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A BEM study of the influence of musicians on onstage sound field measures in auditoria

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ABSTRACT

Many recent studies have sought to assess the acoustical experience of musicians playing in ensembles through development of acoustic measures undertaken on stage in auditoria. It is generally proposed that such measures be undertaken in the presence of stage furniture to better replicate the real conditions onstage with an ensemble present. However, conditions are arguably not necessarily realistic because furniture is customarily removed within 2m radii of the source and receiver to avoid disturbing reflections, and because it is seldom practical to make the measurements with the musicians present. Furthermore, consistency of conditions is also potentially an issue. This paper uses BEM (boundary element method), validated against published full and model scale data, to investigate the differences between sound fields on a stage with an orchestra present and on a bare stage. Sensitivity to perturbations of the stage configuration is also investigated. The results of this study show that for a chamber orchestra, set up on stage, for 250 Hz and above the sound field on an occupied stage differs significantly from an empty stage.

Keywords: Stage Acoustics, Boundary Element Method, Orchestra Attenuation I-INCE Classification of Subjects Number(s): 76 (See `http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf`.)

1. INTRODUCTION

Research into auditorium measures over the past sixty years has produced several useful acoustic parameters to assess the acoustical experience for listeners in venues. More recently, stage measures have also been developed to assess the acoustical conditions for musicians playing in ensembles. In particular, Gade (1) has proposed the onstage acoustic measures known as the 'support measures', which have been included in ISO 3382 the international standard for acoustic measurements (2). In relation to undertaking the support measures, Gade (3) has specified that while stage furniture should be present on stage during measurements all stage furniture must be removed within a 2 m radii of the source and receiver. Gade (3) has also specified that on small stages (suitable for smaller ensembles and chamber orchestras) measurements should be undertaken without furniture present. By specifying these requirements the question arises of how much the presence of stage furniture influences the sound fields onstage and indeed how sensitive is the sound field onstage to the exact configuration of this furniture. Removing all stage furniture within 2 m radii of the source and receiver is clearly intended to avoid strong reflections from nearby objects, which may make the measures unrepeatable. Therefore, consideration must also be given to whether such a distance is appropriate, or to whether the sound field may still be significantly changed by the orientation of objects 2 m from the source and receiver. This paper further investigates these issues with the use of BEM (boundary element method) modelling to investigate stage sound fields with and without the presence of an orchestra. The BEM model is first validated against published full scale and scale model measurements of orchestra attenuation, and then a chamber size orchestra is modelled. This model is used to investigate the change in onstage sound fields with and without the presence of an orchestra and the sensitivity of onstage sound fields to small changes in the orchestra configuration.

2. BACKGROUND

A significant body of work regarding attenuation of sound onstage due to the presence of an orchestra has been undertaken by Dammerud (4). Dammerud used a scale model (1:25) and considered a full symphony orchestra playing on a 10 x 22 m stage. In his scale model no stage shell was installed around the orchestra.

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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.

Previous work on sound attenuation within a symphony orchestra has also been undertaken by Skalevik (5). Skalevik examined attenuation between a source (located at left most first violin) and a receiver (located at rearmost bassoon player). The source-receiver distance was 11.7 m, and various source heights and receiver heights were used. This study undertook stage measurements with a full symphony orchestra present (including seats, musicians, music stands and instruments). Like Dammerud, this study by Skalevik concluded that at 500 Hz and above the presence of the orchestra significantly attenuates the sound as it travelled through the orchestra on stage.

Krokstad (6) and Dammerud (7) have both investigated attenuation onstage due to the presence of seated musicians. Krokstad (6) undertook full scale measurements with a highly simplified case involving two lines of seated people in front of a source. One line consisted of five people and one line consisted of 6 people, with a receiver placed behind the last person in the line of five people. Another receiver was placed 1 m from the source to take a reference measurement. Krokstad then investigated attenuation between the 1 m reference microphone and the microphone 8 m from the source. Figure 1 demonstrates the configuration utilised by Krokstad. 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 (approximately 1.125 m). 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. As discussed earlier in this section, Dammerud then went on to further investigate attenuation along paths within a symphony orchestra. The results from Krokstad and Dammerud, using the configuration used by Krokstad, have been used in this paper to validate the use of BEM (boundary element method) to recreate an orchestra setup. This is discussed further in Section 3. Dammerud's results of attenuation within a symphony orchestra could have also been used to validate the BEM model; however, because validating against this larger model would have required significantly more computational power and time the simpler Krokstad setup was utilised.

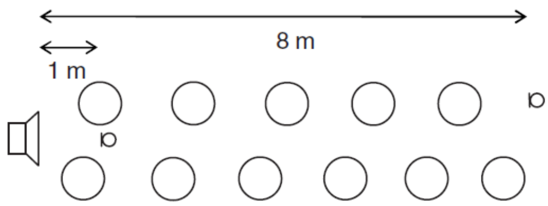

Figure 1 – A plan view of configuration used by Krokstad, with larger circles represented musicians heads and smaller circles representing microphone locations - image taken from (7).

