A BEM STUDY ON THE EFFECT OF SOURCE-RECEIVER PATH ROUTE AND LENGTH ON ATTENUATION OF DIRECT SOUND AND FLOOR REFLECTION WITHIN A CHAMBER ORCHESTRA

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Abstract

In past work stage acoustic parameters have been used with limited success to assess musicians' subjective impressions of acoustic conditions. These parameters are commonly measured either on unoccupied stages, or on stages with furniture only (no musicians) but with a radius of 2 m cleared around both the source and receiver. This study investigates the validity of undertaking such measures on unoccupied stages, by considering the difference in on stage sound fields with and without a chamber orchestra present. This paper uses a previously validated BEM (boundary element method) model of a chamber orchestra for this investigation, and examines six source-receiver paths within the orchestra, two distinct paths each of three different lengths. Consideration is also given to the impact of randomly perturbing the orchestra for each of the six paths, and to the most appropriate distance to clear around the source and receiver to avoid significantly impacting results while maintaining a realistic stage set-up. Using the results of the BEM orchestra model, it was found that, in contrast to the 2.0 m normally recommended, a clear radius of 0.5 m was a good compromise between giving consistent results and clearing too much from the stage for meaningful results. It was also found that the attenuation was strongly affected by path length, but weakly affected by the path route or by perturbations of the orchestra set-up, and corrections are proposed to empty stage measurements (of direct sound and floor reflection only) to account for the presence of an orchestra on stage, for several source-receiver distances.

1. Introduction

Acoustic measurements on stages to assess the acoustical experience of musicians playing in ensemble have been used with limited success [1] [2]. Commonly, stage measurements are undertaken on unoccupied stages, due to the issues associated with taking measurements on occupied stages (tedious for human subjects to occupy stage during measurements and also costly and often impractical). Therefore, one reason for the limited success of such stage measures may be the influence of stage objects: music stands, instruments, seats and the musicians themselves. In reference to undertaking stage measurement to assess auditorium acoustics for symphony orchestras, Gade has suggested including chairs and music stands and clearing a 2 m radius around the source and receiver [3]. The on stage measurement procedure for undertaking measurements in relation to chamber orchestras has been less thoroughly investigated, and is the focus of this paper. A particular issue is that clearing 2 m around both source and receiver would remove the majority of a typical chamber orchestra.

This work follows on from a previous paper [4] which demonstrated a chamber orchestra set up on stage will significantly impact on stage sound fields for the 250Hz octave band and above. The validation of the BEM model of a chamber orchestra was covered in the original paper and it will only be covered briefly here. This paper extends the previous work, by considering several different source-receiver paths within the orchestra, representative of those that might be used in actual measurements. Additionally, the BEM model of the orchestra is updated to include music stands. In this paper, the orchestra is randomly perturbed (each stage object moved by a small amount in a randomly chosen direction), and the BEM model is resolved. This allows consideration to be given to the impact of the specific orchestra configuration on the results. The differences between results on an unoccupied and occupied stage for various source-receiver distances are presented.

2. Background

The influence of an orchestra on the sound fields on a 10 x 22 m stage has been studied by Dammerud using a scale model (1:25) [5]. In this scale model no stage shell was installed around the orchestra. Dammerud examined sound attenuation along three paths within the orchestra, and particularly focused on the degree of sound attenuation between instrument groups known to have difficulties hearing one another. Dammerud found for two of the three paths he considered the attenuation within the orchestra did not deviate significantly from the analytical solution (for direct sound and floor reflection only) until 500 Hz and above; however, for the third path deviation from the analytical solution was noted from 250 Hz and above.

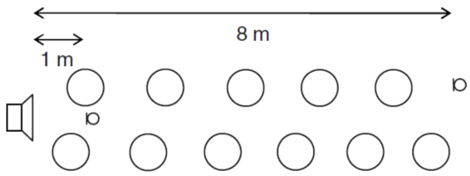


Figure 1: A plan view of configuration used by Krokstad, with larger circles representing musicians' heads and smaller circles representing microphone locations – image taken from [5].

