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MATHEMATICAL ESTIMATION AND EXPERIMENTAL STUDY OF THE BLADDER TYPE WATER MUFFLER

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Using the simulation calculation method to analyze the acoustic characteristics of bladder type water muffler became dramatically difficult due to the non-linear constitutive relationship of the bladder rubber material and fluid - structure coupling effect of the liquid and the silencer. In order to study the acoustic characteristics of the bladder type water muffler, the influence of inner wall flexibility of silencer on the transmission of acoustic wave in liquid and air is considered based on the plane wave assumption, a simplified mathematical calculation model of the transmission loss of the muffler is proposed by the transfer matrix method. Based on the calculation model, the transmission loss of a bladder type water muffler is analyzed and an experimental study is carried out simultaneously. By comparing the experimental results and the calculated results, the correctness and availability of the simplified calculation model are verified. Meanwhile, the influence of the change of the inflating pressure in the bladder and working pressure of the pipe system on the performance of the muffler is also obtained.

Keywords: water muffler, mathematical calculation, transmission loss, transfer matrix

1. Introduction

The noise of the seawater pipeline is a significant component of the underwater radiation noise of ships. With other sources of the noise controlled, the noise of seawater becomes particularly prominent. The use of sea water muffler will reduce the radiation of the ship's seawater pipeline noise to the water, thereby enhancing the stealthiness of the ship or submarine in the water during voyage.

At present, the muffler most commonly used is resistance muffler for the gas pipeline, such as expansion muffler, resonant muffler, interference muffler etc. Researchers at home and abroad have been making close study about this kind of muffler for a long time, and put forward a variety of mature muffler performance calculation methods, which formed a classic silencer acoustic theory. Davis et al[1] first introduced the one-dimensional analytical method into the calculation of the expansion muffler and gave the formula for the muffler transmission loss. Munjal et al[2] first used the transfer matrix method to calculate the transmission loss of the muffler. Munjal's[3] monograph "Acoustic Ducts and Mufflers" gave the calculation method of the expansion muffler and other resistance muffler transfer matrices, which settled the foundation of the classical theory of the muffler. Miles[4] first used the multidimensional analytical method to analyze the acoustic characteristics of the muffler, and obtained the transmission loss of the muffler. Ih and Lee[5] analyzed the acoustic performance of an expansion muffler through a three-dimensional analytical method.

For the muffler with axisymmetric or relatively simple structure, the analysis of the muffler using the transfer matrix method or the multidimensional analysis method can achieve better accuracy and faster calculation speed. However, with the emergence of the complex structure of muffler, such as multi-cavity, connecting pipe, perforated tube, sound-absorbing material, etc., the above theoretical methods for the analysis of such mufflers become much more difficult. Thus, numerical simulation methods such as finite element method (FEM)[6], boundary element method (BEM)[7], finite difference method[8], computational fluid dynamics (CFD) method[9] are widely used to calculate the muffler performance of mufflers.

Water muffler, which has the same silencer principle as the air pipe muffler, is used for the liquid pipe. The bladder type water muffler is a new type of muffler, which has a perforated tube and a rubber bladder inside the expansion chamber structure. Its operation principle is that the pulsating pressure and the noise of the fluid would be absorbed when the bladder is deformed by the pressure of the liquid. Compared with the traditional resistance muffler, the bladder type water muffler has better performance, lower resistance loss, better control effect of low-frequency and smaller size, etc., and it has been widely used in the United States' and Russia's warships currently.

However, it is hardly to find the research literatures on the performance of the bladder type water muffler. What's more , it is also complicated and difficult to analyze the muffler characteristics by using the popular numerical simulation method due to the non-linear constitutive relationship of the bladder rubber material and fluid - structure coupling effect of the liquid and the silencer.

In order to study the acoustic characteristics of the bladder type muffler, based on the classical silencer acoustic theory, the muffler is simplified to a number of simple acoustic units, and the inner wall flexibility of the muffler is considered, a simplified calculation model of the transmission loss of the bladder type muffler is established by using the transfer matrix method. Based on this model, the transmission loss of the bladder type muffler is estimated, meanwhile, an experiment is carried out for verification. The experimental results show that the proposed method is practicable in engineering.

