Optimal Design of Helmholtz Muffler for Air Compressor

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Abstract. Helmholtz muffler is widely used because of its simple structure and good noise elimination effect. In this paper, the method of installing Helmholtz muffler at the outlet of air compressor is adopted to reduce the influence of outlet pressure fluctuation noise on the pipeline system. The optimal relationship between the number of cylinders \( n \) and the installation parameter \( L \) is obtained when using standard high pressure cylinders as Helmholtz silencers. By calculating the transmission loss \( T_L \) of Helmholtz mufflers under different number of standard high pressure cylinders, the results show that Helmholtz muffler has the best muffling effect at 16.17Hz, the transmission loss \( T_L \) reach to 65dB, and has obvious filtering effect on low-frequency noise. At the same time, with the increase of the number of cylinders, which means that the larger the volume of Helmholtz muffler, the better the noise reduction effect.

1. Introduction
Large air compressors with high compression ratio are generally designed with reciprocating structure. Due to the reciprocating motion of the piston, the outlet pressure of the compressor generally has pulsation. The ref.[1] has carried out a detailed study on the pressure pulsation in the compressor. When the pulse frequency appears near the frequency of the pipeline or load structure, it is easy to produce resonance and noise in the pipeline or load. This resonance not only endangers the normal operation of the whole system, but also produces a lot of noise in the pipeline. In order to reduce the impact of pressure fluctuation, on the one hand, the structure of air compressor can be optimized, on the other hand, the method of adding muffler in the pipeline is mainly used [2-4].

In this paper, Helmholtz muffler is adopted to reduce the pressure fluctuation at the outlet of air compressor, and the structure of the muffler is designed. Also the transfer loss which is the parameter of muffler effect is calculated.

2. Helmholtz muffler
The main structure of Helmholtz muffler is shown in Figure 1[5]. It is a simple element filter with the best effect of vibration elimination and filtering. Generally installed at the outlet, it can greatly reduce the pressure fluctuation value. It is widely used in industrial devices of fluid pipeline system, such as chemical equipment, water conservancy machinery, water supply and drainage system, etc.

In Figure 1, the volume of Helmholtz muffler is \( V \), and the length of the pipe connected with the main pipe is \( L \). In order to achieve the best silencing effect of the muffler, the resonance frequency \( f_H \) of the muffler should be the same as the pulsation frequency \( f_p \) produced by the air compressor. Here are:
Figure 1. Structure of Helmholtz muffler.

\[ f_p = f_H = \frac{a}{2\pi} \sqrt{\frac{A}{LV}} \]  

Which, \( f_p \) is the pulse frequency at the outlet of pump or air compressor, \( f_H \) is the resonance frequency of muffler, \( V \) is the volume of muffler, \( A \) is the cross-sectional area of muffler, \( L \) is the length of pipe connecting muffler and main pipeline, \( a \) is the transmission speed of pressure wave in the pipeline.

For rigid pipes, \( a \) is calculated as follows:

\[ a = \sqrt{\frac{K}{\rho}} \]  

Which, \( K \) is the bulk modulus of the fluid, \( \rho \) is the density of fluid.

For a isentropic(adiabatic) process, we can obtain:

\[ K = kp \]  

Which, \( k \) is isentropic index.

For a completely isentropic gas, also we can obtain:

\[ p = \rho RT \]  

Which, \( R \) is the gas constant, general, \( R = 287 J/kg \cdot K \), \( T \) is thermodynamic temperature.

Substitute equation (3) and (4) into equation (2), the transmission speed of pressure wave \( a \) is calculated as follows:

\[ a = \sqrt{\frac{kRT}{\rho}} \]  

However, the general pipeline are elastic pipes. When the fluid in the pipeline is compressed, the pipe wall will also deform, so equation (2) can be modified as follows:

\[ a' = \frac{\sqrt{kRT}}{\sqrt{1 + [(K/E)(D/e)]C_1}} \]  

Which, \( E \) is the elastic modulus(Young's modulus) of pipeline material, \( D \) is the inner diameter of the pipe, \( e \) is the pipe wall thickness, \( C_1 \) is the correction factor of the pipe support condition, as the elastic support pipe. General \( C_1 = 1 \).

3. Design of muffler for air compressor

A air compressor uses three-stage compression to produce high-pressure air, and the main parameters of the air compressor are shown in Table 1 [6]. Now it is necessary to design the muffler at the outlet.
of the air compressor. The inlet air is the air in the standard state, the temperature $T_I$ is 20℃, the standard atmospheric pressure $P_I$ is 101KPa, and the density $\rho_I$ is 1.205kg/m³.

