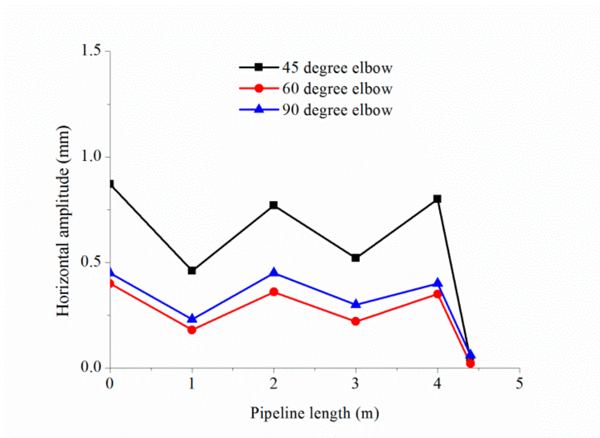

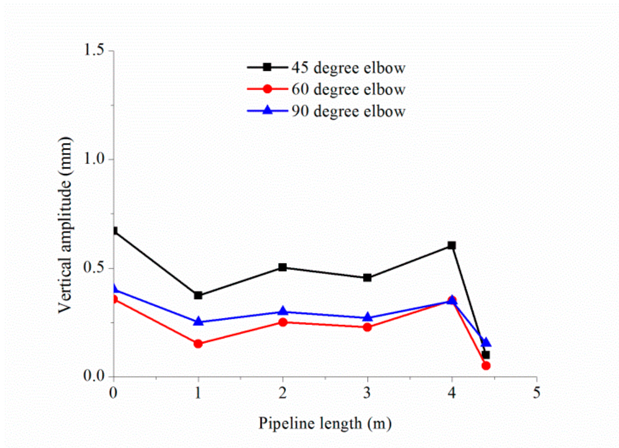

(a) (b)

Figure 11: Vibration test results of pipeline (a) Horizontal amplitude (b) Vertical amplitude

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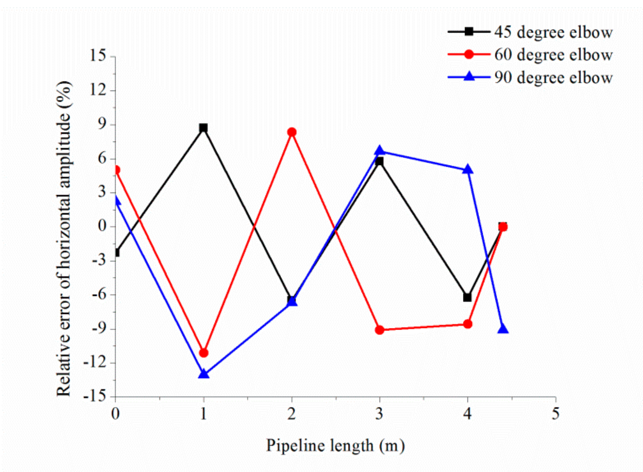

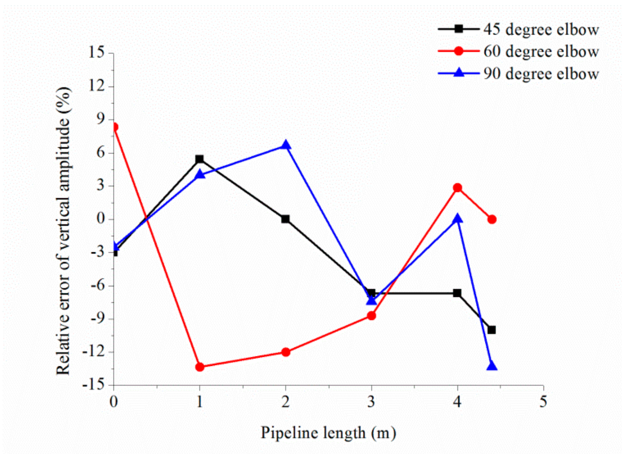

(a) (b)

Figure 12: Relative error of the experimental and numerical simulation results (a) Horizontal amplitude (b) Vertical amplitude

4. Case study

4.1 Project overview

In this paper, FC oil station as an example for the practical application. The station mainly includes pigging area, storage area and transmission area. As the reciprocating pump is located in the transmission area, the pipelines in the transmission area is the object of the study.

Transmission area mainly includes three kinds of equipment: reciprocating pump (piston pump), centrifugal pump and separator. Moreover, this area includes five kinds of pipelines: Main inlet pipe, main outlet pipe, sewage pipe, pump inlet pipe and pump outlet pipe. The density of crude oil is 900 kg/m^3, and the coefficient of elasticity of the oil at the transportation temperature is 2190 MPa. The distribution of the pipelines is shown in **Fig. 13**, in which the sewage pipe, the main inlet pipe and the main outlet pipe are all buried. The specific pipe parameters are shown in **Table 3**, and the soil parameters are shown in **Table 4**.

Before the vibration analysis of the pipelines in the transmission area, the cause of the vibration should be clarified first. One is directly caused by the pump, the other is the vibration caused by the pressure pulsation. Through field investigation, the pump foundation is rammed with reinforced concrete, the rigidity is large, and the pump foundation is connected with the pump body firmly. After examination, no abnormal phenomena such as loosening of anchor bolts have been found. With vibration instrument and hand inspection, the pump runs smoothly and the vibration is very small.