2. The Structure and working principle of the bladder type muffler

The structure of the bladder type muffler is shown in Fig. 1, which consists mainly of perforated structure, tubular rubber bladder, inflatable cavity, outer tube wall, valve etc. Its working principle is: when the pulsating fluids into the muffler through the perforated structure and comes into contact with the bladder, due to the much smaller rigidity of the gas compared with the rigidity of the liquid, thus, the pressure changes of the fluid will quickly affect the gas pressure and volume changes in the bladder. The pressure of the fluid caused by deformation of the bladder can attenuate the pulsation of the fluid, thereby reducing the noise and vibration of the piping system.

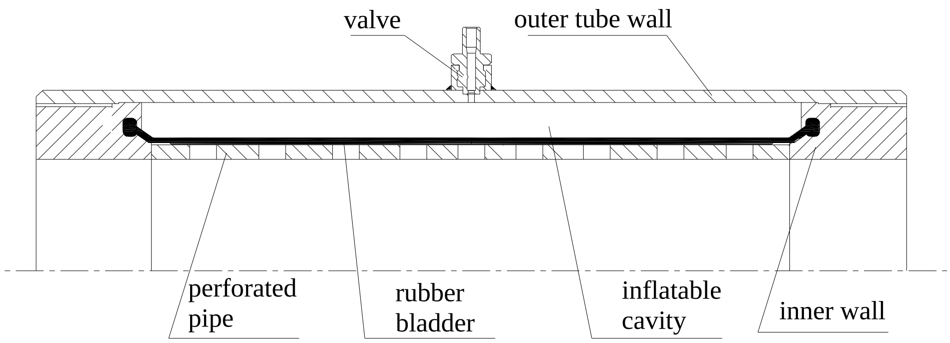

Figure 1: The structure of the bladder type muffler.

3. The transfer matrix method

According to the plane wave hypothesis, the sound pressure and sound quality velocity at the inlet end of the silencer are P_1 and v_1 （$=\rho_1 S_1 u_1$） respectively. The corresponding values at the outlet are P_2 and v_2 （$=\rho_2 S_2 u_2$） . According to the transfer matrix method, the sound pressure and sound mass velocity of the inlet and outlet sections can be expressed as:

$$\begin{Bmatrix} p_1 \\ v_1 \end{Bmatrix} = \begin{bmatrix} A_s & B_s \\ C_s & D_s \end{bmatrix} \begin{Bmatrix} p_2 \\ v_2 \end{Bmatrix} = [T] \begin{Bmatrix} p_2 \\ v_2 \end{Bmatrix} \tag{1}$$

Where, $[T]$ is the transfer matrix of the acoustic unit, A_s、B_s、C_s、D_s are the four pole parameters of the system.

Assuming that the muffler is divided into n units, the transfer matrix of the i-th acoustic unit is T_i. The total transfer matrix of the muffler can be expressed as:

$$[T] = [T_1][T_2][T_3]\cdots[T_n] \tag{2}$$

The relationship between the inlet and outlet parameters of the muffler is:

$$\begin{Bmatrix} p_1 \\ v_1 \end{Bmatrix} = [T] \begin{Bmatrix} p_n \\ v_n \end{Bmatrix} \tag{3}$$

3.1 The calculation method of transmission loss

The transmission loss of the muffler is defined as the difference between the incident sound power level of the muffler inlet and the transmitted sound power level at the outlet when the outlet is not reflected,

$$TL = L_{W_i} - L_{W_t} = 10\lg\left(W_i/W_t\right) \tag{4}$$

Where, W_i and W_t are the incident sound power at the entrance and the transmitted sound power at the exit, respectively.

