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***Research paper***

# Effects of Parameters of Helmholtz Resonator on Transmission Loss of Hybrid Muffler

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**Abstract**

Expansion chamber and Helmholtz resonators are widely used in noise control. In this paper, they are combined to use as a hybrid muffler. The analysis is done to investigate the influence of the parameters of Helmholtz resonator on transmission loss. The transfer matrix method is used in the analysis. The result of transmission loss from the transfer matrix method is validated with the result from experimental two-load method using four microphones impedance tube. After had the transmission loss of the hybrid muffler been validated, the study was proceeded to investigate the effects of parameters of Helmholtz resonator on the transmission loss. The root mean square value of transmission loss were also calculated to compare the transmission losses clearly. In this paper, we investigated the effect of length of the neck of Helmholtz resonator, the effect of diameter of the neck of Helmholtz resonator, the effect of the length of the Helmholtz resonator cavity and the effect of the diameter of the Helmholtz resonator cavity for stationary medium. It is found that the transmission loss is increased when the diameter of the neck of Helmholtz resonator is increased. When the length of the neck is reduced, the transmission loss is increased. The transmission loss can also be increased by reducing the diameter of resonator cavity. It is better to increase the transmission loss at low frequencies by increasing the length of the resonator cavity.

***Keywords***: *Expansion chamber; Helmholtz resonator; Hybrid muffler; Transfer matrix method; Transmission loss.*

## 1. Introduction

Sounds which disturb people or make it difficult to hear wanted sounds are called noise. The muffler is made to reduce the noise of the exhaust system for human comfort. Mufflers are used in many applications such as industries and automobiles. There are two main types of automotive muffler (1) reactive muffler and (2) absorptive muffler [1]. The reactive mufflers apply the interference in the way of gas flowing by reflections. Reflections occurs where there is an area change in the way. The absorptive mufflers reduce the noise by absorbing the sound energy with the application of absorptive materials. In several applications, expansion chambers are used as an effective tool for noise reduction [2]. Resonators are also used as a device to attenuate the noise of the exhaust system. Helmholtz resonator consists of a cavity connecting the main duct by mean of a duct. This resonator is used widely to attenuate the narrow-band low frequency noise [3].

The invention of new design of the muffler is usually a complicated work. Many researchers try to make the new designs of mufflers that can be used in many applications. C.J. Wu et al. [4] made the performance prediction of single-inlet/double-outlet and double-inlet/single outlet expansion chamber mufflers Another researcher Ying-li Shao [5] studied a new type of muffler using both counter phase –counteract and split-gas rushing. The exhaust gas is introduced into the chamber by means of a U-shaped bypass pipe. The low frequency noise can effectively be controlled by the new muffler.

There are researches that use Helmholtz resonator as the noise attenuators. M. B. Xu et al [3] studied about the dual Helmholtz resonator consisting of two resonators in series (neck-cavity-neck-cavity) investigated for transmission loss and resonance frequency as the performance of the resonator. It is stated that a reasonable agreement is made in comparing the transmission loss and the resonance frequency from the lumped and 2D analytical approaches, BEM and experiments. It is also mentioned that while keeping the total volumes of the two cavities, the first resonance frequency may be lowered with the decreasing volumes ratio of $V_1/V_2$. Nearly equal transmission loss can be acquired for dual resonator of the same dimension, but suggested to investigate more about the multiple acoustical performance, by changing (a) radius of the cavity (b) length and radius of the neck. [3]

In this paper, a new design of exhaust muffler is introduced to attenuate the noise of exhaust. A new type of muffler is introduced by using expansion chamber muffler and Helmholtz resonator. The performance of the new designed muffler is investigated using transmission loss (TL) by the transfer matrix method (TMM) [6]. An experiment is done by using the impedance tube method to validate the numerical model. After the model is validated, the performance of the designed muffler is studied by changing the parameters such as (1) diameter of the neck (2) length of the neck and (3) the diameter of Helmholtz resonator cavity and (4) the length of the cavity of Helmholtz resonator in the absence of mean flow as mentioned in [3].

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## 2. Theoretical Approach

### 2.1. Plane Wave Propagation Theory

For plane wave propagation [7-9] in the rigid straight pipe which has a cross-sectional area *S*, length of *L*, and carrying a turbulence incompressible mean flow having velocity *V*, as shown in Figure 1, the sound pressure *p* and the volume velocity *v* can be represented as the sum of left and right travelling waves. By the time the influence of higher order mode effect is neglected, the plane wave propagation model has the validity to use. The relation of sound pressure *p* and volume velocity *v* at the end of upstream (*x=0*) and downstream (*x=L*) is represented by

$$p_1 = Ap_2 + Bv_2 \tag{1}$$

and

$$v_1 = Cp_2 + Dv_2 \tag{2}$$

where *A*, *B*, *C* and *D* are four-pole constants which are dependent on frequency and the acoustic properties of the pipe.

