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Research Article

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Stress analysis of reciprocating pump pipeline system in oil station

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ABSTRACT

The strong vibration of reciprocating pump in oil transportation station pipeline system will seriously affect the safe running of the equipment and pipeline. And the resonance between pipe and equipment will cause more severe damage. Therefore before the formal operation of station, not only static stress analysis, but also modal analysis and vibration analysis are necessary for the reciprocating pump pipeline system. The analysis method using CAESAR II software pipeline system for numerical simulation of the reciprocating pump XX pump station can provide reference for designers and can be used to determine the type and location of pipeline constraints and consequently reduce vibration damage.

Key words: Oil station; Pipeline; static Stress analysis; Modal analysis; Vibration analysis; CAESAR II

INTRODUCTION

Reciprocating pump is one of the most important equipment in oil transportation station. For the reciprocating pump, whether the pipeline structure or oil medium system, they all belong to elastic vibration system. The elastic vibration system will vibrate when it is exposed to exciting force. When the exciting frequency is within the scope of natural frequency of the pipeline system, resonance of the equipment and pipelines happens, which results in severe damage for equipment and pipelines fittings, even out of service for equipment in oil station.

Numerous domestic researchers have performed the analysis on the reciprocating pump system in following aspects: the reasons of resonance, the vibration analysis and calculation, and vibration elimination approaches. The stress analysis technology of long distance oil pipeline is close to mature; however, the stress analysis-based study about the pipeline vibration of the reciprocating pump is almost blank. In this paper, CAESAR II is applied to analyze the static stress, modal and vibration of pipeline systems of reciprocating pump in oil transportation station, which aims to provide standardized design idea for pipeline systems, and guarantee the safety running of equipment and pipelines in oil transportation station [1-8].

METHOD

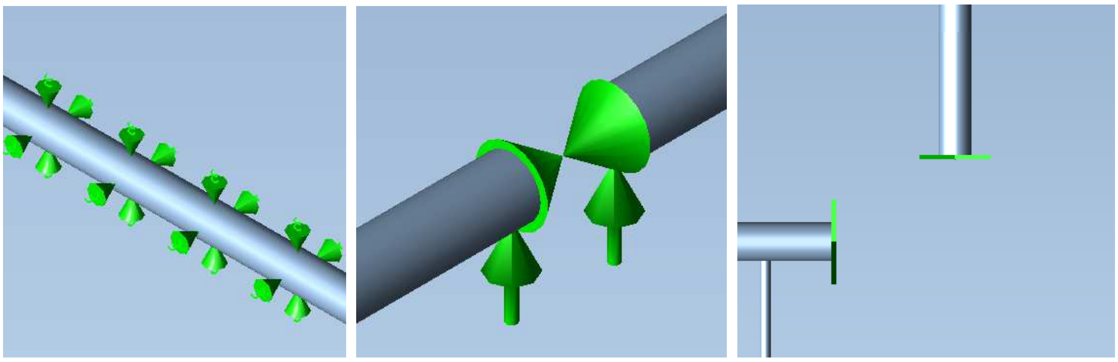
Stress analysis of pipeline system of reciprocating pump in oil transportation station includes three aspects: static stress analysis, modal analysis and vibration analysis.

Static stress analysis

(1) Establishment of the pipeline system: the basic pipeline parameters (i.e. pipeline diameter, pipeline thickness and materials etc.) require inputting into the operation interface and environmental parameters (i.e. pipeline operation temperature and pressure).

(2) Establishment of constrains: based on the engineering practice, constraints need to be simplified, and then input into the operation interface. CAESAR II performed a simulation to three typical constraints (i.e. soil constraint,

valve seat constraint and pump pipe nozzle constraint) of pipeline system in oil station, which is displayed as Figure 1.



(a) Soil constraint **(b) Valve seat constraint** **(c) Pump pipe nozzle**

Fig.1 Layout of Constraint Model

(3) Establishment of load cases: from production to operation, since the medium inside the pipeline and its environment are different at different stages, the load cases require establishing based on different loads.

(4) Exporting analysis results: the analysis report of static stress is generated after calculating by the software.

