

Concert Hall Acoustics: Paper ICA2016-1182

An investigation into the Helmholtz resonators of the Queen Elizabeth Hall, London

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Abstract

An investigation was conducted into the performance of the 2300 Helmholtz resonators of the Queen Elizabeth Hall, as part of acoustic design work undertaken by Ramboll for the refurbishment of the Southbank Centre's East Wing. The reverberation in the hall at low frequencies is controlled by banks of Helmholtz resonators lining the walls. A bank of replica resonators was constructed and practical measurements were undertaken in a reverberation chamber to establish the absorption they provided, and to determine whether any repairs or adjustments are necessary. In addition, the effect of adding a layer of polyurethane foam over the neck to increase the acoustic resistance was investigated, along with the interaction between the resonators and a variable absorption system. The variable absorption system comprised two layers of acoustic curtains, which can be hung in front of the resonators. The combination of resonators and acoustic curtains appeared to provide a very effective broadband absorber suited to amplified music conditions.

Keywords: Helmholtz resonators, low frequency, acoustic curtains, variable absorption

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1 Introduction

An investigation was conducted into the performance of the 2300 Helmholtz resonators of the Queen Elizabeth Hall, as part of acoustic design work undertaken by Ramboll for the refurbishment of the Southbank Centre's East Wing.

The Queen Elizabeth Hall (QEH) opened in 1967 as a smaller chamber-music hall to complement its older and larger neighbour the Royal Festival Hall (RFH) which was primarily designed for symphonic music. The RFH has had a widely-documented history about its acoustics and the improvements that have been made over the years. The acoustics of the QEH have never been greatly analysed or lauded, but the hall in its present state could benefit from improvement. The original RT of 2 seconds (occupied) at mid frequencies has decreased slightly since the introduction of lighting rigs and other clutter to the hall.

The reverberation in the hall at low frequencies is controlled by banks of Helmholtz resonators lining the walls and it is important, as in any refurbishment work, to determine whether their performance has changed over 47 years. Research was conducted into the sound absorption of the resonators to determine whether any repairs or adjustments are necessary.

In addition to restoring the resonators, a variable absorption system was investigated in order to lower the reverberation time of the Queen Elizabeth Hall to be suitable for amplified music concerts. An option for the variable absorption system comprises motorised curtains, which can be lowered from the ceiling void to fully or partially cover the resonators. The absorption provided by the curtains and their effects on the performance of the Helmholtz resonators have also been investigated

2 Replica resonators

2.1 Original Helmholtz Resonators of the QEH

Each individual resonator is a rectangular box with 5cm thick sides and a rectangular aperture on the front face. The cross-sectional area of the aperture is 233cm², which can be reduced by the addition of rectangular plugs of three different sizes to alter the resonant frequency.

The different sizes of the resonator apertures are presented in Table 1 and illustrated in Figure 1.

Table 1: Resonator aperture sizes

Configuration of resonators	Dimensions of aperture	Nomenclature
No Plugs	457mm x 51mm	Size A
All Plug 1	279m x 25mm	Size B
All Plug 2	152mm x 25mm	Size C
All Plug 3	51mm x 25mm	Size D

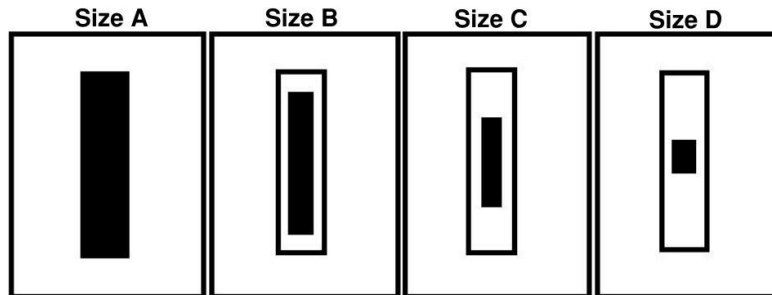


Figure 1: Resonator aperture sizes

2.2 Test specimen

The original plan to remove a resonator box from the QEH Auditorium for testing presented unforeseen difficulty once it was discovered that they are fixed to the walls with asbestos ropes. Mock-ups of the resonators and plugs were therefore constructed for testing in an acoustics laboratory.