When the sound into and out of the muffler is a plane wave, the incident and transmitted sound power can be expressed as:

$$W_i = S_1 I_i = \frac{S_1(1+M_1)^2 \left|P_i\right|^2}{\rho_1 c_1} \tag{5}$$

$$W_t = S_2 I_t = \frac{S_2(1+M_2)^2 \left|P_t\right|^2}{\rho_2 c_2} \tag{6}$$

The transmission loss can be expressed by four pole parameters:

$$TL = 20\lg\left\{\left(\frac{S_1}{S_2}\right)^{1/2}\left(\frac{1+M_1}{1+M_2}\right)\left(\frac{\rho_2 c_2}{\rho_1 c_1}\right)^{1/2}\frac{1}{2}\left|A + B\left(\frac{S_2}{c_2}\right) + C\left(\frac{c_1}{S_1}\right) + D\left(\frac{c_1}{S_1}\frac{S_2}{c_2}\right)\right|\right\} \tag{7}$$

Where, I_i and P_i are the sound intensity and sound pressure at the entrance of the muffler, I_t and P_t are the transmitted sound intensity and the sound pressure at the outlet, respectively. S_1、ρ_1、c_1、M_1 and S_2、ρ_2、c_2、M_2 are the cross - sectional area、the density of the medium、speed of sound and the mach number at the inlet and outlet the muffler.

If the temperature and cross-sectional area of muffler at the entrance and exit are the same, the above formula can be simplified as:

$$TL = 20\lg\left\{\frac{1}{2}\left|A + B\left(\frac{S_1}{c_1}\right) + C\left(\frac{c_1}{S_1}\right) + D\right|\right\} \tag{8}$$

3.2 The Transfer Matrix of the bladder type Muffler

When the liquid passes through the muffler, the pressure of the gas in the bladder will keep balance with the pressure of the liquid at any time due to the much smaller rigidity of the gas compared with the rigidity of the liquid. So the transmission of the acoustic wave in the liquid will be converted into transmission through the gas in the bladder by the deformation of the airbag.

Therefore, this paper suggests that the transmission of the acoustic wave in the muffler can be divided into three stages. The first and third stages are the transmission of acoustic wave in the liquid column at the inlet and outlet. The second stage is the transmission of acoustic wave through the bladder cavity. According to the principle of transfer matrix method, the model of bladder muffler is simplified as the three simple acoustic units shown in Fig. 2. The first and third units are used to describe the transmission of acoustic wave in the liquid column at the inlet and outlet of the muffler and the second unit is used to describe the transmission of acoustic wave in the annular air column at the muffler working section. The above three simple acoustic units can be regarded as circular pipe units with equal cross section.

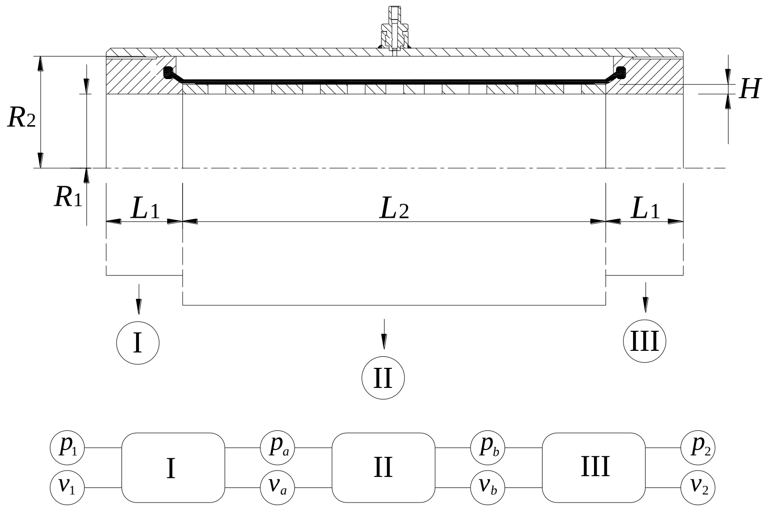

Figure 2: The acoustic units division of the bladder type muffler.

The sound pressure and sound volume velocity at the entrance and exit of the entire muffler are p_1 、 v_1 and p_2 、 v_2 respectively， The sound pressure and sound volume velocities of the inlet and outlet of the second acoustic unit are p_a 、 v_a and p_b 、 v_b .