Modal analysis

(1) Defining the basic parameters: 'Dynamics' modulus of the software requires inputting the lumped mass and parameters of the shock absorber.

(2) Defining the control parameters: When the cut-off frequency is set as 100Hz, and 'Natural Frequencies' of creating a pipeline system is checked, the software will generate the natural frequencies that corresponds to different order numbers.

Vibration analysis

(1) In CAESAR II, the harmonic load is an input, which can be calculated by following steps:

(i). Calculation of the pressure unevenness

$$\sigma_P = (P_{\max} - P_{\min}) / P_m \times 100\% \quad (1)$$

Where:

P_{max}: Maximum pressure;

P_{min}: Minimum pressure;

P_m: Average pressure.

(ii) Calculation of pressure fluctuation

$$\Delta P = 0.5 P_m \times \sigma_P \quad (2)$$

(iii) Calculation of harmonic load

The results of Formula (2) is used to caculate the harmonic load, which is achieved by multiplying the pressure value of key spots and the area of cross-section at corresponding location.

(2) Defining the lumped mass, parameter of shock absorber etc.

(3) Calibrating the vibration according to the Standard of API 618.

Stress calibration standard

The stress calibration of pipeline utilizing CAESAR II follows the ASME B31 standard.

In terms of different load types of pipelines in the oil station, the content of static stress calibration includes primary stress and secondary stress. The primary stress is generated by gravity, external load and inside pressure; and since the load does not include the temperature, the primary stress is called pure cold-state stress; the secondary stress is generated by temperature and is called pure hot-state stress.

The calibration standard of primary stress in ASME B31.3: The sum of longitudinal stress SL generated by gravity and other sustained load should not exceed the allowable stress of hot state Sh, namely

$$S_L \leq S_h \quad (3)$$

The calibration standard of secondary stress in ASME B31.3: The range of displacement stress SE generated by thermal expansion, endpoint displacement and other factors should not exceed the allowable value SA.

$$S_E = \sqrt{(S_b + 4S_t^2)} \leq S_A = f(1.25S_c + 0.25S_h) \quad (4)$$

Where:
S_c: Allowable stress in cold-state;
f: The reduction factor of allowable stress range within the predict service life, which considers the influence from total circles.
S_b: The stress of a pipeline generated by composite bending moment under thermal expansion, cold shrinkage and endpoint displacement;
S_t: The stress of a pipeline generated by torque under the thermal expansion, cold shrinkage and endpoint displacement.

Calibration standard of modal analysis
Calibration of pipeline modal analysis aims to prevent the resonance generated between pipes and equipments. In engineering practice, the frequency range of 0.8~1.2 times natural frequency is called the resonance region, so it is required that the inherent frequency of the pipeline should exceed 1.2 times exciting frequency, that is to keep it away from resonance region.

Calibration standard of pipeline vibration
The objective of pipeline vibration calibration is to check if vibration velocity of a pipeline is within the allowable safety range. API618 provides the corresponding requirements for pipeline vibration [9]:

(1) When the frequency is lower than 10Hz, the allowable amplitude is 0.5 mm peak-peak value;
(2) When the frequency is within 10~200Hz, the allowable amplitude is 32mm/s peak-peak value.

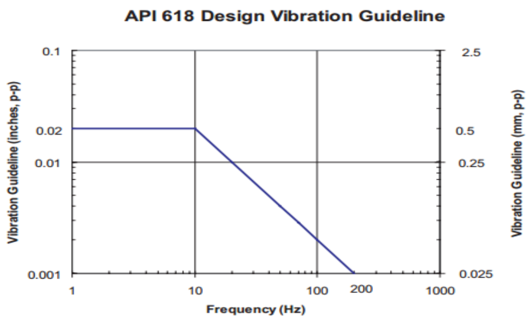


Fig. 2 API 618 Piping design vibration at discrete frequencies

EXPERIMENTAL SECTION

General situation of project
XX oil transportation station is located at western China, there are total four reciprocating pumps equipped at pump house in oil transportation station to transport heavy oil. The rotating speed of pump is 300 r/min; the operation temperature of pipeline is 95 °C; the operation pressure of pipeline is 8MPa. There are two types of pipeline materials, namely L360 and L450, and total four types of pipeline specifications. Table 1 lists the details of each pipeline; Figure 3 shows the effect drawing of simulation of reciprocating pump pipeline system by software. Since the main oil inlet pipeline, the main oil outlet pipeline and the sewage pipe are buried underground, the soil parameters require setting in the software to perform the simulation. Table 2 shows the details of soil parameters. And Table 3 shows the calculation results of harmonic load.