A sample size of 24 resonator cells was constructed from birch-faced plywood to the dimensions of the originals installed in the QEH, comprising six separate boxes of four resonator cells. The test samples were stacked against a wall in order to mimic as far as possible the original placement of the resonators in the QEH (Figure 2).

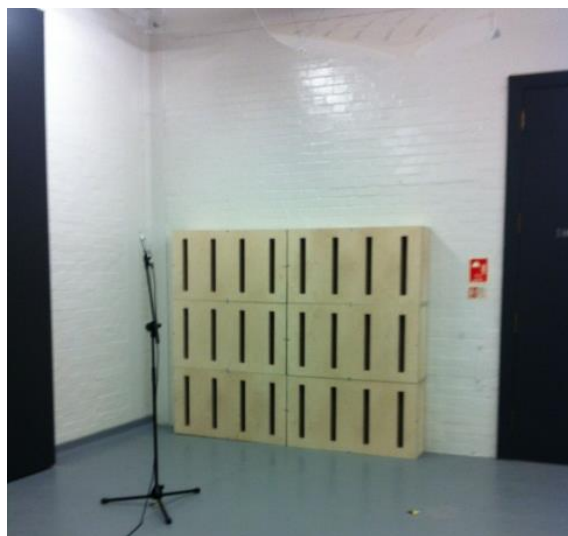


Figure 2: Replica resonators in the reverberation chamber

3 Measurement results

3.1 Absorption coefficients of resonators

Reverberation time (RT) measurements were made with the 24 resonator cells in the following configurations:

- All Size A
- All Size B
- All Size C
- All Size D
- Mixture of resonator sizes (see Table 3)
- All Size A with additional porous absorption
- All Size A with acoustic curtains at 0mm from resonator faces
- All Size A with acoustic curtains at 100mm from resonator faces
- All Size A with acoustic curtains at 200mm from resonator faces.

The measurement results were compared with those of the empty reverberation chamber, to determine both the resonant frequencies of the different resonator types, and the absorption provided by them.

Figure 3 shows the dips in reverberation time produced by each resonator type; the resonant frequencies are presented in Table 2.

