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THE CALCULATING OF AIR COMPRESSOR INLET NOISE SPL

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ABSTRACT

This paper analyses the inlet noise of the piston compressor, and through experiments the main inlet noise source has been found, indicating that for the normal running compressor, the throttling jet noise of the inlet system is much more greater than the noise from valve plate and the impact noise of the piston ring, the throttling jet noise is the main noise source of the inlet system. Based on the above, the calculating formula of the inlet noise Sound Pressure Level (SPL) has been derived, and verified through 20 compressors of 11 types with capacities 0.6--100 M³/min.

SYMBOLS

\( c \) sound wave velocity before jet

\( C_0 \) sound wave velocity after jet

\( D \) first cylinder diameter

\( d \) jet diameter

\( d_s \) equivalent jet diameter

\( g \) acceleration of gravity

\( K \) \( \frac{C_p}{C_v} \)
\( L \) inlet noise SPL

\( L_{ij} \) inlet jet noise SPL

\( L_p \) impact noise SPL of the piston ring

\( L_v \) impact noise SPL of the valve plate

\( M \) Mach number

\( M_s \) equivalent Mach number of the inlet system

\( n \) Lighthill number

\( p \) atmospheric pressure

\( p_j \) jet noise pressure

\( p_0 \) fundamental sound pressure

\( R \) gas constant

\( r \) distance

\( T \) absolute temperature before jet

\( T_0 \) absolute temperature after jet

\( u \) piston velocity

\( V \) jet velocity, impact velocity

\( \varepsilon \) first stage pressure ratio

\( \rho \) air density

\( \eta \) damping coefficient

\( \delta_s \) relative suction pressure loss
INTRODUCTION

The air compressor is of a strong noise source. In order to prevent the noise pollution, limiting the noise has been legislated. So the noise index is important to appraise the air compressor. The noise of the compressor is radiated through the following three:

a) The inlet system noise.
b) The second solid noise transmitted by the machine body.
c) The solid noise produced by mechanical vibration and transmitted through the base.

Among the three the inlet noise is much more greater than the other two. Even if the best muffler is adopted, to the most, the inlet noise may be abated to the noise level transmitted by the machine body. For designing an advanced muffler, the inlet noise SPL must be known. Up to now, many people have done a lot based on the drawing of the compressor to calculate SPL and evident progress have been made. However it is too complicated because of the complicated mathematic model and it is too expensive, sometimes the expenditure is much more than the expenditure spent by building a muffler itself.

The calculating formula for inlet noise SPL derived in this paper has advantages of simple operation and need of no profound mathematics, in addition, it is based on the noise testing.

THE DERIVATION OF THE CALCULATING FORMULA FOR INLET NOISE

The inlet system consists of the all devices from the inlet of the air compressor to the surface - piston top of the first stage. So the noise produced within the inlet system has three sources:
a) The impact noise of the piston ring: the piston ring has three motions (along axis, radius and rotation), in addition, the piston has a simple harmonic motion, so the impact between piston ring and piston groove would occurred.

b) The impact noise of the valve plate: When operation, the valve plate will dash against the spring, valve lift guard, valve seat.

c) Throttling jet noise: The inlet system consists of several series throttlings (air filter, unloader valve, suction valve and so on).

Piling the three components of the noise by decibel, the inlet noise SPL will be given. Let \( L_p, L_v, L_j \) represent the three components of the noise separately. \( L \) represents the noise SPL, then

\[
L = 10 \log(10^{0.1L_p} + 10^{0.1L_v} + 10^{0.1L_j}) \quad (1)
\]

The \( L_j \) may be obtained by aeroacoustic. As for \( L_p \) and \( L_v \), we attain the two parameters by practically testing, then compared with \( L_j \) separately in order to obtain the ratios. The brief follows. After abolishing the impact noise of valve plate and piston ring in any way, then test the inlet noise SPL, that is the throttling jet noise SPL \( L_j \). Thereafter manage to get the piston ring noise back then test the inlet noise SPL, i.e. the decibel sum of \( L_j \) and \( L_p \). Resolving the sum by decibel, the \( L_p \) is obtained. In the same way the impact noise SPL \( L_v \) of the valve plate could be obtained also.