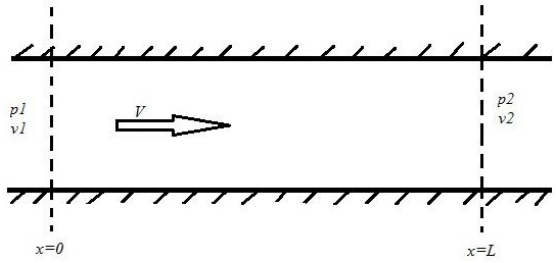



**Fig. 1**: Plane wave propagation in a rigid straight pipe carrying a turbulence incompressible mean flow: p1,v1=pressure and velocity at inlet, p2,v2=pressure and velocity at outlet, V=flow velocity

M. L. Munjal [9] shows that the four-pole constants of the pipe with the non-viscous medium are

$$A = e^{(-jMk_cL)}\cos(k_cL), \tag{3}$$

$$B = jY\,e^{(-jMk_cL)}\sin(k_cL), \tag{4}$$

$$C = (j/Y)\,e^{(-jMk_cL)}\sin(k_cL) \tag{5}$$

and

$$D = e^{(-jMk_cL)}\cos(k_cL) \tag{6}$$

where $M = V/c$ is the mean flow Mach number (*M<0.2*), c is the sound speed (*m/s*), $k_c = k/(1-M^2)$ is the convective wave number (*rad/m*), $k=\omega/c$ is the acoustic wave number, $\omega$ is the angular frequency (*rad/s*), *j* is the square root of -1, $Y=\rho c/S$ is the characteristic impedance, $\rho$ is the density of fluid ($kg/m^3$), and *S* is the cross-sectional area of the pipe. For the stationary medium (without mean flow Mach number), substitute *M*=0 in equations (3) to (6).

### 2.2. Transfer Matrix Method

The transfer matrix is used when the whole system can be represent into the sequence of subsystem that interact only with the subsystem [10]. The transfer matrix relates the sound pressure and velocity at the inlet and outlet of the element such as in a straight pipe as stated above. So, it has a frequency dependent property and it applies the reciprocity principle.

M.L. Munjal [9] expressed the transfer matrix applying on the simple expansion chamber system shown in Figure 2 as follows,

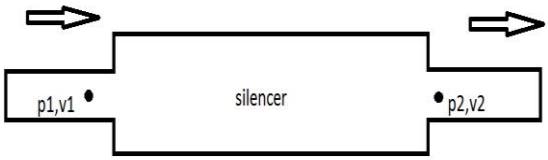



**Fig. 2**: Transfer matrix method measuring points: p1,v1=pressure and velocity at inlet, p2,v2=pressure and velocity at outlet

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} p_2 \\ v_2 \end{bmatrix} \tag{7}$$

where $p_1$ and $v_1$ are the pressure and velocity at inlet and, $p_2$ and $v_2$ are the pressure and velocity at outlet. *A*, *B*, *C* and *D* are the elements of transfer matrix. One advantage of using transfer matrices to describe a muffler is that multiple sub-mufflers can be connected to each other by multiplying the transfer matrices [11].

### 2.3. Transfer Matrix Extraction of the Muffler

In this section, the extraction of transfer matrix is discussed. Transfer matrices are different according to the situation in which they are existed. The transfer matrix of the hybrid is derived by calculating the transfer matrices of the different elements of the designed muffler.

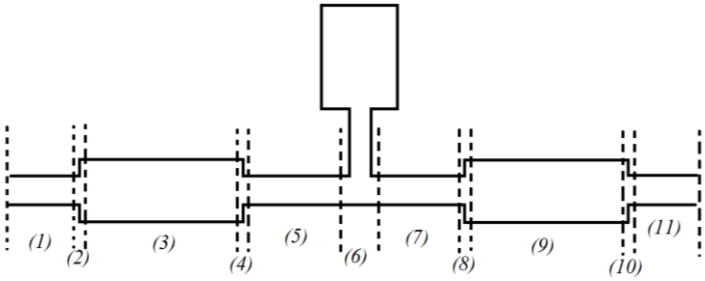



**Fig. 3**: Transfer matrix distribution of Hybrid muffler

Firstly, the transfer matrix for the system is calculated by separating the muffler into simple expansion chamber and Helmholtz resonator. M. L. Munjal [9] expressed the transfer matrices for different geometry of a muffler.

$$T_i = \begin{bmatrix} \cos(kl_i) & jY_i\sin(kl_i) \\ \frac{j}{Y_i}\sin(kl_i) & \cos(kl_i) \end{bmatrix} \tag{8}$$

where '*i*' represents the elements number 1, 3, 5, 7, 9 and 11 in Figure 3.
For the stationary medium, the transfer matrix for sudden expansion or contraction is given by [9]

$$T_2 = T_4 = T_8 = T_{10} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{9}$$

After deriving the transfer matrix of the expansion chambers, the transfer matrix of the Helmholtz resonator is also derived.