3. VERIFICATION OF BEM MODEL AGAINST PUBLISHED RESULTS

A verification study was undertaken to investigate how well results of attenuation through seated musicians using BEM (boundary element method) corresponded with published data. The measurements used in this verification analysis were those undertaken by Dammerud (7) and Krokstad (6), which were discussed previously in Section 2. In the verification analysis (and later for the orchestra model) seated musicians were modelled with a 0.45 m width and 1.2 m overall height. The dimensions were chosen to match those specified as the full size equivalent dimensions from the scale model used by Dammerud (7). Figure 2 shows the seated musician as modelled in the 3D CAD software Autodesk Inventor®.

Krokstad (6) defined attenuation (ΔL) through a group of seated musicians as the difference between unobstructed direct level (at the 1 m reference receiver) and the measured level (at the 8 m receiver). See Figure 1 for the configuration of seated musicians used. Krokstad emitted white noise in 1/3 octave bands from the source (source type not known). Dammerud, using a scale model, used an spark source (omnidirectional) and filtered the received signal into 1/3 octave bands to compare to Krokstad's results. The analysis in this paper used an ideal omnidirectional source (implemented in the BEM software). The analysis in this paper is undertaken in the frequency domain and 1/3 octave bands of ΔL are produced by integrating the relevant region of the pressure squared versus frequency curve for the 8 m receiver and pressure squared versus frequency curve for the 1 m receiver. Thus attenuation (ΔL) may be expressed as

$$\Delta L = 10 \times \log_{10}\left(\frac{E_{\mathrm{ref}}(f_1 - f_2)}{E_{8\,\mathrm{m}}(f_1 - f_2)}\right). \tag{1}$$

where $E_{\mathrm{ref}}(f_1 - f_2)$ is the integrated area (between f_1 and f_2) under the pressure squared versus frequency curve at the reference microphone and $E_{8\,\mathrm{m}}(f_1 - f_2)$ is the integrated area (between f_1 and f_2) under the pressure squared versus frequency curve at the 8 m microphone for the setup utilised by Krokstad. The frequency values (f_1 and f_2) are chosen as upper and lower bounds of the relevant 1/3 octave band.

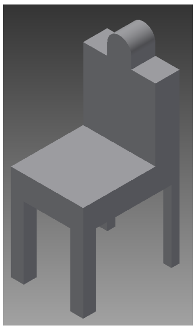

Figure 2 – A seated musician, based on (7), as modelled in Autodesk Inventor®. The overall height of musician is 1.2 m (ear height 1.125 m), with a width of 0.45 m and a length of 0.6 m.

3.1 Implementation of BEM and FEA model for Krokstad Configuration

The configuration of seated musicians (used by Krokstad) was modelled in both finite element software (ANSYS) and two boundary element softwares (ABEC and FastBEM). For accurate solutions using both finite element analysis (FEA) and boundary element method (BEM) the element size utilised should generally be smaller than one eighth of a wavelength of interest. Figure 3 shows that by using an appropriate mesh size the results from the differing programs are very close, as would be expected given each method solves the same wave equation, although via different methods. The model was implemented in the BEM software ABEC using a conventional or full boundary element method. This served as a reference for validating the accuracy of more approximate boundary element methods. However, because of the computational intensity of conventional boundary element method it was only utilised at relatively low frequency. The model was additionally implemented in the BEM software FastBEM. FastBEM offers a full conventional BEM and three alternative solvers that provide various degrees of approximation to the conventional BEM, two of which were investigated (the third of which is only suitable for high frequencies). These solvers were utilised and the results compared to the conventional BEM solutions. Figure 3 shows sound pressure at the 8 m receiver (with a source height of 0.6 m) for the configuration utilised by Krokstad. To produce Figure 3 the source strength was such that on a radius 1 m from the centre of the source the free field sound pressure was 1 Pa. The fast multipole and adaptive cross approximation (ACA) are the two different approximate BEM methods investigated in FastBEM. It is evident from Figure 3 that the fast multipole solver does not show particularly good agreement with conventional BEM for higher frequencies, whereas the ACA solver shows excellent agreement with conventional BEM solver over the range of frequencies tested (from 56 – 1120 Hz.)

3.2 Complex Impedance Values

To achieve reasonable accuracy between the published data and results from the BEM model, a complex impedance on the surface of the model musicians had to be specified in the BEM software. The values for complex impedance were chosen based on the equivalent absorption areas selected by Dammerud for his scale model (7). Dammerud measured these equivalent absorption areas for his model musicians in a scale reverberation chamber, and matched them as closely as possible to the full scale absorption areas for musicians measured in a full sized reverberation chamber by Harwood (8). Equivalent absorption areas are generally related to an absorption coefficient using the following equation

$$\alpha = \frac{A}{S}, \tag{2}$$

where α is the absorption coefficient, S is the object surface area and A is the absorption area of the object. However, Equation 2 is only strictly valid when the absorption coefficient of a flat sample of a material is being measured in a reverberation chamber. In Dammerud's work, the 3D model musicians were placed

