

Postprint of Computational Analysis of Gas Pulsation in Large Reciprocating Compressor Piping Systems

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Date: 2017-11-07T00:00:00+00:00

Abstract

For a large reciprocating piston compressor piping system, calculations and analysis of gas flow pulsation were conducted. Based on plane wave theory and employing the network transfer matrix method, a network analysis model for gas flow pulsation in this complex piping system was established, and corresponding analysis software program code was developed. The first ten natural frequencies of the gas column in the piping system were calculated to determine whether the piping system would resonate. Simultaneously, the pulsation pressures at various nodes in the piping system were computed, with the results satisfying the requirements of the API 618 standard. Research on gas flow pulsation in complex piping systems will provide a theoretical basis for piping system design and the suppression and elimination of gas flow pulsation and piping vibration.

Full Text

Calculation of Gas Pulsation in Large Reciprocating Compressor Piping System

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Abstract

This paper presents the calculation and analysis of gas pulsation for a large reciprocating compressor piping system. Based on plane wave theory and using the network transfer matrix method, a network analysis model for gas pulsation in this complex piping system was established, and corresponding analytical software code was developed. The first ten orders of natural frequencies of the gas column in the piping system were calculated to determine whether resonance occurs in the system. Simultaneously, the pulsating pressure at each node of the piping system was computed, and the results satisfy the requirements of the API 618 standard. This research on gas pulsation in complex piping systems provides a theoretical basis for piping system design and the control and elimination of gas pulsation and pipeline vibration.

Keywords: reciprocating compressor; plane wave theory; network transfer matrix; gas natural frequency; pulsating pressure

Large reciprocating piston compressors serve as power sources for compressing and transporting media, and are widely used in petroleum, chemical, refrigeration, and other industries. Due to limitations on transportation dimensions, weight, and footprint, increasingly stringent demands are placed on the structural compactness, reliability, and operational stability of large reciprocating compressors. However, the intermittent suction and discharge processes of compressors generate strong gas pulsations within pipelines. These pulsations not only affect compressor performance but also induce pipeline vibrations, posing significant threats to production safety. Therefore, investigating the generation mechanism of gas pulsation and calculating the acoustic field distribution of pulsating flow holds important engineering value and practical significance for actively controlling and suppressing gas pulsation in compressor units, reducing or eliminating pipeline vibration, and improving operational economy.

Recent domestic and international research on gas pulsation has primarily employed the transfer matrix method [1], finite element method [2], acoustic-electric simulation method [3], CFD method [4], one-dimensional time-domain flow solution method [5], and commercial software such as Bentley PULS. PULS is specialized foreign software for gas column analysis in pipelines, currently monopolizing the international market. It is not only expensive to purchase but also costly to update. Consequently, developing independent gas pulsation analysis software is extremely important. The transfer matrix method, also known as the network transfer matrix method, is currently the most practical calculation method for engineering design and analysis of gas pulsation in compressor pipelines. Xi'an Jiaotong University has made significant contributions to this field [1], particularly in calculating gas column natural frequencies, gas pulsation, and pressure pulsation, successfully solving practical problems. Li Zhibo [6] used the transfer matrix method to obtain natural frequencies of arbitrarily complex piping systems and the pulsation waveforms and amplitudes at any

location, providing valuable insights. Xu Bin et al. conducted in-depth research on gas pulsation in interstage pipelines [7] and modified the model to address calculation accuracy issues [8], with actual measurements providing highly instructive results. Fan Gen [9] calculated gas column natural frequencies based on the transfer matrix method, studied control methods for pipeline gas pulsation, effectively reduced vibrations in compressor unit outlet pipelines and corresponding accessories, and ensured safe and stable operation of the entire unit—results of great significance.

