Gas column resonance analysis of reciprocating compressor

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Abstract. The oscillation process based on acoustic vibration system and electrical circuit can be described by the same type of differential equation. MATLAB/SIMULINK was used to establish the electrical model of the outlet piping system of the 2D-90Mg-2.5/1.5 type air combined compressor in the laboratory. The natural frequency of the gas column is obtained and compared with the results of finite element analysis. It is proved that the electrical simulation method is feasible and simple to calculate the natural frequency of gas column in compressor pipeline system.

1. Introduction
The gas filled in the pipeline of reciprocating compressor can form an elastic vibration system with continuous mass due to the compressibility of the gas. When a gas column with a agreed boundary condition is subjected to an initial disturbance, the free vibration frequency is the natural frequency of the gas column. When the natural frequency of the gas column coincides with the excitation frequency of the compressor, the gas column resonance will occur, resulting in a strong pipeline vibration. Therefore, the natural frequency of the gas column must be calculated during piping, which is of great significance to avoid the resonance of the gas column and to reduce the vibration of the pipeline. Common methods to calculate the natural frequency of gas column are transfer matrix method, finite element method and frequency response function method. The calculations are complicated. The natural frequencies of complex tubular gas columns are calculated based on acoustic and electrical simulation.

2. Basic principles
2.1 Acoustic and electrical simulation method
The helmholtz resonator is a basic device in the acoustic system, as shown in figure .1. Because of its structural characteristics, the helmholtz resonator can be used as a model to analyze the airflow vibration and an important device to reduce the airflow pulsation in pipelines.

![Fig.1 helmholtz resonator](image-url)
Gived hotz resonator structure is simple, contains a volume V containers and a length of neck L, including the circulation section size of the neck is s. gived hotz gas movement law in the resonator is: when the helmhotz-kirchhoff hotz neck length of the resonator and the actual fluctuations compared to the wavelength of the very small, the neck tube can be expressed as the quality of gas. When the mass block moves, the pressure inside the container will change. Gas compressibility is represented by the volumetric elastic modulus K, which refers to the volume reduction of a gas with volume V due to an increment generated by pressure.

\[ K = -\frac{\delta p}{\delta V} \]

Based on this, the motion differential equation of helmholtz resonator system is derived as follows:

\[ \rho_0 L \frac{d^2x}{dt^2} + R \frac{dx}{dt} + \rho_0 c^2 \frac{V}{V} = \frac{p(t)}{S} \]

Where: \( V \) -- the original volume of the gas; \( C \) -- speed of sound, m/s; -- average (absolute) temperature; \( R \) -- damping coefficient \( x \) -- gas displacement, m; \( F \) -- the force applied, N; \( L \) -- length of pipe, m; -- pressure increment, Pa; \( K \) -- elastic modulus of gas; -- initial density of the gas, kg/m; \( S \) -- flow area of the pipeline; \( Sp_{of \ t} \) -- excitation force, N. In the power system, the RLC ac series circuit is shown in figure 3, and its motion differential equation can be expressed as:

\[ L_e \frac{d^2x}{dt^2} + R_e \frac{dx}{dt} + \frac{1}{C_e} q = E(t) \]

Where, -- the inductance of the coil, H; -- resistance; -- capacitance, F; \( E(t) \) -- supply voltage, V; \( Q \) -- charge, C.

### 2.2 Circuit Resonance Principle

In a single-port circuit system with inductance, capacitance and resistance elements, when the operating frequency of the circuit is adjusted to the phase of the voltage at the circuit end and the phase of the current are the same, the changing waveforms of the two parameters will superposition each other, and the circuit resonance is said to have occurred. As shown in figure 4, the series circuit is composed of R, L and C elements. When the circuit suffers from circuit resonance, it is called series resonance.
2.3 Establishment of equivalent circuit

2.3.1 Establishment of equivalent circuit of equal section straight pipe unit. As shown in FIG. 6, the straight pipe with equal cross-section is discretized. The pipe is divided into small sections with the length, and in the region of and, it can be deduced as follows according to the three fluid equations:

\[
R_i + L \frac{di}{dt} = U_1 - U_2, \quad C \frac{du_2}{dt} = i_1 - i_2
\]

Where: C -- capacitance, F; U -- voltage, V; R - resistance, Ω; I -- current, A; L -- inductance, H.