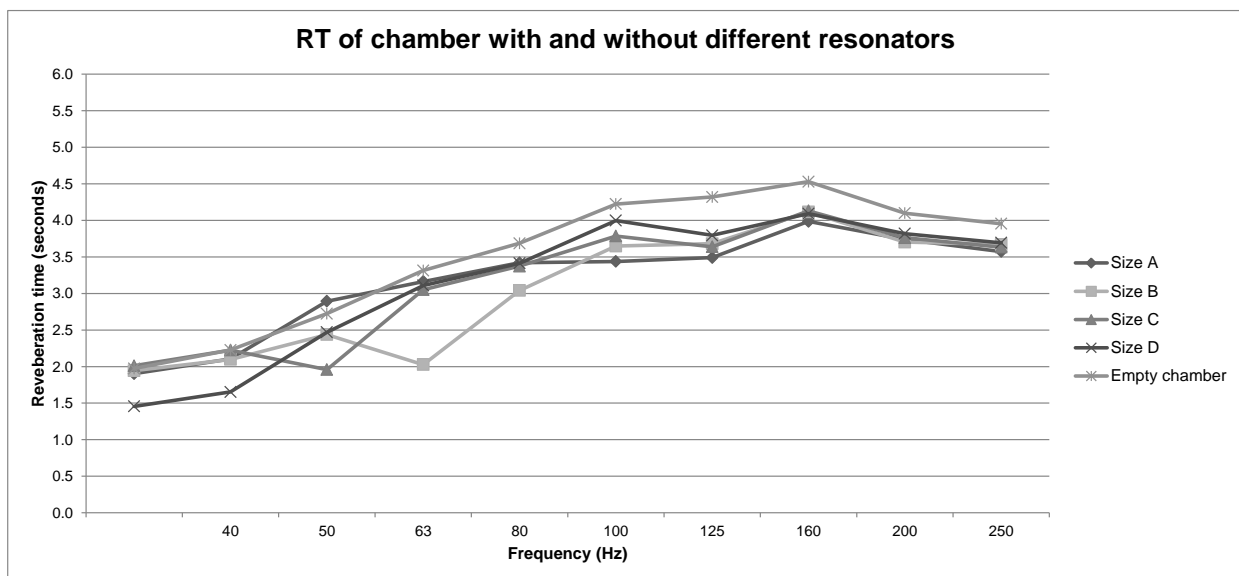


Figure 3: Dips in reverberation time with each resonator type

Table 2: Resonant frequencies

Resonator Aperture	Resonant frequency band(s)
Size A	100-160 Hz
Size B	80 Hz
Size C	63 Hz
Size D	40 Hz

Figures 4 to 7 show the corresponding absorption coefficient graphs across the frequency spectrum for all resonator sizes, against their calculated resonant frequencies.

