Noise reduction in a large enclosure using single, dual and ensconced Helmholtz resonators

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Helmholtz resonators reduce the noise level especially at the low frequency end of the sound spectrum. This study explores the amount of reduction for different configurations of Helmholtz resonators coupled to a relatively large-sized enclosure through detailed experiments. The experiments were performed in a ~1.2 m^3 enclosure. The eigenfrequencies of the enclosure were calculated theoretically and verified experimentally. Thereafter, a tunable piston–cylinder-type Helmholtz resonator was designed to target a particular frequency, which was coupled to the enclosure volume. The location of the resonator was chosen to lie close to the anti-nodal plane. The results obtained showed a substantial decrease in sound pressure level. A study was also made with two Helmholtz resonators with identical resonance frequency and mounted at separate anti-nodal planes; this configuration showed a still larger reduction in the sound pressure level. Resonator placed inside the cavity volume was further explored to increase the applicability of the Helmholtz resonator; encouraging results were obtained for two cases considered here.

Keywords: Dual resonators, Helmholtz resonator, room-like enclosure, shielded resonator, sound pressure level.

HELMHOLTZ resonators (HRs) are often used as a narrow-band sound absorption device in noise control of a reverberant enclosure[1–7]. The air mass inside the resonator neck vibrates when such a Helmholtz resonator is appropriately positioned, owing to the force produced by the incident sound pressure at the aperture of the resonator. Resonance occurs in the resonator if its natural frequency matches that of the targeted enclosure mode, trapping a large part of the input energy in a relatively narrow band. Attenuation of sound occurs in the enclosure due to acoustic interaction between the primary and secondary (formed by volume velocity out of the resonator) sound fields, leading to energy dissipation in the resonator. The Helmholtz resonator can be used for noise reduction in various applications including ducts and ventilation systems. Coupling of the Helmholtz resonator to a large enclosure has however received little attention[8] and forms the subject of the current study.

The natural frequency of a Helmholtz resonator can be controlled by adjusting the resonator neck dimensions, cavity volume or both. One major drawback of a basic Helmholtz resonator is that the operational frequency is fixed; hence, alteration in the frequency of noise in the surrounding will not be attenuated. In addition, while a reduction in noise occurs at the target frequency, under certain conditions, this can be accompanied by an increase in noise at certain other frequencies. In order to overcome the first drawback, studies have focussed on the use of adaptive Helmholtz resonators. For example, Neise and Koopman[9] studied the use of adjustable quarter wavelength resonators to attenuate the blade passage frequency tone of centrifugal fans. In their experiments, changing the cavity length via a movable Teflon piston resulted in different resonance frequencies of the resonators. They reported that the use of adjustable resonators provided reduction in blade passage frequency tones of up to 18 dB with no adverse effects on the fan performance. Little *et al.*[10] proposed an electro-rheological fluid-based intelligent Helmholtz resonator for use as an adaptive engine mount. Tuning of the resonator was achieved by changing the neck cross-sectional area; thereby varying the neck inertance of the device. The electro-rheological fluid valve provided continuous tuning as opposed to the use of valves with discrete tuning. Esteve and Johnson[11] designed a tunable HR and developed a control scheme to tune the HR to the natural frequencies of a cavity. Kela[12] explored the use of adjustable HR to hydraulic systems.

Krause *et al.*[13] performed experiments with variable volume and neck Helmholtz resonators to suppress noise in automotive tailpipes. Matsuhisa *et al.*[14] developed a resonator in which the volume was changed by displacing a piston within the cavity. Tuning of the resonator, which was used as a side branch in a duct, was achieved by comparing the phase of the sound pressure in the duct with that in the resonator cavity. Anti-resonance of the duct and resonator system was achieved by adjusting the resonator cavity such that the phase difference was 89°. They reported reduction in sound pressure levels of 29 dB for speaker-driven system and 19 dB for fan-driven

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system. Lamancusa[15] proposed two variable volume resonator configurations. The volume was varied either by displacing a piston inside the cavity or by manipulating closeable partitions within the cavity. He provided evidence for loss greater than 29 dB under certain conditions. Esteve and Johnson[16] studied reduction in noise transmission in a coupled structural–acoustic system. They considered a cylindrical structure coupled to a Helmholtz resonator and distributed vibration absorbers. Their simulation results suggest 6–8 dB reduction in noise transmission. Their approach was subsequently refined, as discussed in Esteve and Johnson[11]. Bellucci *et al.*[17] explored the possibility of applying Helmholtz resonators for damping low-frequency pulsations (Strouhal number of 0.6) in gas turbine combustion chambers. A significant reduction in the normalized acoustic pressure was noted at the design frequency. Their results suggest that the low-pulsation operating regime of the engine can be extended significantly using a HR. Li *et al.*[18] explored the use of T-shaped HR for noise reduction.

Kela[12] has noted that Helmholtz resonators are still not well studied. Specifically, reduction of sound transmission with HR coupled to a large enclosure does not seem to have been adequately studied earlier. The present study was undertaken with the dual objectives of: (i) employing multiple Helmholtz resonators and (ii) ensconcing and placing them inside the system volume, to understand the amount of noise reduction in these configurations.

A Helmholtz resonator coupled to a large enclosure was therefore subjected to extensive experimentation. In most of the experiments, HR was placed at around one-third the height of the enclosure, which corresponds to approximately ear-height in a typical room. The location and orientation of the Helmholtz resonators were changed. Two resonators tuned to the same frequency were studied to determine their effectiveness. Further, the location of the Helmholtz resonators was changed to be mounted inside the enclosure boundaries, as opposed to the general method of mounting them on the boundary wall from outside with the neck flushed with the enclosure boundary. Studies were made with HR ensconced in wooden boxes such that it does not become a part of the enclosure volume. This novel method gave encouraging results and forms one of the primary contributions of this work. We suggest employing this configuration in future buildings as it circumvents the practical difficulty of drilling the enclosure walls. The following section gives details about the set-up employed and experimental procedure.