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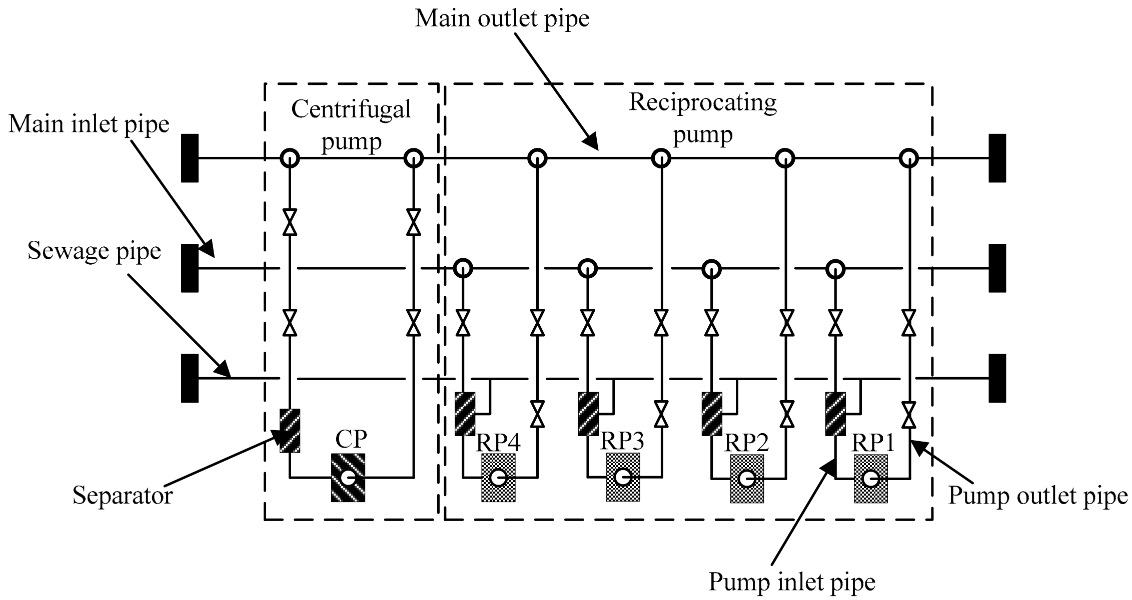
296 It is clear that the vibration caused by pump (motor) is not the cause of pipe vibration, but it is clear
297 that the object of this paper is the vibration caused by pipe pressure pulsation.



298
299 Figure 13: Sketch map of pipeline distribution in the transmission area (Note: RP represents the
300 reciprocating pump, CP represents centrifugal pump)

301 Table 3: Parameters of pipelines in transmission area

Items	Main inlet pipe	Main outlet pipe	Sewage pipe	Pump outlet pipe (Reciprocating pump)	Pump inlet pipe (Reciprocating pump)
Diameter (mm)	355.6	559	89	273	323
Thichness (mm)	9.5	5.2	4	7.8	5.2
Insulation thickness (mm)	60	60	/	60	60
Pipe material	X65	X65	20# steel	X65	X65
Medium density in pipe (kg·m^{-3})	900	900	/	900	900
Regional level			Level 2		
Pipe installation temperature (℃)	10	10	10	10	10
Operating temperature (℃)	95	95	/	95	95
Operating pressure (MPa)	1.6	8	/	8	1.6

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Table 4: Soil parameters

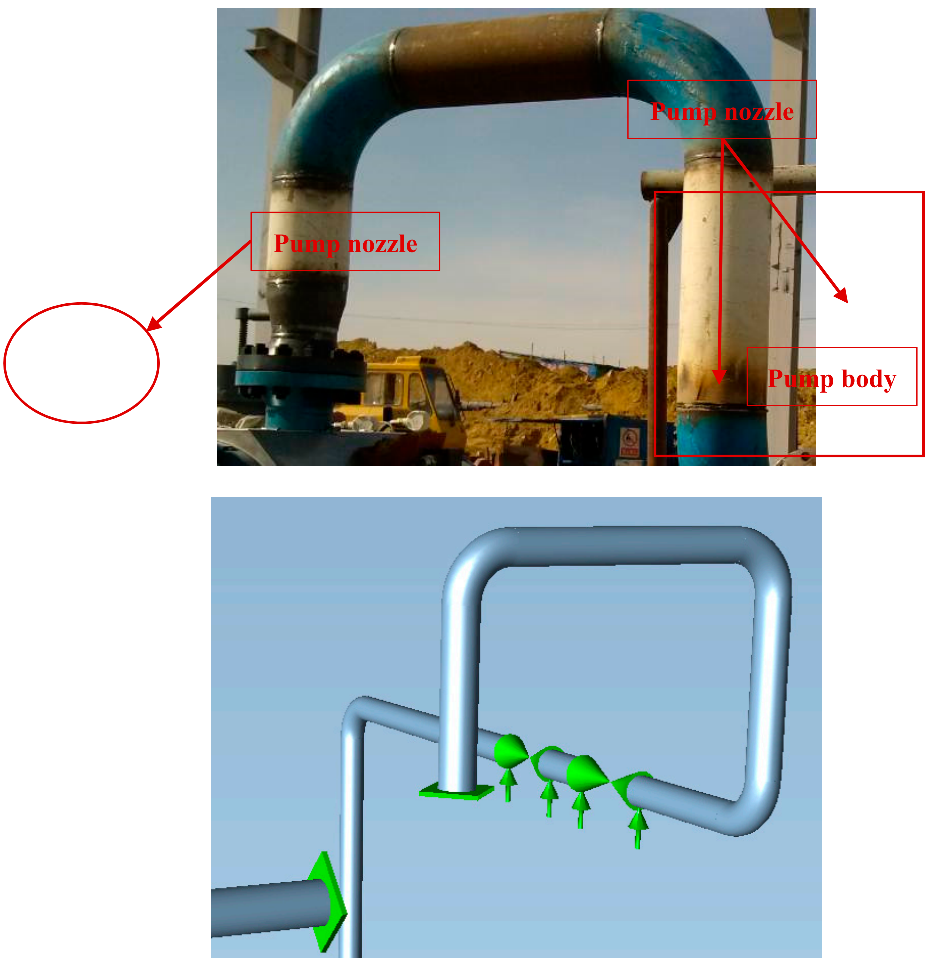
Soil properties	Clay
Soil density (kg/m^3)	2000
Soil friction angle (Degree)	22
Cohesion (kPa)	50
Overburden compaction multiplier	3
Buried depth (m)	1~2.5

4.2 Constraint models of pipeline

According to the field investigation, the pipeline constraints mainly include: Pump nozzle, valve, flange, valve seat, soil.