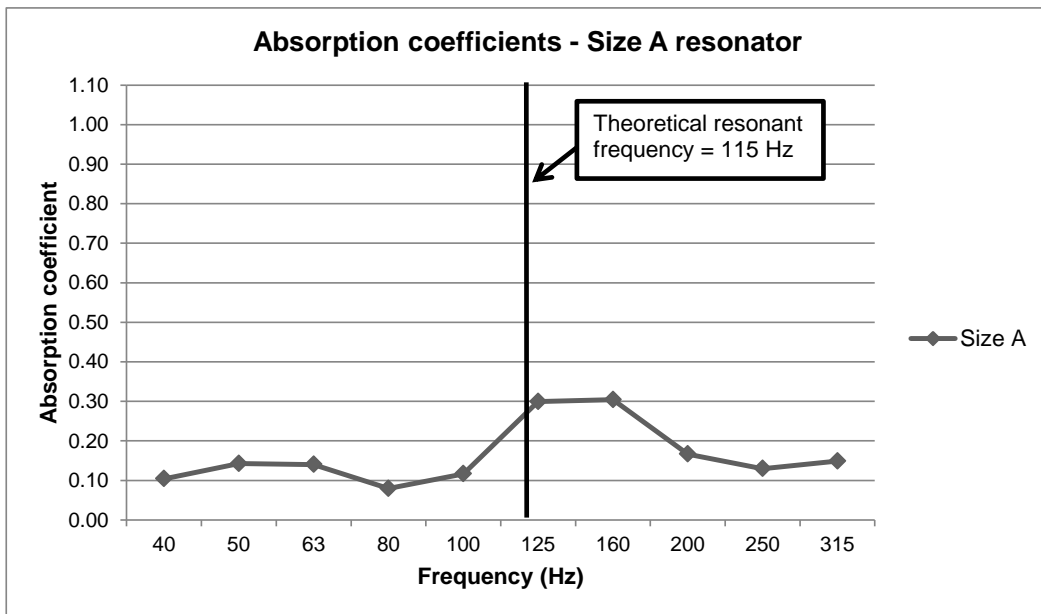


Figure 4: Absorption coefficients of Size A resonator

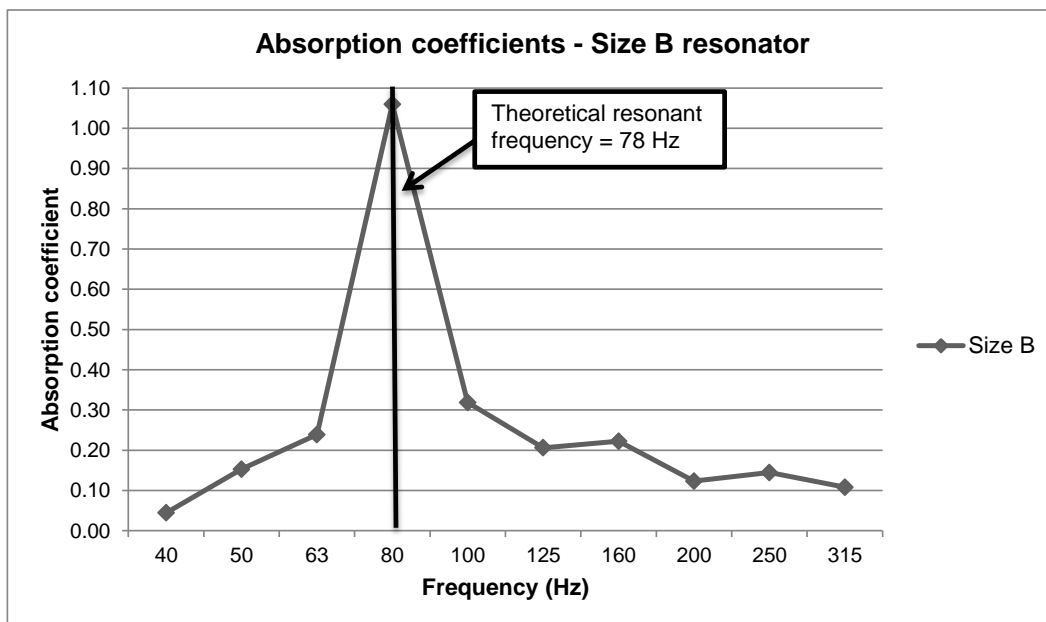


Figure 5: Absorption coefficients of Size B resonator

Resonator theory states that elongating or narrowing the aperture size produces a higher peak. This is evident in the Size B resonator, which has a long, narrow aperture and the highest absorption peak.

