

Study of Expansion Chamber Muffler Characteristics using Pink and White Noise Sources

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Received 3 May 2021, accepted in final revised form 24 September 2021

Abstract

The primary objective of the study is to compare the insertion loss in an expansion chamber muffler using white and pink noise. White noise has equal power per hertz over the entire range of frequencies, while the power per hertz in pink noise decreases with increasing frequency. Nonetheless, as the width of successive octaves increases, pink noise renders equal power per octave. The sound pressure level at the output port of the expansion chamber muffler is recorded using an acoustic analyzer, maintaining a constant input for the corresponding noise source. Radon Soft, V1.21, has been used for white and pink noise. The response of three different mufflers with varying lengths and cross-sections is investigated for insertion loss, bandwidth, and dissipation: M_1 with $m = 4.78$ (constant length), M_2 with $m = 7.27$ (variable length), and M_3 with $m = 12.14$ (variable length). The experimentally obtained insertion loss and the nature of response are compared with the theoretical estimates of transmission loss.

Keywords: Expansion chamber muffler; Insertion loss; Pink noise; Transmission loss; White noise.

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doi: <http://dx.doi.org/10.3329/jsr.v14i1.53262> J. Sci. Res. **14** (1), 67-77 (2022)

1. Introduction

Noise pollution due to vehicle exhaust is one of the prime concerns causing health issues like stress, tinnitus, cognitive impairment, and even cardiovascular illness. In terms of pressure, the exhaust noise is about ten times more than all other structural factors noises combined [1,2]. Hence, most governments worldwide have recognized the need to regulate vehicular noise pollution on a priority basis. Expansion chamber mufflers, designed for a specific range of frequencies, are used to minimize the exhaust noise of vehicular emission to a large extent [3-5]. Hence, enhancing the efficiency of these mufflers turns out to be an important task, considering the rate at which noise pollution increases with the number of vehicles on roads going up every day. Nonetheless, a combination of reactive and dissipative mufflers makes the noise reduction system more effective and achieves high efficiency at most frequencies.

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Mufflers are primarily low pass acoustic filters classified into reactive and dissipative types and fall under passive noise control devices. In the dissipative type of muffler, sound energy is reduced by using absorptive materials (at times implemented by using a porous pipe). Although the dissipative mufflers create significant backpressure, they are not as effective as reactive mufflers. A reactive muffler uses an expansion chamber designed to reduce SPL over a specific bandwidth [2,6] by employing a change in the geometry introduced at inlet and outlet pipes. Noise reduction is based on destructive interference brought about by a change in impedance due to its geometry.

Mufflers are evaluated over the transmission and insertion loss that they bring about. Transmission loss is defined as the difference between the sound power incident at the muffler and transmitted by the muffler [7]. The larger the expansion ratio, the higher is the transmission loss [6]. The transmission loss can be safely calculated by knowing the dimensions of the muffler [8]. On the other hand, insertion loss is the difference in the noise SPL with and without the muffler [7]. Studies have been carried out to check for an increase in transmission loss by adding a side branch to the expansion chamber. Several studies have been made by adding chambers within the expansion chamber. However, none of the studies addresses the response of the muffler to white and pink noise concurrently. Our work uses these as inputs in the characterization of the expansion chamber muffler to improve its design.

The characterization process involves determining insertion loss at various frequencies [9] in the range generated as pure tones and comparing those with the transmission loss curves. Instead, white and pink noise allows us to carry a detailed analysis of the design at hand, as engine noise does not comprise pure tones but is always a mix of a range of frequencies in various amplitudes and phases. White and pink noise comprises all frequencies, but white noise has equal power per hertz over all frequencies, whereas the power per hertz in pink noise decreases as the frequency increases. Nonetheless, as the width of successive octaves increases, equal power per octave is received.

The primary objective of our work is to study the response of the expansion chamber muffler by exposing it to white and pink noise and obtain insertion loss and its dependence on various parameters governing reactive mufflers.

2. Experimental

2.1. Expansion chamber muffler

An expansion chamber muffler comprises two tubes of different cross-sections joined linearly (Fig. 1). This arrangement has a predictable transmission loss with maxima at $f=nc/4l$ ($n=1,3,5,\dots$), where c is the speed of sound and l is the corrected length of the expansion chamber muffler. If the inlet and outlet tubes are extended within the chamber, it is called an extended inlet and outlet expansion chamber. The benefit of this design is that part of the chamber between the extended pipe and the sidewall acts as a side branch resonator, thereby improving transmission loss [6] shown in Fig. 1.