(1) Pump nozzle

The nozzle and the equipment are connected by flanges. Usually the pump flange is used as a fixed point analog (Anchor), which means that the line displacement and angular displacement in the three directions are all bound, and the constraint can be applied to the nozzle without displacement. Usually, the pump flange is modeled as a fixed point (Anchor), which means that the line displacement and angular displacement in the three directions are all bound, and the constraint can be applied to the nozzle without displacement, as shown in **Fig. 14**.



(a) (b)

Figure 14: Pump nozzle (a) Physical map (b) Numerical simulation model in CAESAR II software

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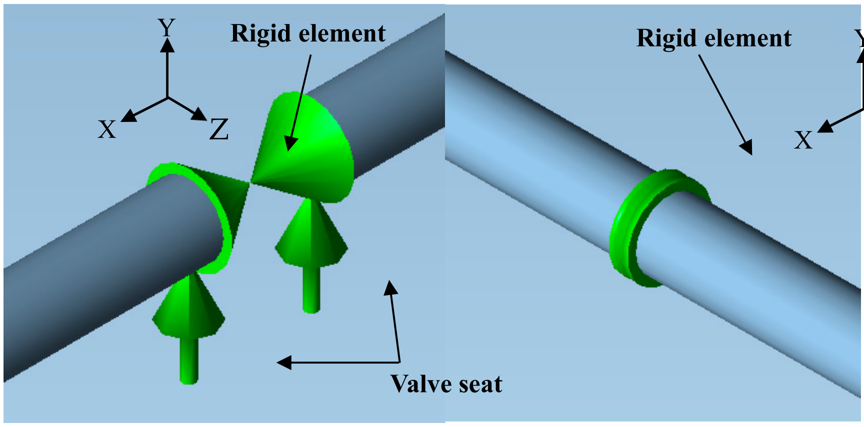
(2) Valve and flange

Due to the large rigidity of the valves and flanges on the pipes, it is generally considered that they do not deform in the mechanical analysis and often represent a concentrated mass, so the model can be simplified by rigid elements, as shown in **Fig. 15**. According to the type of valve and flange, find the corresponding weight in the corresponding standard or sample, and enter the model. If its stiffness and mass can not be determined, the stiffness can be taken in accordance with the 10 times the thickness of the nozzle, concentrated quality can be taken in accordance with 1.75 times "weight + medium weight + insulation layer weight".

(a)



(b) (c)

Figure 15: Rigid element (a) Physical map of flange (b) Numerical simulation model of valve in CAESAR II software (c) Numerical simulation model of flange in CAESAR II software

(3) Valve seat

The valve seat is equivalent to the load bearing bracket, which is a rigid, one point on the lower part of the pipe, only used to block the downward displacement of the pipe. In CAESAR II, the +Y is represented as a unidirectional upward constraint, indicating that the binding force acts in the +Y direction of the pipe. As the pipe moves relative to the structure, a friction model must be established, in which the direction of the friction force is the same as the direction of the pipe movement, as shown in **Fig. 15 (b)**. The coefficient of friction is defined between the valve seat and the valve, for the contact between steel and steel, the coefficient of friction is 0.3.

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(4) Four-directional guide

Four-directional guide is usually used in the oil station to limit the displacement of the pipe in the horizontal and vertical directions. It has a good effect on the control vibration. Same as the one-way constraint, the friction coefficient is defined when the constraint is set, as shown in **Fig. 16**.

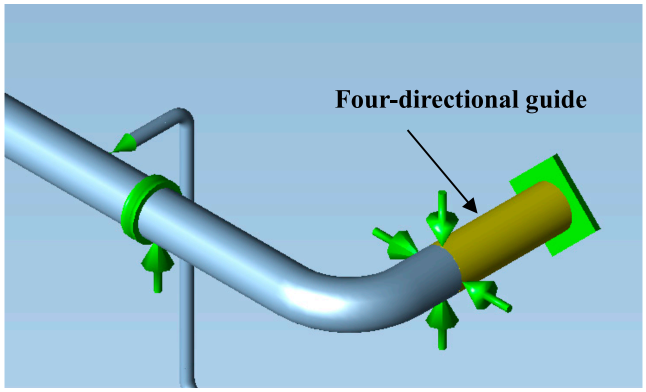

Figure 16: Numerical simulation model of our-directional guide in CAESAR II software

(5) Soil

ALA model was used in soil section, practical content can be found in reference [16].

4.3 Pipeline overall model

The overall model of FC oil station can be seen in **Fig. 17**, and partial magnification can be seen in **Fig. 18**.