For the first and third units, consider the effect of the inner wall flexibility of the muffler on the transmission of the acoustic wave in the inlet and outlet liquid column. The transfer matrixes can be written as follow:

$$\begin{Bmatrix} p_1 \\ v_1 \end{Bmatrix} = \begin{bmatrix} a_1 & b_1 \\ c_1 & d_1 \end{bmatrix} \begin{Bmatrix} p_a \\ v_a \end{Bmatrix} = \begin{bmatrix} \cos k_{mp} L_1 & j \dfrac{\rho c_{mp}}{S_1} \sin k_{mp} L_1 \\ j \dfrac{S_1}{\rho c_{mp}} \sin k_{mp} L_1 & \cos k_{mp} L_1 \end{bmatrix} \begin{Bmatrix} p_a \\ v_a \end{Bmatrix} \tag{9}$$

$$\begin{Bmatrix} p_b \\ v_b \end{Bmatrix} = \begin{bmatrix} a_3 & b_3 \\ c_3 & d_3 \end{bmatrix} \begin{Bmatrix} p_2 \\ v_2 \end{Bmatrix} = \begin{bmatrix} \cos k_{mp} L_3 & j \dfrac{\rho c_{mp}}{S_3} \sin k_{mp} L_3 \\ j \dfrac{S_3}{\rho c_{mp}} \sin k_{mp} L_3 & \cos k_{mp} L_3 \end{bmatrix} \begin{Bmatrix} p_2 \\ v_2 \end{Bmatrix} \tag{10}$$

where， $c_{mp} = \dfrac{c}{\sqrt{1 + 2\rho c^2 R_1 / (\rho_{cm} h_{cm} c_{np}^2)}}$ is the speed of the sound in the liquid when the flexibility of the inlet and outlet wall of the Muffler is considered; L_1 and L_3 are the length of the inlet and outlet straight pipe of the muffler, respectively; ρ is the density of the liquid in the pipe; c is the speed of sound in the liquid; $k_{mp} = \omega / c_{mp}$ is the wave number; ρ_{cm} is the density of the wall material of the inlet and outlet sections; h_{cm} is the thickness of the pipe wall of the inlet and outlet sections; $c_{np} = \sqrt{\dfrac{E_{cm}}{\rho_{cm}(1-\nu^2)}}$ is the velocity of the longitudinal wave in the pipe wall; E_{cm} is the Elastic modulus of wall material; ν is the Poisson's ratio of the wall material; S_1 and S_3 are the cross-sectional area of the fluid at the inlet and outlet pipes; R_1 is the radius of the inside wall of the pipe.

For the second unit of the muffler with bladder-containing pipe section, based on the above assumption, the transmission of sound waves in the circular air column section is considered, the transfer matrix is as follow:

$$\begin{Bmatrix} p_a \\ v_a \end{Bmatrix} = \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix} \begin{Bmatrix} p_b \\ v_b \end{Bmatrix} = \begin{bmatrix} \cos k_a L_2 & j\dfrac{\rho_a c_a}{S_3}\sin k_a L_2 \\ j\dfrac{S_3}{\rho_a c_a}\sin k_a L_2 & \cos k_a L_2 \end{bmatrix} \begin{Bmatrix} p_b \\ v_b \end{Bmatrix} \tag{11}$$

where, L_2 is the length of the middle tube with bladder; $\rho_a = 1.4\dfrac{P_w}{c_a^2}$ is the density of air under working pressure; P_w is the air pressure inside the bladder; c_a is the speed of sound in the air; $k_a = \omega / c_a$ is the wave number; $S_3 = \pi\left[R_2^2 - (R_1+H)^2\right]$ is the cross-sectional area of the bladder.

According to Eq. (3), the transfer matrix of the entire muffler system is as follow:

$$\begin{Bmatrix} p_1 \\ v_1 \end{Bmatrix} = [T]\begin{Bmatrix} p_2 \\ v_2 \end{Bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{Bmatrix} p_2 \\ v_2 \end{Bmatrix} \tag{12}$$

Where, $[T] = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} a_1 & b_1 \\ c_1 & d_1 \end{bmatrix}\begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix}\begin{bmatrix} a_3 & b_3 \\ c_3 & d_3 \end{bmatrix}$ is the transfer matrix of the muffler.