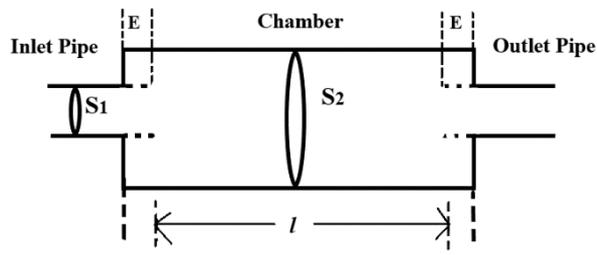


Fig. 1. Expansion chamber muffler with length correction.

The testing setup comprises of a function generator viz. Scientific SM 5077 for pure tones, a Unisound SSB-45M amplifier, and a horn drive unit AHUJA AV-60 (Fig. 2).

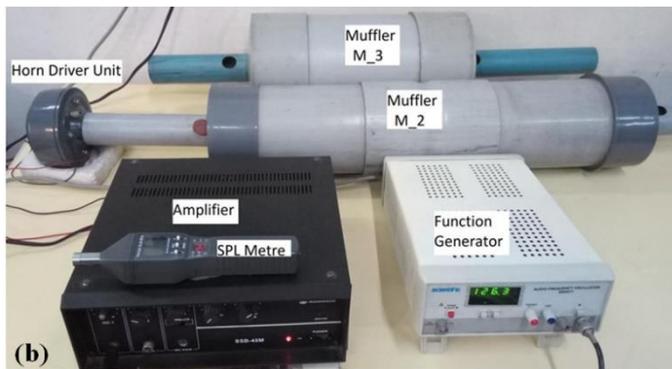
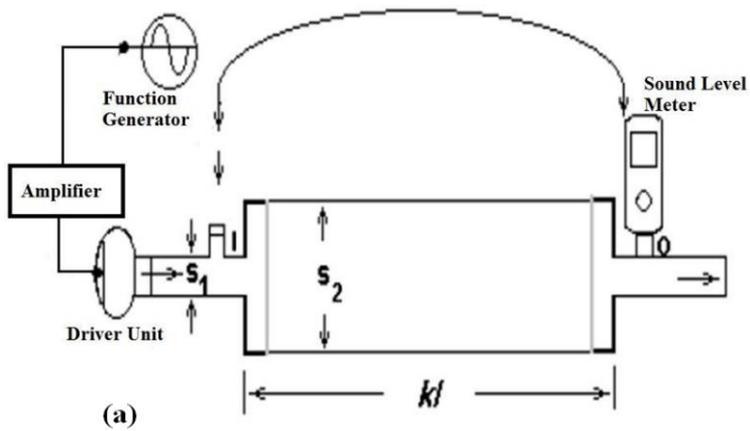


Fig. 2. (a) Schematic diagram and (b) actual lab experiment.