Experimental set-up

A wooden enclosure with dimensions $L_x = 1.835$ m, $L_y = 1.184$ m and $L_z = 1.1$ m having a thickness of 1.8 cm is modelled as a reverberant enclosure (Figure 1). The resonance frequencies at their respective modes are summarized in Table 1, where k is the wave number

$$k = \sqrt{k_x^2 + k_y^2 + k_z^2} = \pi\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2},$$

$$k_x = \frac{n_x\pi}{L_x},\ k_y = \frac{n_y\pi}{L_y},\ \ k_z = \frac{n_z\pi}{L_z},$$

n_x, n_y, n_z are positive integers (eigenmode) and the corresponding frequency is the eigenfrequency. The Helmholtz resonator is located at the nodal plane for all the measurements.

An electromagnetic actuator (acoustic speaker) of diameter 50 mm, operating at an input voltage of 4 V (rms) is employed for generating the noise. The input voltage to the actuator is maintained constant and the frequency of excitation is controlled by a signal generator and monitored using an oscilloscope (Tektronix, TDS 2022B). A half-inch free-field B&K microphone is employed for measuring the noise level. The sound signal from the microphone is fed to data acquisition and signal conditioning system (National Instruments, V08X1837B, PXI 1050). This amplified signal is used directly by advanced sound measurement/analysis software to determine the sound pressure level (SPL), and further for Fast Fourier Transform (FFT) analysis of the signal. The measurements are performed for various locations of the speaker and microphone.

A cylindrical neck Helmholtz resonator made of plastic with wall thickness of 10 mm is employed in the measurements. The resonance frequency of the resonator is calculated as

$$\omega_H = c\sqrt{\frac{S}{L_{\mathrm{eff}}V}}, \tag{1}$$

where $L_{\mathrm{eff}} = L + 1.7a$ (ref. 3), L is length of the neck, a the radius of the neck, c the speed of sound through air, S the cross-sectional area of the neck and V is the cavity volume. The theoretically calculated value of natural frequency (from eq. 1) is experimentally verified.

Helmholtz resonator coupled with an enclosure

Figure 2 presents the results for the enclosure with no HR. The speaker is excited with a sinusoidal waveform with a constant excitation voltage. A single frequency (starting from 85 Hz) is fed to the speaker; subsequently, the frequency is increased in small increments and the measurement is repeated. The decibel (dB) value corresponding to the excitation frequency is obtained from the FFT of the recorded signal. Likewise by changing the frequency, subsequent dB values are obtained. The

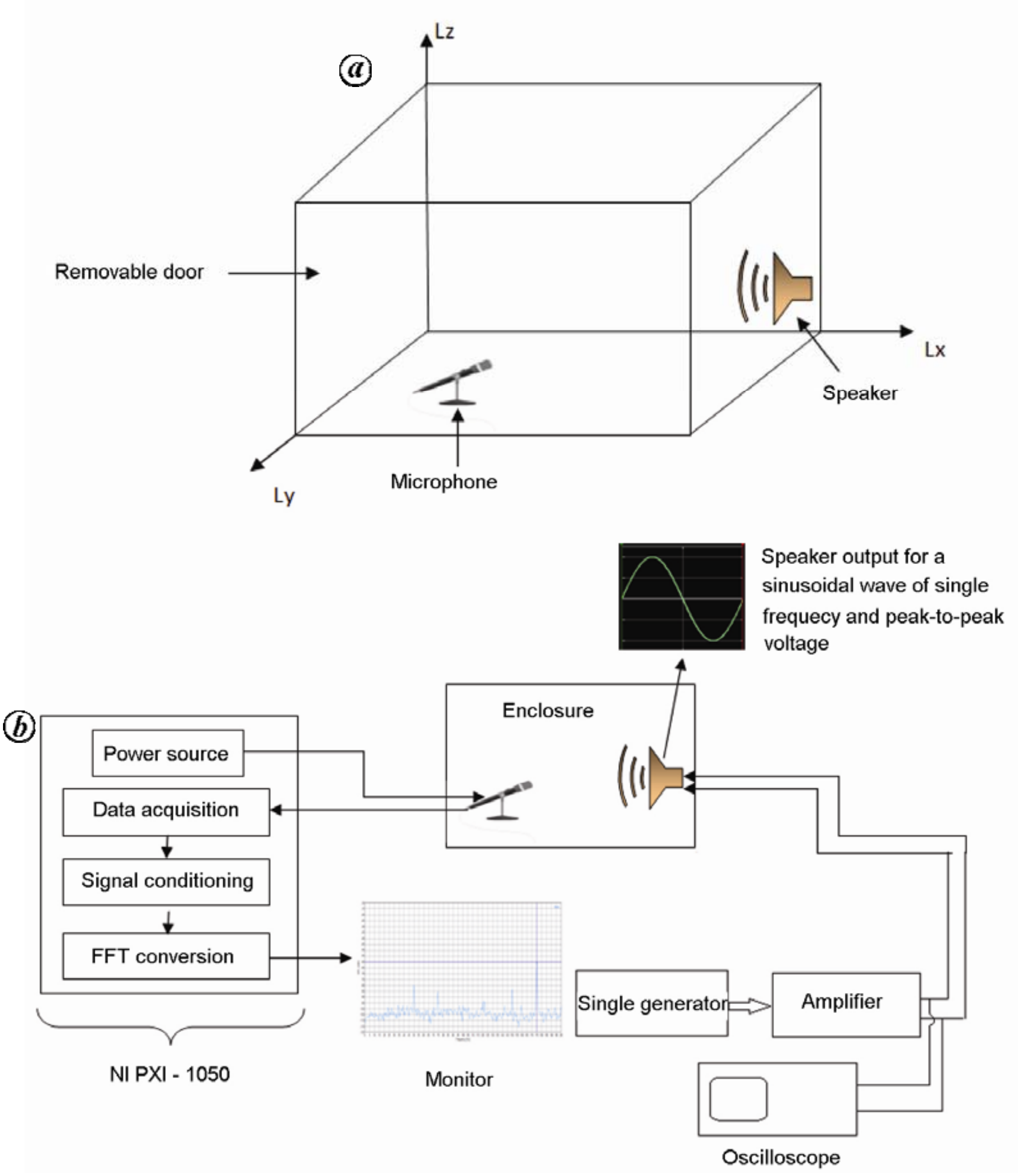


Figure 1. Schematic of the experimental set-up: ***a***, Enclosure (L_x = 1.835 m, L_y = 1.184 m and L_z = 1.1 m); ***b***, Instrumentation employed in the measurements.

theoretically calculated eigenfrequencies and those experimentally determined agree reasonably well. The minor deviation could be because of the ideal boundary conditions assumed in the theoretical calculations, which is usually not the case in practice; also owing to the presence of sound radiation and viscous losses at the Helmholtz resonator neck not accounted for in the calculations. Figure 2 helps validate the measurements. The measurements are repeated with the source fixed at a particular point and the microphone moved to three different locations on the floor. The measured resonance frequencies from the three experiments agree well, thereby demonstrating repeatability in the measurements.

