inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

An experimental investigation of cavity noise control using mistuned Helmholtz resonators

V Surya Narayana Reddi CHINTAPALLI; Chandramouli PADMANABHAN[1]

Machine Design Section, Department of Mechanical Engineering,
Indian Institute of Technology Madras, Chennai, 600036, India

ABSTRACT

The major objective of this paper is to demonstrate higher noise reduction when an acoustic cavity is coupled to a combination of Helmholtz resonators (HRs) tuned to slightly different frequencies. An acoustic cavity, whose first two modes are close to each other, is selected for carrying out experiments. These are carried out to understand the behaviour of the coupled Helmholtz resonator-cavity system; the cavity is excited using two speakers and sound pressure is measured using two microphones on a rotating boom.

When a resonator is coupled to a cavity, the acoustic natural frequency to which it is tuned, splits into two modes, one below and one above the original frequency. When multiple resonators are used, it is demonstrated that higher noise reduction can be achieved by mistuning them to the new split frequencies rather than tuning all of them exactly to the first cavity mode. Similarly, higher noise reduction is seen when resonators are placed near edges/corners of the cavity walls than at the centres of the boundary walls. In all these cases anti-nodal locations are selected for superior noise reduction. A detailed study has been carried out and guidelines for tuning resonators for superior noise control is proposed.

Keywords: Resonator Mistuning, Cavity Noise Reduction   I-INCE Classification of Subjects Number(s): 34.3
(See `http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf`.)

1. INTRODUCTION

Low frequency noise in cavities can be reduced with the use of Helmholtz resonators (HRs). Most of the literature on coupled cavity-resonator systems, deal with situations where the resonator frequency is tuned exactly to the first cavity mode. The earliest work on the coupling of tuned HRs was carried out by Fahy and Schofield (1) in their paper on the interaction between a HR and an acoustic mode of an enclosure. They established that when a resonator tuned to the natural frequency corresponding to an acoustic mode of an enclosure, is coupled to the enclosure, two new coupled modes are produced of which the natural frequencies lie on either side of the original frequency. The separation between the new frequencies is proportional to the value of a coupling parameter, which increases with the ratio of enclosure volume to resonator volume, and with the modal pressure amplitude at the position of the resonator, and is largest for oblique modes and smaller for axial modes.

Cummings (2) presented the multi-mode theory for the scattering of the sound field in a cavity by using an array of resonators as an improvement on single mode treatments. The Cummings model faced a singularity issue as it was based directly on impedances of the resonators instead of the single-degree-of-freedom (SDOF) model approach by Fahy and Schofield. Li and Cheng (3) replaced the Cummings (2) resonator model with that of Fahy and Schofield (1). This avoided the singularity problem faced by Cummings (2). Doria (4) carried out an investigation on tuning a double resonator to two modes of the cavity. He presented the effect of the resonator on higher order modes. The results obtained by Fahy and Schofield (1) were confirmed and additional conclusions regarding the enhancement of higher mode frequencies by the resonator were presented. Johansson and Mendel (5) in their paper established that the acoustic coupling between closely located acoustic resonators will have significant effect on the resonance properties. They described the coupling by the mutual impedance between the neck openings, and an additive reflection impedance modification to the radiation impedance. Esteve and Johnson (6) have carried out extensive studies on noise reduction using HRs and distributed vibration absorbers (DVA). They showed that lightweight DVA and small HR treatment can significantly

[1]mouli@iitm.ac.in

reduce the sound transmission in an enclosure as long as the structure and the cavity are lightly damped, which is usually the case at low frequencies in aerospace applications.

Nair et al. (7) analyzed the coupled resonator cavity system numerically and experimentally and established the effect of damping and increasing resonator volume fraction on the attenuation of the targeted mode. They have confirmed that introduction of a resonator tuned to the cavity mode introduces two coupled modes asymmetrically placed about the original cavity mode and the spacing between two coupled modes increases with increasing resonator cavity volume ratio. They showed that a volume fraction of about 1 % gives adequate attenuation of a cavity mode. Enhancing the damping of resonators, results in higher noise reduction in the frequency range around the targeted mode, for a given volume fraction of the resonator. More recently Biswas and Agrawal (8) analyzed that the amount of noise reduction for different configurations of Helmholtz resonators coupled to a relatively large-sized enclosure.