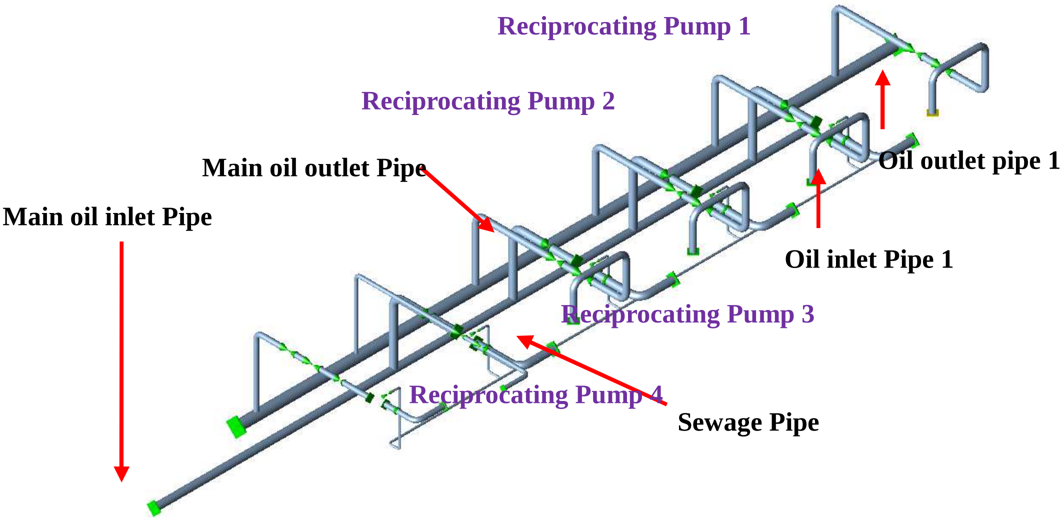


Fig. 3 Simulation of reciprocating pump pipeline system by CAESAR II

Table 1 Pipe Parameters of Pump Pipeline System in XX Oil Station

Parameter \ Pipeline	Main oil outlet pipe	Main oil inlet pipe	Oil outlet pipe 1	Oil inlet Pipe 1
Pipeline Diameter /mm	355.6	559	273	323
Pipeline Thickness /mm	9.5	5.2	7.8	5.2
Insulation Thickness /mm	60			
Corrosion Allowance /mm	1			
Pipeline Material	L450	L450	L360	L450
Oil Density /kg·m^{-3}	900			
Class of Area	Level 3 Area			
Installation Temp. of Pipeline /°C	10			
Operation Temp. /°C	95			
Operation Pressure /MPa	8			

Table 2 Soil Parameters of Buried Pipeline of Pump Pipeline System in XX Oil Station

Friction Coefficient	Density / kg·m^{-3}	Buried depth of pipe /m	Internal friction Angle/ °	Backfill compaction coefficient	Yield displacement coefficient	Thermal expansion coefficient/ (L/L/°C)
0.6	2600	2	37	5	0.015	11.214

Table 3 Calculation Results of Harmonic Load (partial of list)

Node	Position (type)	Phase angle	Direction of harmonics force	Harmonics force /N
1520	Elbow pipe	0.00	Z axis	952.55
10180	Tee fitting	270.66	Y axis	-128.12

RESULTS AND DISCUSSION

Static stress analysis

According to the stress analysis report generated by CAESAR II, the position and value of maximum stress of the full length of pipeline can be obtained. Table 4 shows the calibration of maximum primary and secondary stress of reciprocating pump pipeline system in XX oil station in operation condition.