Figure 3 shows SPL versus frequency with the speaker placed at one corner of the room on the floor. The microphone placed on the floor (inset, Figure 3) captures the SPL. The measurements were performed under two conditions: without and with the Helmholtz resonator mounted on the side wall. The results show that there is no significant difference between the two cases up to about 165 Hz. Subsequently, the difference in SPL values and percentage reduction (also plotted in the figure) change their sign multiple times. A maximum reduction of 6.6 dB (or about 7% with respect to the without HR case) occurs at 182 Hz. Notice that SPL actually increases at both 183 and 197 Hz in the presence of HR. Thus we see that for the given speaker and microphone position, if the excitation noise source has a frequency of 182 Hz, the design HR is effective in significantly reducing the noise level. However, the same HR is not

Table 1. Eigenfrequencies and eigenmodes for the enclosure studied

c (m/s)	l_x (m)	l_y (m)	l_z (m)	Volume (m^3)	Room temperature			
346.6	1.835	1.184	1.100	2.390	26°C			
Eigenmodes	Eigenvectors			Wavenumbers				Eigenfrequencies
	n_x	n_y	n_z	k_x	k_y	k_z	k	f (Hz)
1	1	0	0	1.71	0.00	0.00	1.71	94.48
2	0	1	0	0.00	2.65	0.00	2.65	146.43
3	0	0	1	0.00	0.00	2.86	2.86	157.61
4	1	1	0	1.71	2.65	0.00	3.16	174.27
5	1	0	1	1.71	0.00	2.86	3.33	183.76
6	2	0	0	3.43	0.00	0.00	3.43	188.96
7	0	1	1	0.00	2.65	2.86	3.90	215.14
8	1	1	1	1.71	2.65	2.86	4.26	234.97
9	2	1	0	3.43	2.65	0.00	4.33	239.06
10	2	0	1	3.43	0.00	2.86	4.46	246.07
11	3	0	0	5.14	0.00	0.00	5.14	283.45
12	2	1	1	3.43	2.65	2.86	5.19	286.34
13	0	2	0	0.00	5.31	0.00	5.31	292.86
14	1	2	0	1.71	5.31	0.00	5.58	307.73
15	0	0	2	0.00	0.00	5.71	5.71	315.23
16	3	1	0	5.14	2.65	0.00	5.78	319.04
17	1	0	2	1.71	0.00	5.71	5.97	329.08
18	0	2	1	0.00	5.31	2.86	6.03	332.58
19	1	2	1	1.71	5.31	2.86	6.27	345.74
20	2	2	0	3.43	5.31	0.00	6.32	348.53
21	0	3	0	0.00	7.96	0.00	7.96	439.29

effective, or may even worsen the situation, at certain other frequencies. The above measurements are in general agreement with those of Li *et al.*[18].

Effects of position and orientation of the microphone on SPL level

The results in this section bring out the effects of position of the microphone, its orientation and position of the speaker on reduction in SPL. These measurements are made in order to understand the amount of noise reduction in different parts of the room with a single noise source and a single HR placed in the room. Note that the HR is placed at around one-third the height of the enclosure, which corresponds to approximately ear-height in a typical room.

Figure 4 shows the results obtained with the same speaker position and excitation voltage, but with the microphone position shifted to the middle (inset). These measurements are over a smaller range of frequency; the earlier results have already shown that the effect of HR is limited to a narrow band around its resonance frequency. The current measurements are therefore confined to this range. The maximum reduction of 10 dB (13.7%) occurs at 183 Hz, which is accompanied by significant reduction at 182 Hz as well. Broad side peaks adjacent to 183 Hz, showing that the HR has an adverse effect in these bands, are apparent from these results as well.

Further experiments were carried out with the microphone positions varying along the line of the resonator. However, position of the HR is invariant across the various set of measurements. These positions and results are shown in Figures 5 and 6. A maximum reduction of 5% and 8% in noise level is noted for the respective cases. It is therefore obvious that there is a change in the level of noise reduction for the same noise frequency at different locations of the enclosure. Subsequent experiments also confirm this result.

Figure 7 presents the results where the microphone position is the same as that of Figure 4, but with a different orientation. Notice that for the results in Figure 7, the microphone is neither pointing towards the speaker nor towards the HR, which is unlike that for Figure 4. However, the nature of the curves in the two figures is similar. A substantial reduction in SPL at 182 Hz is again noted from Figure 7. These preliminary measurements suggest that the orientation of a free-field microphone at a particular spot does not have much effect on the SPL level.

Limited experiments with a different position of the noise source were undertaken for a fixed position of the microphone. The change in position of the noise source in Figure 8 with respect to Figure 6 is apparent (inset, Figures 6 and 8). Figures 6 and 8 show a SPL reduction of 7 and 4 dB respectively, at 180 Hz frequency.