Therefore, there is the equivalent relationship of the system:

\[
L = \frac{\delta x}{S}, \quad R = \frac{\lambda \delta x m_0}{2 \pi D \rho S}, \quad C = \frac{S \delta x}{a^2}, \quad \dot{m} = i, \quad p = U
\]
Equivalent circuit of volume unit:

The equivalent circuit of the volume unit is shown in figure 1.8. 1 and 2 are used to represent the inlet and outlet of the volume element. In the process of gas flow, the change of gas is regarded as an adiabatic change, and no heat exchange occurs. Under the assumption that the volume cavity is very small, the pressure values at each point in the cavity are considered to be consistent. Therefore, the equation of continuity with the container is as follows:

\[ \rho_0(S_1u_{t1} - S_2u_{t2}) = V \frac{\partial p_t}{\partial t} \]

Type in the:

- \( S_1 \) — Equal area at inlet, m²
- \( S_2 \) — 6/5000  Equal exit area, m²
- \( V \) — Volume of container, m³

By: \( a^2 \overset{\partial p_t}{\partial \rho_t} \), So this is going to be zero: \( S_1u_{t1} = S_2u_{t2} \), namely: \( m_1 = m_2 \)

In the circuit: \( C \frac{\partial u_{t2}}{\partial t} = i_1 - i_2 \); Among them \( m \) Equivalent to i, so: \( C = \frac{v}{a^2} \)

Equivalent circuit of branch pipeline unit:

The equivalent circuit of the branch pipeline unit is shown in figure 1.8. The pressure of the main pipe system at the branch of the series pipe is equal to the pressure of each branch pipe, and the sum of the flow of each branch pipe is the flow of the main pipe. A branch pipe is equivalent to a branch in a circuit. In the equivalent circuit, the voltage at each branch point is equal, and the current in the dry circuit is

Equivalent circuit of parallel pipe unit:

The equivalent circuit of the parallel pipeline unit is shown in FIG.10. In the pipeline system, the sum of the gas masses of the two branches is the sum of the main pipeline, and the flow through the outlet does not change. The flow velocity changes. Parallel pipeline circuit is actually two branch pipeline circuit together, the two processes are inverse.
Fig. 9 Equivalent circuit of parallel pipe unit

Other basic equivalent circuits:

According to the above principle, the inductance and capacitor elements in the circuit affect the main parameters of the natural frequency of the circuit, and the equivalent circuit of the gas column model can be established. According to the boundary conditions:

When the pipe opens: \( p = 0, \ u \neq 0 \); Open equivalent circuit: \( U = 0, i \neq 0 \);

When the pipe is closed: \( p \neq 0, u = 0 \); Closed equivalent circuit: \( U \neq 0, i = 0 \);

(1) Open the pipe at one end and close the pipe at the other end. The equivalent circuit is shown in Figure .10.

Fig .10 Equivalent circuit with one end open and the other end closed

(2) Pipeline with closed ends at both ends, equivalent circuit is shown in Figure .11.

Fig.11 Equivalent circuit of pipeline with two closed ends

(3) For the pipeline with two ends as the beginning, the equivalent circuit is shown in Figure .12

Fig.12 Equivalent circuit of the pipeline starting at both ends
2.4 Calculation of natural frequencies of gas columns in complex pipelines

2.4.1 Establishment of acoustic and electrical analog equivalent circuits. The 2D-90 composite compressor comprises a constant section tube, a reducing tube, a volume unit, a branch and a confluence unit. The pipe is open at one end and closed at the other end. Dividing pipeline microelement meets the requirement of accuracy $\delta x / L < 0.05$. The equivalent value of $L$ and $C$ is calculated, and the equivalent circuit is established. The equivalent parameters of the exhaust outlet circuit are shown in Table 1.