Assumptions:
- The compression process is isentropic (adiabatic).
- There is no loss before and after compression.
- The air is dry.

### Table 1. The parameters of air compressor.

| Primary pressure (MPa) | Secondary pressure (MPa) | Outlet pressure $P_O$ (MPa) | Outlet air temperature $T_O$ (℃) | Speed $r$ (r/min) |
|------------------------|--------------------------|-----------------------------|----------------------------------|------------------|
| 0.40-0.57              | 3.44-4.21                | 10                          | 180                              | 970              |

The material of pipeline is copper, and the parameters of pipeline are shown in Table 2.

### Table 2. The parameters of pipeline.

| Young's modulus (Pa) | Poisson's ratio | Internal diameter (m) | Thickness (m) |
|----------------------|-----------------|------------------------|---------------|
| $1.2 \times 10^{11}$ | 0.35            | 0.06                   | 0.003         |

### 3.1. Calculation of transmission speed of pressure wave

The isentropic index $k$ of dry gas with pressure of 10.1325MPa and temperature of 176.85℃Cis 1.4498[8], and the outlet pressure $P_O$ of air compressor is 10MPa, the temperature $T_O$ is 180℃. In the calculation, the isentropic index is approximately taken as 1.4498. From equation (5), the transmission speed of pressure wave can be calculated as:

$$a = \sqrt{kRT} = \sqrt{1.4498 \times 287 \times (180 + 273)} = 434.15 \text{ m/s}$$

The relationship between air density and pressure before and after compression is as follows:

$$\frac{P_O}{\rho_O} = \frac{P_I}{\rho_I}$$

Then, the density of compressed air is:

$$\rho_O = \frac{P_O \rho_I}{P_I} = \frac{10 \times 1.205}{0.101} = 119.3$$

According equation (3) and (4), the bulk modulus of air is:

$$K = k \rho_O RT_O = 1.4498 \times 119.3 \times 287 \times (180 + 273) = 2.248 \times 10^7 \text{ Pa}$$

According equation (6), the transmission speed of pressure wave $a'$ in pipeline can be obtained:

$$a = \frac{a'}{\sqrt{1 + [(K/E)(D/e)]C_1}} = \frac{434.15}{\sqrt{1 + (2.248 \times 10^7 / 1.2 \times 10^{11})(0.06 / 0.003) \times 1}} = 433.34 \text{ m/s}$$

### 3.2. Helmholtz muffler design

According to equation (1) and the calculated value of transmission speed of pressure wave $a$, the resonance frequency of muffler $f_H$ can be obtained like that:
The pulse frequency at the outlet of air compressor $f_p$ is:

$$f_p = \frac{970}{60} = 16.17 \text{Hz}$$

Which, $f_H = f_p$, we can obtained that:

$$\omega_H = \omega_p = 69 \sqrt{\frac{A}{LV}} = 16.17$$

From equation (9), it can be seen that the silencing effect of muffler is not only related to the structure parameters of the muffler, like $A$ and $V$, but also to its installation parameter $L$. In the design of muffler, the structure and installation of muffler can be designed at will according to the selected parameters. At this time, in order to reduce the randomness of the design work, we can use the existing product container to design the muffler structure, and then optimize the structure design.

When the standard capacity gas cylinder was used to be Helmholtz muffler, and the inner diameter of the existing high-pressure gas cylinder is 0.46m, and the volume is 0.41m$^3$, and the numbers of high-pressure gas cylinder required is $n$ ($n = 1, 2, 3, \cdots$), at this time, the volume of muffler $V$ is total volume of high-pressure gas cylinder, and the value is $n \times 0.41$. So only the parameters of $L$ needs to be calculated.

From equation (9), the structure installation parameter $L$ and the numbers of high-pressure gas cylinder required can be obtained like that:

$$17.1669 \times 1.0 = 46.92$$

This equation can be simplified as:

$$498.7 = n \times L$$

From equation (10), because the numbers of high-pressure gas cylinder required can only take integer values, so the number of high-pressure cylinder to be need is $7$, and the structure parameter $L$ is 1.07m; when the number $n$ is 8, the structure parameter $L$ is 0.937m, and when the number $n$ is 9, the structure parameter $L$ is 0.833m.