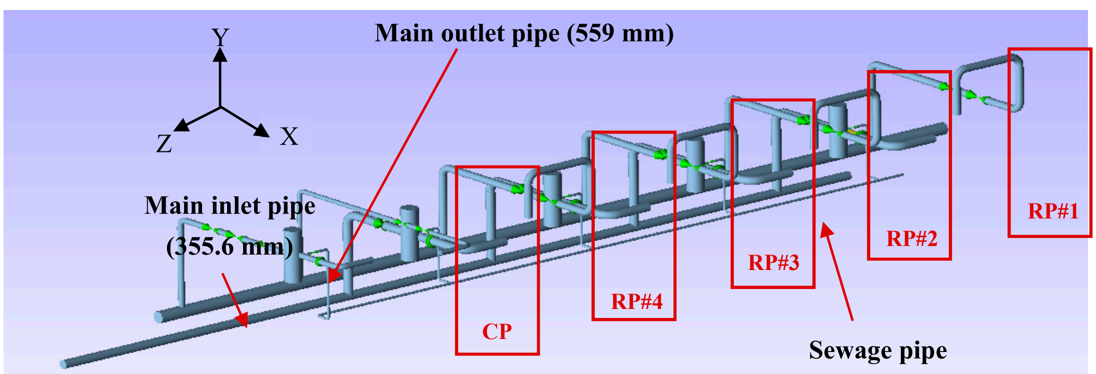

Figure 17: Overall model of pipelines and equipment of transmission area

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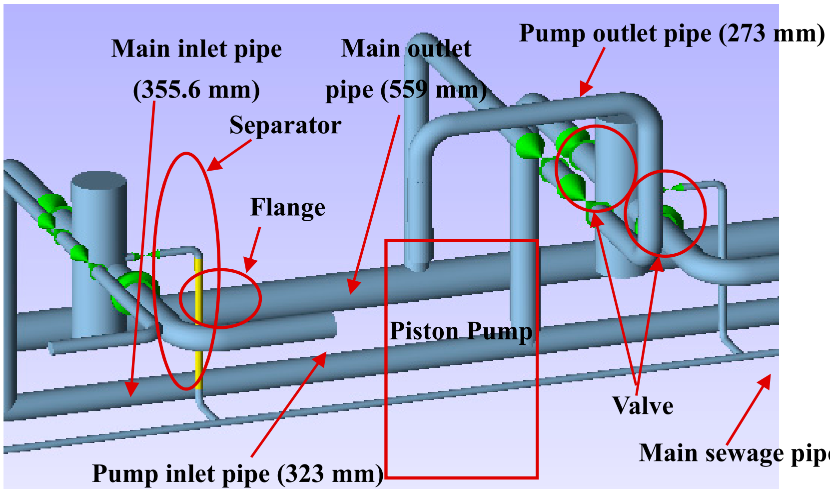

Figure 18: Partial magnification model

4.4 Action location and calculation result of imbalanced excited force

The calculation results of the imbalanced excited force of the RP1 pump outlet pipe and the pump inlet pipe at the elbow and tee are shown in **Table 5**. The location of the imbalanced excited force is shown in **Fig. 19**.

Table 5: Calculation results of imbalanced excited force of RP1 pump pipe

Pipe type	Location	Pressure pulsation ΔP (Pa)	Imbalanced excited force (N)	Direction	Phase angle (degree)
Pump outlet pipe	RP1-B1	14885.64	1094.09	Y	0
	RP1-B2	43780.53	-3217.87	Z	3.05
	RP1-B3	67202.83	-4939.41	Y	5.52
	RP1-B4	146123.10	-10740.05	X	14.21
Main outlet pipe	T1	184644.40	-13571.36	Y	18.64
Pump inlet pipe	RP1-B5	2874.95	310.49	Z	0
	RP1-B6	15768.83	-1703.03	X	6.72
Main inlet pipe	T2	23691.54	-2558.69	Y	11.29

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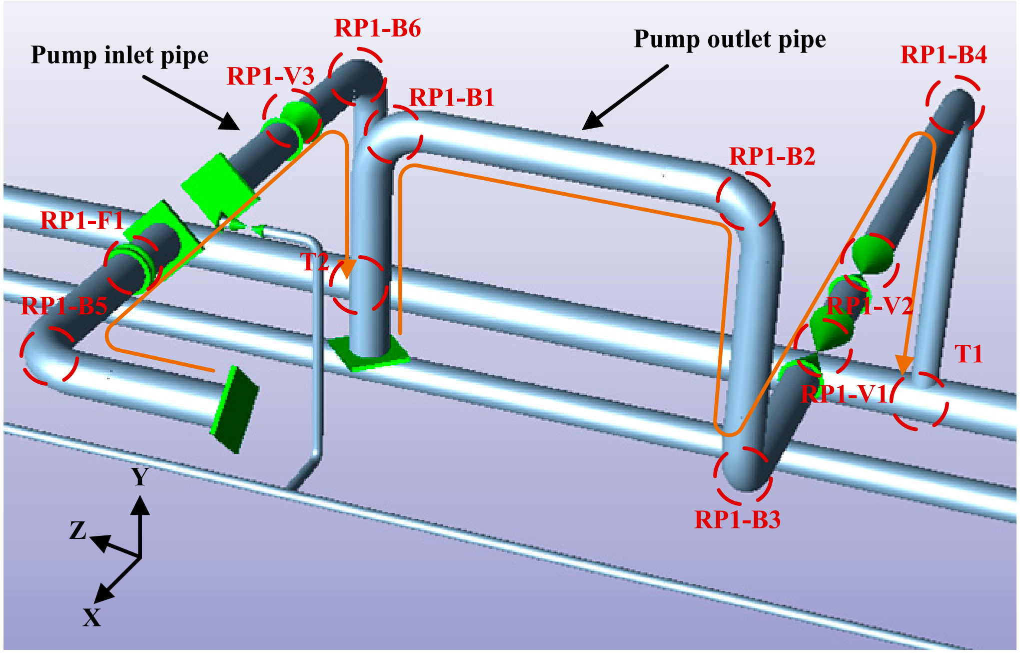


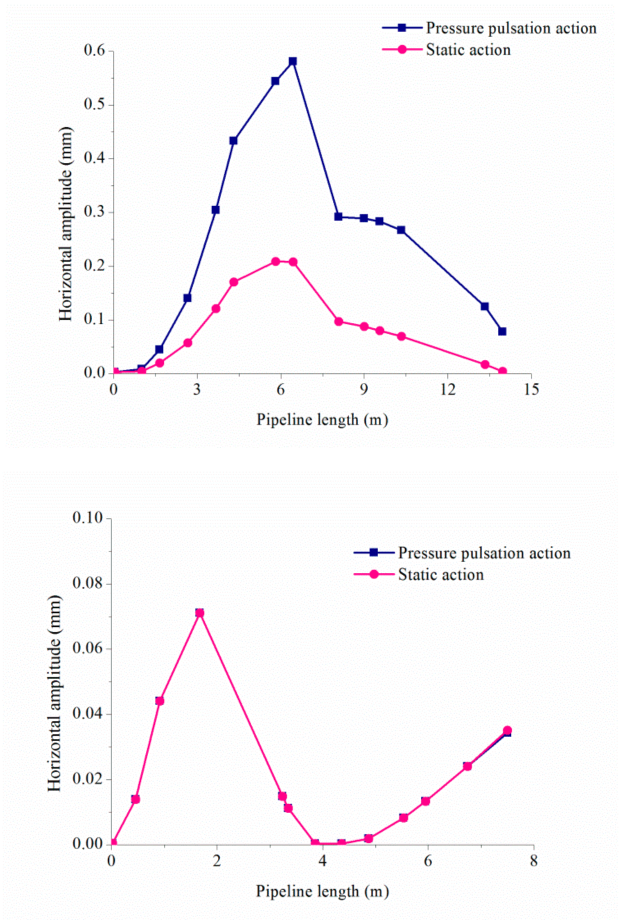
Figure 19: The location of the imbalanced excited force