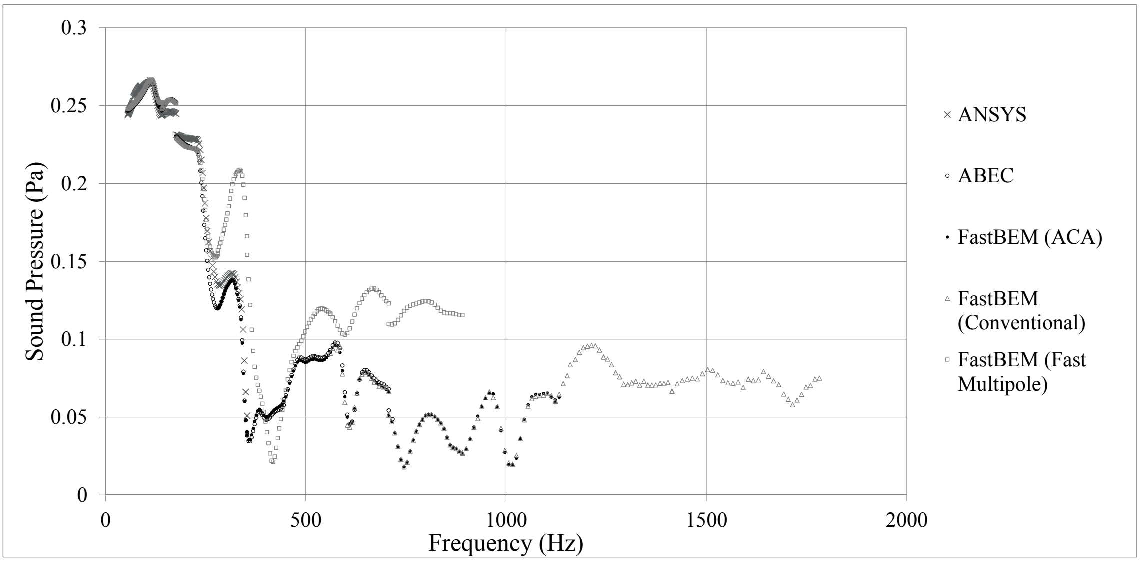

Figure 3 – Comparison of sound pressure at 8 m from source for configuration used by Krokstad. Results are from ANSYS, ABEC and FastBEM (3 different solvers). Note the discontinuities relate to changes in complex impedance.

in a reverberation chamber, and thus the absorption coefficients computed using Equation 2 are only very approximate. This was done to provide at least a starting point for appropriate absorption coefficients. The model musicians have an approximate surface area of 1.7 m^2 each.

The absorption coefficients were then converted to complex impedance values. Equivalent absorbing area (or the corresponding absorption coefficients) only provide information regarding the change in amplitude of the sound wave once reflected by the object, not the change in phase. In the present work, the imaginary part of the complex impedance (corresponding to a change in phase) was assumed to be zero. From this assumption the absorption coefficient could be converted to a complex impedance by

$$Z_s = M + Xi = Z_o \times \frac{1+R}{1-R} = Z_o \times \frac{1+\sqrt{1-\alpha}}{1-\sqrt{1-\alpha}} \tag{3}$$

where, Z_s is the specific acoustic impedance, Z_o is the characteristic acoustic impedance of the medium (air), M is the real part of the specific acoustic impedance, X is the imaginary part of the specific acoustic impedance and R is the reflection factor. Equation 3 is valid for normal incidence waves. The characteristic acoustic impedance is defined in terms of the density of the medium (ρ) and the speed of sound in the medium (c) by the following equation

$$Z_o = \rho c. \tag{4}$$

The reflection factor, R (generally also complex but assumed to be real here) is related to absorption coefficient, α by

$$|R| = \sqrt{1-\alpha}. \tag{5}$$

Table 1 summarises the absorption area per musician from Dammerud's scale model, the equivalent absorption coefficients found based on surface area of musicians, and the corresponding reflection factor and complex impedance (assuming positive real reflection factor, as well as three other cases which are discussed in Section 3.3). Table 1 only specifies absorption coefficients down to 125 Hz, however in later investigations the 62.5 Hz octave is also considered. For the 62.5 Hz octave the absorption coefficient from the 125 Hz octave was utilised as this was the best available information.

3.3 Investigation of Altering Impedance Value

The absorption coefficients from which complex impedance values were found do not give any information about the magnitude of real and imaginary impedance. As discussed in Section 3.2 the imaginary component of complex impedance has thus far been assumed to be zero. To examine the sensitivity of the results to the real and imaginary components of impedance the argument of R in Equation 5 was changed while keeping the magnitude (hence α) constant.

Table 1 – Absorption coefficients and corresponding impedance values based on Dammerud's absorption areas. Case 1 corresponds to maximum real complex impedance, case 2 corresponds to maximum imaginary complex impedance, case 3 corresponds to minimum imaginary complex impedance and case 4 corresponds to minimum real complex impedance.