On the compressor L2-10/8-I, the above experiment is carried on. The impact noise depends on the damping coefficient \( \eta \) of the parts and the dashing load \( mv \). To prevent the impact noise, the material with high damping coefficient \( \eta \) and less density is used in place of the
cast iron piston ring and steel valve. In this case, \( L_p \) and \( L_v \) are nulled, so \( L_j \) is obtained. Thereafter, get the \( L_p \) and \( L_v \) back in turn to test the inlet noise, \( L_p \) and \( L_v \) are obtained separately. The result shows \( L_p \) and \( L_v \) are so much less than \( L_j \) that they could be neglected completely, i.e. the inlet noise of the compressor depends on the throttling jet noise, in that case

\[
L = 10 \log 10^{0.1L_j} = L_j
\]  

(2)

Let us calculate \( L_j \) by aeroacoustics. The formula for SPL is

\[
L = 20 \log \frac{p}{p_0}
\]

I.e.

\[
L = 20 \log \frac{p_j}{p_0}
\]  

(3)

Where \( p_p \) is the excess pressure of the throttling jet noise. The formula is

\[
p_j = \frac{1}{4} \sqrt{\frac{wce^2}{\pi \rho}}
\]  

(4)

For the air flow speed of the inlet system, the Mach Number \( M < 1 \), so the throttling jet noise power \( W \) may calculated using Lighthill speed to the eighth power formula

\[
W = \frac{n e^2 d^2 v^8}{C_0 C_0^5}
\]  

(5)

Where \( n \) represents the air density, \( C \) represents the sound speed. From a single stage cylinder and the inlet system continuous equation we can get

\[
V = \left( \frac{D}{d} \right)^2 u
\]  

(6)

And

\[
C = \frac{p}{RT}
\]

\[
C = \sqrt{KgRT}
\]

(7)  

(8)
The throttling jet is of an isentropic process, so
\[ \frac{p}{\rho^k} = \text{const} \]

Differentiate it and the formula (7), we can get
\[ \frac{dp}{\rho} = k \frac{d\rho}{\rho} \]
\[ \frac{d\rho}{\rho} = \frac{dp}{p} - \frac{dT}{T} \]

Based on the above two equations, we get
\[ \frac{dT}{T} = \frac{K-1}{K} \cdot \frac{dp}{p} \]
\[ \frac{\Delta T}{T} = \frac{K-1}{K} \cdot \frac{\Delta p}{p} \] (9)

Because of the relative pressure loss \( \Delta p/p \) is very small. We can see from (9), that the relative temperature variation is very small, too. In this case, we consider that the pressure, temperature are not changed before and after the throttling, i.e. \( p_0 = p, T_0 = T \). So from (7), (8) we get \( \rho_0 = \rho, C_0 = C \). Considering
\[ V = NC \] (10)

The formula of inlet system jet noise power of the air compressor is represented
\[ W = nkgpuD^2M^7 \] (11)

the inlet system consists of several throttlings in series, showing as Fig. 1.

Based on the formula (11), the following throttling jet noise powers are given:
\[ W_1 = nkgpuD^2M_1^7 \]
\[ W_2 = nkgpuD^2M_2^7 \]
\[ \vdots \]
\[ W_i = nkgpuD^2M_i^7 \]

Summing them, the total throttling jet noise power of the inlet system
\[ W = W_1 + W_2 + W_3 \ldots + W_i \]
\[ = n \text{k}g \text{pu}D^2 \sum_{i=1}^{N} M_i^7 \]  
(12)

Let \[ M_s^7 = \sum_{i=1}^{N} M_i^7 \]  
(13)

The \( M_s \) represents the equivalent Mach Number. Let the equivalent throttling corresponding to the \( M_s \) is \( d_s \), then Fig. 2 is equivalent to Fig. 1. Substituting (13) into (12) and considering \( M \) may be expressed as pressure loss \( \delta_s \)

\[ M_s = \sqrt[2]{\frac{2 \delta_s}{K}} \]

the formula (11) may be expressed as

\[ W = n \text{k}g \text{pu}D^2 \left( \frac{2 \delta_s}{K} \right)^{7/2} \]  
(14)

According to (4), (2), (14), the formula is reformed as

\[ L = 20 \log \left[ \frac{D}{P_o} \left( \frac{n \text{k}g \text{mu}}{\pi \beta} \right)^{1/2} \left( \frac{\delta_s}{K} \right)^{7/4} \right] \]