5. Results

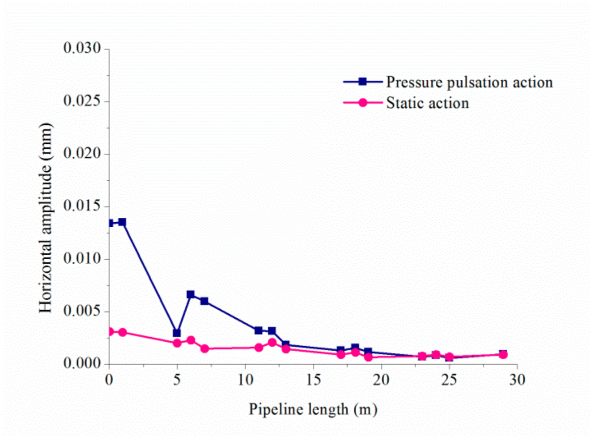
In order to study the influence of pressure pulsation on the pipeline, this paper analyzes two working conditions: (1) RP1 pump runs separately; (2) RP1 and RP2 run together.

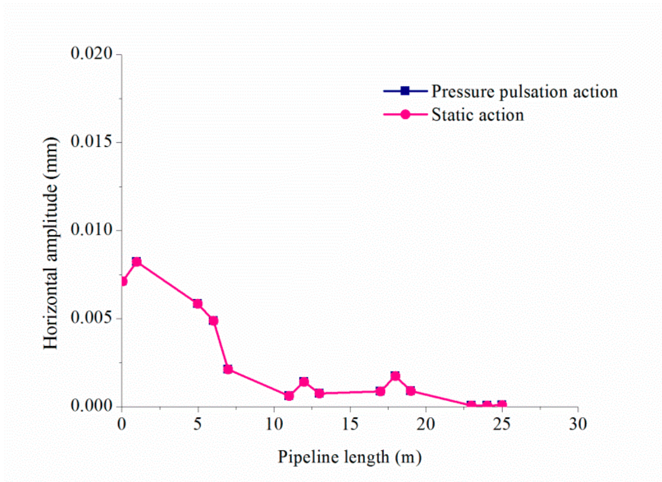
5.1 RP1 pump runs separately

Fig. 20 and **Fig. 21** show the maximum amplitudes of the horizontal and vertical directions of each pipe, and **Table 6** shows the summary of the maximum amplitude and location.


Pressure pulsation action
Static action
Horizontal amplitude (mm)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
3
6
9
12
15
Pipeline length (m)
Pressure pulsation action
Static action
Horizontal amplitude (mm)
0.00
0.02
0.04
0.06
0.08
0.10
0
2
4
6
8
Pipeline length (m)

(a) (b)





(c) (d)

Figure 20: Horizontal amplitude of pipes (a) RP1 pump outlet pipe (b) RP1 pump inlet pipe (c) Main outlet pipe (d) Main inlet pipe

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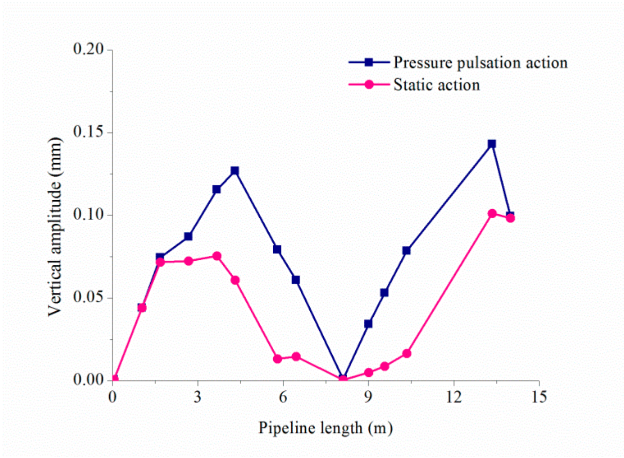

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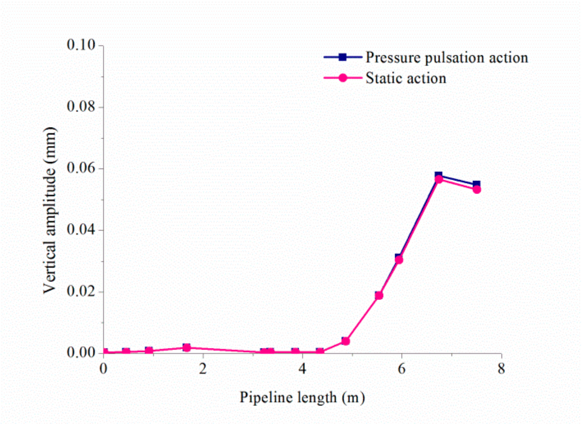