Frequency (Hz)		125	250	500	1000	2000
Scale model absorption area (m^2)		0.07	0.24	0.41	0.7	0.86
Absorption Coefficient (α)		0.04	0.14	0.24	0.40	0.50
R	Case 1	0.98	0.93	0.87	0.77	0.71
	Case 2	0.98 + 0.02i	0.92 + 0.07i	0.83 + 0.12i	0.75 + 0.19i	0.67 + 0.24i
	Case 3	0.98 - 0.02i	0.92 - 0.07i	0.83 - 0.12i	0.75 - 0.19i	0.67 - 0.24i
	Case 4	-0.98	-0.93	-0.87	-0.77	-0.71
$Z_s(\mathrm{kg/m^2s})$	Case 1	4.2×10^4	1.18×10^4	6.4×10^3	3.5×10^3	2.7×10^3
	Case 2	21141 + 21136 i	5878 + 5862 i	3245 + 3214 i	1770 + 1714 i	1327 + 1251 i
	Case 3	21141 - 21136 i	5878 - 5862 i	3245 - 3214 i	1770 - 1714 i	1327 - 1251 i
	Case 4	4.9	16.7	30.3	56.2	75.9

The complex impedance values specified in Table 1 were trialled. They correspond to maximum or minimum real impedance, and maximum or minimum imaginary impedance for a given α. Figure 4 shows the change in ΔL for the setup utilised by Krokstad for these different complex impedance values. As can be seen the results are insensitive to change in real and imaginary impedance magnitude, except for the case of minimum real impedance. The cases of maximum or minimum imaginary impedance are similar to maximum real impedance because they correspond to only a very minimal phase change in reflection (ranging from about 1° for $\alpha = 0.04$ to 19° for $\alpha = 0.5$), not a complete reversal (180°).

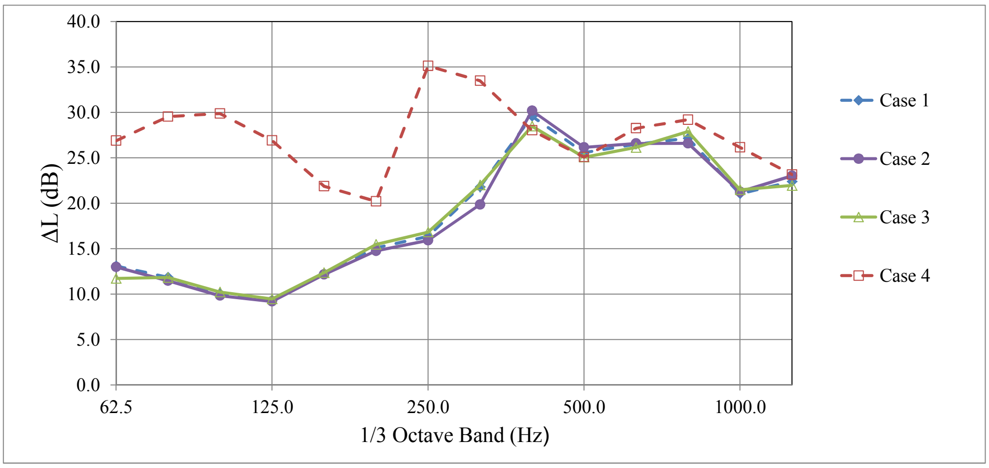

Figure 4 – Effect of altering real and imaginary complex impedance components on ΔL for the setup of Figure 1. See Table 1 for defintions of Cases 1–4.

Another analysis considered how sensitive results were to changing the magnitude of absorption coefficient. This was done as the absorption coefficients used can only be considered approximations to the true absorption coefficients required to produce the desired equivalent absorption area values. The absorption coefficients were increased and decreased by 0.1 to observe the impact on results. The absorption coefficients were increased by 0.1 over the full frequency range of interest (from 62.5 Hz to 2000 Hz), whereas the absorption coefficients were only decreased by 0.1 for 200 Hz and above, because the absorption coefficient used below 200 Hz was 0.04 and therefore could not be lowered by 0.1. Below 200 Hz a perfectly reflective (rigid) condition was instead applied. As the impact of real and imaginary complex impedance magnitudes had already been investigated the case of real positive R (meaning zero imaginary impedance) was used for this investigation. Figure 5 shows that the effect of a 0.1 change in the absorption coefficient is generally negligible (averaged over 1/3 octave) and at worst produced a $\pm$ 2 dB change in level.

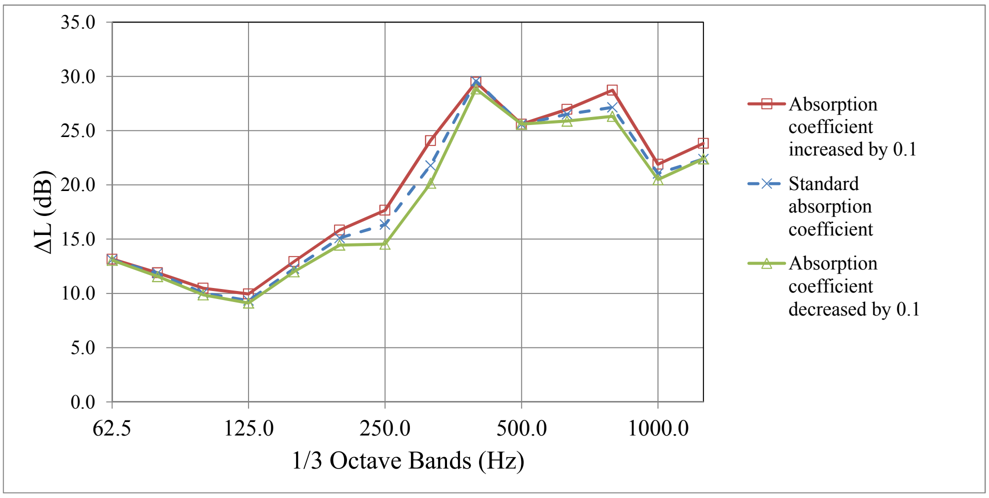

Figure 5 – Effect of increasing and decreasing absorption coefficient by 0.1 on ΔL for the setup of Figure 1.