Table 4 Calibration of Maximum Primary and Secondary Stress of Reciprocating Pump Pipeline System in XX Oil Station in Operation Condition

Type	Stress/ MPa	Node	Stress ratio/ %	Calibrated Stress/ MPa
Primary Stress	133.09	10160	75.1	177.20
Secondary Stress	189.18	24640	55.6	340.39

Table 4 exhibits that the stress analysis report can not only show the stress, stress ratio, but also the generated location. The stress ratios of primary and secondary stress of reciprocating pump pipeline system are less than 100%, which does not exceed the maximum allowable value of pipeline stress that meets the criteria of stress safety.

Modal analysis

Modal analysis needs to analyze the oil inlet pipeline system and oil outlet pipeline system separately; and CAESAR II is able to generate the natural frequency of pipeline system automatically. Figure 4 and Figure 5 display the natural frequencies of first ten-order of oil inlet pipeline and oil outlet pipeline separately. Figure 6 also shows the first two-order vibration modes of the pipeline system, in which the vibration modes of pipeline systems can be found out.

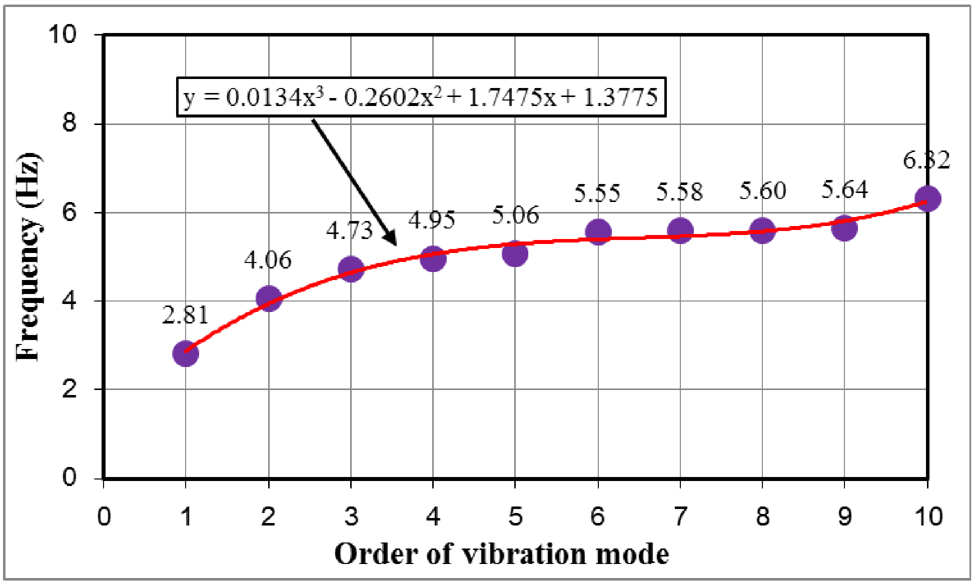


Fig. 4 Natural frequency analysis of oil inlet pipeline system

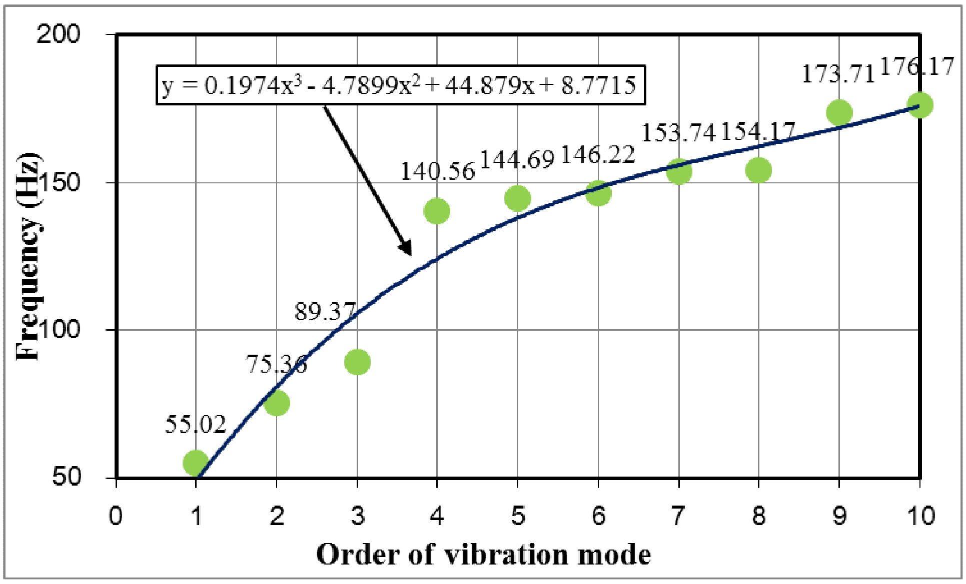
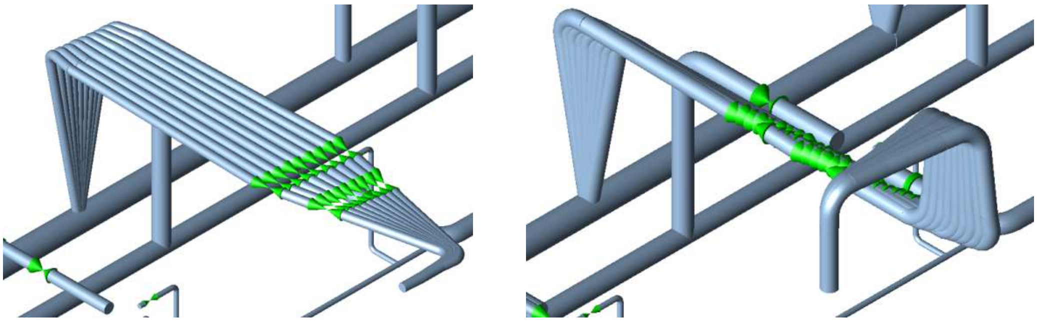


Fig. 5 Natural frequency analysis of oil outlet pipeline system



(1) First order **(2) Second order**

Fig. 6 Diagram of first order and second order of oil inlet pipe simulated by CAESAR II

From Figure 4 and 5, with the increasing of vibration mode order, the natural frequencies of oil inlet pipeline and oil outlet pipeline increase in varying degrees, which exhibits a general uptrend. The natural frequency of the oil outlet pipeline is higher than the oil inlet pipeline. Since the rotating speed of the reciprocating pump is 300 r/min and the exciting frequency is 5Hz, the minimum natural frequency (first order natural frequency) of the pipeline system for resonance prevention should larger than 5×1.2=6Hz. But the natural frequency of oil inlet pipeline is 2.81Hz<6Hz, which does not meet the standard requirement, so the resonance between the oil inlet pipeline and equipments would occur, and vibration reduction measures needs to be taken. The first order natural frequency of oil outlet pipeline is 55.02Hz>6Hz, which meet the standard requirement, so there is no need to take vibration reduction measures.

According the engineering experiences, the main approach for vibration reduction of pipeline systems is to install the oriented support and load-bearing support at elbow pipe and flange. The oriented support with four-direction restraints is added in original model, which is close to the elbow of oil inlet pipeline; and the load-bearing support is added in the position of flange; then the modal analysis is performed again. After running by the software, Figure 7 displays the effect drawing of the simulation; and Figure 8 shows the natural frequencies of first ten-order.