### 2.4. Helmholtz Resonator System

Attaching a resonator on a duct reduces the noise at a specific frequency which is the characteristics of the resonator's geometry [12]. In deriving the transfer matrix of Helmholtz resonator, the

two end-correction factors of the neck of the resonators are involved as a key issue in theoretical analysis of a HR system. They are (1) the neck-cavity interface end-correction factor and (2) the neck-duct interface end-correction factor. These two factors must be added to the actual physical length of the neck of HR in order to obtain the effective neck length. The Helmholtz resonator including the end-correction factors is shown in Figure 4.

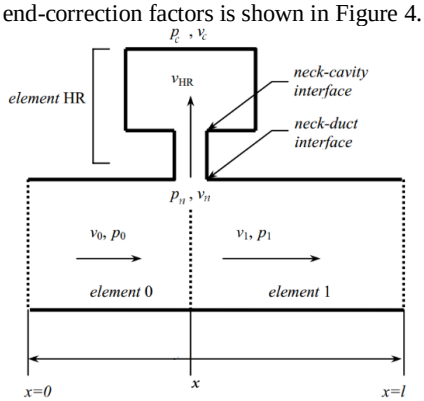



**Fig. 4**: Schematic of HR system: $v_0$,$p_0$=velocity and pressure at element 0, $v_1$,$p_1$=velocity and pressure at element 1, $p_n$,$v_n$=pressure and velocity at neck of HR, $p_c$,$v_c$=pressure and velocity of cavity, $v_{HR}$=velocity inside HR

The expression for the neck-cavity interface end correction factor is given by [13]

$$\delta_{n-c} = 0.82r\left(1-1.33\frac{r}{R}\right) \tag{10}$$

where $r$ is the radius of the neck of the HR, and $R$ is the radius of the cavity of HR.

On the other hand, the expression for the neck-duct interface end-correction factor is derived based on the ratio of neck and duct diameter using boundary element analysis. The expressions are given by [14]

$$\delta_{n-d} = r\left\{0.8216-0.0644\left(\frac{r}{a}\right)-0.694\left(\frac{r}{a}\right)^2\right\};\frac{r}{a}\le 0.4\ ,$$

(or)

$$\delta_{n-d} = r\left\{0.9326-0.6196\left(\frac{r}{a}\right)\right\};\frac{r}{a}>0.4 \tag{11}$$

where '$r$' is the radius of the neck of HR and '$a$'is the radius of the duct to which HR is mounted.

## 2.5. Transfer Matrix of Helmholtz Resonator

The transfer matrix of the Helmholtz resonator is derived according to the descriptions from the Figure-5. According to the continuity condition, the volume velocity and pressure are locally maintained at junction *x*. Thus,

$$p_0(x) = p_1(x) = p_n(x) \tag{12}$$

$$v_0(x) = v_n(x) + v_1(x) \tag{13}$$

Putting equation (12) and (13) in matrix form,

$$\begin{bmatrix} p_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} p_1 \\ v_n + v_1 \end{bmatrix} \tag{14}$$

$$\begin{bmatrix} p_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{v_n}{p_1} & 1 \end{bmatrix}\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} \tag{15}$$

From equation (12), $p_1(x) = p_n(x)$ and also the acoustics impedance of just outside the opening of HR is $Z_{HR} = \frac{p_n}{v_n}$ , the equation (15) can be rewritten as

$$\begin{bmatrix} p_0 \\ v_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{HR}} & 1 \end{bmatrix}\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} \tag{16}$$

Hence, the transfer matrix of Helmholtz resonator is represented as

$$T_6 = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z_{HR}} & 1 \end{bmatrix} \tag{17}$$

By relating the pressure and volume velocity at the opening of neck and at the end of the cavity, the transfer matrix of the Helmholtz resonator is expressed as

$$\begin{bmatrix} p_n \\ v_n \end{bmatrix} = \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix}\begin{bmatrix} A_c & B_c \\ C_c & D_c \end{bmatrix}\begin{bmatrix} p_c \\ v_c \end{bmatrix} \tag{18}$$

where,

$$A_n = D_n = \cos(k(l_n + \delta_{n-c} + \delta_{n-d})),$$

$$B_n = jY_n \sin(k(l_n + \delta_{n-c} + \delta_{n-d})),$$

$$C_n = \frac{j}{Y_n}\sin(k(l_n + \delta_{n-c} + \delta_{n-d})),$$

$$A_c = D_c = \cos kl_c,\ B_c = jY_c \sin kl_c,\ C_c = \frac{j}{Y_c}\sin kl_c$$

Let us write the resultant matrix of equation (18) as,

$$\begin{bmatrix} p_n \\ v_n \end{bmatrix} = \begin{bmatrix} A_{HR} & B_{HR} \\ C_{HR} & D_{HR} \end{bmatrix}\begin{bmatrix} p_c \\ v_c \end{bmatrix} \tag{19}$$