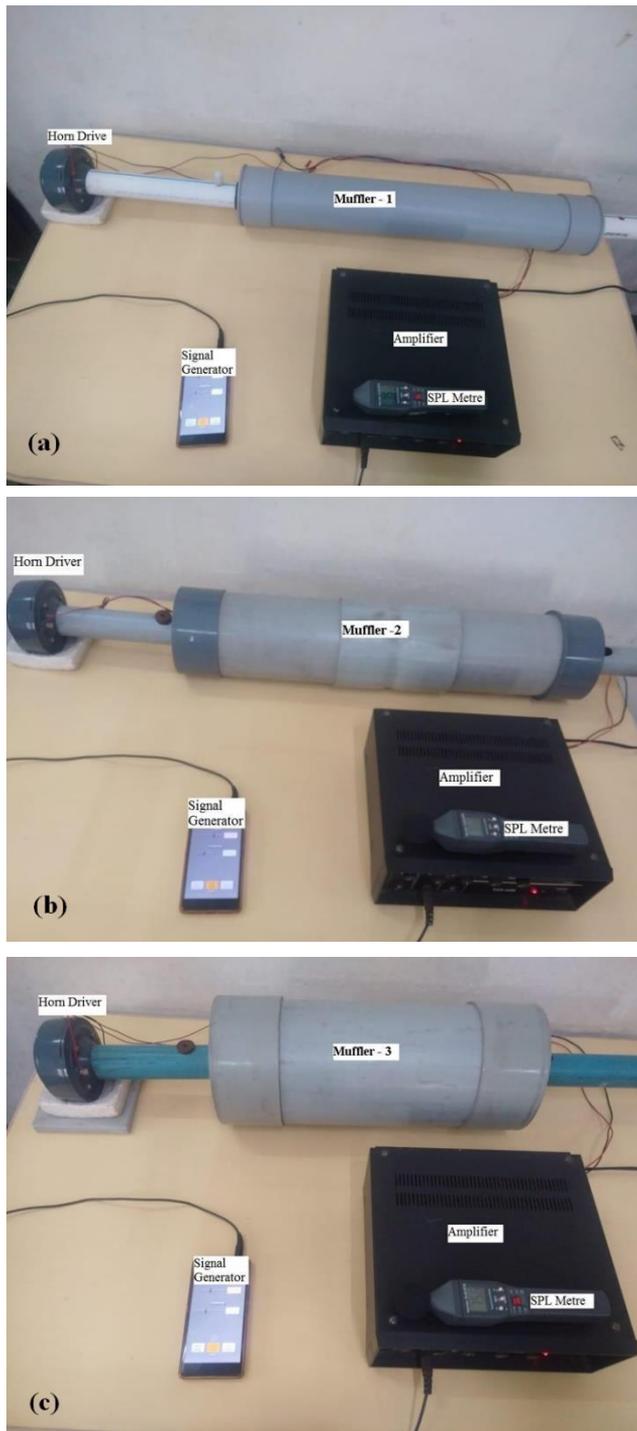


Fig. 3. Actual laboratory equipment (A) M₁ with $m=4.78$ and length constant (B) M₂ with $m=7.27$ and length-variable (C) M₃ with $m=12.14$ and length variable.

A sound level meter Vernier SLM-BTA is used to measure the SPL dBA. The input dBA is set at a constant value, and the corresponding output is measured. The RadonSoft, V1.21 app is used in place of the function generator as a source for white and pink noise investigation (Fig. 3). The mufflers M_1, M_2, and M_3, are studied for pure tones, white, and various pink noise frequencies (150, 200, 250, 500, and 1000 Hz) with regards insertion loss (IL).

2.2. Length correction and speed of sound

Length correction is applied or added to the actual length of a resonance pipe to determine its precise resonance frequency. A simple notion is that the fundamental resonance occurs when the resonating length is a quarter of the sound wavelength. However, it is observed that the practical frequency deviates a little from the ideal value, and hence, one must incorporate length correction (Fig. 1). The length correction is given by:

$$\text{Acoustic chamber length} = \text{Geometric chamber length} - (2 * E), \quad (1)$$

Where, E is end correction

The dependence of the speed of sound ' c ' on temperature is also accounted for by using the equation:

$$c = 331.4 + 0.6 * T(^{\circ}\text{C}), \quad (2)$$

where,

The speed of sound at 20 °C is 331.4 m/s and c is the speed of sound at T °C.

The mufflers studied here are lab-grade expansion chamber mufflers, and the focus of the work is to study their response to pink and white noise. The TL and IL values for pure tones are compared with their response to these noise sources at room temperature.

2.3. Methodology

The three mufflers have varying cross-sections, and two of them include a feature in design that allows us to vary their lengths, viz. M_2 with $m = 7.27$ and M_3 with $m = 12.14$, where m is the ratio of cross-sections of the chamber to inlet or the outlet pipe. A total of five cases change the length for M_2, and another two cases change the length for M_3 have been investigated. M_1 with $m = 4.78$ is a constant length muffler.

The procedure involves the following steps:

Step 1: SPL is adjusted to 85 dBA at the input port of the muffler using a suitable driver frequency, and the output is recorded at the output port using an acoustic analyzer. Frequency is then varied while maintaining constant amplitude. Insertion loss is determined by taking the difference of SPL dBA values at the input and output ports corresponding to each frequency [10].

Step 2: The signal generator is replaced by the RadonSoft, V1.21 app for white noise. The amplitude is so adjusted that the SPL is set to 85 dBA at the input port. The corresponding output is recorded at the output port. The insertion loss is determined using these two values.

Step 3: The RadonSoft, V1.21 app source is now set to pink noise. The frequency is set to 150 Hz. Amplitude is maintained at 85 dBA at the input port. The corresponding output is measured. The insertion loss is determined. The same is repeated for pink noise by setting frequency values to 200, 250, 500, and 1000 Hz.