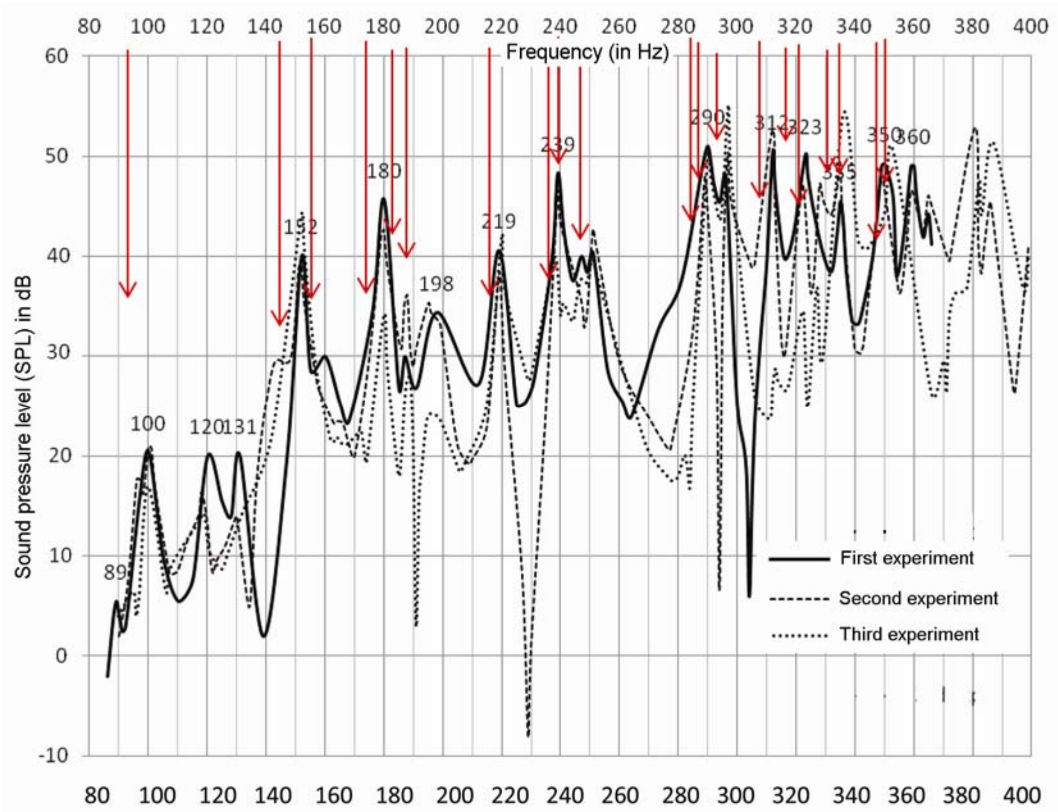


Figure 2. Frequency versus amplitude plot for the enclosure. Vertical arrows show the position of theoretically calculated eigenfrequencies of the enclosure. Peaks denote the experimentally obtained resonance at the respective modes. Three experiments were carried out for the range of frequencies with the source fixed at a particular point while the microphone was placed at three different locations.

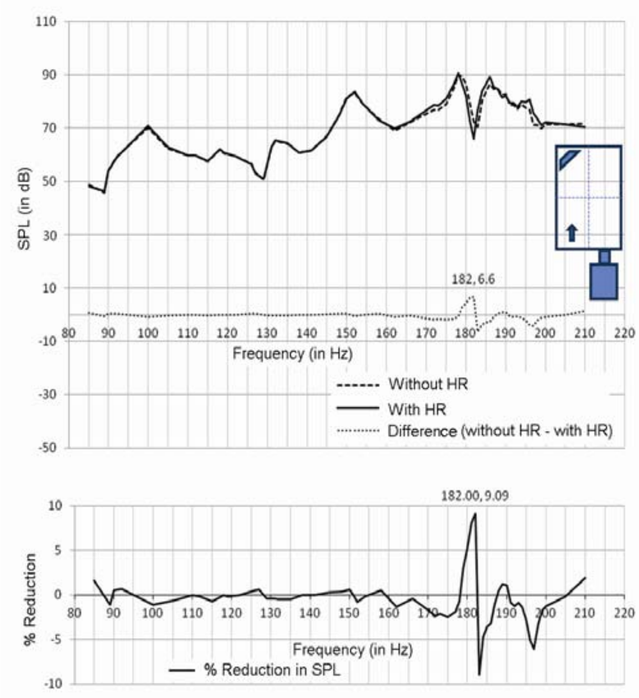


Figure 3. (Top) Sound pressure level (SPL) versus excitation frequency. (Bottom) Percentage reduction in SPL. Designed Helmholtz resonator (HR) frequency is 182 Hz. (Inset) Relative position of the speaker, microphone (arrow) and resonator in the enclosure.

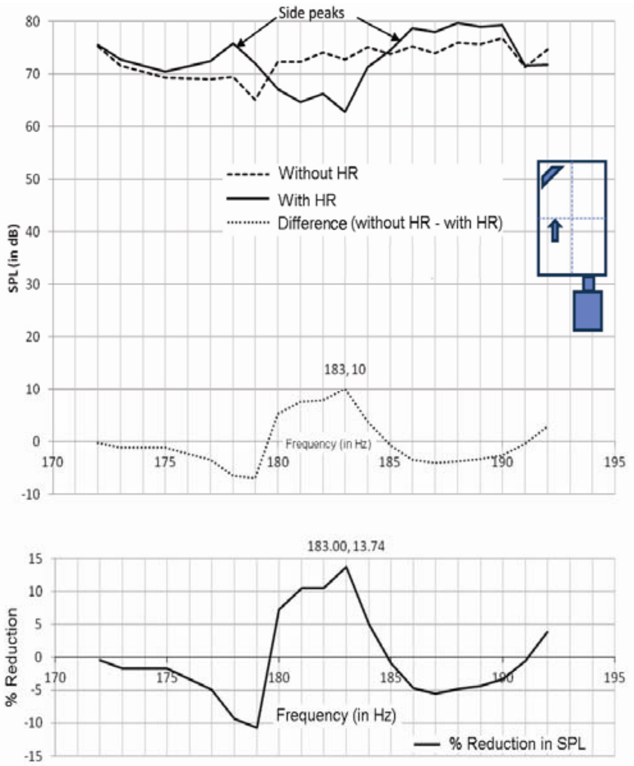


Figure 4. Same as Figure 3, but for different microphone position.

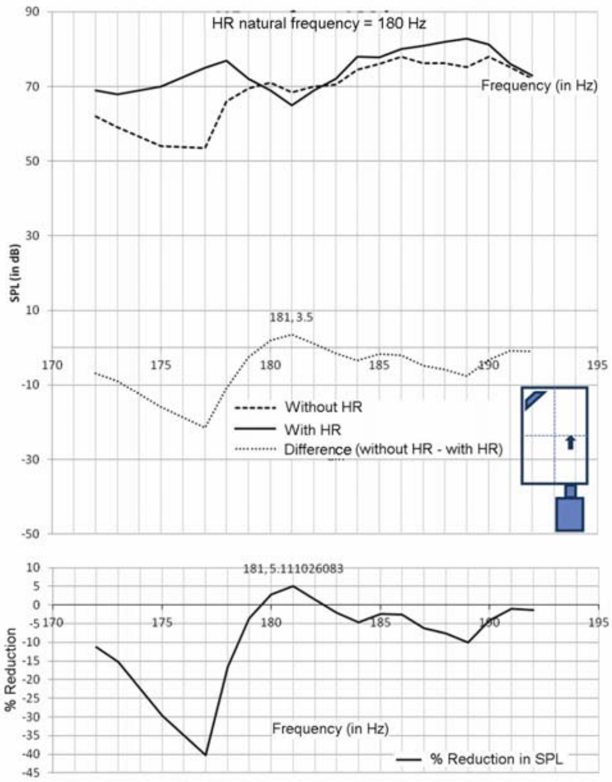


Figure 5. (Top) SPL versus excitation frequency. (Bottom) Percentage reduction in SPL. The designed HR frequency is 180 Hz. (Inset) Relative position of the speaker, microphone (arrow) and resonator in the enclosure.