Krokstad [6] has also investigated attenuation on stage through full scale measurements with a highly simplified case of seated musicians, shown in Figure 1. Krokstad investigated attenuation between the 1 m reference microphone and the microphone 8m from the source. Krokstad used three source heights (0.6 m, 0.9 m and 1.3 m) and kept the receiver height constant at musician ear height. The loudspeaker type used in measurements by Krokstad is unknown. Dammerud recreated the setup used by Krokstad with a 1:25 scale model and compared results to validate the accuracy of his scale model. Dammerud states that his scale model set up, replicating the conditions used for Krokstad's full scale measurements, produced results deviating from Krokstad by +1 and -2 dB at 1 and 2 kHz; however, he does not give details of agreement at other frequencies [5]. In a previous paper by the authors the Krokstad set-up was modelled in BEM software, and agreement over the full frequency range of interest was considered (63-1000 Hz) [4]. This validation process resulted in the musician geometry and surface impedance used for the chamber orchestra BEM model used in the present paper; and is further discussed in Section 3.

3. BEM Modelling of on stage sound fields

3.1 Implementation of Orchestra Geometry in BEM Software.

A chamber orchestra was modelled in BEM software FastBEM® to allow on stage sound fields with the orchestra present to be investigated. For accurate solutions using BEM the element size utilised should generally be smaller than one eighth of a wavelength of interest, and this was always maintained when solving the BEM orchestra model. Seated musicians were modelled with a 0.45 m width and a 1.275 m overall height and a length of 0.6 m. Music stands were also included in the orchestra model (unlike in previous work in [4]). The faces of the music stands were modelled with a 0.5 m width and 0.325 m height. The bottom of the music stand face is 0.76 m from stage floor. No pole was modelled for the music stands, meaning they were effectively just a floating music stand face. This was done because the slender pole would require many elements to model but would not significantly impact the low to mid frequencies (the general range of interest).

3.2 Complex Impedance Values Applied to Orchestra Geometry

The complex impedance values applied to the surface of the seated musicians were chosen based on the equivalent absorption areas selected by Dammerud for his scale model [5]. The equivalent reflection coefficients were assumed to be positive and real for this analysis since this gave good results in previous work and the solution was found to be insensitive to the phase of the reflection over a moderate range [4]. The choice of complex impedance values (and musician geometries) were validated by recreating a BEM model of the set-up used by Krokstad. This validation is discussed in depth in [4]. Good agreement between Krokstad's results and the BEM model of the same set-up were found over the full frequency range of interest generally within ±4 dB [4]. The complex impedance values used are shown in Table 1.

Table 1: Absorption coefficients, α, corresponding reflection coefficient, $|R|$, and impedance Z_s applied to surfaces of seated musicians based on Dammerud's absorption areas, A [5].

Octave (Hz)	125	250	500	1000	2000
A (m^2)	0.07	0.24	0.41	0.7	0.86
α	0.03	0.12	0.2	0.35	0.43
$\lvert R\rvert$	0.98	0.94	0.89	0.81	0.76
Z_s (kg/m^2s)	46547	12987	7241	3870	2975

Table 2: The standard absorption coefficients and corresponding reflection coefficient and complex impedance values applied to music stands, and the lower and upper absorption coefficients trialled.

Octave (Hz)	125	250	500	1000	2000
α standard	0.28	0.22	0.17	0.09	0.1
$\lvert R\rvert$	0.85	0.88	0.91	0.95	0.99
Z_s (kg/m^2s)	5026	6639	8848	17471	163916
α lower	0.01	0.04	0.05	0.04	0.05
α upper	0.28	0.43	0.2	0.25	0.15

As well as the seated musicians, complex impedance values had to be applied to music stands. Maximum, minimum and typical absorption coefficients based on 1 cm thick plywood were taken from [7], see Table 2. Again, the reflection coefficient (R) was assumed to be real and positive. Tables 1 and 2 only specify absorption coefficients down to 125 Hz, however in later investigations the 62.5 Hz octave is also considered. As will be shown in later investigations, for the 62.5 Hz octave the on stage sound fields are virtually unchanged by the presence of stage geometry, meaning the impedance values in this octave band are not crucial. In each case a curve was fitted to the data for absorption coefficient versus frequency, so that the impedance values were gradually changed with frequency. This avoided sudden jumps in curves plotted against frequency due to a sudden change in impedance at a change in octave band.

3.3 Investigation of Complex Impedance Values Applied to Music Stands

An investigation considered the sensitivity of results to the complex impedance values specified for the music stands. This was done because while the geometry of the stands should be quite realistic for the frequency range of interest, the complex impedance values specified were based on absorption coefficients for wood, and it was not known how well this represents the real impedance of music stands. The impedance of actual music stands may be quite variable depending on the kind of stand used (wood, metal, wire frame etc.) This investigation used the setup utilised by Krokstad with music stands introduced in front of the seated musicians as shown in Figure 2. The impedance values specified to the musician geometry were those used for the validation analysis in Section 3.2. The source was at a height of 1 m from the stage floor, and the receiver 1.2 m from the stage (these heights correspond to those used in later orchestra attenuation analyses).