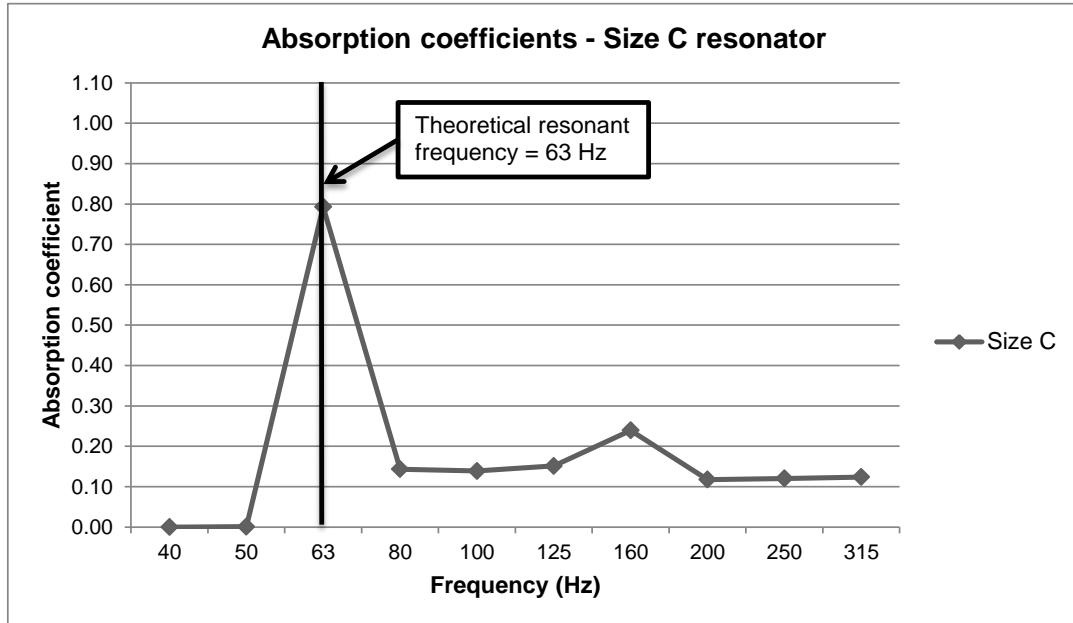


Figure 6: Absorption coefficients of Size C resonator

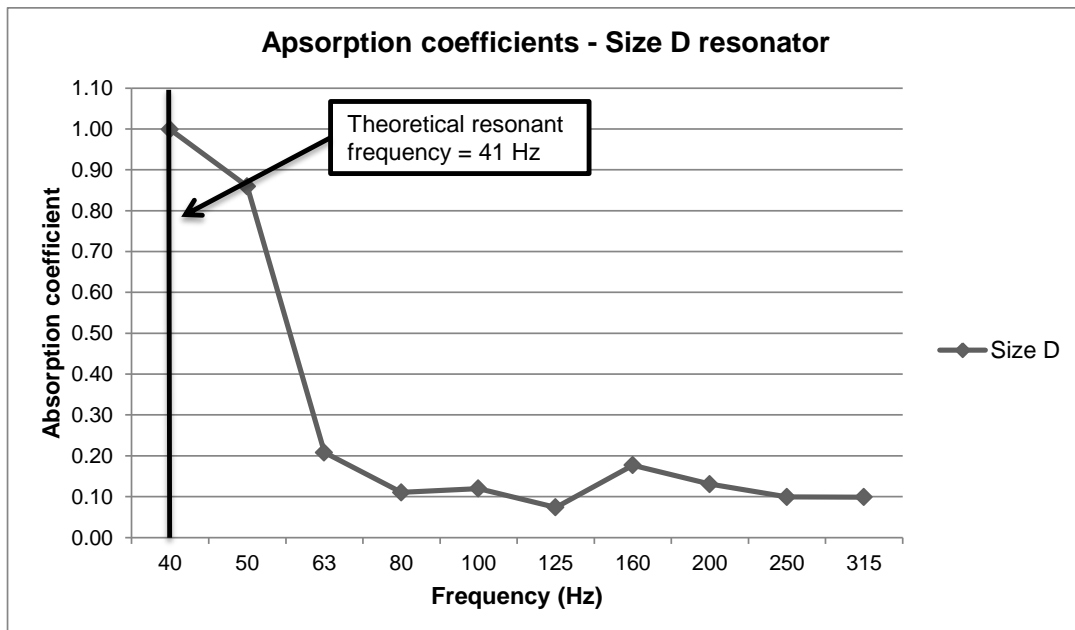


Figure 7: Absorption coefficients of Size D resonator

Figure 8 shows a graph of the absorption coefficients of the resonators with a mixture of different opening sizes, as they are configured in the Queen Elizabeth Hall (Figure 9). The composition of the resonator section is given in Table 3.

Resonator aperture	Number	Percentage of total
Size A	8	33%
Size B	5	21%
Size C	4	16%
Size D	7	30%