This paper establishes a mathematical model and network transfer analysis model for gas pulsation analysis in complex piping systems of large reciprocating piston compressors based on plane wave theory. Using MATLAB, a gas pulsation analysis program was developed and applied to analyze and calculate the gas pulsation in the outlet piping system of a large reciprocating compressor from an enterprise. The natural frequencies of the gas column and pulsating pressures were obtained, and the rationality of the piping system design was evaluated and analyzed by comparing the results with the API 618 standard, providing a theoretical basis and improvement direction for compressor unit piping system design and vibration suppression.

1 Mathematical Model

Research on gas pulsation primarily consists of two parts: calculating the natural frequencies of the gas column to avoid resonance bands of compressor excitation frequencies (0.8~1.2)f, and calculating pulsating pressure to keep it within standard limits. This paper employs the network transfer matrix method to calculate both gas column natural frequencies and gas pulsating pressure.

1.1 Mathematical Model for Gas Column Natural Frequency Calculation

Under normal conditions, the pulsation value of gas pressure in pipelines is a very small fraction of the average pressure (generally within 8% based on double amplitude), which satisfies the assumptions of plane wave theory. Therefore, gas pulsation in reciprocating compressor pipelines can be analyzed using plane wave theory.

Based on the gas continuity equation, motion equation, and wave equation, and neglecting the average gas flow velocity, the plane wave equation can be obtained [1]:

$$22222tppatx \quad jwxajwtxatpAeBe \quad 00u \ 01ttuptx \quad 200ttpuatx \quad ()()1xxjwjtjwtaatuAeBea$$

Where tp represents pulsating pressure, tu represents pulsating velocity, ρ is gas density, a is gas sound speed, and A , B are complex constants determined by pipeline boundary conditions.

A complex piping system can be considered as composed of basic pipeline elements such as constant-section pipes, vessels, confluence points, and reducers.

According to network transmission matrix theory, the relationship between pulsating pressure and pulsating velocity at nodes between elements can be established. Assuming the pulsating pressure and velocity at the start and end of the compressor piping system are p_1 , u_1 , p_2 , u_2 respectively, the transmission matrix equation is:

$$211221nppuu \quad \text{MMMiM}$$

Where M represents the transmission matrix of each pipeline element. Based on boundary conditions, the natural frequency equation of the gas column in the piping system can be obtained, and the natural frequencies of each order can be calculated using MATLAB programming.

1.2 Mathematical Model for Pulsating Pressure Calculation

To calculate pressure pulsation magnitude, damping must be considered. The linear damping wave equation is:

$$2222210tttpppRxaat$$

Where R is the pipeline damping coefficient, expressed as $R = 4\lambda u_0/D$; λ is the friction coefficient between gas and pipe wall; D is the pipe inner diameter (m); and u_0 is the average gas flow velocity in the pipe (m/s).

The solution to equation (7) is:

$$+jk(x)jkxjwttpAeBee$$

Where w is the pulsating angular frequency, $\alpha = R/(2a)$, and $k = w/a$.

First, harmonic analysis is performed on the compressor's suction and discharge curves to obtain pulsating mass flow rates of each order. Then, based on the transmission matrices of each element, the total transmission matrix of the piping system is obtained to calculate pulsating pressures of each order. Finally, by superimposing pulsating pressures of all orders, the pulsating pressure at any point in the piping system can be obtained. The network transfer matrices for common elements can be found in reference [1].

2 Case Study

2.1 Network Calculation Model

The compressor cylinder arrangement is symmetrically balanced with 6 columns and 6 cylinders, double-acting. The medium in the piping system is mixed process gas with an average molecular weight of 17.3 g/mol. The compressor speed is 994 r/min, with suction pressure of MPa, suction temperature of °C, discharge pressure of 6 MPa, and discharge temperature of 93.9 °C.

For modeling and calculation, the following assumptions were made for the compressor unit discharge piping system: 1. Temperature and pressure measurement devices in the system are neglected; 2. Valves are treated as variable

cross-sections, while filters, scrubbers, and buffer tanks are treated as volume elements; 3. The condenser is simplified into five components: two front-end headers, a rear-end header, and two connecting pipes. The front and rear headers are treated as volume elements, and connecting pipes as constant-section pipes; 4. Flanges are not considered, and normally open valves are treated as straight pipes; 5. Drain systems and vent pipelines are not considered for their effect on the gas column.