If the length and cross-sectional area of the inlet and outlet sections are equal, we can get $A = a_2a_1^2 + c_2b_1a_1 + b_2a_1c_1 + a_2b_1c_1$, $B = 2a_2a_1b_1 + b_2a_1^2 + c_2b_1^2$, $C = 2a_2a_1c_1 + b_2c_1^2 + c_2a_1^2$, $D = A$.

According to Eq. (8), the transmission loss of the muffler can be written as:

$$TL = 20\lg\left\{\frac{1}{2}\left|A + B\left(\frac{S_1}{\rho c_{mp}}\right) + C\left(\frac{\rho c_{mp}}{S_1}\right) + D\right|\right\} \tag{13}$$

4. Case study and Experiment

According to the estimation method proposed in this paper, the transmission loss of the bladder type water muffler is calculated. The structural parameters of the muffler are shown in Table 1, and the inflating pressure of the airbag is set as 0.5Mpa, 1.0Mpa, 1.5Mpa and 2.0Mpa, respectively. The one-third octave spectra (20Hz -1000Hz) of the transmission loss under four conditions are shown in Fig. 6 to Fig. 9.

Table 1: The structural parameters of the bladder muffler

structural parameter	**value**	**structural parameter**	**value**
ρ (kg/m^3)	1250	L_2 (m)	0.35
c (m/s)	1520	L_3 (m)	0.105
R_1 (m)	0.05	E_{cm} (N/m^2)	1.2E+11
R_2 (m)	0.072	ρ_{cm} (kg/m^3)	8900
H (m)	0.016	h_{cm} (m)	0.023
L_1 (m)	0.105	c_a (m/s)	340

In order to verify the correctness of the estimation results, the performance test of the muffler of the same specification is carried out. There are many test methods for the measurement of transmission loss, such as impulse method, decomposition method, two-source method and two-load method, etc. In this paper, the two-source method is adopted. Readers can refer to the specific measurement principles and methods in reference [10]. The Test measurement diagram is shown in Figure 1, the test site is shown in Fig. 2. Similarly, when the pressure of the bladder were set as 0.5Mpa, 1.0Mpa, 1.5Mpa, 2.0Mpa, the one-third octave spectra (20Hz -1000Hz) of the transmission loss are shown in Fig. 6 to Fig. 9.

It should be noted that the muffler works effectively only when the inflation pressure in the bladder is lower than the pressure of water in piping system. So in the test process, the water pressures of the pipeline system were set to 0.6MPa, 1.1MPa, 1.7MPa, 2.2MPa in the above four conditions.

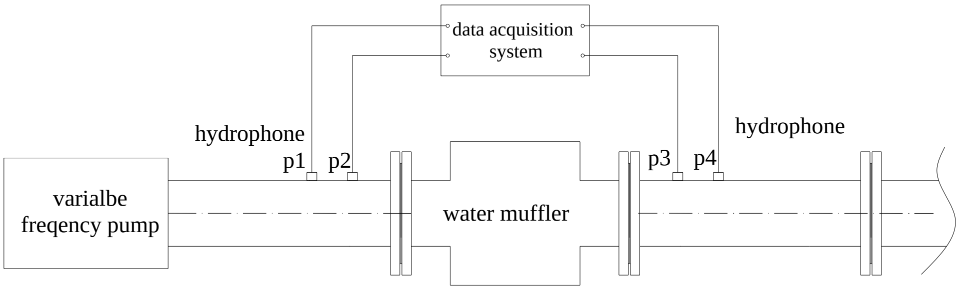

Figure 3: The measurement diagram of the experiment.

Figure 4: The testing ground.