As the end of the resonator is solidly terminated, there will be no flow at the end of the cavity $(v_c = 0)$ . Substituting $v_c = 0$ in equation (19), the acoustic pressure and volume velocity at the opening of the neck becomes

$$p_n = A_{HR}\, p_c \tag{20}$$

$$v_n = C_{HR}\, p_c \tag{21}$$

By dividing equation (20) by equation (21), it gives the input impedance of the HR as

$$\frac{p_n}{v_n} = Z_{HR} = \frac{A_{HR}}{C_{HR}} \tag{22}$$

## 2.6. Overall Transfer Matrix of the Hybrid Muffler

The overall transfer matrix relation of the system in figure 3 can be written as the multiplication of all the adjacent individual transfer matrices. Therefore, the overall transfer matrix of the system becomes

$$T_{overall} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = T_1T_2T_3T_4T_5T_6T_7T_8T_9T_{10}T_{11} \quad (23)$$

where $T_{11}$, $T_{12}$, $T_{21}$ and $T_{22}$ are the elements of the overall transfer matrix of the system.

### 2.6. Transmission Loss Evaluation

Transmission loss only depends on the muffler and not on the source. Transmission loss is considered as the best parameter to use in calculating the performance of a muffler comparing to others. Transmission loss (decibels) is defined as the difference between the incident sound power and transmitted sound power [11]. Transmission loss which can be calculated through transfer matrix is given [9], where $Y_n$ is the characteristic impedance of last part of muffler and $T_{ij}$ is the elements of total transfer matrix, as in equation (24)

$$TL = 20\log\left[\left(\frac{Y_n}{Y_1}\right)^{\frac{1}{2}}\left|\frac{T_{11}+T_{12}/Y_n+T_{21}Y_1+T_{22}Y_1/Y_n}{2}\right|\right] \quad (24)$$

## 3. Mathematical Model

In this paper, a study is done by modelling a hybrid muffler and the performance of muffler is validated by an experimental result. In modelling the muffler, the design of muffler is shown in Figure 5.

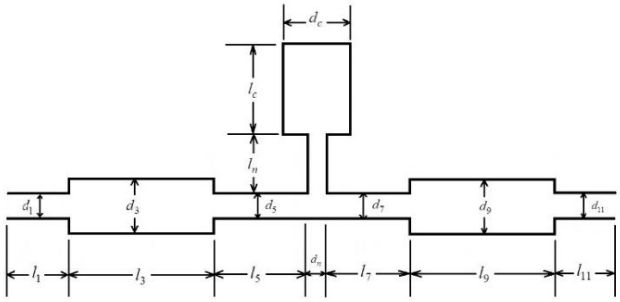



**Fig. 5**: Design parameters of the hybrid muffler: $d_1$, $d_5$, $d_7$, $d_{11}$= inlet and outlet pipes diameters of expansion chambers, $d_3$, $d_9$= diameter of expansion chambers, $d_c$= diameter of Helmholtz Resonator cavity, $d_n$= diameter of neck of Helmholtz Resonator, $l_1$= length of inlet pipes of front expansion chamber, $l_3$, $l_9$= length of expansion chambers, $l_5$= length of outlet pipe of front expansion chamber, $l_n$= length of neck of Helmholtz Resonator, $l_c$= length of Helmholtz Resonator cavity, $l_9$= length of inlet pipe of rear expansion chamber, $l_{11}$= length of outlet pipe of rear expansion chamber

The parameter values of hybrid muffler are shown in Table 1. These values are used only for the investigation of the muffler transmission loss and influences of parameters. These values can be optimized later by using optimization methods.

**Table 1**: Parameter values of hybrid muffler

| Parameter | Symbol | Dimension(mm) |
|---|---|---|
| Inlet and outlet pipes diameters of expansion chambers | $d_1$, $d_5$, $d_7$, $d_{11}$ | 34.86 |
| Diameter of expansion chambers | $d_3$, $d_9$ | 100 |
| Diameter of Helmholtz Resonator cavity | $d_c$ | 60 |
| Diameter of neck of Helmholtz Resonator | $d_n$ | 20 |
| Length of inlet pipes of front expansion chamber | $l_1$ | 60 |
| Length of expansion chambers | $l_3$, $l_9$ | 150 |
| Length of outlet pipe of front expansion chamber | $l_5$ | 120 |
| Length of neck of Helmholtz Resonator | $l_n$ | 50 |
| Length of Helmholtz Resonator cavity | $l_c$ | 100 |
| Length of inlet pipe of rear expansion chamber | $l_9$ | 150 |
| Length of outlet pipe of rear expansion chamber | $l_{11}$ | 60 |

The transmission loss of the muffler is calculated by transfer matrix method and the result is compared to the result that obtained by an experiment. The experiment was done by two-load method using four microphones impedance tube [15-20]. The comparison is shown in Figure-6. The transmission loss value is complicated until frequency of 200 Hz in experimental result because of the vibrations, external noises, electric noises and other environmental noises, etc [21]. Beyond 200 Hz, the pattern and humps of the transmission losses in both numerical and experimental are quite similar. The maximum transmission loss of the numerical result is 46 dB and that of experimental result is 50 dB at 1700 Hz as shown in Figure 6. The results from numerical result is similar to the experimental results in shape and amplitude of transmission loss except some errors which may be because of the small dimension difference in length of the muffler for experiment. The result from the numerical model has quite good agreement with the experimental result. Thus, the numerical model can be used for further investigations.