Based on these assumptions, the actual piping system was simplified, with results shown in Figure 1 [Figure 1: see original paper], which represents the network impedance model for analyzing gas pulsation in the piping system.

In the gas pulsation analysis, the piping system is divided into 45 elements and 46 nodes. Nodes 1, 3, 5, 12, 14, and 16 are the exhaust ends of the six cylinders, node 40 is the acoustic open boundary condition (process gas outlet), and node 46 is the acoustic closed boundary condition (nitrogen replacement port, where the valve on this branch pipeline is normally closed).

2.2 Calculation of Gas Column Natural Frequencies

For acoustic boundaries, open ends have pulsating pressure $p = 0$, while closed ends have pulsating velocity $u = 0$. The non-zero endpoint p or u is set to 1, and the end connected to the cylinder is treated as a closed end. The resonance region is defined as the area between 0.8 and 1.2 times the gas column natural frequency.

Using the transmission matrix method, the first ten orders of natural frequencies of the gas column in the discharge piping system and the resonance regions were calculated, as shown in Table 1 .

Table 1 Gas natural frequency and resonance region

f / Hz	(0.8~1.2)f / Hz
0.56~0.83	
1.89~2.83	
2.48~3.72	
4.13~6.19	
6.36~9.53	
7.95~11.92	
10.10~15.15	
12.30~18.46	
14.26~21.39	
15.33~23.00	

The compressor excitation frequency f is calculated by equation (9):

$$f = (n \cdot m \cdot N) / 60$$

Where N is compressor speed (r/min), and m equals 1 for single-acting and 2 for double-acting cylinders. The calculated main excitation frequency of the compressor is 33.13 Hz. The results show that the compressor excitation frequency effectively avoids the first ten orders of resonance regions of the gas column, indicating that resonance between the compressor and gas column in the pipeline will not occur.

2.3 Pressure Pulsation Calculation

2.3.1 Pressure Pulsation Control Standards The degree of pressure pulsation is evaluated using pressure non-uniformity δ , defined as:

$$\delta = (P_{\max} - P_{\min})/P_0 = \Delta P/P_0$$

Where P_{\max} is maximum instantaneous gas pressure (MPa), P_{\min} is minimum instantaneous gas pressure (MPa), ΔP is maximum pressure pulsation amplitude (MPa), and P_0 is average gas pressure.

According to the fifth edition of API 618 released in 2007, pressure pulsation control standards throughout the system are summarized as follows [10]:

(a) Maximum allowable pressure pulsation at compressor cylinder flanges

The unfiltered pressure pulsation non-uniformity at compressor cylinder flanges should be limited to below 7% or the value calculated by:

$$\delta = [R] \times 100\%$$

$$\text{Where } [R] = (400/350) \times (a/(P_0 \cdot I \cdot D \cdot f))$$

Where a is gas sound speed (m/s), P_0 is average absolute pressure in the pipeline (MPa), D is pipe inner diameter (mm), and f is pulsation frequency (Hz).

(b) Maximum allowable pulsation range at buffer device pipe connections or beyond

Buffer devices should limit pressure non-uniformity on the pipe side to the range specified by equation (12).

2.3.2 Harmonic Analysis of Pulsating Velocity Nodes 1, 3, 5, 12, 14, and 16 are boundary conditions at compressor exhaust ends where pulsating velocity is known. Fourier harmonic analysis was first performed on pulsating velocity and pulsating mass flow rate. The first ten harmonics of pulsating velocity and mass flow rate at node 1 are shown in Table 2. Although harmonic coefficients differ at other exhaust endpoints, their amplitudes are the same as at node 1 and are not listed here. For double-acting cylinders, the harmonic with maximum amplitude is the second order, whose frequency equals the main excitation frequency.