3.4 Comparison of BEM results with Krokstad and Dammerud

The results available from Dammerud and Krokstad were used to validate the BEM model. Attenuation (ΔL), which was previously defined in Equation 1, was used to compare BEM results with Krokstad's data. As mention in Section 2, Krokstad used three source heights (0.6 m, 0.9 m and 1.3 m) and then presented his final results as an average of ΔL values at each source height. Krokstad computed ΔL for 1/3 octave bands between 62.5 Hz and 8000 Hz. Dammerud computed ΔL for 1/3 octave bands at 1000 Hz and 2000 Hz. This study has focused on low frequencies only, and validation with Krokstad's results was achieved close to 2000 Hz.

The complex impedance values used in this analysis correspond to maximum real complex impedance (Case 1 from Table 1).

Figure 6 shows attenuation values for Krokstad's full scale measurements compared with the values found from the BEM model. Dammerud states that his scale model set up, replicating the conditions used for Krokstad's full scale measurements, produced ΔL values deviating from Krokstad by +1 and -2 dB at 1 and 2 kHz (7). As can be seen in Figure 6 a similar level of agreement is achieved with the BEM model. Overall for the frequencies tested the BEM model results deviate less than $\pm$ 4 dB, with the exception of 400 Hz where a difference closer to 6 dB was observed. In Figure 3 a sharp dip in sound pressure is observed near 400 Hz in the BEM solution (this dip is also observed for plots of sound pressure versus frequency with source heights 0.9 m and 1.3 m). The BEM solution will capture this dip exactly, whereas experimental measurements shall have some level of smearing which could account for the more significant difference between BEM and experimental results at 400 Hz.

As well as the approximate impedance values used, there are several other reasons which may explain the variation found between the full scale measurements and the BEM model results. Firstly, the type of source used by Krokstad is unknown and may not have been an omnidirectional source (as was utilised in the BEM model). Even if an omnidirectional source was used it would not have been ideal as is the case in the BEM model. The BEM model also is not influenced by sources of measurement error, such as background noise. The exact location (and indeed geometry) of the seated musicians during full scale measurements was not provided, meaning the locations chosen in the BEM model may differ slightly. Additionally, the floor in the BEM model was assumed to be perfectly rigid. An impedance value could have easily been applied to the floor within the BEM model; however, because there was no information on which to base this choice a rigid floor was assumed. Floors in auditoria are generally highly reflective (close to rigid), and it is likely a space with a highly rigid floor was utilised during the full scale measurements. Lastly, the real measurements would most likely have been undertaken in a real room with some reflections from surrounding surfaces, even if nominally anechoic, whereas the implementation in BEM software allowed for a 'infinite' space to be utilised.

4. INVESTIGATION OF ONSTAGE SOUND FIELDS

4.1 Chamber orchestra BEM model

A chamber orchestra was modelled in the BEM software FastBEM to investigate the sound fields onstage with an orchestra present, using the same identical musician of Figure 2 (used in the validation process, discussed in Section 3). 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

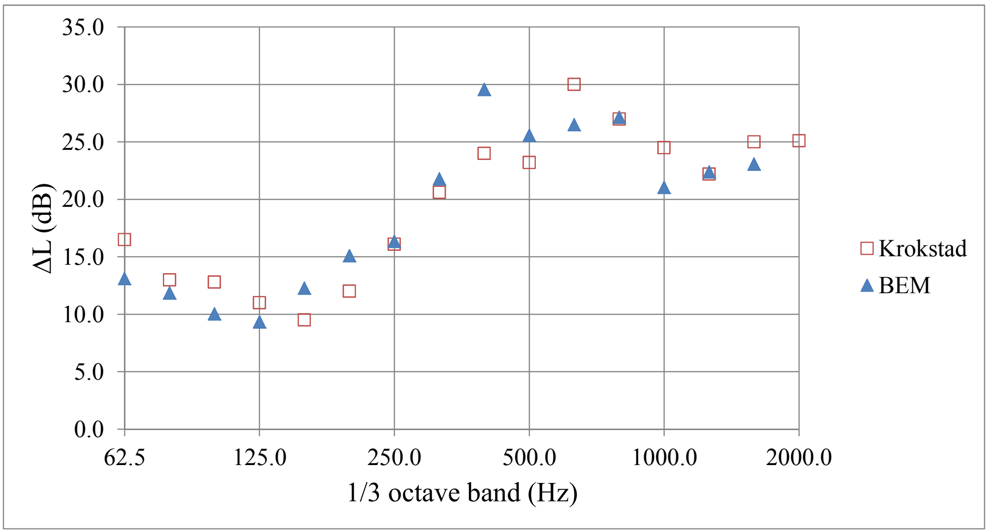

Figure 6 – Comparison of ΔL (average ΔL for source heights 0.6 m, 0.9 m and 1.3 m) varying with 1/3 octave bands from full scale measurements and BEM model.