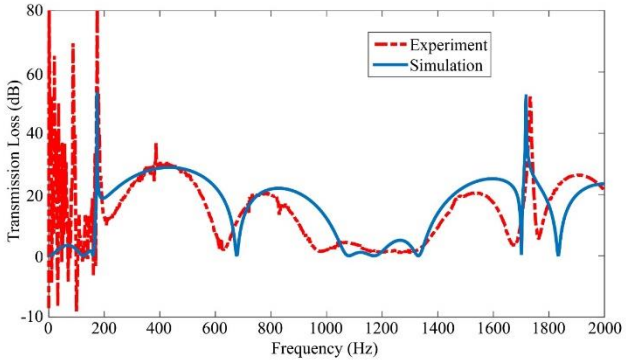



**Fig. 6**: Transmission loss comparison between Transfer Matrix Method and Experimental result

## 4. Results and Discussions

In this section, the influences of parameters of Helmholtz resonator such as diameter and length of neck of Helmholtz resonator, the diameter and length of cavity of Helmholtz resonator. The decreasing and increasing values of each parameters are studied separately to get clear influences of decreasing and increasing of each parameter. The root mean square values of transmission losses are also stated to compare the values of transmission losses of each parameter.

### 4.1. Effect of Change in Diameter of Neck of Helmholtz Resonator

In this case, the influence of the diameter of the neck of Helmholtz resonator is studied. First, the diameter is changed from 20 mm to 15 mm, 10 mm and 5 mm. The results are shown in Figure 7. When the diameter is decreased, the transmission loss decreases from 60 dB to 20 dB between the frequencies of 0 Hz and 200 Hz and the highest peaks of the transmission loss shift to the lower frequency. The transmission loss value decreases in the range of 200 Hz to 600 Hz, and the transmission loss increases between 600 Hz and 900 Hz. But, from 1000 Hz to 2000 Hz, the transmission loss value does not vary obviously with the decrease in diameter of neck of Helmholtz resonator with the maximum value of 70 dB around the frequency of 1700 Hz.

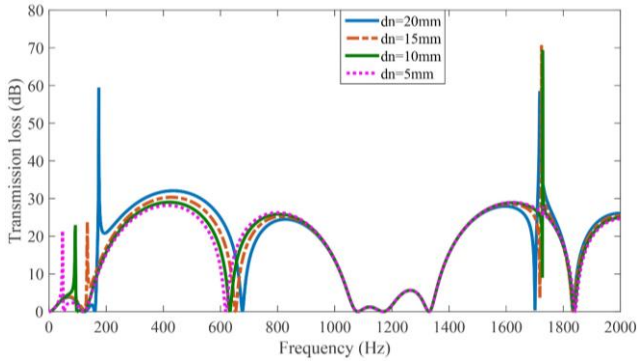



**Fig. 7**: Decrease in diameter of the neck of the Helmholtz resonator

The RMS values of transmission loss of decreasing the diameter of the neck of Helmholtz resonator is shown in Table 2. The RMS values of transmission loss become lower than the original value with the decreasing values of diameter of neck of Helmholtz resonator.

**Table 2**: RMS values of transmission loss of decreasing the diameter of neck of Helmholtz Resonator

| Diameter, dn (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 20 | 26.09 | (original) |
| 15 | 25.44 | -2.49% |
| 10 | 24.93 | -4.45% |
| 5 | 24.64 | -5.56% |

The diameter of the neck of Helmholtz resonator is increased from 20 mm to 25 mm, 30 mm and 35 mm. The results are shown in Figure 8. When the diameter of the neck is increased, the peak of the transmission loss at low frequency decreases for the 25 mm diameter. But the peak increases for 30 mm diameter and 35 mm diameter reaching up to about 110 dB for the latter. The transmission loss values between 700 Hz and 1000 Hz decrease with the increase of diameter of neck of Helmholtz resonator. The transmission loss values do not change between 1000 Hz and 1500 Hz meaning there is no effect of neck diameter of Helmholtz resonator in this frequency range. The transmission losses between 1500 Hz and 1600 Hz decrease with the increase of diameter values. Beyond the frequency of 1700 Hz, the transmission loss values do not change obviously according to the increasing of diameter of neck of Helmholtz resonator.