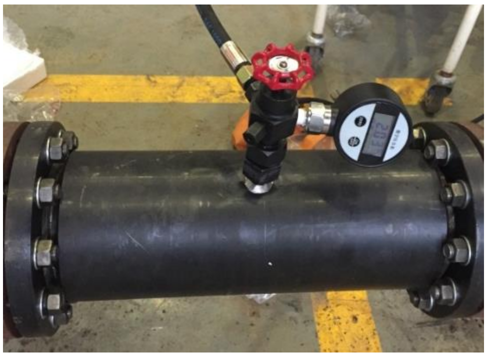

Figure 5: Physical prototype of the bladder type water muffler.

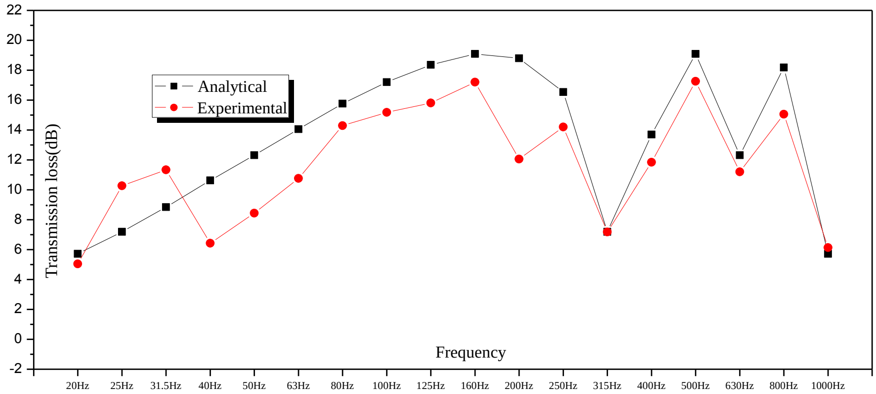

Figure 6: The one-third octave spectra of the transmission loss (Pw=0.5Mpa).

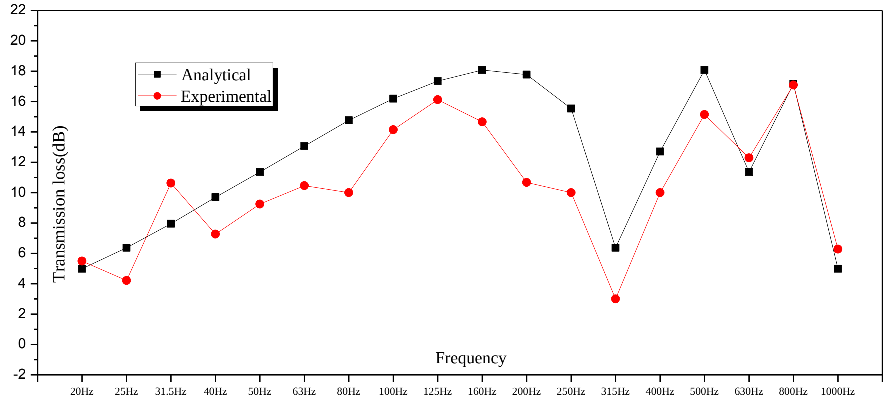

Figure 7: The one-third octave spectra of the transmission loss (Pw=1.0Mpa).

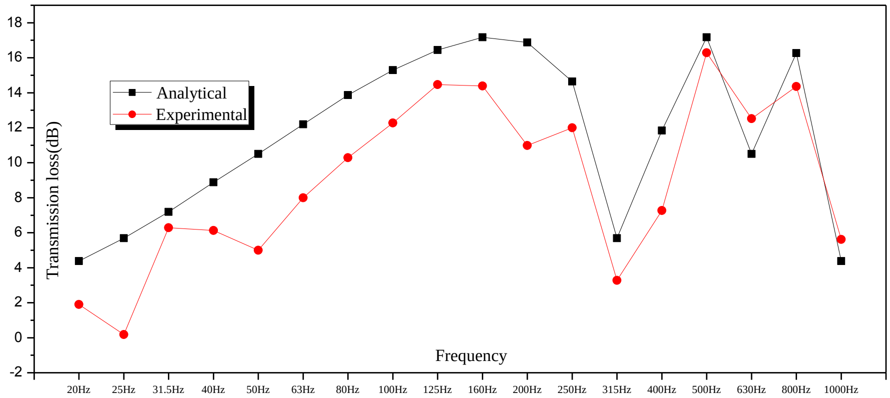

Figure 8: The one-third octave spectra of the transmission loss (Pw=1.5Mpa).