The minimum and maximum absorption coefficients applied to music stands for the modified Krokstad setup are listed in Table 2. These correspond to the approximate minimum and maximum absorption coefficients listed for wood in [7]. The corresponding reflection coefficients were again assumed to be positive and real. The variation in ΔL (defined as SPL (sound pressure level) at receiver relative to direct free field SPL at receiver) at the 8 m receiver from minimum and maximum absorption coefficient is shown in Figure 3. It is evident from Figure 3 that the results are insensitive to the selection of absorption coefficient. Hence it was deemed that further investigations into appropriate absorption coefficients for stands were unnecessary, and the standard absorption coefficients specified in Table 2 were used in later investigations.

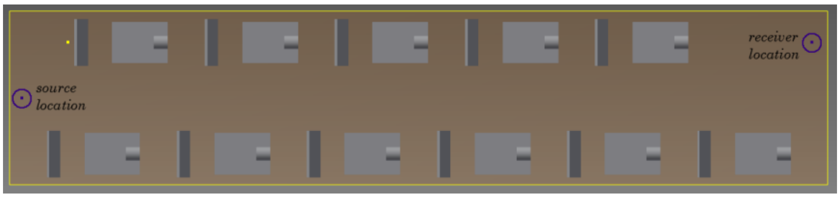


Figure 2: Krokstad setup with music stands introduced (plan view).

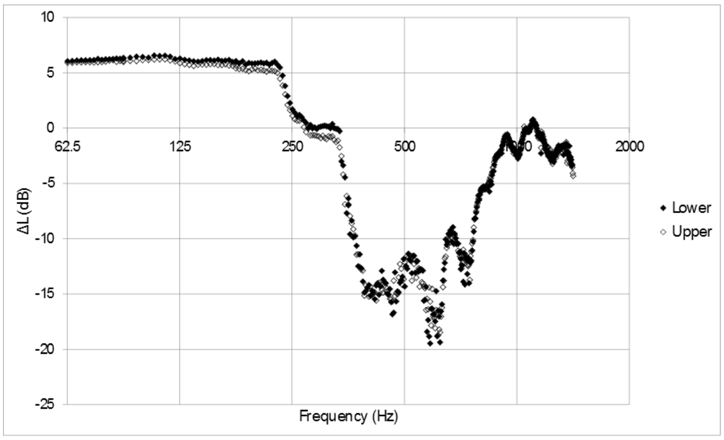


Figure 3: ΔL (relative to direct free field sound level) varying with frequency for Krokstad setup with music stands introduced. Lower and upper α values are as listed in Table 2.

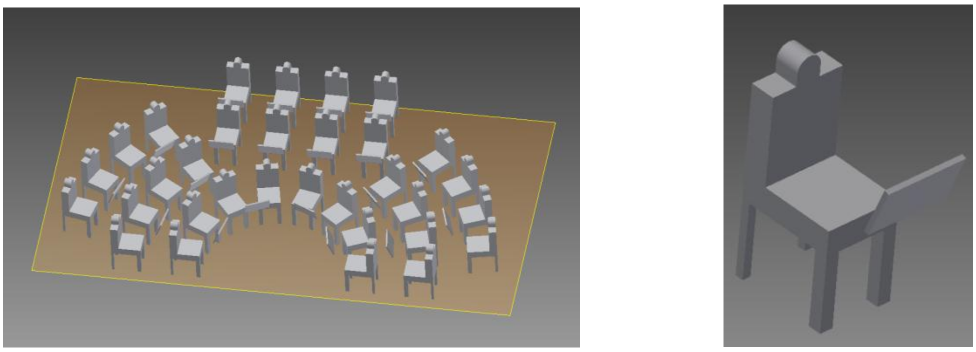
3.4 Measurement Configurations Investigated and Results

The chamber orchestra modelled in the BEM software FastBEM® used the same musician and stand as used in the validation process, discussed in Section 3.2. The orchestra consisted of 32 musicians. This is a relatively large chamber orchestra, which may help demonstrate a more extreme case of change in sound fields with and without the orchestra present. A symmetry condition was specified to create a perfectly rigid stage floor. No stage shell was modelled, meaning only the floor, seated musicians and stands would impact the stage sound fields. As there is no stage enclosure in the model higher order reflections are ignored; hence, this analysis is most relevant to impact of stage geometry on the early arriving sound energy (associated with ensemble conditions for musicians). The chamber orchestra, as modelled in Autodesk Inventor®, is shown in Figure 4. The innermost row of strings (arranged in circular arcs) has a radius of 2 m. The second row of strings has a radius of 3.2 m. The first row of winds (arranged in straight lines) is a distance of 3.5 m from front of stage with spacings of