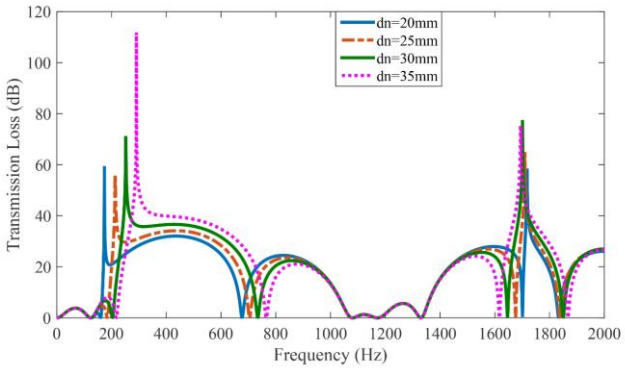



**Fig. 8**: Increase in the diameter of neck of the Helmholtz resonator

The RMS values of transmission loss of muffler for increasing the diameter of neck of Helmholtz resonator is shown in Table 3. The RMS value of transmission loss of hybrid muffler become higher than the original value with the increase of diameter of the neck of Helmholtz resonator.

**Table 3**: RMS values of transmission loss of increasing the diameter of neck of Helmholtz Resonator

| Diameter, dn (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 20 | 26.09 | (original) |
| 25 | 26.68 | 2.26% |
| 30 | 27.03 | 3.6% |
| 35 | 26.94 | 3.26% |

## 4.2. Effect of Change in Length of Neck of Helmholtz Resonator

As the second case, the effect of the length of the neck of Helmholtz resonator is studied. First, the length of the neck is reduced step by step from 50 mm to 40 mm, 30 mm and 20 mm. The effects of decreasing the length of the neck of Helmholtz resonator is shown in Figure 9. As far as the length of the neck is reduced, the transmission loss of the muffler increases respectively in the frequencies range from 180 Hz to 800 Hz. After that range of frequencies, the transmission loss is reduced according to the reduction of length of the neck respectively from frequencies range between 800 Hz and 1000 Hz. There are no changes between the frequencies range of 1000 Hz and 1600 Hz. After that, the transmission loss increases with the decrease in the length of the neck from range of 1600 Hz to 1900 Hz, with the maximum transmission loss of 80 dB with the length of 30 mm. Beyond frequency of 1900 Hz, the transmission loss reduces with the decrease of length of neck of Helmholtz resonator.

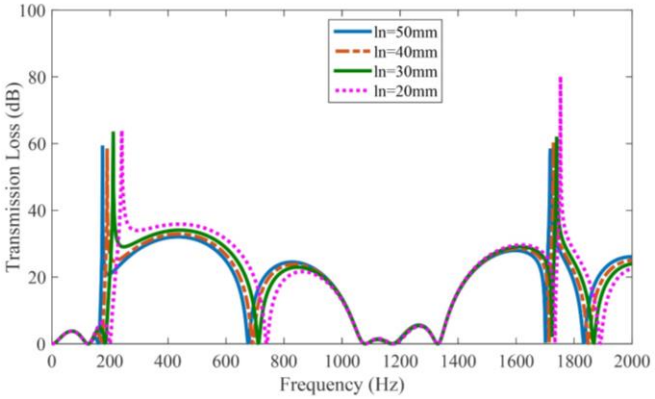



**Fig.9:** Decrease in the length of the neck of Helmholtz resonator

The results of RMS values of transmission loss for decreasing the length of neck of Helmholtz resonator are shown in Table 4. The RMS value of transmission loss of hybrid muffler become lower than the original value when the length of neck of Helmholtz resonator is decreased.

**Table 4:** RMS values of transmission loss of decreasing the length of the neck of Helmholtz resonator

| Length, ln (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 50 | 26.09 | (original) |
| 40 | 25.04 | -4.02% |
| 30 | 24.00 | -8.01% |
| 20 | 22.62 | -13.3% |

The length of the neck of the Helmholtz resonator is increased from 50mm to 60mm, 70mm and 80mm as shown in Figure 10. The transmission loss of the muffler reduces with respect to the increasing of the length of the neck between the frequencies range of 200 Hz and 750 Hz as compared to original values. But between range of 750 Hz and 1000 Hz, the transmission loss becomes increased in small amount with increase of length of the neck. Between range of 1000 Hz and 1500 Hz, there is no difference in transmission loss showing there is no effect in this region. Between range of 1600 Hz and 1800 Hz, the transmission loss values increase as compared to the original value and the transmission loss peaks shifted to the lower frequency values. The transmission loss value with the neck length of 80 mm goes up dramatically with the peak of 76 dB.

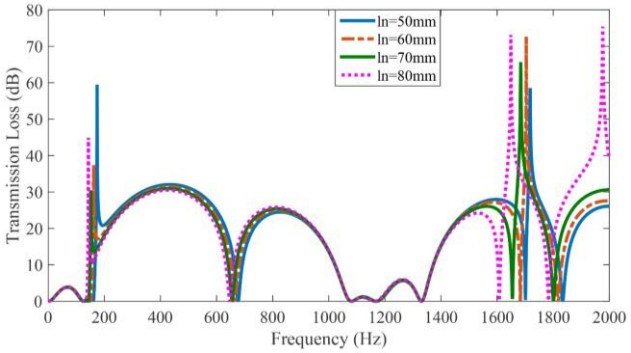



**Fig.10**: Increase in the length of the neck of Helmholtz resonator

The results of RMS values of transmission loss for increasing the length of neck of Helmholtz resonator are shown in Table 5. The RMS value of transmission loss of hybrid muffler become higher than the original value when the length of neck of Helmholtz resonator is increased.