Although a fair amount of work has been done on coupling a tuned HR to a cavity, not much has been reported on coupling a HR whose frequency is slightly away from the first cavity mode. The objective of the present work is to study the coupling of HRs tuned exactly to the first cavity mode frequency as well to frequencies slightly different from it. A detailed experimental study is carried out determine the frequency combinations which result in maximum noise reduction in coupling a resonator to the cavity. Detailed experiments have been carried out to determine the resonator locations for maximum noise attenuation.

2. EXPERIMENTAL SET-UP

Experiments have been performed on a rectangular acoustic cavity with the first two modes being 163.5 Hz and 178 Hz (close to each other). The cavity dimensions are length L_a = 0.994 m, breadth B_a = 0.494 m and height H_a = 1.094 m. The resonators used in the experiments have a cylindrical volume with diameter D = 135.2 mm and height L1 = 79.8 mm. The orifice diameter d = 16.5 mm. These dimensions are kept constant, while the length of the orifice is varied to change the natural frequency of the resonator as desired. Three frequencies are chosen for tuning the HR they are 156 Hz, 163.5 Hz (first cavity mode) and 167 Hz respectively.

2.1 HR-cavity coupling

The experimental set-up, schematic is shown in Figure 1 and photograph in Figure 2. The rectangular cavity is covered with a metal plate by using M8 bolts on all the four flanges of the cavity. A rubber sheet is used to avoid leaks from the cavity. Several holes were drilled on all the six faces of the cavity (including top cover) for resonator mounting. Each hole is provided with a cover plate to close it when not in use. These holes are at the anti-node locations of the targeted mode so as to be more effective in noise reduction. Resonators are flush mounted using a metal bush which serves as the orifice of the resonator. A rotating boom is used to take the readings at various locations inside the cavity. The boom can be rotated about its axis as well as translated along its axis. The boom is provided with a provision for mounting microphones at various radial locations. With this boom, a large number of readings can be taken with minimal effort. Two JBL 6 × 9” coaxial speakers were placed on two sides of the cavity for the excitation. The two speakers are connected in phase to the amplifier which controls the sound coming from the speakers. The output from the amplifier is connected to a 4-channel LDS Dactron Focus Data Acquisition System for data acquisition. LDS Dactron uses RT Pro application software for reading and analyzing the transducer data signals. A 4-channel power module type 12AN maintains a constant RMS voltage of 0.1 volts. In LDS Dactron a white noise signal with 3200 Hz span is generated using a waveform source and fed to the two speakers controlled by the amplifier. Two 1/2 inch 01dB-Stell free field microphones are used for the measurement. Microphones are calibrated using 01dB-Stell sound calibrator before measurements are made. The maximum frequency of interest is limited to 1000 Hz with linear averaging; Hanning window function is used with 50 averages.

First the empty rectangular cavity natural frequencies are obtained through the averaged pressure response. Pressure response at 30 locations inside the cavity through rotating boom is obtained for calculating overall sound pressure level (SPL) and various cavity modes of the rectangular cavity. The analysis is performed for a frequency range of 130-190 Hz with a frequency resolution of 0.5 Hz for calculating the overall SPL. Now, the tuned resonator is coupled to the cavity and the response is measured again at the same 30 locations. The difference in overall SPL of both the measurements gives the amount of noise reduced inside the cavity.