Table 2 The first 10 order of harmonics for the pulsating velocity and mass flow rate at node 1

Order	Pulsating Velocity Component (m/s)	Pulsating Mass Flow Rate Component (kg/s)
1		
2		
...		
10		

Figure 2 [Figure 2: see original paper] shows the pulsating velocity curve within one period. The curve conforms to the exhaust velocity pattern of double-acting cylinders. Additionally, the pulsating velocity amplitudes at the shaft side and cover side of the compressor are asymmetric due to the piston rod occupying certain cylinder volume at the shaft side, causing structural asymmetry.

2.3.3 Calculation of Pressure Non-Uniformity Based on the element transmission matrices of each component, pulsating pressure harmonics at each point can be obtained. Due to the large number of nodes, only pressure amplitudes at compressor exhaust endpoints and buffer tank outlets are listed here, as shown in Tables 3 and 4 .

Table 3 Pressure amplitude of node 1 at exhaust pore

Re/Pa	Im/Pa	Pm/Pa	d/rad

Where Re is the real part of the solution, Im is the imaginary part, Pm is pressure amplitude, and d is phase angle.

By superimposing pulsating pressure amplitudes of all orders according to their phase relationships, the total pressure waveform at endpoint 1 was obtained, as shown in Figure 3 [Figure 3: see original paper]. The maximum pulsating pressure is 81,700 Pa, the minimum is -102,910 Pa, occurring at rotation angles of 2.26 rad and 5.82 rad respectively. With an average internal pressure of 6 MPa, the pressure non-uniformity is 3.08%.

Table 4 Pressure amplitude of node 7 at the outlet of the buffer

Re/Pa	Im/Pa	Pm/Pa	d/rad

By superimposing pulsating pressure amplitudes according to their phase relationships, the total pressure waveform at endpoint 7 was obtained, as shown

in Figure 4 [Figure 4: see original paper]. The maximum pulsating pressure is 1,564.6 Pa, the minimum is -1,200 Pa, occurring at rotation angles of 0.71 rad and 5.74 rad respectively. With an average internal pressure of 6 MPa, the pressure non-uniformity is 0.046%.

Similarly, the maximum and minimum pulsating pressures at all points in the pipeline can be determined, and pressure non-uniformity can be calculated and compared with API 618 standards, as shown in Table 5 .

Table 5 Pressure un-uniformity of each node

Node Description	Max Pressure (Pa)	Min Pressure (Pa)	Avg Pressure (Pa)	Non-Uniformity Value	API 618 Allowable Value
Cylinder exhaust port Buffer tank outlet					

The results show that pressure non-uniformity after the buffer tank is far below the API 618 allowable value, indicating that pressure non-uniformity in subsequent piping will also meet standard requirements.

Conclusions

Based on plane wave theory, this paper established mathematical and network transfer analysis models for gas pulsation analysis in complex piping systems of large reciprocating piston compressors, and developed a gas pulsation analysis program using MATLAB. The program was applied to analyze gas pulsation in the outlet piping system of a large reciprocating compressor from an enterprise, obtaining calculation results for gas column natural frequencies and pulsating pressures, and evaluating the rationality of the piping system design.

The results indicate that the first ten orders of gas column natural frequencies in this piping system range from 0.7 to 19.16 Hz, which effectively avoids the compressor excitation frequency of 33.13 Hz, demonstrating that low-order gas column resonance will not occur in this system. Additionally, the pressure non-uniformity at compressor exhaust ports is 3.1%, below the API 618 allowable value of 7%, and the pressure non-uniformity at buffer tank outlets is 0.046%, far below the API 618 allowable value of 0.51%. This confirms that the piping system design is rational and will not cause severe vibrations.

The developed gas pulsation analysis software can determine gas column natural frequencies, pulsating pressures at each node, and pressure non-uniformity, ef-

fectively predicting gas pulsation in compressor piping systems. This provides a theoretical basis for piping system design and gas pulsation reduction, ensuring safe and efficient unit operation.

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Acknowledgments: This research was funded by the National High-tech Shipbuilding Research Program (Project No. 0214120042).

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.