Step 4: Steps 1, 2, and 3 are repeated for an input SPL of 95 dBA. The same procedure is repeated for all three mufflers viz. M_1, M_2 and M_3.

3. Results and Discussion

3.1. TL, IL, bandwidth, and Q factor

The transmission loss curve at room temperature is plotted by using the standard formula

$$TL = 10 \log_{10} \left\{ 1 + \frac{1}{4} \left(m + \frac{1}{m} \right)^2 \sin^2 kl \right\} \quad (3)$$

Where,

TL is Transmission Loss due to muffler

$m = S_2/S_1$; S_2 = area of cross-section of the chamber and S_1 = area of a cross-section of the inlet pipe

l = length of central chamber in meter

k is wave number that can be given as $2\pi/\lambda$.

The frequency value corresponding to the TL_{max} is determined for each muffler. The Insertion Loss is calculated by using the equation:

$$IL = SPL_{i/p} - SPL_{o/p} \quad (4)$$

Where,

$SPL_{i/p}$ is the sound level meter reading at the input of the muffler

$SPL_{o/p}$ is the sound level meter reading at the output of the muffler

The insertion loss is plotted against frequency values. The bandwidth (IL_{max} -3dB) is determined. We may have more than one value for bandwidth corresponding to each effective length as more than one peaks occur. The bandwidth and Q factor are determined for each muffler (Table 1).

From Table 1, The maximum value of transmission loss TL_{max} for an 85 dB input is 7.93 dB for M_1, 11.37 dB for M_2, and is a high of 15.72 dB for M_3. Likewise, the maximum insertion loss is seen to rise with the increase in 'm'. IL_{max} is 8.7 dB for M_1, 11.7 dB for M_2, and 16.3 dB for M_3.

If the ratio m is maintained constant and the length of the chamber is varied, then TL_{max} remains unchanged. However, the frequency at which TL_{max} occurs changes. In the case of M_2, for a change in effective length from 0.35 to 0.75 m, TL_{max} remains almost unchanged (11.32 dB and 11.37 dB). However, the corresponding frequency (at which TL_{max} occurs) changes from 300 to 125 Hz. On the other hand, the IL_{max} value rises to 11.7 dB and then falls off to 8.6 dB with an increase in length, while the corresponding frequency decreases from 400 to 200 Hz. In M_3, for the corrected lengths 0.325 m and 0.405 m, TL_{max} remains constant at 15.7 dB with decreasing frequency while IL_{max} increases with decreasing frequency.

Table 1. TL, IL, Bandwidth, and Q factor values corresponding to 85 dB.

Sl No.	Type of Muffler	Resonating Length m	Corrected Length m	Transmission Loss		Insertion Loss corresponding to 85 dB			
				TL _{max} dB	Corresponding Frequency Hz	IL _{max} dB	Corresponding Frequency Hz	Band Width (FWHM) Hz	Q Factor
1	M_1 m= 4.78	0.68	0.67	7.93	125	8.7	225	34.74	6.48
2		0.35	0.303	11.36	300	8.6	225	37.78	5.95
3	M_2	0.635	0.588	11.37	150	10	400	98.66	4.05
4	m = 7.27	0.655	0.608	11.36	150	11.7	225	24.81	9.07
5		0.675	0.628	11.32	150	11.3	225	23.56	9.55
6		0.745	0.698	11.37	125	10.9	225	23.57	9.54
7	M_3	0.375	0.325	15.72	275	8.6	200	58.31	3.43
8	m= 12.14	0.455	0.405	15.7	225	13.1	275	57.25	4.8
						16.3	250	45.8	5.46

In M_1, for a corrected length of 0.67 m and an IL_{max} of 8.7 dB, bandwidth turns out to be 34.74 Hz, and the Q factor is 6.48, whereas in the case of M_2, for a corrected length of 0.588 m and an IL_{max} of 11.7dB, the bandwidth is 24.81Hz with a Q factor of 9.07. In M_3, for a corrected length of 0.405 m and an IL_{max} of 16.3 dB, the bandwidth is 45.8Hz, and the Q factor is 5.46. In M_2, for lengths varying from 0.35 m to 0.66 m, the bandwidth value decreases from 37.78 to 23.56 Hz (for a peak corresponding to 225 Hz), while IL_{max} varies from 8.6 to 11.7 dB. The Q value rises from 5.95 to 9.55 and again falls to 3.43 - the Q factor increases with effective length, reaching a peak value and again decreasing for an 85 dB input.