Considering the air compressor, \( K = 1.4 \), \( \beta = 0.1 \), \( P_o = 2 \times 10^{-5} \text{N/m}^2 \). Substituteing them into the above formula

\[ L = 188.64 + 35 \log \delta_s + 20 \log \frac{D}{P_o} + 10 \log \beta + 10 \log n \]
(15)

That is the final formula for inlet noise SPL of the air compressor. That is the final formula for inlet noise SPL of the air compressor. Where the limits of constant \( n \), according to Lighthill, are taken from \( 3 \times 10^{-5} \) to \( 1.8 \times 10^{-4} \). Based on the vast amount of data tested on the compressor L2-10 \( \beta \)-I, the constant \( n \) should be taken as \( 1.8 \times 10^{-4} \). So

\[ L = 151.19 + 35 \log \delta_s + 20 \log \frac{D}{P_o} + 10 \log \beta \]
(16)
Where the air compressor parameters $\delta_s$, $D$, $u$, are all known, $r$ represents the distance to test the noise. So it is convenient to calculate the air compressor inlet noise SPL through the formula (16). If the pressure loss $\delta_s$ of the inlet system is unknown, it may be looked up through Fig. 3 and corrected using $(u/3.5)^2$.

VERIFICATION OF THE FORMULA CORRECTNESS

To verify the correctness of this formula (16), this paper gives 20 compressors under 10 types and 6 capacities (0.6, 3, 10, 20, 40, 100 M$^3$/min). The last practically tested and calculated through the formula (16) are all shown in the table 1, from which we can see that they are nearly equal. The 19 errors are all small (0.2% - 3.8%) except one error is greater (6.8%).

To a certain extent, the result is satisfied, because there are lots of factors to affect the noise test, such as the atmospheric ambient, the circumstances of testing the noise, the instrument correctness, the skill of the operators and machine running state, and so on, even for the same one machine, the difference is unavoidable.
<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>Q (\text{m}^3/\text{min})</th>
<th>(D) (\text{m})</th>
<th>(u) (\text{m/s})</th>
<th>(\delta) (%)</th>
<th>(r) (\text{m})</th>
<th>(L=151.19+35\lg\delta+20\lg\frac{D}{r}+10\log\text{gu})</th>
<th>Measuring SPL (dB)</th>
<th>Error %</th>
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<tbody>
<tr>
<td>1</td>
<td>2V-0.6/7-B</td>
<td>0.6</td>
<td>0.09x2</td>
<td>2.66</td>
<td>6</td>
<td>1</td>
<td>(L=151.19-42.76-17.91+4.25=94.77)</td>
<td>92</td>
<td>3.0</td>
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<tr>
<td>2</td>
<td>2V-0.6/7-B</td>
<td>0.6</td>
<td>0.09x2</td>
<td>2.66</td>
<td>6</td>
<td>1</td>
<td>(L=151.19-42.76-17.91+4.25=94.77)</td>
<td>94</td>
<td>0.8</td>
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<td>3</td>
<td>V-3/8-1</td>
<td>3</td>
<td>0.21</td>
<td>3.59</td>
<td>6</td>
<td>1</td>
<td>(L=151.19-42.76-15.55+5.55=100.43)</td>
<td>99.5</td>
<td>0.9</td>
</tr>
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<td>4</td>
<td>2V-3/8-1</td>
<td>3</td>
<td>0.25</td>
<td>2.92</td>
<td>6</td>
<td>1</td>
<td>(L=151.19-42.76-12.04+4.65=101.04)</td>
<td>102</td>
<td>0.9</td>
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<td>6</td>
<td>0.21x2</td>
<td>3.59</td>
<td>6</td>
<td>1</td>
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<td>0.5</td>
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<td>6</td>
<td>L2-10/8-I</td>
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<td>(L=151.19-38.39-11.21+5.93=107.52)</td>
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<td>(\text{error})</td>
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<td>L3.5-20/7</td>
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<td>0.38</td>
<td>3.92</td>
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<td>0.5</td>
<td>(L=151.19-38.39-2.38+5.93=116.35)</td>
<td>118.5</td>
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<td>4L-20/8</td>
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<td>0.400</td>
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<td>6</td>
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<td>0.5</td>
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<td>1.55-40/8</td>
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<td>3.7</td>
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