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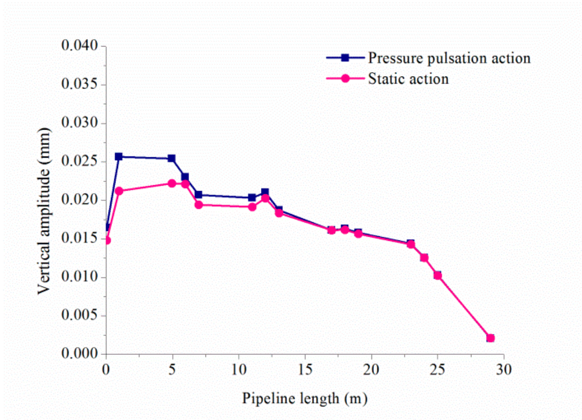
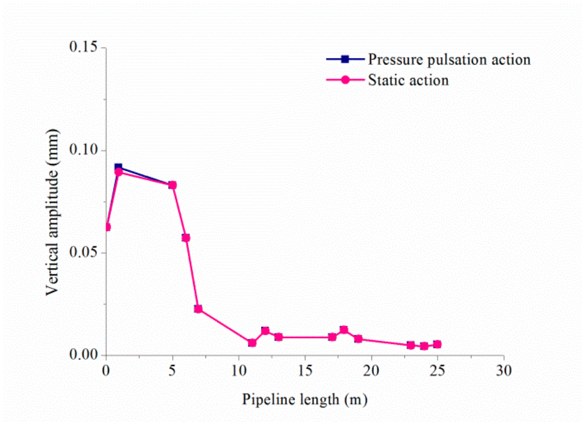
379 (a) (b)





(c) (d)

Figure 21: Vertical amplitude of pipes (a) RP1 pump outlet pipe (b) RP1 pump inlet pipe (c) Main outlet pipe (d) Main inlet pipe

Table 6: Summary of the maximum amplitude and location

Pipeline type	Horizontal direction		Vertical direction	
	Amplitude (mm)	Location	Amplitude (mm)	Location
RP1 pump outlet pipe	0.58	RP1-B3	0.14	RP1-B4
RP1 pump inlet pipe	0.07	RP1-B5	0.06	RP1-B6
Main outlet pipe	0.01	T1	0.03	T1、T3 中部
Main inlet pipe	0.008	T2	0.09	T2

It can be concluded from **Table 6** that the maximum horizontal or vertical amplitude of each pipe is mostly produced in the elbow and tee, and the horizontal amplitude of the elbow is larger than the vertical amplitude. However, the vertical amplitude is greater than the horizontal amplitude at the tee of the straight pipe section. In addition, the following conclusions can be obtained:

(1) Imbalanced excited force has a great influence on the vibration of the pump outlet pipe (The amplitude increases by 5%~140%) and the main outlet pipe (The amplitude increases by 5%~360%), and has little influence on the vibration of the pump inlet pipe (The amplitude increases by 1%~10%).

(2) Although the imbalanced excited force is generated at the elbow, the vibration of the straight pipe is affected in varying degrees (rise).

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5.2 RP1 and RP2 run together

Table 7 shows the summary of the maximum amplitude and location.

Table 7: Summary of the maximum amplitude and location

Pipeline type	Horizontal direction		Vertical direction	
	Amplitude (mm)	Location	Amplitude (mm)	Location
RP1 pump outlet pipe	0.40	RP1-B3	0.12	RP1-B4
RP1 pump inlet pipe	0.07	RP1-B5	0.06	RP1-B6
RP2 pump outlet pipe	0.67	RP2-B3	0.15	RP2-B4
RP2 pump inlet pipe	0.07	RP2-B5	0.06	RP2-B6
Main outlet pipe	0.01	T3	0.03	T3
Main inlet pipe	0.01	T2	0.09	T2

According to **Table 6** and **Table 7**, the situations of single pump operation and double pumps operation are compared, the main conclusions are as follows:

(1) In the case of double pump operation, the maximum horizontal amplitude and vertical amplitude of the RP1 pump outlet pipe are significantly lower than those of the case of RP1 single pump operation (The horizontal amplitude decreases by about 31%, and the vertical amplitude decreases by about 15%), the change of horizontal amplitude and vertical amplitude of the RP1 pump inlet pipe is not obvious, and the amplitude of RP2 pump outlet pipe is higher than that of RP1 pump in all directions.

(2) Whether the single pump operation or multi pump operation, the pump outlet pipe has the largest amplitude, so the focus of the vibration reduction study is pump outlet pipe.

6. Discussions

In this paper, several factors influencing the vibration of the pipeline are analyzed: flow, pressure, temperature, crude oil density and foundation settlement, and the measures of vibration reduction are put forward.

6.1 Flow rate

The flow fluctuation will be occurred during the reciprocating pump operation, according to the testing data of FC oil station, flow rate of single pump is 220 m^3/h, and the minimum flow rate is 71.4% of the normal pump output, that is, 157.08 m^3/h. Therefore, take the RP1 pump outlet pipe as an example, the vibrations of pipe in the case of flow rate from 150 m^3/h to 220 m^3/h are discussed. The results can be seen in **Table 8**.

Table 8: The maximum amplitudes of RP1 outlet pipe at different flow rates

Flow rate (m^3/h)	Horizontal vibration		Vertical vibration	
	Amplitude (mm)	Location	Amplitude (mm)	Location
150	0.572	RP1-B3	0.136	RP1-B4
160	0.573		0.136	
170	0.573		0.136	
180	0.575		0.137	
190	0.576		0.138	
200	0.577		0.139	
210	0.579		0.139	
220	0.580		0.140	

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It can be concluded from **Table 8** that: The flow rate change of the reciprocating pump has little effect on the amplitude of the pipe.

6.2 Pressure

The actual operation pressure of the pipeline is lower than the design pressure, and the regulation of pressure is frequency conversion control. For the FC oil station, when the pump outlet manifold pressure is higher than 7.04 MPa, the reflux valve opens; when the pump outlet manifold pressure is higher than 8 MPa, the oil pump automatically stops. Therefore, the vibrations of pipe in the case of pressure from 6.0 MPa to 8.0 MPa are discussed. The results can be seen in **Table 9**. From Table 9, it can be concluded that the horizontal amplitude and vertical amplitude increase with the increase of pressure.