In the case of M_1, according to Table 2, for the corrected length of 0.67 m and IL_{max} of 5.1 dB appearing at 150 Hz, the bandwidth is 24.81 Hz, and the Q factor is 6.04. However, for an IL_{max} of 6.8 dB appearing at 200 Hz, the bandwidth is 37.21 Hz, and the Q factor is 5.37. In M_2, for a corrected length of 0.628 m and IL_{max} of 15.2 dB, appearing at 225 Hz, the bandwidth is 12.4 Hz, and the Q factor is 18.14. In M_3, for the corrected length of 0.325 m and IL_{max} of 18.2 dB, appearing at 250 Hz, the bandwidth is 41.22 Hz, and the Q factor is 6.06.

The variation in bandwidth and Q factor with effective length is not linear for the 95 dB input. The maximum value of the Q factor is 18.14 for $l = 0.628$ m, which is the highest in all cases. Also, the Q factor values are higher for 95 dB input than for 85 dB input.

Table 2. TL, IL, Bandwidth, and Q factor values corresponding to 95 dB.

Sl No.	Type of muffler	Resonating length m	Corrected length m	Transmission loss		Insertion loss corresponding to 85 dB			
				TL _{max} dB	Corresponding frequency Hz	IL _{max} dB	Corresponding frequency Hz	Band width (FWHM) Hz	Q Factor
1	M_1 m= 4.78	0.68	0.67	7.93	125	5.1	150	24.81	6.04
						6.8	200	37.21	5.37
2		0.35	0.303	11.36	300	13	225	18.9	11.9
						11	350	94.47	3.7
3	M_2	0.635	0.588	11.37	150	15	225	14.88	15.11
4	m = 7.27	0.655	0.608	11.36	150	12.8	225	26.05	8.64
5		0.675	0.628	11.32	150	15.2	225	12.4	18.14
6		0.745	0.698	11.37	125	10.7	225	21.09	10.67
7	M_3	0.375	0.325	15.72	275	18.2	250	41.22	6.06
8	m= 12.14	0.455	0.405	15.70	225	16.3	250	45.8	5.46

3.2. Response to pink and white noise

The IL for each of the mufflers is recorded for white and pink noise. IL_{max} values corresponding to each frequency in pink noise (150, 200, 250, 500, and 1000 Hz) are determined.

Table 3. Comparative study of Noise, Pink Noise, and White Noise for 85 dBA.

Sl. No.	Type of Muffler	Resonating Length m	Corrected Length m	Insertion Loss corresponding to 85 dBA							
				IL _{max} dB	Corresponding Frequency Hz	Pure tone					White noise dB
						Pink noise 150 Hz	Pink atnoise 200 Hz	Pink noise at 250 Hz	Pink noise at 500 Hz	Pink noise at 1KHz	
1	M_1 m= 4.78	0.68	0.67	8.7	225	2.9	2.4	2.5	2.3	2.5	3.3
				8.6	225	6.7	6.9	7.3	5.3	5.1	6.8
2		0.35	0.303	10	400	6.7	6.9	7.3	5.3	5.1	6.8
3	M_2	0.635	0.588	11.7	225	9.1	8.8	8.5	9.3	9.2	10.7
4	m = 7.27	0.655	0.608	11.3	225	8.5	8.7	8.8	8.5	9.6	11.2
5		0.675	0.628	10.9	225	9	8.6	8.5	9	7.8	8.1
6		0.745	0.698	8.6	200	9.2	9.2	7.9	5.6	6.5	9.8
7	M_3	0.375	0.325	13.1	275	10.3	10.8	10.74	5.7	6.2	14.3
8	m= 12.14	0.455	0.405	16.3	250	12.6	12.5	12.8	11.1	10	15

Table 4. Comparative study of noise, pink noise, and white noise for 95 dBA.