**Table 5**: RMS values of transmission loss of increasing the length of the neck of Helmholtz resonator

| Length, ln (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 50 | 26.09 | (original) |
| 60 | 27.53 | 5.52% |
| 70 | 30.63 | 17.4% |
| 80 | 38.94 | 49.25% |

### 4.3. Effect of Change in Diameter of Neck of Helmholtz Resonator Cavity

As another case, the influence of the diameter of Helmholtz resonator cavity is studied. The diameter of the cavity is decreased from 60 mm to 50 mm, 40 mm and 30 mm as shown in Figure 11. When the diameter of the Helmholtz resonator cavity is decreased, the transmission loss increases as compared to the original values. The transmission loss peaks of the cavity diameter values shifted to higher frequency value between the frequencies range of 200 Hz and 500 Hz. There are no changes between the frequencies of 500 Hz to 1600 Hz. Between the range of frequencies 1600 Hz and 2000 Hz, the transmission loss changes only a little as compared to the original transmission loss value.

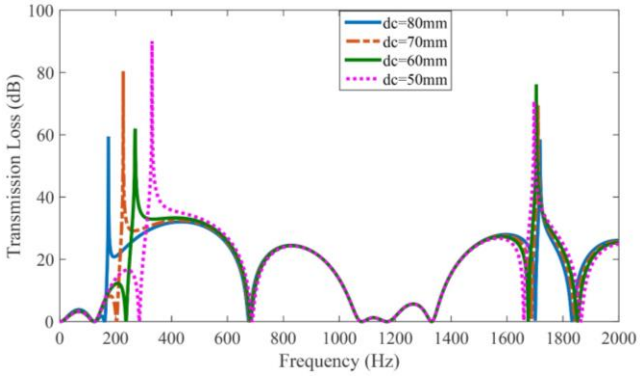



**Fig. 11**: Decrease in the diameter of Helmholtz resonator cavity

The results of RMS values of transmission loss for decreasing the diameter of Helmholtz resonator cavity are shown in Table 6. the RMS value of transmission loss of hybrid muffler become lower than the original value when the diameter of Helmholtz resonator cavity is decreased.

**Table 6:** RMS values of transmission loss of decreasing the diameter of Helmholtz resonator cavity

| Diameter, dc (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 80 | 26.09 | (original) |
| 70 | 25.95 | -0.54% |
| 60 | 25.73 | -1.38% |
| 50 | 25.41 | -2.61% |

The diameter of the cavity also increased in order to study the influence of diameter. The diameter is increased from 60 mm to 70 mm, 80 mm and 90 mm as shown in Figure 12. The transmission loss decreases with the increase of diameter of cavity, which is between 130 Hz and 210 Hz range of frequencies. At the frequencies over 210 Hz, the transmission loss becomes the same value for all diameters values for 210 Hz to 2000 Hz range of frequencies. There are changes at 1700 Hz with transmission loss of 90 dB with diameter of 90 mm.

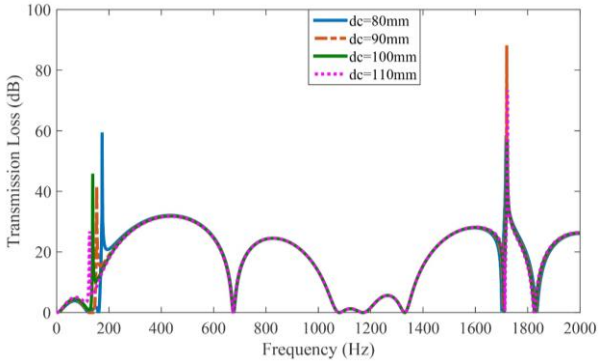



**Fig. 12:** Increase in diameter of the Helmholtz resonator cavity

The results of RMS values of transmission loss for increasing the diameter of Helmholtz resonator cavity are shown in Table 7. The RMS values of transmission loss of hybrid muffler become higher than the original value when the diameter of Helmholtz resonator cavity is increased.