Table 9: The maximum amplitudes of RP1 outlet pipe at different pressures

Pressure (MPa)	Horizontal vibration		Vertical vibration	
	Amplitude (mm)	Location	Amplitude (mm)	Location
6.0	0.517	RP1-B3	0.127	RP1-B4
6.5	0.527		0.130	
7.0	0.535		0.135	
7.5	0.575		0.137	
8.0	0.580		0.140	

6.3 Temperature

Because FC oil station transports heavy oil, the oil temperature is higher (up to 95℃), in order to explore the influence of temperature on the pipeline vibration, the vibrations of pipe in the case of temperature from 25℃ to 95℃ are discussed. The results can be seen in **Fig. 22**.

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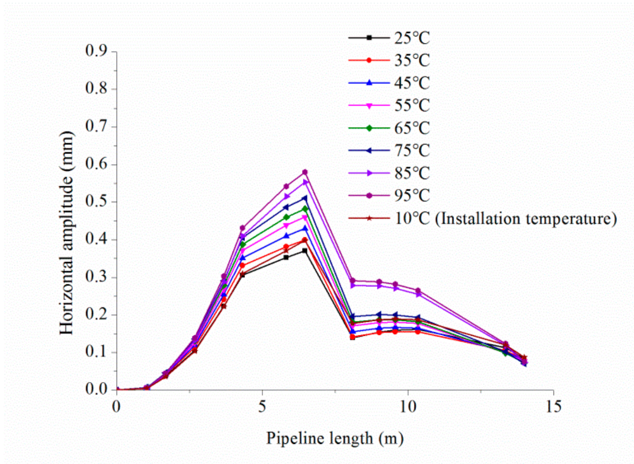

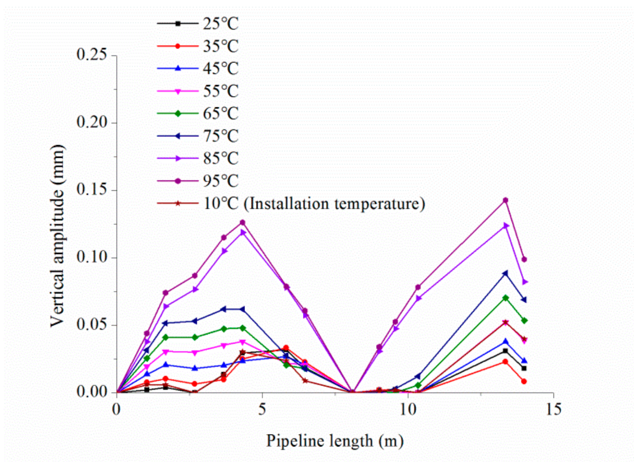

(a) (b)

Figure 22: Amplitude distribution of RP1 pump outlet pipe at different temperatures

As shown in **Fig. 22**, with the increase of temperature, the horizontal amplitude of pipeline (95 ℃ and 10℃ compared) increased by about 64%, the vertical amplitude increased by 2729%, and when the temperature is higher than 85℃, the influence of temperature on the vertical amplitude has improved significantly.

6.4 Crude oil density

According to the design data, the crude oil density of FC oil station is in the range of 850-950 kg/m^3, and the influence of crude oil density on pipeline vibration is discussed.

As shown in **Table 10**, the maximum horizontal amplitude and vertical amplitude increase with the increase of crude oil density, but the change is little, which shows that the density of crude oil has little influence on the vibration of reciprocating pump pipes.

Table 10: Maximum amplitudes of RP1 outlet pipe at different crude oil densities

Crude oil density (kg/m^3)	Horizontal vibration		Vertical vibration	
	Amplitude (mm)	Location	Amplitude (mm)	Location
850	0.577	RP1-B3	0.139	RP1-B4
900	0.580		0.140	
950	0.585		0.143	

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6.5 Foundation settlement

Many pipelines are laid on soft soils. The foundation has a low bearing capacity and a large deformation after loading. It is easy to make the pipeline to be cracked, twisted or inclined due to foundation settlement. In this paper, the foundation settlement of the pump outlet pipe is discussed. There are two possible locations for foundation settlement: fulcrum 1 and fulcrum 2

This paper discusses the pump outlet pipe to produce fulcrum foundation settlement situation, there may be two places of settlement: fulcrum 1 and fulcrum 2 (as shown in **Fig. 23**), are the valve seat on the pipeline. The operation conditions of foundation settlement can be seen in **Table 11**, and the settlement is assumed to be 3 cm.

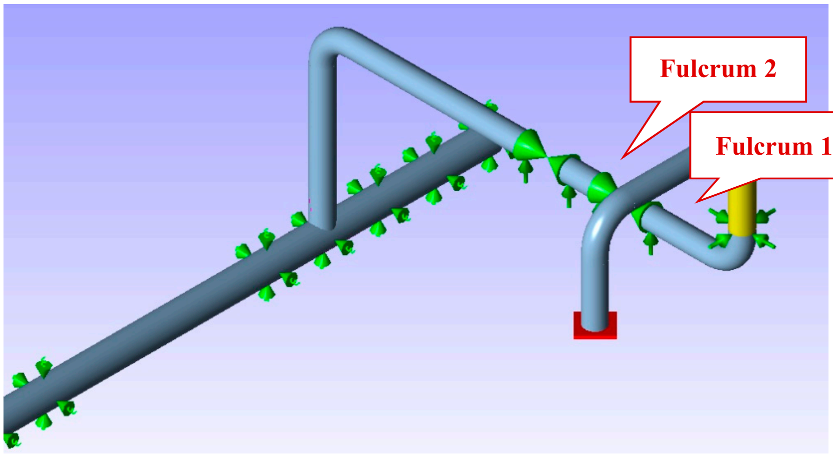

Figure 23: Foundation settlement locations

Table 11: Operation conditions of foundation settlement

Operation conditions	Description
1	Fulcrum 1 settlement
2	Fulcrum 1 and the fulcrum 2 all have settlement
3	Fulcrum 2 settlement
4	Fulcrum 1 and the fulcrum 2 are free of settlement