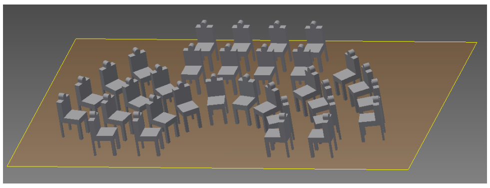

Figure 7 – Chamber orchestra setup

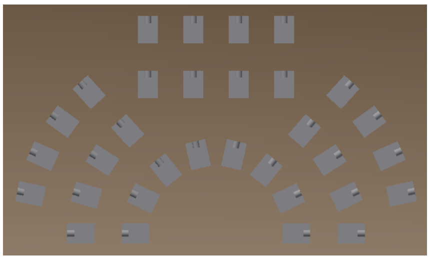

Figure 8 – Chamber orchestra setup (plan view).

present. A symmetry condition was specified to create a perfectly rigid stage floor. No stage shell was modelled, meaning only the floor and seated musicians would impact the stage sound fields. This allowed for an investigation of the difference between onstage sound fields on an empty stage (reflections from floor only) and on a stage with seated musicians. The chamber orchestra, as modelled in Autodesk Inventor®, is shown in Figure 7, and in plan view in Figure 8. The innermost row of strings has a radius of 2 m. The second row of strings has a radius of 3.2 m. The first row of winds is a distance of 3.5 m from front of stage with spacings of 0.6 m. The second row of winds is a distance of 4.7 m from front of stage. The four additional musicians on either side are a radius of 4.4 m from the conductor's position. The surfaces of seated musicians were assigned the complex impedance values determined from the earlier analysis (see Case 1 in Table 1).

4.2 Analysis of onstage attenuation

Attenuation (ΔL) was defined previously in Equation 1 as the sound level difference between the 8 m and 1 m microphone for the configuration used in full scale measurements undertaken by Krokstad. For the orchestra model, attenuation (ΔL) shall now be redefined as

$$\Delta L = 10\log_{10}\left(\frac{E_\mathrm{r}(f_1 - f_2)}{E_\mathrm{d}(f_1 - f_2)}\right) \tag{6}$$

where $E_\mathrm{r}(f_1 - f_2)$ is the integrated area under pressure squared versus frequency curve (between f_1 and f_2) at receiver with the modelled orchestra present, including floor reflections, but no stage shell, and $E_\mathrm{d}(f_1 - f_2)$ is integrated area under pressure squared versus frequency curve (between f_1 and f_2) at the receiver from direct sound and floor reflection only (equivalent to an empty stage). The values of f_1 and f_2 are chosen as the lower and upper frequency limits of the relevant 1/3 octave band. This definition will allow for comparison of sound levels on an empty stage and a stage containing an orchestra. The sound energy at receiver due to direct sound and floor reflection may easily be computed analytically. For a single frequency emitted from the source the sound pressure pattern moving away from the source shall have significant peaks and troughs, where constructive and destructive interference occur. This is not a particularly realistic case as single frequencies alone will almost never occur on stage, and instead one third octave bands will be utilised.

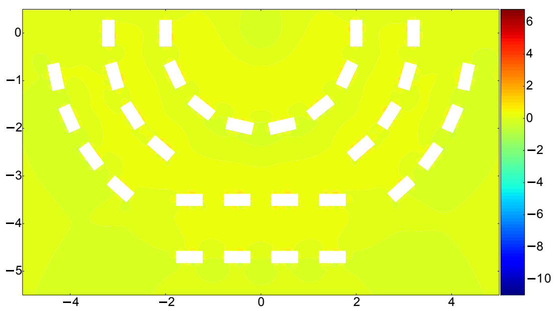

Figure 9 – ΔL for 62.5 Hz (1/3 octave band) for standard orchestra configuration.

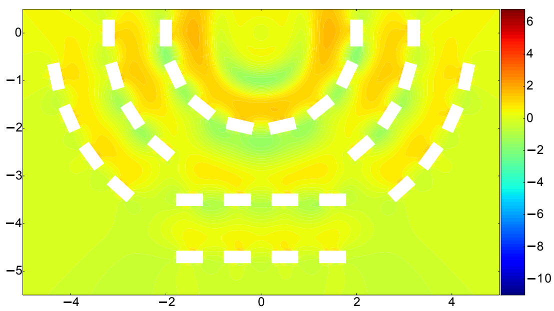

Figure 10 – ΔL for 125 Hz (1/3 octave band) for standard orchestra configuration.