**Table 7:** RMS values of transmission loss of increasing the diameter of Helmholtz resonator cavity

| Diameter, dc (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 80 | 26.09 | (original) |
| 90 | 26.22 | 0.5% |
| 100 | 26.31 | 0.84% |
| 110 | 26.38 | 1.11% |

As the fourth case, the change in the length of the Helmholtz resonator cavity is studied. The length of the resonator cavity is decreased from 100 mm to 90 mm, 80 mm and 70 mm as shown in Figure 13. Between the frequencies range of 180 Hz and 210 Hz, the transmission loss values decrease except the length of 80 mm with the decrease of length of the resonator cavity. From 210 Hz to 1600 Hz frequency range, there is no change in transmission loss because Helmholtz resonator does not have any effect for these frequency ranges. From 1600 Hz to 2000 Hz frequency range, the transmission loss values go up for 100 mm length and 90 mm length. The transmission loss for 100 mm length is 60 dB and that of 90 mm length is 63 dB and the transmission loss values for length of 80 mm and 70 mm remain the same at 30 dB between that frequencies range.

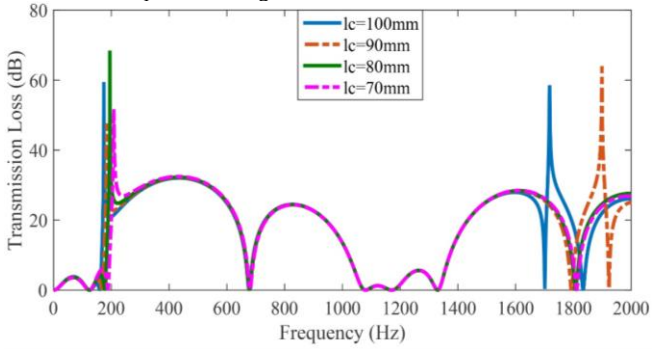



**Fig.13:** Decrease in length of Helmholtz resonator cavity

The results of RMS values of transmission loss for decreasing the length of Helmholtz resonator cavity are shown in Table 8. The RMS values of transmission loss of hybrid muffler become higher than the original value when the length of Helmholtz resonator cavity is decreased except 90 mm length which has the least performance in low frequency noise.

**Table 8:** RMS values of transmission loss of decreasing the length of Helmholtz resonator cavity

| Length, lc (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 100 | 26.09 | (original) |
| 90 | 25.09 | -3.83% |
| 80 | 27.62 | 5.86% |
| 70 | 26.85 | 2.87% |

The length of the Helmholtz resonator cavity is also increased from 100 mm to 110 mm, 120 mm and 130 mm respectively as in Figure 14. The transmission losses of the muffler decrease with the increase of the length of the cavity between the frequencies range of 190 Hz to 210 Hz. The resonator cavity does not have any effect on the transmission loss between the frequencies range of 200 Hz and 1300 Hz. The transmission loss peak values decrease and move to lower frequency values between the range of 1300 Hz and 1800 Hz. The transmission loss values do not change and are the same for all Helmholtz resonator cavity length values between the frequencies range of 1800 Hz and 2000 Hz.

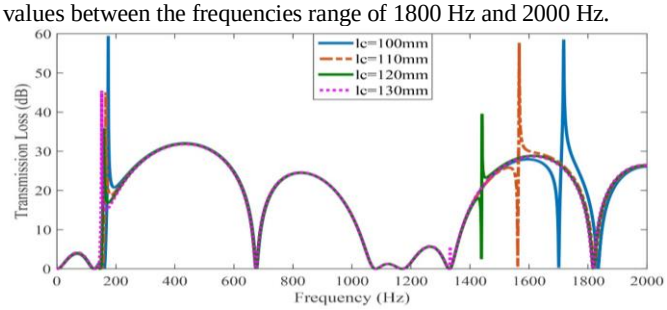



**Fig.14:** Increase in length of Helmholtz resonator cavity

The results of RMS values of transmission loss for decreasing the length of Helmholtz resonator cavity are shown in Table 9. The RMS values of transmission loss of hybrid muffler become higher than the original value when the length of Helmholtz resonator cavity is increased.

**Table 9:** RMS values of transmission loss of increasing the length of Helmholtz resonator cavity

| Length, lc (mm) | Transmission loss (dB) | Percentage of increase |
|---|---|---|
| 100 | 26.09 | (original) |
| 110 | 26.30 | 0.8% |
| 120 | 26.41 | 1.23% |
| 130 | 26.49 | 1.53% |

## 5. Conclusion

The muffler is made a new design and the design contains simple expansion chamber and the Helmholtz resonator. The transmission loss of the muffler is calculated by plane wave theory and the transfer matrix method. The model is validated by the experimental result. The influence of the parameters of the Helmholtz resonator is studied and the results are shown in figures. The Helmholtz resonator have more effects on the transmission loss in low frequencies between 150 Hz and 1000 Hz.

When the diameter of the neck is increased, the transmission loss also increased. When the length of the neck is reduced, the transmission loss is increased. When the diameter of the resonator cavity is reduced, the transmission loss values increase with the highest of 104 dB with 50 mm diameter. By the time the length of the resonator cavity is reduced, the transmission loss is increased around 200 Hz frequency with the highest of 60 dB at 90 mm length. As the length of the resonator cavity is increased, the transmission loss values become increased with the highest of 68 dB with 110 mm length. For low frequencies, the increasing of the length of the cavity is better for case of change in resonator cavity length.

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