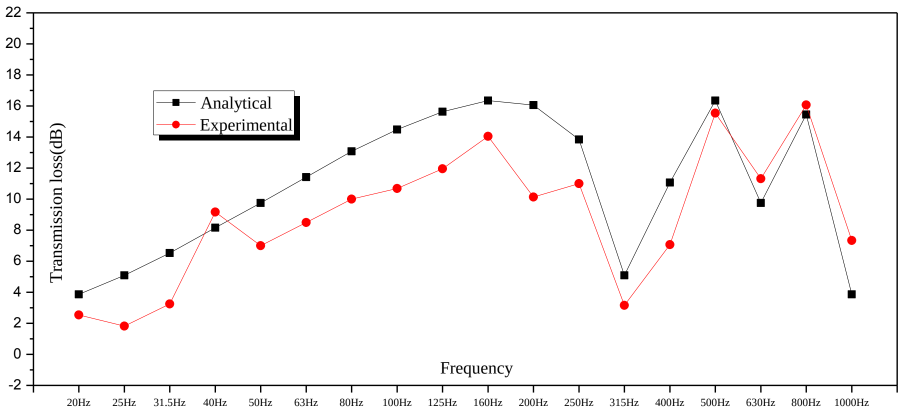

Figure 9: The one-third octave spectra of the transmission loss (Pw=2.0Mpa).

It can be seen that the estimated results of this method is well consistent with the experimental results, which basically reflects the variation tendency that the transmission loss varies with frequency, especially in the middle and high frequency range. However, this method has some prediction error in the low frequency range, which indicates that the method may not accurately reflect the low frequency muffling properties of the rubber material. Even though, from the perspective of engineering estimation, the calculation method contains sufficient accuracy, making it of certain reference value for design.

At the same time, in order to analyze the effect of the bladder pressure on its muffling performance, the total sound pressure level (20Hz -1000Hz) of transmission loss of the muffler under different working conditions is obtained as shown in Fig. 10. It can be seen from the figure that with the increase of the inflation pressure of the airbag, the total sound pressure level (20 Hz -1000Hz) of transmission loss of the muffler decreases gradually, that is, the performance of the muffler decreases gradually with the increase of the airbag pressure.

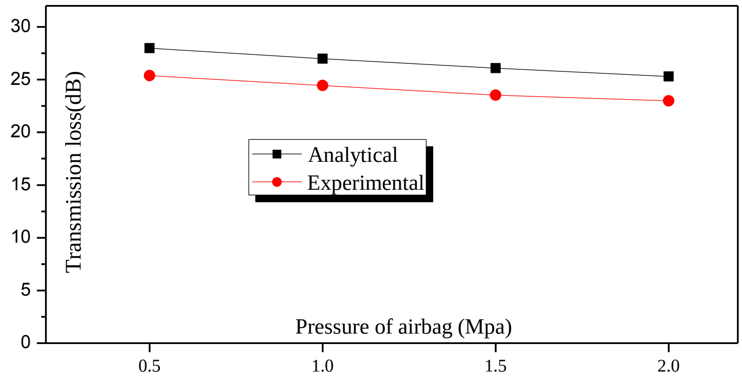

Figure 10: The total sound pressure level (20Hz -1000Hz) of transmission loss in different conditions.

5. Conclusion

The method of estimating the transmission loss of the bladder type water muffler proposed in this paper can be a valuable reference for design, and the estimation results can basically reflect the variation law of the transmission loss of the muffler. This estimation method has better prediction accuracy in the middle and high frequency band, though there are some errors in the low frequency band. The calculation results and the experimental results show that the transmission loss of the muffler has a certain relationship with the inflatable pressure of the airbag. With the increase of the pressure in the bladder, the transmission loss of the muffler is gradually reduced, that is, the muffler performance of the muffler is gradually weakened.

6. Acknowledgment

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