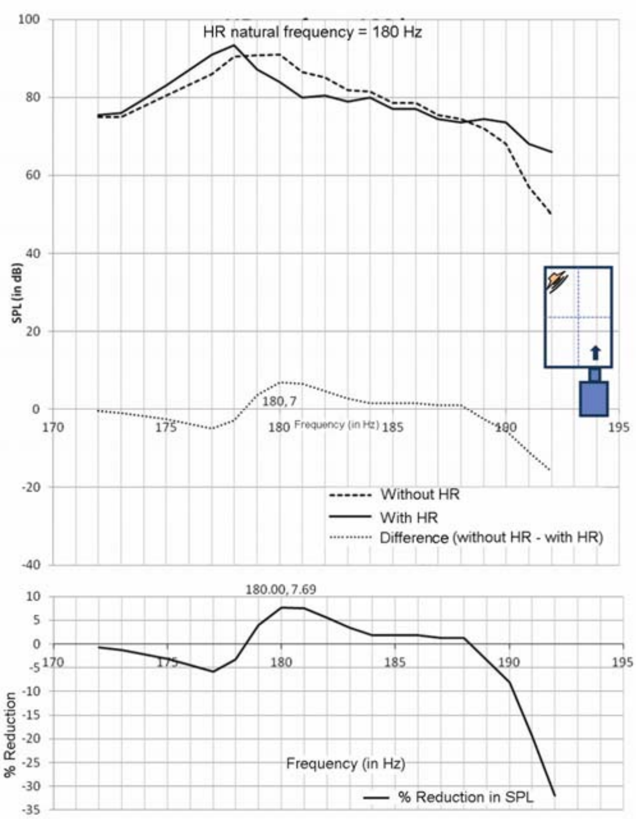


Figure 6. Same as Figure 5, but for different microphone position.

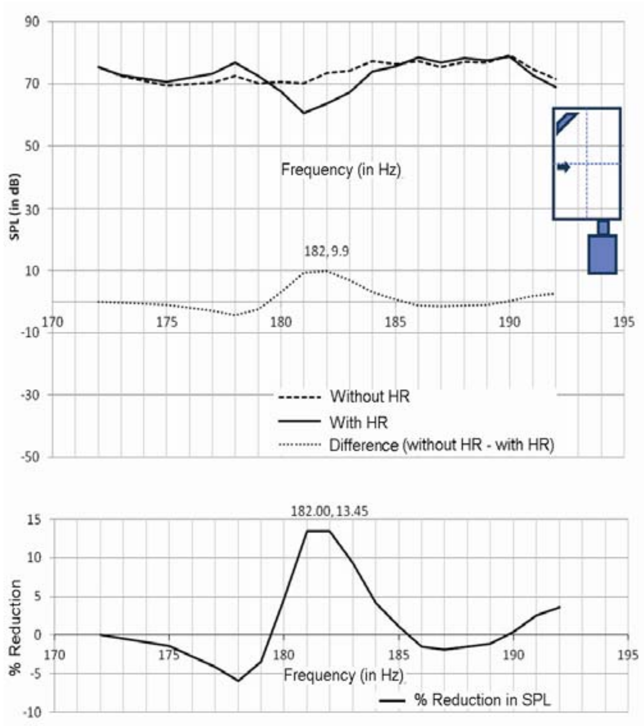


Figure 7. Same as Figure 3, but for different microphone position and orientation.

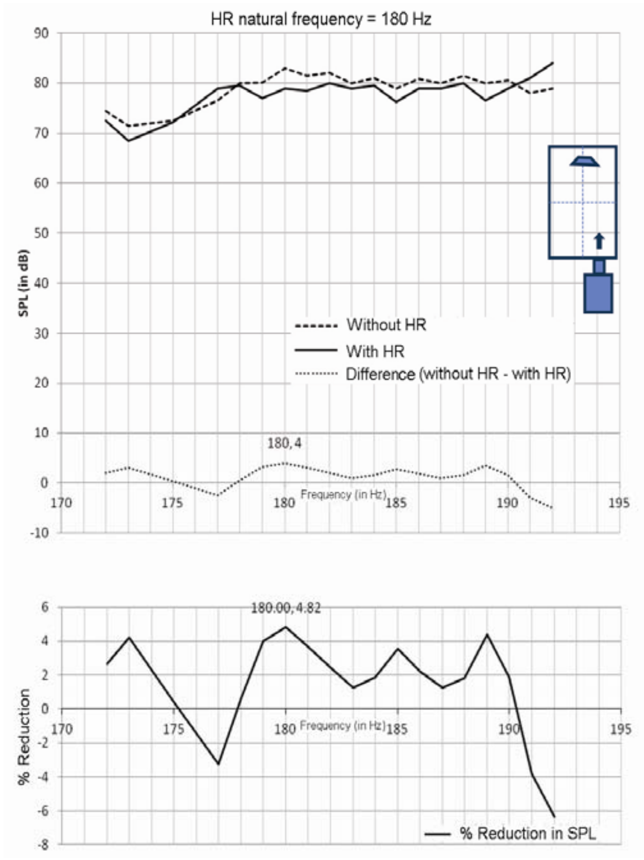


Figure 8. Same as Figure 5, but for different speaker and microphone positions.

Noise reduction in the enclosure

It has been observed from the different cases that whatever be the position of the microphone or the speaker, there is a certain and significant reduction of noise when the excitation frequency matches with the natural frequency of the Helmholtz resonator. In all the cases, the HR is positioned at the anti-nodal plane pertaining to that natural frequency of HR; this position of HR corresponds to where the maximum reduction is obtained. There is however variation in noise level reduction with location for a given noise source.