2.2 HR experimental modelling

Experiments are conducted to tune the HRs to the selected cavity frequencies. The experimental set-up schematic is shown in Figure 3, while Figure 4 shows the photograph of the set-up in the laboratory. This set-up uses a B & K sound source (at a distance of 40 cm from the resonator mouth) connected to a 4-channel LDS Dactron Focus Data Acquisition System (DAQ) with RT Pro application software for reading and analyzing

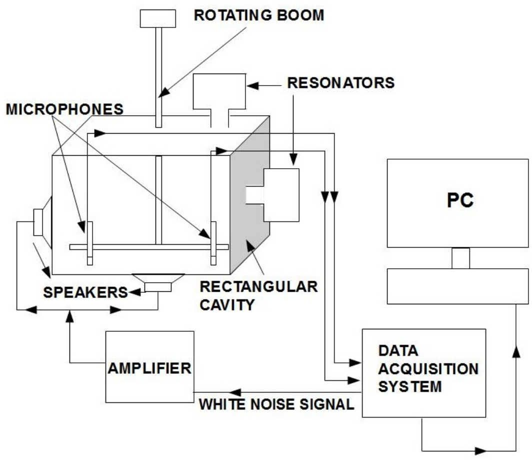

Figure 1 – Schematic diagram of the coupled experimental setup

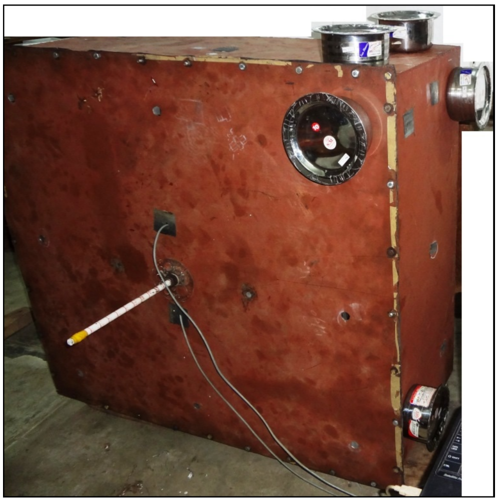

Figure 2 – Photograph of the coupled test setup

the transducer signals. A 4-channel power module from GRAS (Model 12AN) maintains a constant RMS voltage of 1.5 volts. In LDS Dactron, a pseudo random signal with 6400 Hz span is generated, which is fed to the B & K sound source. The resonator is fixed to the stand by means of a fixture. Two 1/2 inch 01dB-Stell free-field microphones are used for the measurement. Microphones are calibrated using 01dB-Stell sound calibrator before measurements are made. Microphones are fixed at two locations, with one microphone (P_1) being placed inside the resonator cavity through a hole in the back of the resonator, sealed with an O-ring. The second microphone (P_2) is kept 30 mm below the resonator, at an axial distance reasonably away from the mouth, ensuring that it does not obstruct the direct sound field between resonator and the sound source. A transfer function, $\frac{P_1}{P_2}$, between the first microphone (output) and the second microphone (input) is calculated to identify the natural frequencies of the resonator. The coherence between the input and output signals is also checked for linearity and ensuring appropriate signal to noise ratio; the frequency of interest is upto 1000 Hz and linear averaging with Hanning window function is used.

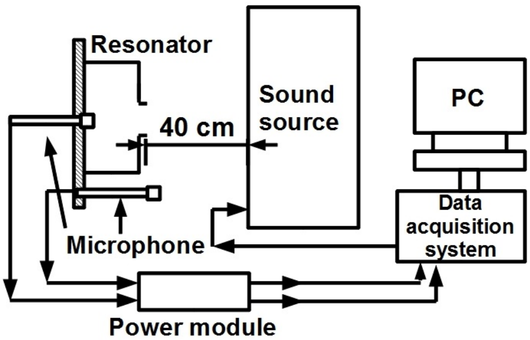

Figure 3 – Schematic diagram of the HR experimental setup

Figure 4 – Photograph of the HR test setup

3. RESULTS AND DISCUSSION

3.1 HR tuned to cavity frequency

From Figures 5 and 6 it is clear that the first mode splits into two coupled frequencies on either side of the original frequency as observed by Fahy (1). When HRs are tuned exactly to 163.5 Hz, a reasonable reduction occurs at 178 Hz, which shows that in cavities with close modes, resonators are helpful in reducing noise over a broader frequency range. When a single orifice HR is tuned to 163.5 Hz it splits the first cavity mode into two modes with the overall amplitude lower than the original cavity mode. The split modes are at 156 and 167 Hz , with the 156 Hz peak slightly smaller than that of the 167 Hz peak. One mode each is added to the two split modes when one increases the number of resonators tuned to the cavity mode. This can be seen in Figure 6 where the peaks for the 5 HR case are numbered for ease of identification. The single HR was mounted on the