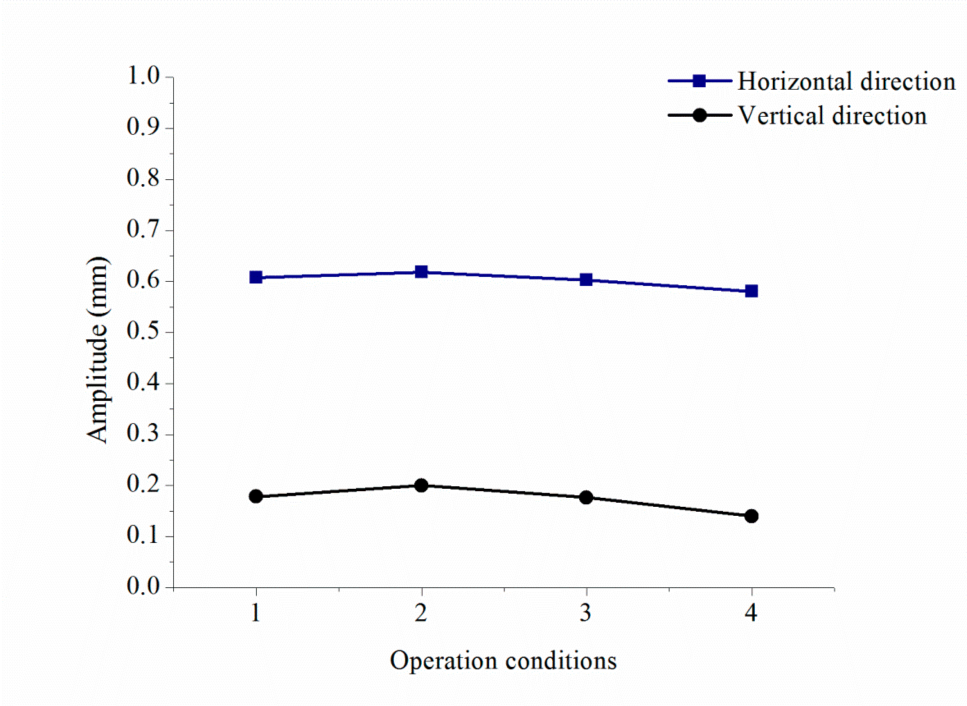

Figure 24: Horizontal and vertical amplitudes of four settlement conditions

It can be seen from **Fig. 24**, the amplitude of the condition 2 is the maximum in the four conditions, and the increase is obvious. The amplitude of the condition 1 is larger than that of the condition 3, indicating that the settlement of the fulcrum 1 is more dangerous in the case of a single fulcrum settlement. In actual engineering, the fulcrum 1 and fulcrum 2 should be prevented from settling at the same time.

6.6 Vibration reduction measures

In engineering, vibration reduction can be achieved by increasing the rigidity of the pipeline. The greater the rigidity, the higher the natural frequency of the pipe, the less likely it is to cause resonance. Usually, four-directional guide are added in the vicinity of the elbow. Therefore, considering the eight locations of constraints added to the pump outlet pipe, as shown in **Fig. 25**, the natural frequency is calculated. The analysis results are shown in **Table 12**.

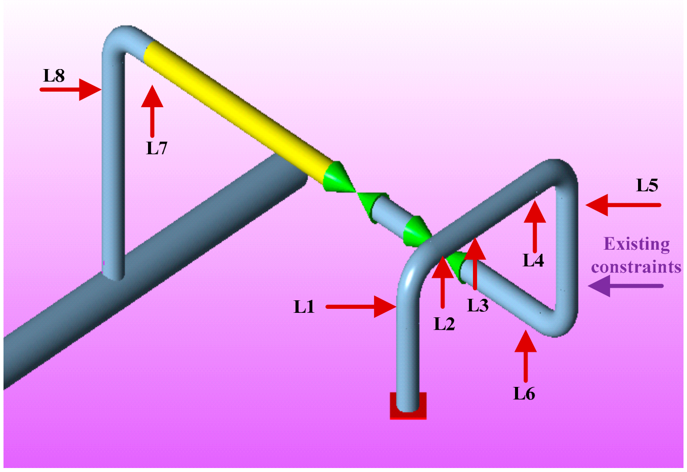

Figure 25: Eight locations of constraints added to the pump outlet pipe

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Table 12: First order natural frequency of the pump outlet pipe after the constraint is added

Location of the constraint	First order natural frequency (Hz)
L1	6.97
L2	6.98
L3	6.99
L4	7.00
L5	7.02
L6	7.29
L7	10.76
L8	9.75

As can be seen in **Table 12**, adding the four-directional guide to the L7 position improves the first order natural frequency of the pump outlet pipe preferably, so when the pipeline is modified, the four-directional guide may be added to the L7 position. At the same time, evaluate the amplitude of pipe after L7 after the constraint is added, the maximum amplitude decreased from 0.58 mm to 0.27 mm, the maximum amplitude of the horizontal direction decreased from 0.14 mm to 0.04 mm. Therefore, the addition of four-directional guide at L7 location can effectively reduce the pipeline vibration amplitude. Since there is only one elbow in the vicinity of the L7 location and the constraint is less, it can be deduced: The restraint can be greatly reduced by adding constraints to the long straight pipe with few bends and few constraints.

7. Conclusions

(1) Maximum horizontal or vertical amplitude of each pipe is mostly produced in the elbow and tee, imbalanced excited force has a great influence on the vibration of the pump outlet pipe and the main outlet pipe. Although the imbalanced excited force is generated at the elbow, the vibration of the straight pipe is affected in varying degrees.

(2) The flow rate change of the reciprocating pump and the density of crude oil have little effect on the amplitude of the pipe. Horizontal amplitude and vertical amplitude increase with the increase of pressure. When the temperature is higher than 85℃, the influence of temperature on the vertical amplitude has improved significantly.

(3) In actual engineering, it should be possible to prevent the simultaneous settlement of multiple places.

(4) The restraint can be greatly reduced by adding constraints to the long straight pipe with few bends and few constraints.

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