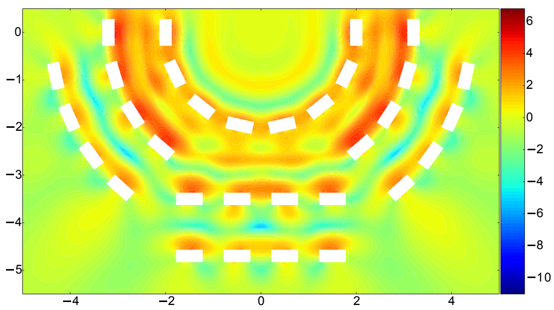

Figure 11 – ΔL for 250 Hz (1/3 octave band) for standard orchestra configuration.

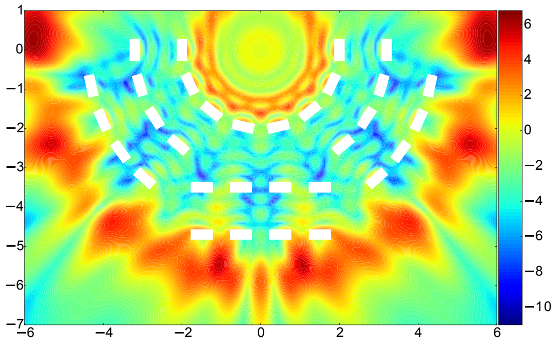

Figure 12 – ΔL for 500 Hz (1/3 octave band) for standard orchestra configuration.

4.3 Contours of ΔL

One third octave band contours of ΔL have been produced for the source located at the conductor's position (corresponding to the origin in all figures presented) and using the chamber orchestra configuration shown in Figures 7 and 8, with a 1 m source height. The conductor's position was chosen to illustrate sound attenuating throughout the entire orchestra. In future investigations the source positions could also be altered, as multiple source locations are generally used for onstage acoustic measurements. The contour plots have been produced on a surface at 1 m height above the stage floor, this corresponds to the suggestion in ISO 3382 to undertake measurements with source and receiver height of 1 m (2). At 1 m height from the floor the musicians' bodies will pass through the field of interest. The area filled by the musicians themselves and a small distance away from the musicians have been removed in the contour plots. This was done to avoid comparing sound pressure levels on the surface of seated musicians (which had been specified with absorbing properties) to the analytical solution. Each contour shows a 10 m by 6 m region of stage, with the exception of the 500 Hz contours which have been extended to show a 12 m by 8 m region to show more clearly interference effects.

An orchestra configuration will never be truly symmetric and will have some randomness to the set-up onstage. An analysis was undertaken to consider the impact of minor random changes to the positioning of seated musicians to the observed contours. Each seated musician was moved by 0.1 m in a randomly chosen direction (front, back, left or right). The musicians were still constrained to be facing the conductor where appropriate. The contours of ΔL were created for this slightly altered set up to allow comparison between the initial orchestra set up and the case with random perturbations introduced. The same scale range is provided for ΔL in all contours to allow for comparisons to be more easily drawn.

5. DISCUSSION

For wavelengths significantly larger than typical musician dimensions and spacings, the musicians will appear virtually 'invisible' to the sound waves. This is the case at the lowest 1/3 octave band considered, 62.5 Hz (see Figure 9). For 62.5 Hz (1/3 octave) values of ΔL were found to be between -0.5 and +1.2 dB. At 125 Hz (1/3 octave band) minimal impact on the sound field was still observed, with values of ΔL between -2 dB and +2 dB found (see Figure 10). At such frequencies undertaking acoustic measurements on an empty stage could be considered valid. However, at 250 Hz (1/3 octave) values of ΔL between -5.5 dB and +5 dB were observed (see Figure 11). While at 250 Hz (1/3 octave) only small regions onstage have ΔL values as high as +5 dB and as low as -5.5 dB, it still indicates that sound levels at some locations on stage do vary significantly

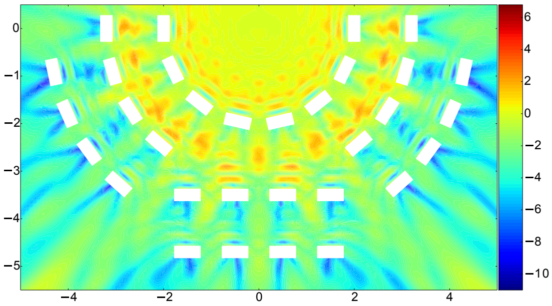

Figure 13 – ΔL for 794 Hz (1/3 octave band) for standard orchestra configuration.

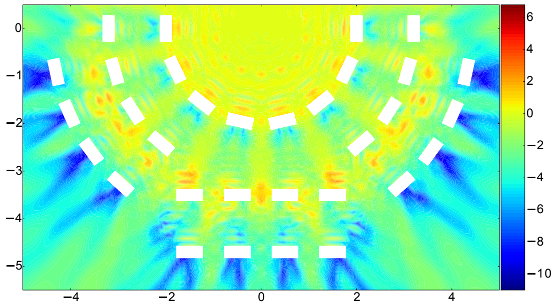

Figure 14 – ΔL for 1000 Hz (1/3 octave band) for standard orchestra configuration.