0.6m. The second row of winds is a distance of 4.7 m from front of stage. The music stands were placed 0.8 m from the musicians' heads, with shared stands for each string desk and individual for the wind. The chamber orchestra in its default configuration is symmetric about a centre line perpendicular to the front of stage. The chamber orchestra has been modelled to be as realistic as possible (including seated musicians and music stands); however, it will still be a simplification of the true conditions on stage as the musicians' instruments are not present and because instrument directivity will also impact the on stage sound fields. Although there is the potential to include instrument directivity in the model for this work an omnidirectional source will be used for simplicity and to correspond to the current measurements practices on real stages. The directivity of musical instruments normally deviates significantly from omnidirectional at frequencies of 1 kHz [8] and above, whereas the focus of this investigation is on the 1000 Hz octave band and below.

In this analysis stage objects within a 2 m radius of the source and receiver have not been removed, as suggested by Gade [3]. Instead a radius of 0.5 m was cleared, generally resulting in only a single player and music stand at the position of the source and receiver being removed. This is because clearing 2 m radii near source and receiver equates to a significant portion of the on stage furniture and thus produces unrealistic stage conditions little different from a bare stage. However, as a significant radius of stage furniture is not cleared near source and receiver the exact location of nearby objects to the source and receiver may more significantly impact on the on stage sound fields. To investigate this further the stage objects were randomly perturbed and the stage sound fields again investigated. Each on stage object was moved randomly forward or back (perpendicular to the stage front) by 100 mm and randomly left or right (parallel to stage front) also by 100 mm, or randomly chosen to not move. The forward and back movement choice was separate from the left and right movement, meaning a stage object may be moved left or right but not forward or back, or alternatively may be moved both left or right and forward or back, or alternatively not moved at all, giving 9 possible locations. The purpose of this exercise was to create an orchestra configuration which was still plausible but no longer symmetric and crucially different to the previously investigated case (if only subtly).

The on stage fields with the orchestra present will now be analysed (with the use of BEM) for several specific cases using different source-receiver locations, for both the standard orchestra configuration and orchestra configuration with perturbations. A quantity ΔL will be used in this analysis, defined as the difference between the SPL at the receiver and the free field direct SPL for the same receiver distance (i.e. the SPL that would be found in anechoic conditions).



(a) (b)

Figure 4: (a) Chamber orchestra set up (floor shown for visualisation purposes, bit modelled by using a reflected image of setup) (b) close-up showing detail of a musician as modelled.

A total of six source-receiver paths within the orchestra were considered. In each case a source height of 1.0 m and a receiver height of 1.2 m were used. Cases 1, 2 and 3 had a source-receiver path lengths of 5.86 m, 8.61 m and 6.93 m respectively. For each case two distinct paths within the orchestra (with the same path length) were examined, and these were labelled A and B. For example, case 1A or case 1B both had a source-receiver path length of 5.86 m. Additionally, the impact of random perturbations was examined - the standard orchestra configuration case was labelled with an additional 1 and the perturbed orchestra configuration case was labelled with an additional 2. For example, case 1A without perturbations was labelled case 1A.1 and case 1A with perturbations was labelled case 1A.2. The paths for cases 1A through to 3B are shown in Figure 5. The curve of ΔL versus frequency for case 1A, for both the standard orchestra (case 1A.1) and perturbed orchestra (case 1A.2) and the empty stage, is shown in Figure 6. The same information is presented for cases 1B, 2A, 2B, 3A and 3B in Figures 7, 8, 9, 10 and 11 respectively.