Z=0.546 m plane (anti-node); similarly for 3 and 5 HRs different anti-nodal planes are identified for mounting. Table 1 shows the results for the decrease in sound pressure level (SPL) (dB) with the increase in number of resonators. The spacing between the two modes on either side of 163.5 Hz increases with increase in the number of HRs. Also one can see that the second mode peak shifts to the right even though it was not targeted.

The resonators were placed at different locations of the cavity and the results thus obtained clearly indicates that maximum sound pressure level reduction is observed when they are well separated from each other. It is clear from Table 1 that there is a leveling of the noise reduction beyond the use of 5 HRs.

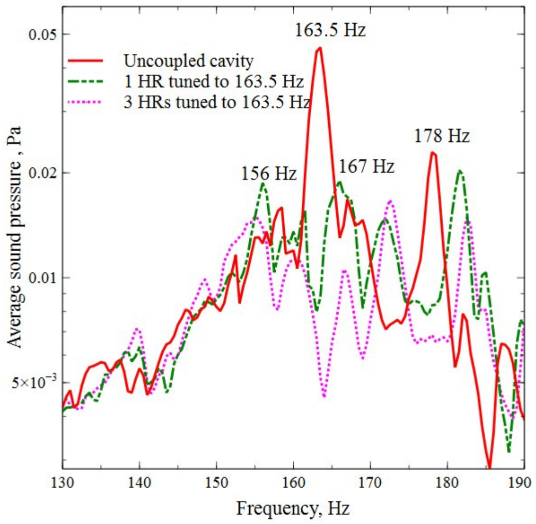

Figure 5 – Effect of increasing number of HRs on cavity response (1 HR and 3 HRs with cavity)

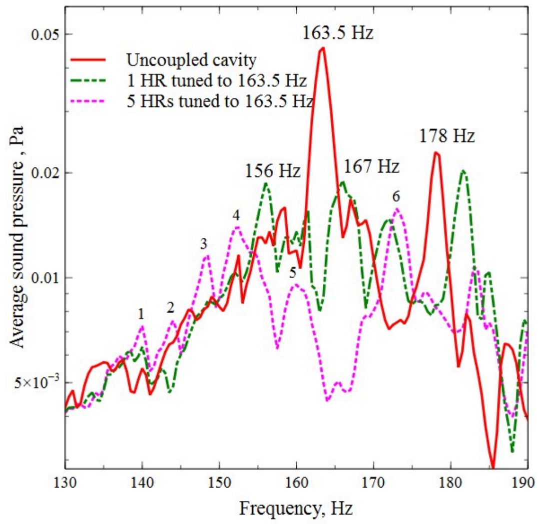

Figure 6 – Effect of increasing number of HRs on cavity response (1 HR and 5 HRs with cavity)

Table 1 – Decrease in SPL (dB) when HRs are exactly tuned to the first acoustic mode of the cavity.