### 3.3. Calculation of transmission loss of Helmholtz muffler

Transmission loss is often used to describe the silencing effect of muffler. The transmission loss of Helmholtz muffler is [9]:

$$TL = 10 \log \left[ 1 + \frac{VA}{4LA_p^2} \left( \frac{f}{f_H} - \frac{f_H}{f} \right) \right]$$

Which, $TL$ is the transmission loss of Helmholtz muffler, $A_p$ is the sectional area of pipeline. When $n = 7$, the value $V$ is:

$$n \times 0.41 = 7 \times 0.41 = 2.87$$

And the structure parameter $L$ is 1.07m, substitute equation (9) into equation (11):
When \( n = 8 \), the value \( V \) is:

\[
 V = n \times 0.41 = 8 \times 0.41 = 3.28
\]

And the structure parameter \( L \) is 0.937m, substitute equation (9) into equation (11):

\[
 TL = 10 \log[1 + \frac{1.8208 \times 10^4}{(16.17 - \frac{f}{16.17})}] 
\]

When \( n = 9 \), the value \( V \) is:

\[
 V = n \times 0.41 = 9 \times 0.41 = 3.69
\]

And the structure parameter \( L \) is 0.833m, substitute equation (9) into equation (11):

\[
 TL = 10 \log[1 + \frac{2.3117 \times 10^4}{(16.17 - \frac{f}{16.17})}] 
\]

According equation (12), (13) and (14), we can obtain the change of transmission loss \( TL \) with frequency \( f \) under difference number of high-pressure cylinder which were used to be muffler, like Figure 2.

![Figure 2. The change of transmission loss \( TL \) with frequency \( f \) under difference number of high-pressure cylinder which were used to be muffler.](image)

4. Conclusion
In this paper, Helmholtz muffler is used to eliminate the air noise caused by the pressure fluctuation at the outlet of air compressor. Because the effect of muffler is related to the structure and installation of muffler, it is difficult to design it. By using standard high-pressure gas cylinder as Helmholtz muffler, the optimal relationship between the number of gas cylinders \( n \) and the structure installation parameter \( L \) can be obtained like equation (10).
And the change of transmission loss $TL$ with frequency $f$ under difference number of high-pressure gas cylinder which were used to be muffler was also be studied. From figure 2, the results shows that:

- When the frequency of pressure fluctuation at the outlet of air compressor is 16.17Hz, the silencing effect of Helmholtz muffler is the best, the transmission loss $TL$ reach to 65dB;
- Compared with high frequency, the transmission loss curve of Helmholtz muffler is steeper in the low frequency, which shows that it has a better effect on the low frequency;
- When the frequency $f$ is greater than 16.17Hz, the higher the frequency is, the worse the effect is;
- Under the condition of satisfying the optimization equation (10), the more the number of cylinders, which mean the larger the volume of muffler, the better the noise reduction effect.

Reference

[1] Y K Yuan, J T Yang and Q Gao 2005 Study of Pressure Pulsation in Discharge Muffler of Rotary Compressor Journal of Appl Sci & Tech vol 12 pp 40-42
[2] X Y Gao, J Xiong, S L Chen, K F Wang and M H Chen 2018 Research and application of rotor compressor exhaust cavity resonance noise Proceedings of China Household Appliance Technology Conference pp 602-606
[3] X D Sun, H J Lu, H Sun, H B Sun and C Liu 2017 Study on suction of compressor based on helmholtz resonator Technical acoustics vol 36 4 Aug pp 242-245
[4] X L Xing, M L Ren, Y Gu and B J Yao 2006 Analysis for influence of bulk-cavity effect on compressor’s pressure pulsation Gas turbine experiment and research vol 19 4 Nov pp 11-15
[5] Y G Cai 1990 Fluid transmission pipeline dynamics Ningbo:Zhejiang University Press chapter 2 pp 2-11 and chapter 4 pp 185-190
[6] Y Z Liu 2005 Research on Carbon Deposit of 66-10 Ship High Pressure Air Compressor Compressor technology vol 4 pp 43-45
[7] T C Xia 2006 Engineering fluid mechanics Shanghai:Shanghai Jiaotong University Press chapter 10 pp 239-241
[8] J R Zhang, T Y Zhao 1987 Handbook of thermophysical properties of engineering materials Beijing:new era press chapter 5 pp 203
[9] P G Cao, Z W Dou and G Chen 2016 Application of Helmholtz resonator in the suction muffler of refrigerator compressor Proceedings of China Household Appliance Technology Conference pp 691-695