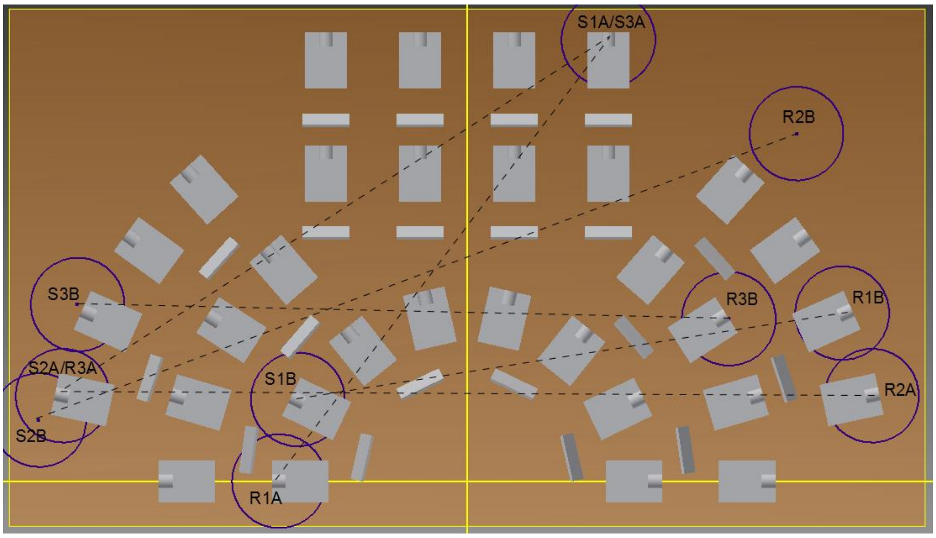


Figure 5: The orchestra paths investigated as modelled in Autodesk Inventor®. S stands for 'source' and R stands for 'receiver'. The circles shown have a radius of 0.5 m and any stage furniture within this region on stage was removed for that case.

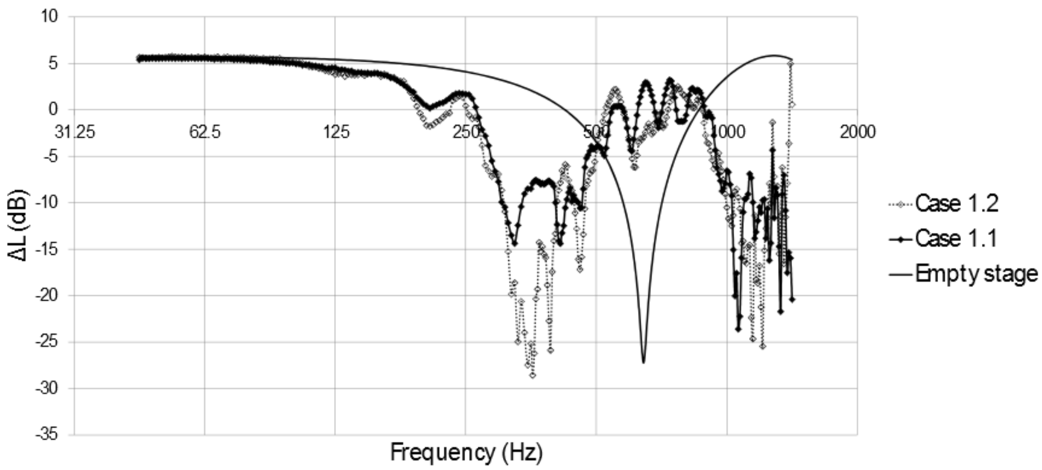


Figure 6: ΔL versus frequency for Case 1A (with and without random perturbations) compared to analytical solution

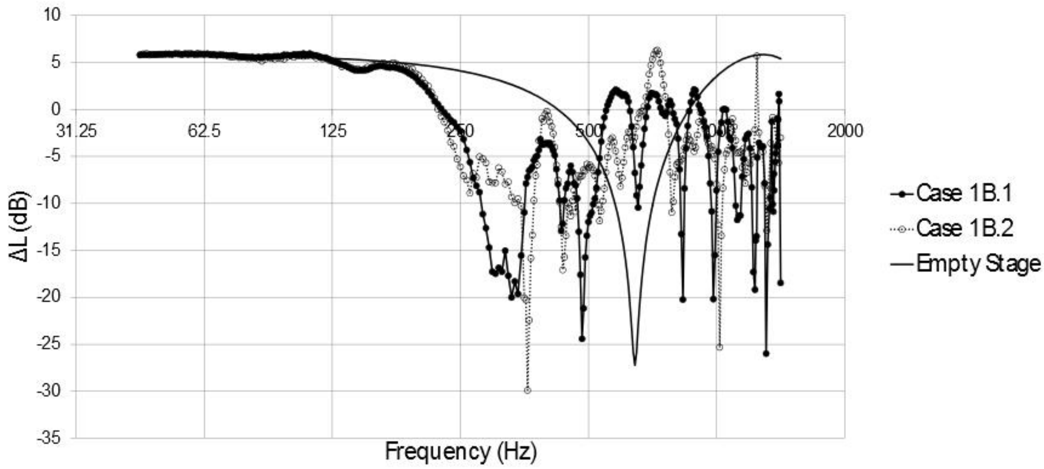


Figure 7: ΔL versus frequency for Case 1B (with and without random perturbations) compared to analytical solution