Table 3: Proportion of resonators in mixture

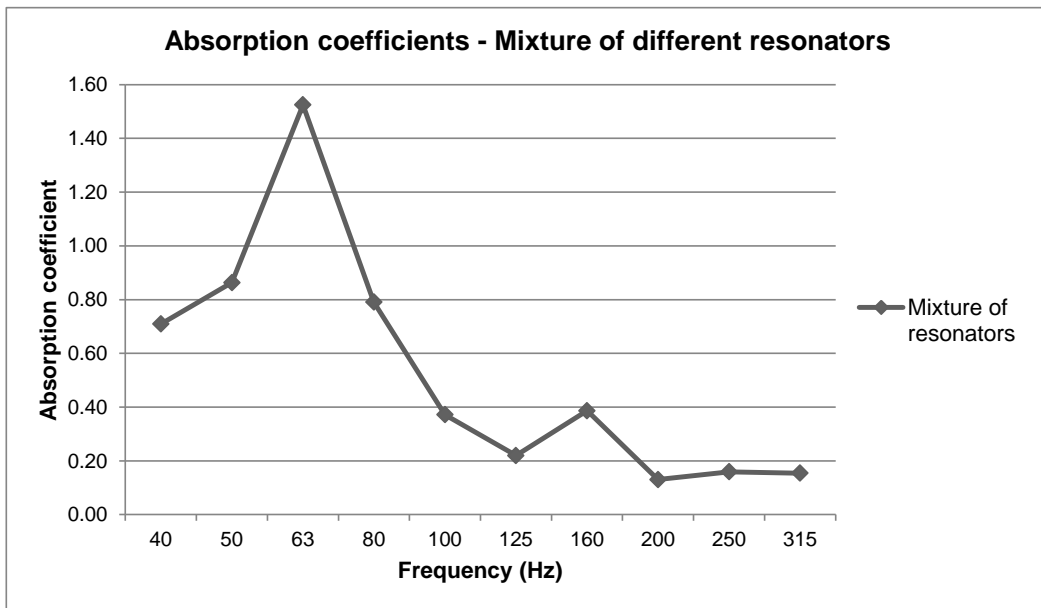


Figure 8: Absorption coefficients of the resonators with a mixture of different aperture sizes

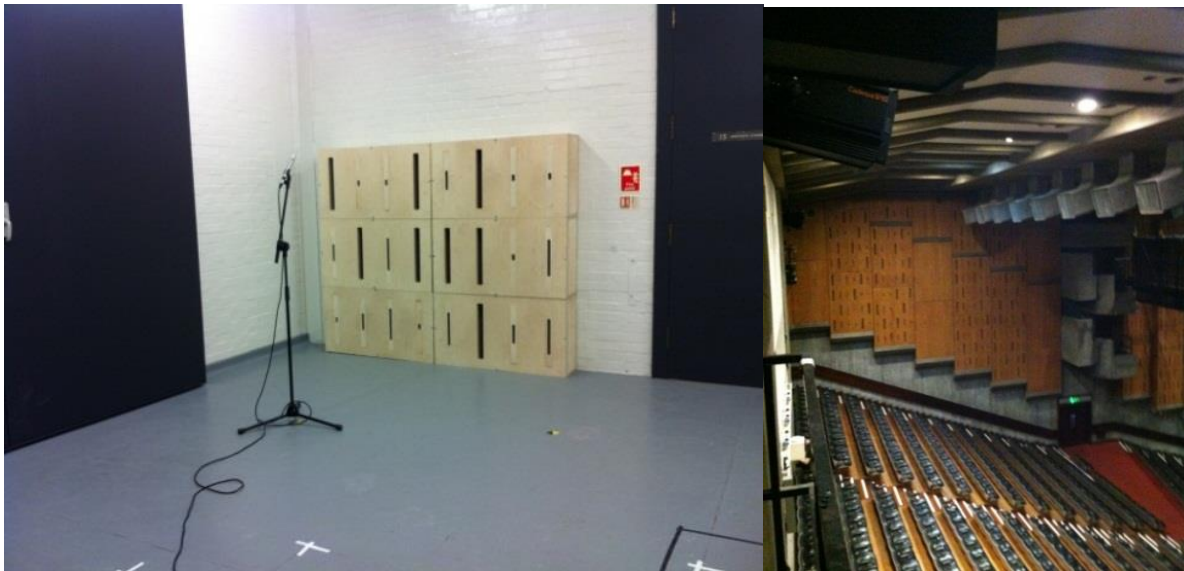


Figure 9: Mixture of resonators in chamber and in QE

3.2 Effects of Additional Absorption

3.2.1 Porous Absorption – Polyurethane Foam (over the aperture)

The resonators were re-tested with 25mm thick polyurethane foam inserted into the cells, behind the neck. The purpose of the foam is to increase the airflow resistance in the mouth of the resonator, as this creates extra friction and therefore extra absorption.

This treatment was included in the original resonator design but the polyurethane foam has disintegrated over time. Figure 10 shows a graph of how the polyurethane foam has affected the absorption provided by the Size A resonators. It can be seen from the graph that the addition of the polyurethane foam not only broadens the frequency response of the resonators but also increases its response in the resonant frequency band.