In order to see this spatial variation in noise level more clearly, the entire enclosure was bifurcated into nine zones, and additional experiments were undertaken. The corresponding reduction in SPL for an excitation frequency of 180 Hz, and fixed positions of speaker and microphone is shown in Figure 9. The plan view of the enclosure in Figure 9 shows that for the conditions tested the noise reduction ranges from 3 to 9 dB. Minimum reduction is noticed closest to the speaker; the maximum reduction is however not closest to HR, but the mid-plane of the room.

Dual HR coupled with an enclosure

The aforementioned results show a reduction in noise level with a single HR. In an effort to increase the magnitude of reduction, limited experiments with two HRs are performed. Both these resonators were positioned at anti-nodal planes (Figure 10). Figure 10 presents results for three cases – when only Helmholtz resonator-1 (HR1) is present, when only HR2 is present and when both HR1 and HR2 are present. The measurements are compared with the baseline case of no HR being present. The resonance frequency of these Helmholtz resonators is 166 Hz.

Figure 10 shows that a maximum reduction of 7.7 dB is obtained at 166 Hz when only HR1 is coupled with the enclosure. Similarly, a maximum reduction of 12.1 dB is obtained at 167 Hz when only HR2 is coupled with the enclosure. When both the resonators are combined, the maximum reduction in SPL is 15.2 dB at 166 Hz. Thus a combination of Helmholtz resonators located at different anti-nodal planes leads to a reduction in SPL, which is more than that obtained from individual HRs. The amount of reduction is however not the arithmetic sum of the two reductions, but larger than the individual effects.

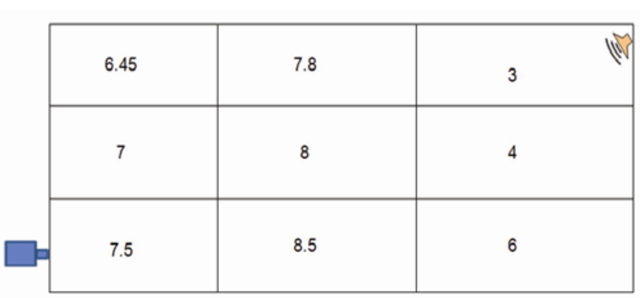


Figure 9. SPL reduction across various zones inside the enclosure (in dB). The relative position of the speaker and resonator in the enclosure is also shown.

This result demonstrates the potential of employing more than one HR to attain an improvement in the sound-level reduction. It is further noted that in practice there is enough space on the enclosure walls to mount these multiple Helmholtz resonators. Employing multiple resonators appears to be a logical extension of using a single HR; however, this idea has not been explored earlier to the best of our knowledge. Doria[19] and Griffin *et al.*[20] developed a mathematical model for dual HR and showed that it can provide a wider bandwidth of attenuation. The HRs are mechanically coupled (neck–cavity–neck–cavity) in their case; their configuration is therefore different than that employed in the present work. Use of dual HR for reduction over a larger bandwidth has recently been revisited by Xu *et al*.[21]. However, in these studies, HRs were employed to target two different frequencies, and not designed to increase the magnitude of noise reduction at a single frequency as explored in the present study. Yu and Cheng[22] employed two *T*-shaped acoustic resonators (and not HRs) coupled to an enclosure. Thus the use of multiple HR appears to be novel.

Effects of placing the Helmholtz resonator inside the enclosure

Experiments were carried out to study the effectiveness of the Helmholtz resonator when placed inside the system volume rather than mounting it on the wall. This is an important practical aspect because drilling a hole on the wall for the purpose of mounting a HR is sometimes not permissible (for example, in the engine room of a ship). Here, we explore placing the HR on the inside of the wall surface.

Two methods are employed while placing the Helmholtz resonator inside the enclosure. In the first case, the Helmholtz resonator is placed just inside the enclosure near the wall (left column, Figure 11). In the second case, the experiment is repeated with the Helmholtz resonator ensconced in a wooden box (right column, Figure 11). The box is stuck to the enclosure wall such that the Helmholtz resonator becomes detached from the enclosure volume. To check the robustness of the results, the microphone is shifted to various positions as shown in Figure 11.

It is seen that in seven out of the eight cases considered here, there has been a reduction in SPL at 179 Hz, which is close to the designed Helmholtz resonator natural frequency of 178 Hz. A Helmholtz resonator ensconced in a wooden box is preferable to one just kept inside for positions 1 and 2. However, it is vice versa for positions 3 and 4.