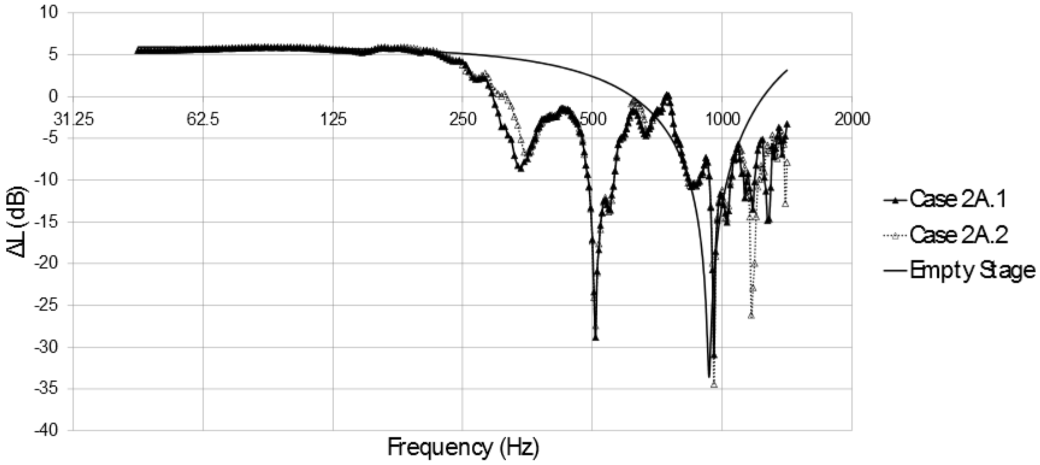


Figure 8: ΔL versus frequency for Case 2A (with and without random perturbations) compared to analytical solution

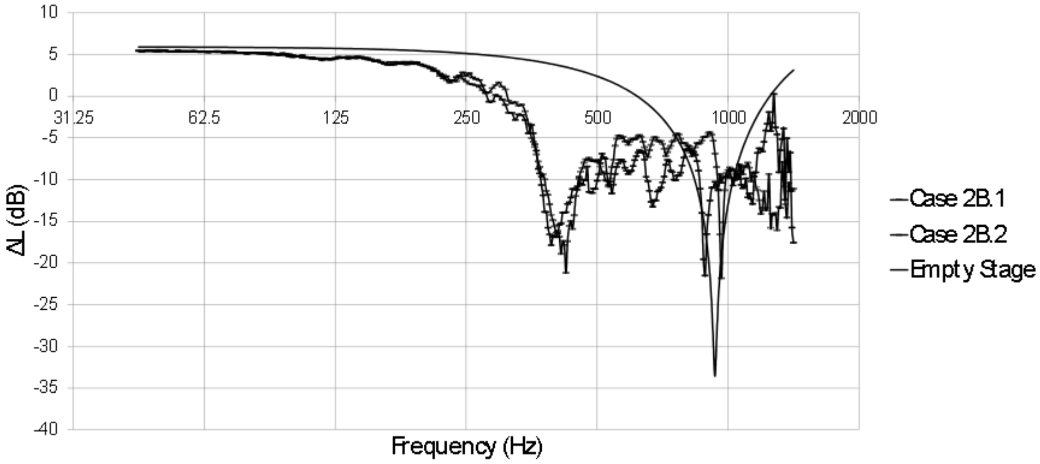


Figure 9: ΔL versus frequency for Case 2B (with and without random perturbations) compared to analytical solution