Number of HRs	SPL, in dB
1	2.2
3	4.0
5	4.5
6	4.7

3.2 HR tuned to other frequencies

Six HRs are selected as a base line for determining the applicability of HRs tuned to other frequencies. Experiments are performed by tuning the HRs to three selected frequencies. One frequency is the first cavity frequency (163.5 Hz) and the others are 156 Hz and 167 Hz respectively. These are the two split frequencies when a single HR tuned to the first acoustic mode is coupled to the cavity. Thirteen different combinations based on these three frequencies were investigated for maximum noise reduction. For each of these combinations, five different zones on the cavity (L1 to L5 as shown in Figure 7) were selected for mounting the resonators. From this large set of experiments, four frequency combinations-all 6 HRs tuned to 163.5 Hz, all 6 HRs tuned to 167, 3 tuned to 156 and 3 to 167 Hz and 2 HRs each tuned to 156, 163.5 and 167 Hz are chosen. Figures 8 to 10 show their performance when they are mounted at zone L5 (which happens to be the best zone for noise reduction). Table 2 lists the average noise reduction for the six cases. One can see that the maximum noise reduction occurs for 3 HRs tuned to 156 Hz and 3 HRs tuned to 167 Hz and for 2 HRs each tuned to 156 Hz, 163.5 Hz and 167 Hz. This implies that one needs to have HR combinations which include sufficient number of resonators tuned to the lower split frequency (156 Hz in this case) and to the upper split frequency (167 Hz in this case) for better noise reduction. The same trend was seen for the L1 zone where the mistuned combinations are about 2 dB better than the tuned case.

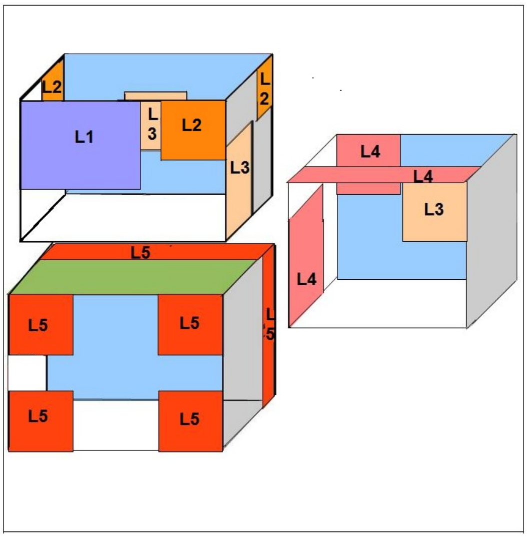

Figure 7 – Locations considered for coupling HRs to the cavity

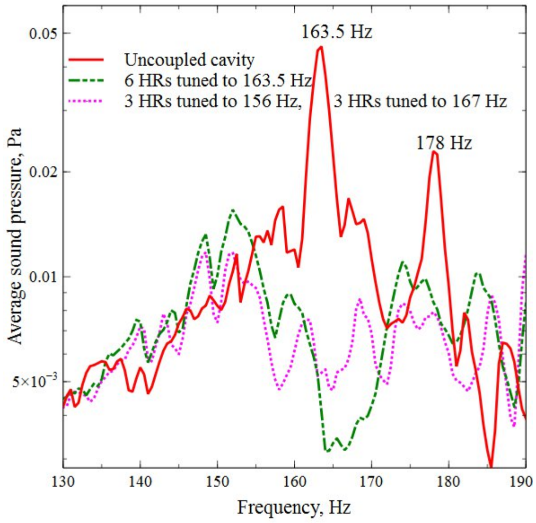

Figure 8 – Average sound pressure of 6 HRs tuned to 163.5 Hz and 3 HRs to 156 Hz and 3 HRs to 167 Hz

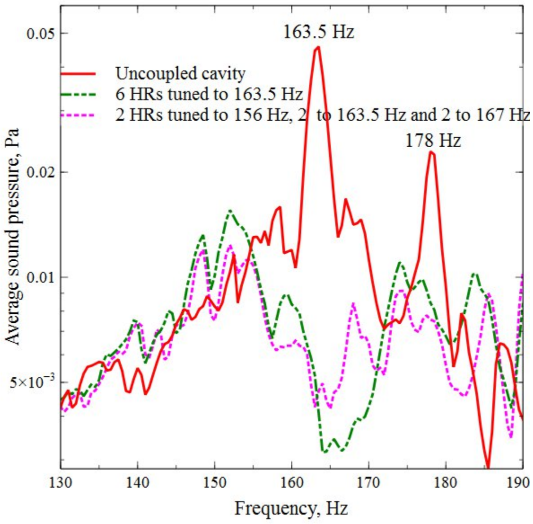

Figure 9 – Average sound pressure of 6 HRs tuned to 163.5 Hz and 2 HRs to 156 Hz, 2 HRs to 163.5 Hz and 2 HRs to 167 Hz