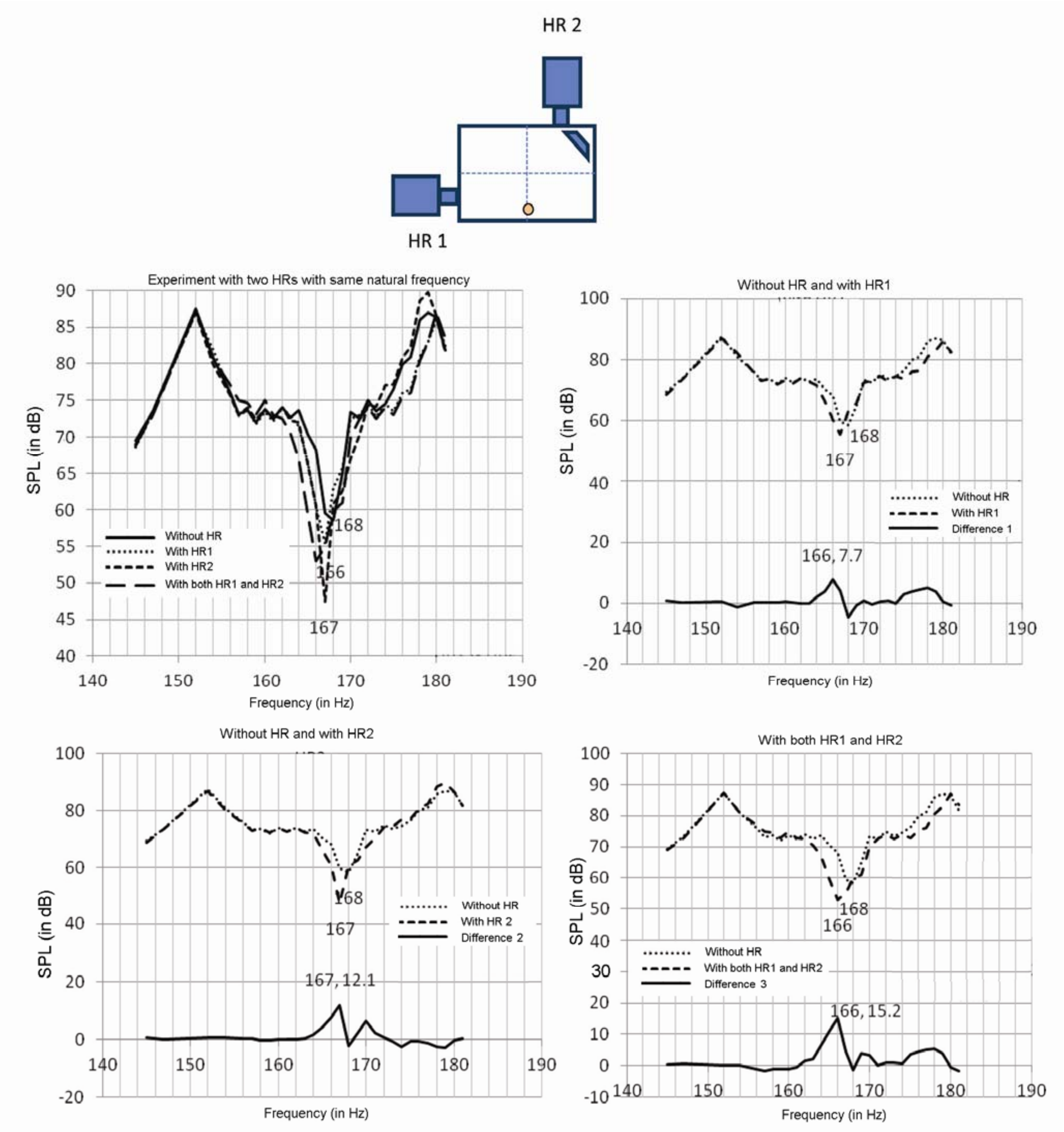


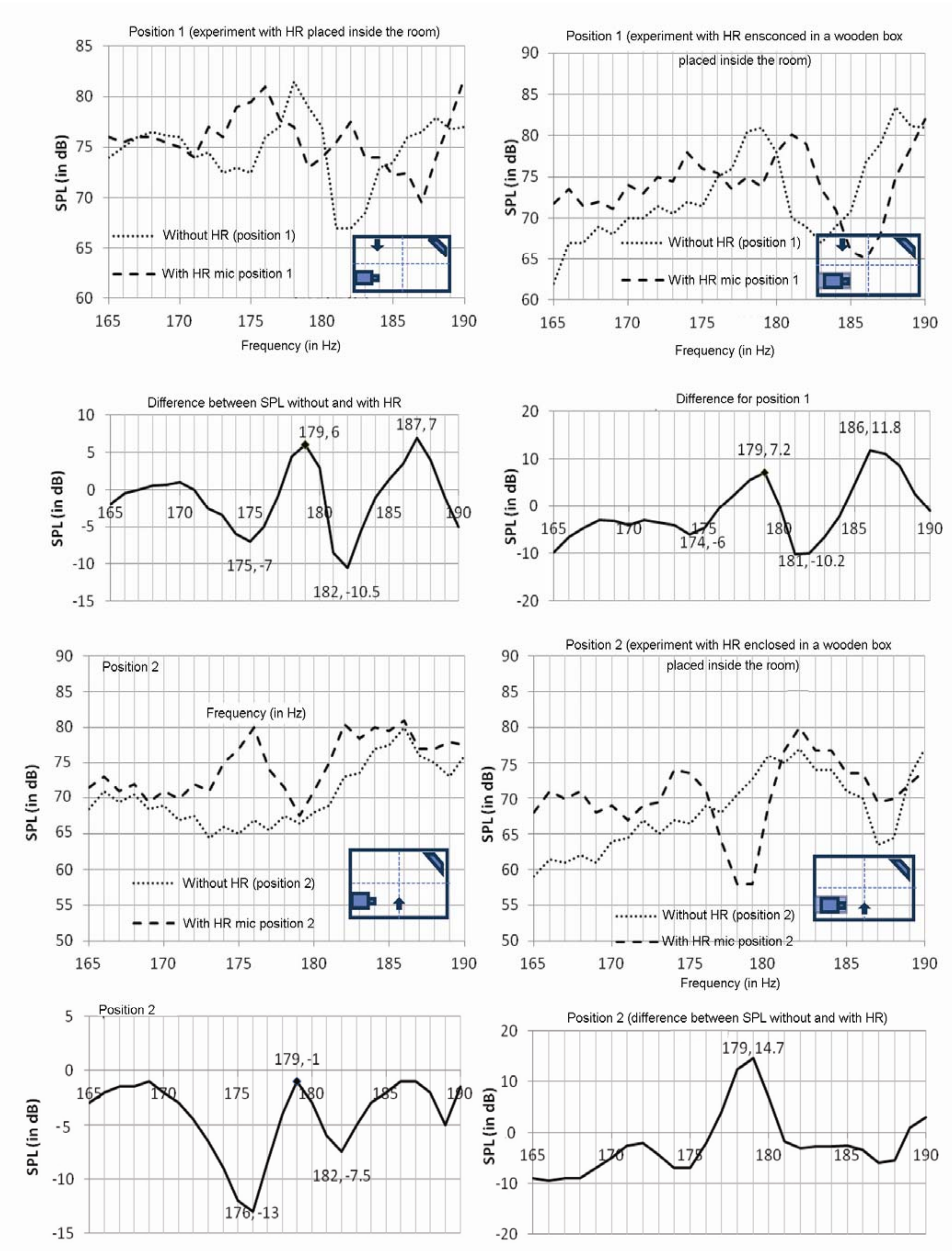
Figure 10. SPL versus excitation frequency for HR1 and HR2 and their combination thereof. The percentage reduction in SPL is also plotted. The designed HR frequency is 166 Hz. (Top) Schematic diagram shows the relative position of the speaker, microphone (dot) and resonator in the enclosure.