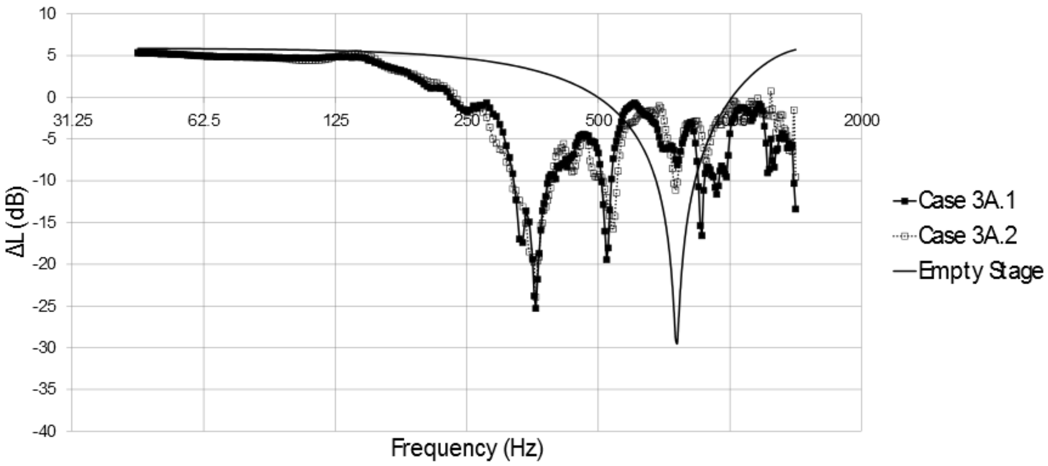


Figure 10: ΔL versus frequency for Case 3A (with and without random perturbations) compared to analytical solution

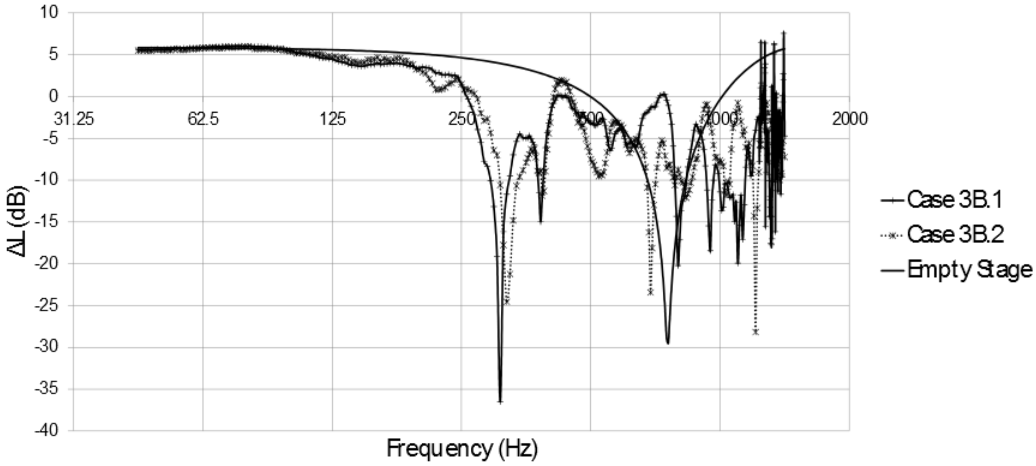


Figure 11: ΔL versus frequency for Case 3B (with and without random perturbations) compared to analytical solution

4. Discussion of BEM Modelling Results

The results of the investigation of stage sound fields for occupied and unoccupied stages have been presented as curves of ΔL versus frequency in Figures 6-11. Comparing the results for cases 1A, 2A and 3A it is clear that a similar trend is evident in all cases despite the different source-receiver distance. The BEM model curves initially are quite comparable to the analytical solution, then the BEM model curves begin to dip before the analytical solution, and then there are various peaks and dips at higher frequency (i.e. 500 Hz octave and above). The dip in the empty stage result is due to destructive interference when the direct sound and floor reflection paths differ by half a wavelength. The first dip for the occupied stage is always at a lower frequency than for the unoccupied stage, indicating the floor reflection path is altered more by the stage furniture than the direct path, which is expected since it has more objects to travel around.

Although the BEM model implemented does not consider stage enclosure reflections, this work does begin to indicate how different an empty and occupied stage measurement may be. It is of interest to therefore consider what octave band average 'corrections' would need to be applied to the empty stage (analytical) solution to account for the presence of the orchestra. Any correction would be dependent on source-receiver distance, since the analytical solution being corrected would vary depending on source-receiver distance. In Tables 3, 4 and 5 the corrections to the empty stage solutions for the different source receiver distance considered are presented. The average correction and the standard deviation of the correction are presented for each source-receiver distance. Note it is not meaningful to take the average of values in decibels. The average correction in decibels was calculated by finding the average pressure squared value for a given source-receiver distance and then converting to decibels using the following equation

$$\text{Average correction} = 10\log_{10}(p^2)_{av} \quad (1)$$

where $(p^2)_{av}$ is the average of p^2 for a given source-receiver distance. Similarly, as the standard deviation of decibels cannot be calculated directly from the values in decibels, the standard deviation of the pressure squared values was calculated and converted to a range in dB using the following equation

$$\text{Std} = 10\log_{10}\left((p^2)_{av} + \frac{\sigma_{p^2}}{2}\right) - 10\log_{10}\left((p^2)_{av} - \frac{\sigma_{p^2}}{2}\right) \quad (2)$$

where $(p^2)_{av}$ is defined above, and σ_{p^2} is the standard deviation of the p^2 for a given source-receiver distance.