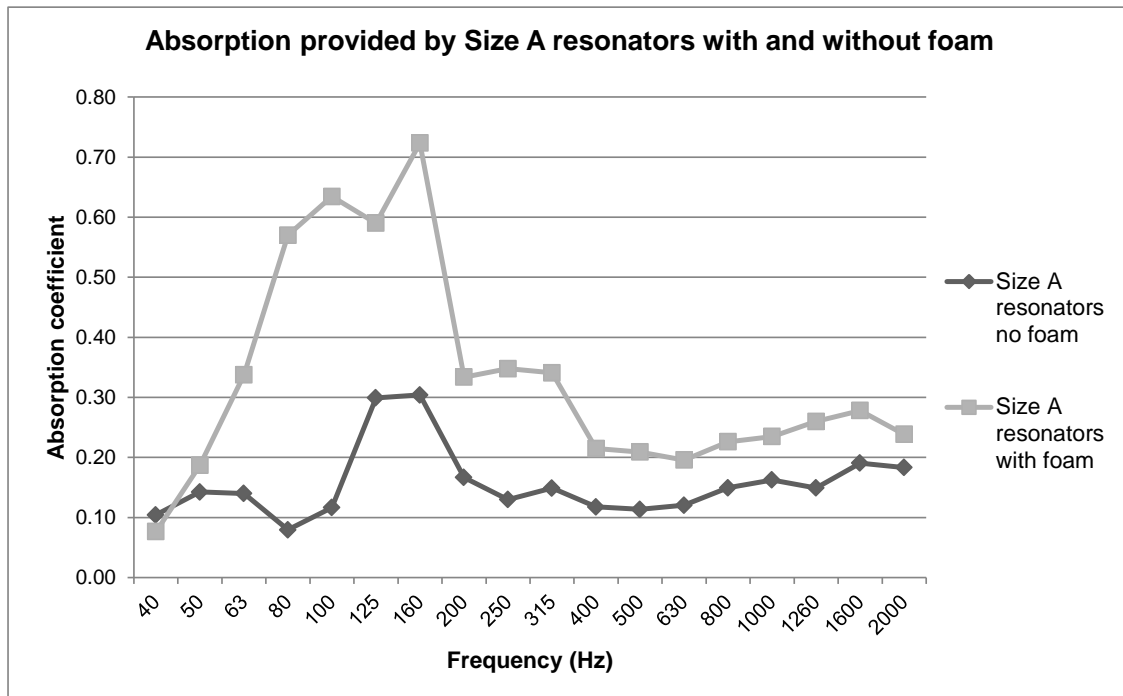


Figure 10: Absorption provided by Size A resonators with additional polyurethane foam

3.2.2 Acoustic Curtains in front of the resonators

A variable acoustic system was tested, consisting of two layers of acoustic curtain, 100mm apart, which could be hung at different distances from the face of the resonators; a photograph of this arrangement can be seen in Figure 11.

In order to determine what impact the spacing would have on the performance of the resonators, the curtains were tested at 0mm, 100mm and 200mm from the front faces; the results can be seen in Figure 12 (the curtain system is designed so that it can be hung at different distances from the resonators – the manufacturer specifies a maximum distance of 200mm for normal hanging).