### Table 1. Equivalent parameter data of the circuit

| Pipe unit number | Pipe length (200) | Diameter mm | Cross-sectional area $m^2$ | Inductance $L$ | Capacitance $C$ |
|------------------|------------------|-------------|-----------------------------|---------------|-----------------|
| 1                | 710              | 100         | 0.00785                     | 0.452         | 6.893E-08       |
| 2                | 227              | 50          | 0.00196                     | 0.578         | 5.51E-09        |
| 3                | 1886             | 50          | 0.00196                     | 4.803         | 4.578E-08       |
| 4                | 773              | 50          | 0.00196                     | 1.968         | 1.876E-08       |
| 5                | 1886             | 50          | 0.00196                     | 4.803         | 4.578E-08       |
| 6                | 235              | 50          | 0.00196                     | 0.598         | 5.704E-09       |
| 7                | 710              | 100         | 0.00785                     | 0.452         | 6.893E-08       |
| 8                | 2500             | 50          | 0.00196                     | 6.366         | 6.068E-08       |
| 9                | 1886             | 50          | 0.00196                     | 4.803         | 4.578E-08       |
| 10               | 773              | 50          | 0.00196                     | 1.968         | 1.876E-08       |
| 11               | 235              | 50          | 0.00196                     | 0.598         | 5.704E-09       |
| 12               | 895              | 50          | 0.00196                     | 2.279         | 2.172E-08       |
| 13               | 895              | 50          | 0.00196                     | 2.279         | 2.172E-08       |
| 14               | 1508             | 80          | 0.00503                     | 1.5           | 9.37E-08        |
| 15               | 500              | 80          | 0.00503                     | 0.497         | 3.107E-08       |
| 16               | 250              | 80          | 0.00503                     | 0.249         | 1.553E-08       |
| 17               | buffer           | 0           | 0.1075                      | 0             | 3.431E-07       |
| 18               | 2000             | 80          | 0.00503                     | 1.989         | 1.243E-07       |

The equivalent simulation circuit is established, as shown in Figure 13.

![Fig. 13 Equivalent simulation circuit](image-url)
Circuit description:
Each subsystem of this circuit represents each pipe unit. From the equivalent pipeline, it can be known that only inductance and capacitor elements are needed in each subsystem, and capacitor is only used as an energy storage element. By step signal sent by the Timer control circuit switch on and off, switch circuit when the power supply To an initial voltage circuit, switch, after began To free oscillation circuit, the To Workspace module will record the oscilloscope shows the whole data, circuit from 3 seconds the power switches off the free oscillation of system began, the Powergui module of data collected by fast Fourier transform, the vibration spectrum. In the vibration spectrum diagram, the first peak value appears is the natural frequency of the circuit, that is, the fundamental frequency of the pipeline system, and the following several peak values are the multiple frequencies of each order of the pipeline. Theoretically there is no energy loss in the circuit during the entire circuit oscillation process, so the natural frequency of the gas column through the whole pipe through this analog way.

2.4.2 Simulation results. The results of acoustic and electrical simulation method are shown.

![Fig.14](Number of pipeline micro-elements 20) ![Fig.15](Number of pipeline micro-segments: 100)

![Fig.16](200 microelements of pipeline)

| Order | Time (s) | 20 copies of the results | Results of 100 | Results of 200 |
|-------|---------|--------------------------|---------------|---------------|
| 1     |         | 25.66                    | 23.48         | 23.37         |
| 2     |         | 48.68                    | 43.11         | 42.66         |
| 3     |         | 63.96                    | 57.05         | 56.12         |
| 4     |         | 68.52                    | 62.72         | 61.11         |
| 5     |         | 76.56                    | 71.68         | 70.38         |

Comparison of natural frequency results of gas columns in complex pipelines is shown in Table 3

| Order time | The transfer matrix sends the calculated frequency | The transfer matrix sends the calculated frequency | Vibration frequency |
|------------|-----------------------------------------------|-----------------------------------------------|-----------------|
|            |                                               |                                               |                 |
3. Analysis of simulation results:

1. It can be seen from the above table that the calculation results of the transfer matrix method and the acoustic emf method are similar, which indicates that the acoustic emf method is effective in solving the natural frequency of the air column.

2. Compared with the natural frequency and excitation frequency of the air column, the low order frequency of the 2D-90 combined compressor is not in the resonance frequency band of the excitation frequency, so the air column resonance will not occur.

3. The accuracy of the acoustic and electrical simulation method to solve the natural frequency of compressor pipeline is verified. It is concluded that when the accuracy requirement is in line with $\delta x/L < 0.05$, the electrical simulation results are close to the theoretical results, and its accuracy can be recognized.

Conclusion:

1. By using MATLAB/SIMULINK simulation software and based on the vibration theory and fluid equation analysis method, the relationship expressions between the acoustic vibration system unit and each circuit element of the fluid in the pipeline are analyzed and derived, and the equivalent elements and circuits of the straight pipe, volume buffer and each pipeline combination in the pipeline system are determined.

2. The accuracy of the acoustic and electrical simulation method to solve the natural frequency of compressor pipeline gas column is verified. It is concluded that when the accuracy requirement is in line with $\delta x/L < 0.05$, the electrical simulation results are close to the theoretical results, and its accuracy can be recognized.

3. Acoustic and electrical simulation method is more intuitive in solving the natural frequency of compressor pipelines. It can also simulate changing pipe layout by directly changing the parameters of components in the circuit.

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