The results presented in Tables 4, 5 and 6 indicate that regardless of the exact path through the orchestra or the introduction of random perturbations to the orchestra configuration, if the source-receiver distance is the same the correction to be applied to the analytical solution will be very similar. This is indicated by the low standard deviations found; standard deviations were less than 1 dB (i.e. within just noticeable difference (JND)), with the exception of only two cases. This suggests that clearing a radius of only 0.5 m around the source and receiver is sufficient, and that there is the potential to take empty stage measurements and apply corrections to obtain meaningful stage acoustic parameters.

Notably, all average corrections ranged between -8.6 and +0.6 dB, indicating that the presence of the orchestra on stage almost always caused attenuation when averaged over an octave band.

The path length was observed to make a significance difference to attenuation of sound due to the presence of the orchestra. For example, a musician at 5.86 m will hear the 250 Hz band as 2.52 dB softer than a musician at 8.61 m, but will hear the 500 Hz band as 8.20 dB louder. Therefore the colouration of the direct sound heard by different musicians can differ by as much as 10 dB over an octave.

Table 3: Octave band average correction values (dB) to the empty stage solution for various cases with source-receiver distance 5.86m. Average and Std are defined in equations (1) and (2).

Octave (Hz)	Case 1A.1	Case 1A.2	Case 1B.1	Case 1B.2	Average	Std
62.5	-0.26	-0.10	0.04	-0.01	-0.08	0.11
125	-1.12	-1.20	-0.40	-0.39	-0.76	0.38
250	-4.85	-5.99	-5.40	-5.07	-5.30	0.42
500	1.21	0.20	0.81	0.20	0.62	0.44
1000	-7.06	-6.96	-6.48	-5.82	-6.55	0.51

Table 4: Octave band average correction values (dB) to the empty stage solution for various cases with source-receiver distance 8.61m. Average and Std are defined in equations (1) and (2).

Octave (Hz)	Case 2A.1	Case 2A.2	Case 2B.1	Case 2B.2	Average	Std
62.5	-0.17	-0.13	-0.57	-0.58	-0.36	0.21
125	-0.09	-0.05	-1.29	-1.28	-0.64	0.60
250	-2.33	-1.91	-3.66	-3.47	-2.78	0.74
500	-6.13	-5.76	-11.54	-9.23	-7.58	2.08
1000	-7.98	-8.10	-8.69	-9.63	-8.55	0.62

Table 5: Octave band average correction values (dB) to the empty stage solution for various cases with source-receiver distance 6.93m. Average and Std are defined in equations (1) and (2).

Octave (Hz)	Case 3A.1	Case 3A.2	Case 3B.1	Case 3B.2	Average	Std
62.5	-0.83	-0.82	0.06	-0.05	-0.39	0.42
125	-1.05	-1.11	-1.12	-0.84	-1.03	0.12
250	-5.59	-5.64	-4.31	-4.44	-4.95	0.62
500	-4.02	-4.39	-2.48	-3.37	-3.50	0.75
1000	-6.51	-4.87	-3.25	-5.37	-4.84	1.22

5. Further Work

The BEM model of a chamber orchestra could be further improved by including instrument geometries. Additionally, further validation of the complex impedance values may be beneficial due to the uncertainties associated with the full scale measurements by Krokstad [7] which were used to validate the model. Finally, the model currently only considers attenuation of direct sound (and floor reflection) and inclusion of a stage enclosure would allow for a more thorough investigation of how the orchestra impacts on stage sound fields, such as investigating how the orchestra attenuates the first order reflections from the stage enclosure. This would be difficult to achieve by modelling the entire stage enclosure in BEM software (due to computational limits); however, a shoe box stage enclosure could be modelled with the use of symmetry.

6. Conclusion

This paper has demonstrated the impact of a chamber orchestra on stage sound fields, by considering several paths within the orchestra (both with the same and different source-receiver distances). It is clear that for the 250 Hz octave and above the orchestra begin to significantly attenuate the direct sound/floor reflection and that colouration of the direct sound may vary as much as 10 dB over an octave for different path lengths. It has also been shown that regardless of the path within the orchestra a similar level of attenuation occurs for a given source-receiver distance. Additionally, the impact of randomly perturbing the orchestra has been examined, and it has been shown that with only 0.5 m radius cleared around source and receiver the results are reasonably consistent regardless of the exact orchestra configuration.

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