Figure 11: Variable absorption system

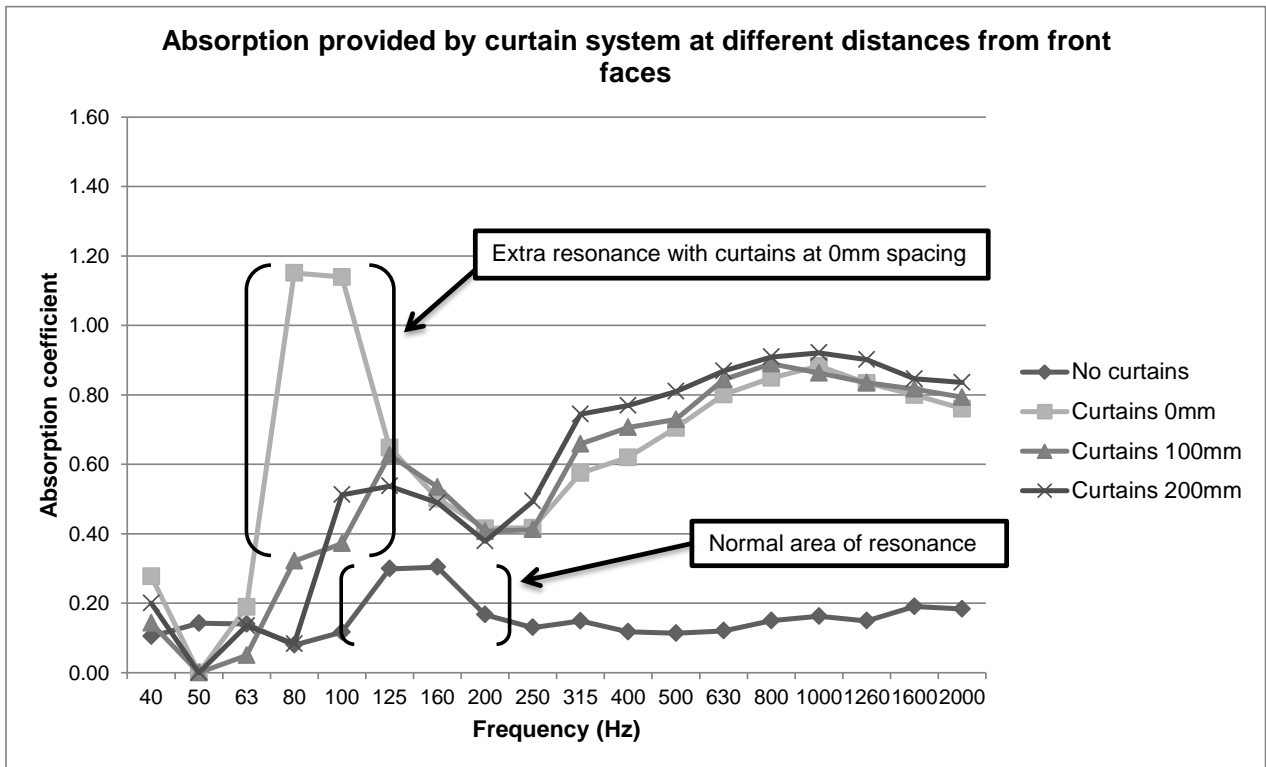


Figure 12: Additional absorption provided by acoustic curtains interacting with resonators

As can be seen from the graph, placing the curtains at 0mm from the front face of the resonator bank seems to alter its response; the resonant frequency band seems to have shifted lower to provide extra absorption at 63 Hz and above. The most interesting result, however, is that it has not counteracted the absorption at the normal resonant frequency band (between 100 and 160 Hz), but rather has boosted this absorption as well.

This implies that adding curtains increases not only the mid and high frequency absorption, which is usually the case, but also increases the low frequency absorption, which is highly desirable. The combination of curtains and Helmholtz resonators has the potential to provide a highly effective broadband variable absorption system.

The frequency response of the resonators does not seem to have shifted with the curtains at 100mm and 200mm spacing, but the absorption is still boosted in the normal resonant band. However, in this configuration the absorption at the resonant frequency is approximately 50% as effective as with the 0mm spacing.

4 Conclusion

A number of tests have been carried out on a set of replica Helmholtz resonators, in order to measure and determine the current performance of the original resonators installed inside the Queen Elizabeth Hall, London.

In addition to testing the resonators themselves, additional measurements were made to assess the interaction between the resonators and additional absorption systems; polyurethane foam covering the apertures and acoustic curtains hung in front. The results of these measurements have been summarized and analysed in this report, and include interesting interactions between the absorption systems and the resonators, particularly with the acoustic curtain system.

The curtains were found to significantly increase the absorption provided by the Helmholtz resonators, not only at the mid and high frequencies, as expected, but at the low frequency end of the spectrum. This suggests that acoustic curtains deployed in front of the resonators have the potential to create a very effective system for use during amplified music concerts, where extra bass absorption is needed. Further investigation of a variable absorption system combining acoustic curtains and Helmholtz resonators merits additional research.