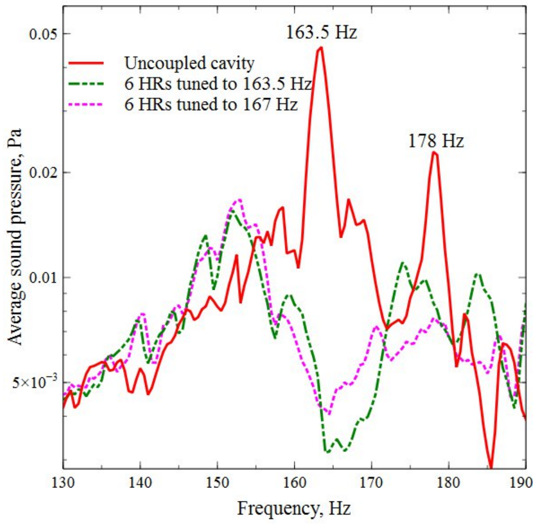

Figure 10 – Average sound pressure of 6 HRs tuned to 163.5 Hz and 6 HRs tuned to 167 Hz

Table 2 – Decrease in SPL (dB) when HR combinations are tuned to different frequencies.

Coupled HRs combination	SPL (L_5) in dB	SPL (L_1) in dB
6 HRs @ 156 Hz	4.5	3.1
6 HRs @ 163.5 Hz	4.7	3.2
6 HRs @ 167 Hz	5.0	4.4
3 HRs @ 156 Hz & 3 HRs @ 167 Hz	5.9	5.0
3 HRs @ 163.5 Hz & 3 HRs @ 167 Hz	4.5	3.8
2 HRs each @ 156 Hz, 163.5 Hz & 167 Hz	5.8	5.0

4. CONCLUSIONS

In this paper, the effect of detuning the HR natural frequency on noise reduction in a cavity has been explored. A rather large set of experiments have been conducted on various HR combinations coupled to a rectangular cavity. From these experiments it is concluded, that it is better to tune the HR frequencies, to both the lower and upper split mode frequencies corresponding to a single HR tuned exactly to the acoustic mode of the cavity. It is felt that this is due to the targeting of the new split peaks with the mistuned HRs. When HRs are placed at corners/edges/where maximum number of surfaces meet, the amount of noise reduced is higher than when they are placed close to each other. More investigation on the reasons for the improved performance of the mistuned HRs is being carried out.

REFERENCES

1. Fahy F J. Schofield C. A note on the interaction between a Helmholtz resonator and an acoustic mode of an enclosure. Journal of Sound and Vibration. 1980;72(1):365-378.
2. Cummings A. The effects of a resonator array on the sound field in a cavity. Journal of Sound and Vibration. 1992;154(1):25-44.
3. Li D. Cheng L. Acoustically coupled model of an enclosure and a Helmholtz resonator array. Journal of Sound and Vibration. 2007;305(1):272-88.
4. Doria A. Control of acoustic vibrations of an enclosure by means of multiple resonators. Journal of Sound and Vibration. 1995;181(1):673-85.
5. Johansson T A. Kleiner M. Theory and experiments on the coupling of two Helmholtz resonators. Journal of Acoustical Society of America. 2001;110(3):1315-1328.
6. Esteve S J. and Johnson M E. Reduction of sound transmitted into a composite cylinder using Distributed Vibration Absorbers and Helmholtz Resonators. Journal of the Acoustical Society of America. 2002;112(6):2040-2048.
7. Nair U S. Shete C D. Subramoniam A. Handoo K L. Padmanabhan C. Experimental and computational investigation of coupled resonator cavity systems. Applied Acoustics. 2010;71(1):61-67.
8. Biswas S. Agrawal A. Noise reduction in a large enclosure using single, dual and ensconced Helmholtz resonators. Current Science. 2013;104(1):1681-1691.