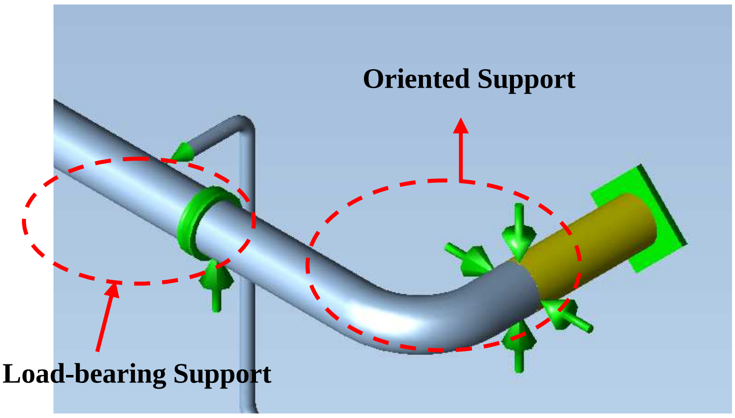


Fig. 7 Simulation of oil inlet pipeline system after adding restraints

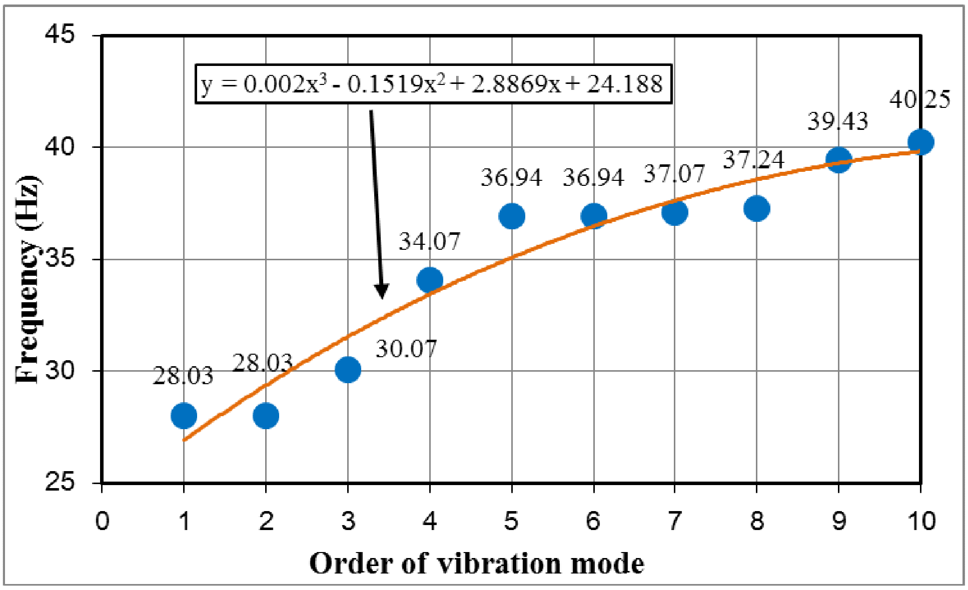


Fig. 8 Natural frequencies of improved oil inlet pipeline system

From Figure 8 it can be concluded that the minimum natural frequency of improved pipeline system is 28.03Hz, which is much larger than 6Hz, so the resonance between pipelines and equipments would not occur. The effective improvement of pipe rigidity and increasing of natural frequency of pipeline system are verified by adding the oriented support to the position close to the elbow pipeline and adding the load-bearing support to flange position, which is able to prevent the occurring of resonance effectively since the exciting frequency is not within the range of natural frequency.

Vibration analysis
Assuming the reciprocating pump 1 to 4 run together, vibration analysis is performed by CAESAR II, which concludes that the maximum displacement occurs at node 10200, the maximum displacement is 0.059mm, and the frequency is 16.326Hz, as well as the phase angle is 79.62°. The vibration speed of pipeline system is 12.098mm/s, which is lower than the specified value 32mm/s from API618, so the pipeline vibration meets the requirement.

$$V=2\pi fA \tag{5}$$

Where:
V: Vibration speed, mm/s;
f: Vibration frequency, Hz;
A: Amplitude, mm.

CONCLUSION

This paper puts forward the difference of stress analysis and research between reciprocating pipeline and long distance oil transportation pipeline, which is that the stress analysis of oil transportation pipeline in oil station includes static stress analysis, modal analysis and vibration analysis. The standards of stress calibration, resonance calibration and vibration calibration of oil transpiration pipeline in pump house of oil station are identified. The methods for stress analysis, modal analysis and vibration analysis of reciprocating pump pipeline system in oil station are proposed.

By the software simulation of CAESAR II, the effective improvement of pipe rigidity and increasing of natural frequency of pipeline system are verified by adding the oriented support and load-bearing support to the elbow pipeline and valve, which prevents the occurring of resonance effectively.

The methods for stress analysis, modal analysis and vibration analysis of reciprocating pump pipeline proposed in this paper can be applied for technological design of oil transportation station, which will effectively increase the operation reliability of equipments and pipeline.

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