Sl. No	Type of muffler	Resonating length m	Corrected length m	Insertion loss corresponding to 95 dBA							
				Pure tone		Pink noise at 150 Hz	Pink noise at 200 Hz	Pink noise at 250 Hz	Pink noise at 500 Hz	Pink noise at 1KHz	White noise
				IL_{max} dB	Corresponding frequency Hz						
1	M_1 m = 4.78	0.68	0.67	5.1	150	3.2	3.4	3.9	3.5	3.8	4.5
				6.8	200						
2		0.35	0.303	13	225	6.8	7	7.6	7	6.5	7
				11	350						
3	M_2 m = 7.27	0.635	0.588	15	225	9.3	9.4	9.1	9.6	9.1	10.6
4		0.655	0.608	12.8	225	9.3	9.3	9	9.7	10.1	11.1
5		0.675	0.628	15.2	225	9.1	9.2	8.8	8.5	9	9.5
6		0.745	0.698	10.7	225	8.6	9.4	9.2	8.3	7.3	9.9
7	M_3	0.375	0.325	18.2	250	13.6	13.2	12.6	9	9.8	16.2
8	m = 12.14	0.455	0.405	16.3	250	13	13	13.5	13.7	13.4	15.6

According to Tables 3 and 4, the value of insertion loss increases with an increase in the ratio of cross-section m for white noise. IL_{max} for an 85 dBA input, in the case of M_1, is 3.3 dB for corrected length $l=0.67$ m, whereas it is 11.2 dB, in case of M_2, for the corrected length of 0.608 m. The same is 15 dB for M_3 for a corrected length of 0.405 m. IL_{max} for a 95 dBA input is 4.5 dB for M_1 with a corrected length $l=0.67$ m, 11.1 dB for M_2 with a corrected length of 0.608 m, whereas it is 16.2 dB for M_3 for corrected length 0.325 m.

IL_{max} in case of white noise first rises and then falls with increasing corrected length while m is constant. In the case of M_2 at 85 dB input, as l increases from 0.303 m to 0.698 m, IL initially rises from 6.8 dB to 11.2 dB and then falls to 9.8 dB. Also, for a 95 dBA input, IL increases from 7 dB to 11.1 dB and then falls to 9.9 dB as the length increases over the same range.

In the case of M_2, when using pink noise, for a fixed cross-section ratio m , as the length increases IL_{max} first rises and then falls, especially at higher octaves. This variation is apparent at the 85 dB input. Also, in M_3, as the length increases, the IL_{max} value rises significantly in higher octaves irrespective of the input dBA. The overall picture shows that IL_{max} is always higher in white noise than in pink noise. The same is shown with the bar chart in Fig. 4.

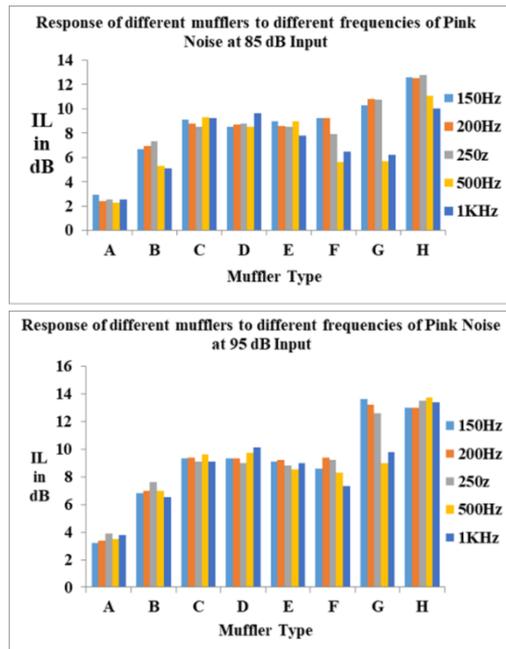


Fig 4. Insertion Loss (IL) in case of mufflers M₁, M₂ and M₃ to pink noise ranging from 150 Hz-1 KHz at 85 dB input and 95 dB input; Where, A is M₁ ($l=0.67$ m), B is M₂ ($l=0.30$ m), C is M₂ ($l=0.588$ m), D is M₂ ($l=0.608$ m), E is M₂ ($l=0.628$ m), F is M₂ ($l=0.698$ m), G is M₃ ($l=0.325$), H is M₃ ($l=0.405$ m).

4. Conclusion

The TL_{max} and IL_{max} values increase with an increase in m viz. ratio of cross-sections of expansion chamber muffler [11]. The frequency corresponding to TL_{max} and IL_{max} decreases with an increase in effective length. The bandwidth and Q factor variation with effective length is nonlinear for higher inputs SPL (95 dBA). The maximum value of the Q factor is 18.14 for $l = 0.628$ m, which is the highest in all cases. Also, the Q factor values are higher for 95 dB input than for 85 dB input, implying that the response is sharper at higher inputs. There is a significant reduction in bandwidth with an increase in input SPL dBA. In the case of white noise, IL_{max} increases with an increase in the ratio of cross-section m and is observed first to rise and then fall with increasing lengths while m is constant.

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