When two Helmholtz resonators are placed inside the enclosure volume, a significant reduction (over and above that for a single HR) in SPL was noted. Thus the two ideas proposed here – of using multiple Helmholtz resonators and ensconcing them – can be combined for achieving good results in various practical situations.

Conclusions

The following conclusions can be drawn from this study:

(i) Helmholtz resonators can be advantageously utilized for noise reduction in large enclosures. Our results show that reduction of at least 3 dB is possible close


Position 1 (experiment with HR placed inside the room)
SPL (in dB)
Frequency (in Hz)
Without HR (position 1)
With HR mic position 1
Position 1 (experiment with HR ensconced in a wooden box
placed inside the room)
Difference between SPL without and with HR
179, 6
187, 7
175, -7
182, -10.5
Difference for position 1
179, 7.2
186, 11.8
174, -6
181, -10.2
Position 2
Without HR (position 2)
With HR mic position 2
Position 2 (experiment with HR enclosed in a wooden box
placed inside the room)
179, -1
176, -13
182, -7.5
Position 2 (difference between SPL without and with HR)
179, 14.7

(*Contd*)

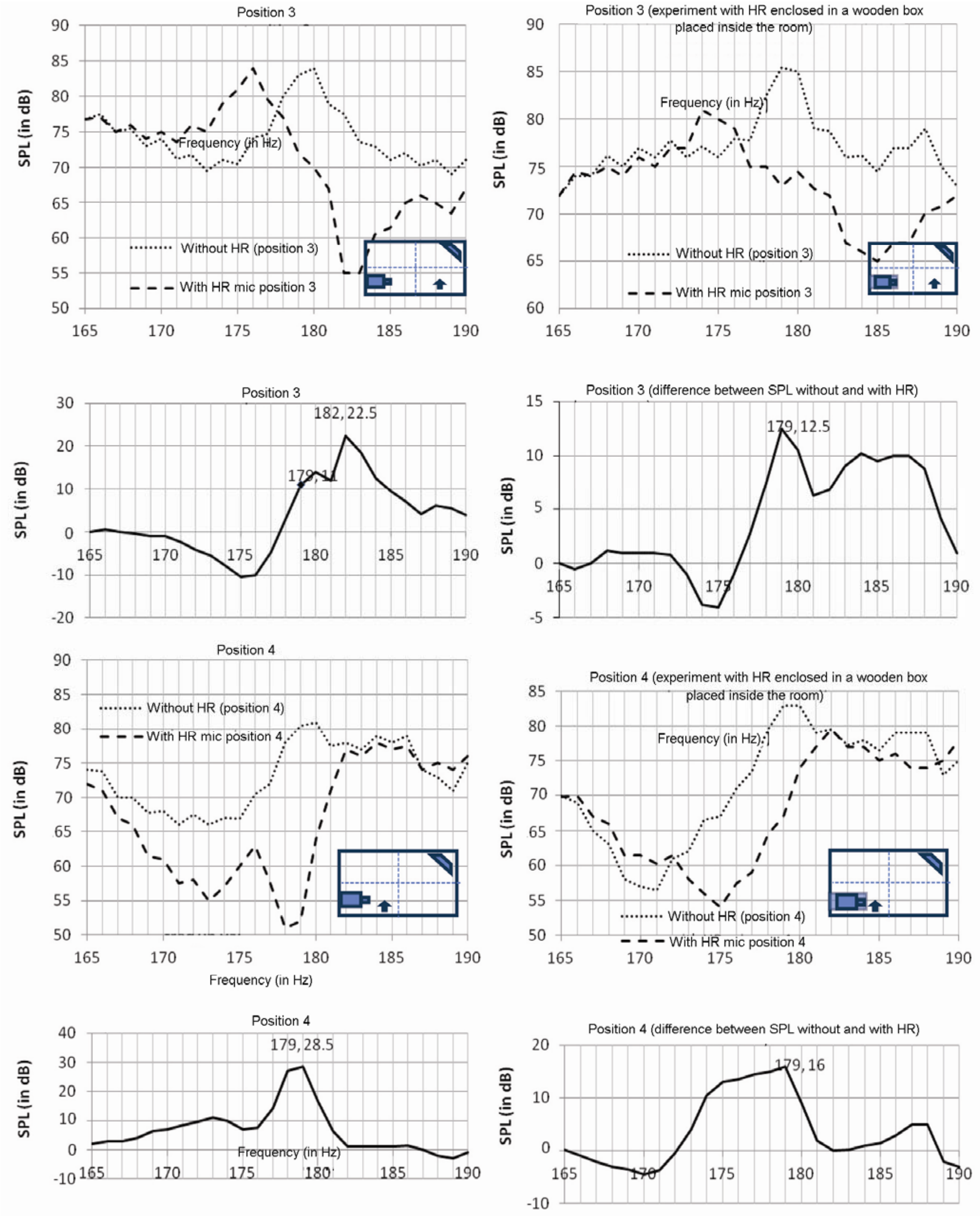


Figure 11. SPL versus excitation frequency. The percentage reduction in SPL is also plotted. (Inset) Relative position of the speaker, microphone (arrow) and resonator in the enclosure. The first column from top to bottom are experiments done with only the HR having natural frequency = 178 Hz at various positions of the microphone. The second column are experiments done with HR ensconced in a wooden box at the same location. Readings are for various positions of the microphone.

to the source, which increases to 9 dB in the mid-plane of the room. The results further confirm that any excitation outside the natural frequency of the HR may not be attenuated; rather the HR may even have an adverse effect at those frequencies.

(ii) Additional Helmholtz resonators can be mounted for further reduction in noise level. Our results with dual HR indicate that the amount of reduction is however less than the arithmetic sum of reductions from individual resonators.

(iii) Different models have been proposed for mounting the Helmholtz resonator on the walls of the enclosure. One of them is to ensconce the Helmholtz resonator inside a wooden box mounted against the wall, with the cavity volume of the resonator placed near the wall and the mouth of the Helmholtz resonator facing the sound source. Fair amount of success has been achieved following this method, thus doing away with the drilling of holes on the enclosure boundary.

These results clearly suggest that HR can be employed for noise reduction in large rooms. The noise reduction is not just confined near HR; it occurs throughout the room. The amount of reduction can be increased by employing multiple resonators and ensconcing them can solve the problem of mounting HRs.

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