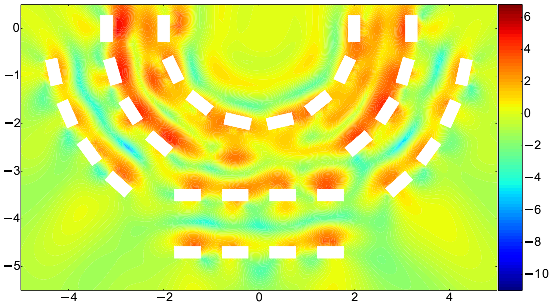

Figure 15 – ΔL for 250 Hz (1/3 octave band) for orchestra configuration with random perturbations introduced.

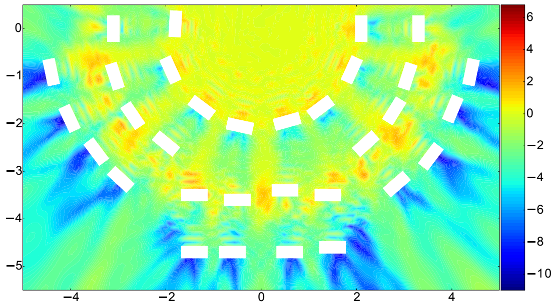

Figure 16 – ΔL for 1000 Hz (1/3 octave band) for orchestra configuration with random perturbations introduced.

from an empty stage. Therefore, removing furniture within 2 m radii of the source and receiver (virtually equivalent to removing all stage furniture for a chamber orchestra setup) would not give a particularly good indication of sound fields onstage with a chamber orchestra present for 250 Hz and above.

For intermediate frequencies significant diffraction, scattering and interference effects are expected, most prominently when the wavelength is a simple ratio with relevant dimensions. These effects lead to counter-intuitive sound fields, which are difficult to predict without modelling. For example, for 500 Hz contour (1/3 octave), see Figure 12, positive values of ΔL are observed behind the orchestra, indicating higher sound pressure levels in the these locations than if the orchestra were not present. Figure 12 also shows other constructive and destructive interference patterns within the orchestra. For 500 Hz (1/3 octave) values of ΔL between -9.2 and +6.3 dB were observed.

For high frequencies (wavelength much less than relevant objects) behaviour similar to light is expected, with shadows behind objects and reflections in front. This is visible for 794 Hz (1/3 octave) and 1000 Hz (1/3 octave) contour plots of ΔL, see Figures 13 and 14. The magnitude of reflections from objects will also generally be lower at higher frequencies (as the absorption coefficient, α, specified increases). Additionally, at higher frequencies interference effects, which may raise sound level at certain locations, become less prominent. At 1000 Hz (1/3 octave) ΔL values between -11 dB and +2.5 dB were observed - the maximum ΔL being notably less than the +6.3 dB at 500 Hz (1/3 octave).

An investigation also considered the change in sound field with some random variation in the positions of seated musicians (the alterations made to orchestra configuration were discussed in Section 4.3). The observed contours do not dramatically differ following the random perturbations, see Figures 15 and 16. For the 250 Hz (1/3 octave) and 1000 Hz (1/3 octave) the min and max ΔL values were virtually unchanged. However, some minor changes to the ΔL pattern (not just magnitude) were observed, and while the ΔL contours may appear to be little changed when viewed relative to the obstacles, it is noted that gradients near obstacles are often high and there may be quite significant changes to ΔL at fixed points in absolute space. More pronounced changes, for minor random changes to the orchestra configuration, would be expected if more objects (music stands and instruments) were included on stage. In particular, if music stands were included and given a highly reflective property (as may indeed be the case for solid music stands) this would almost certainly lead to more significant changes in sound fields depending on the placement on the stands. This issue is the justification behind undertaking measurements on stage with no objects within some distance of the source and receiver - to avoid taking a measurement in a location where the sound level has been significantly increased or decreased by nearby objects. However, for a small chamber orchestra setting virtually all onstage furniture may need to be removed leading to invalid measurements conditions, as demonstrated in this paper.

With BEM modelling, contour plots of attenuation have been produced rather than attenuation at single locations or along paths (as may be computed using full scale or scale model measurements). From the contours it is evident that the sound field can vary significantly throughout the orchestra, which indicates that different players may have significantly different acoustical experiences on the same stage. BEM modelling could be used to further investigate musicians' experiences within an orchestra, for example in relation to the precedence effect.

The precedence effect is a documented acoustic phenomenon - when two sounds arrive at a listener the perceived direction of the sound is based on whichever sound arrives first, as long as the later arriving sound is less than 10 dB greater than the first (9). The attenuation values found in this paper (sound may be reduced by up to 11 dB due to the presence of the orchestra), indicate that reflected sound arriving later from a stage enclosure may be high enough to confuse musicians' perception of direction of sound (at certain frequencies). This may ultimately limit musicians ability hear each other and play together. BEM may be a route to further investigate the effect of such phenomenon on orchestra musicians; however, implementing a stage enclosure in the model may be necessary for such analysis. Including a stage enclosure in a BEM model would incorporate the influence of the reverberant field (reflections paths off walls and ceiling being easily greater than 15–20 m and corresponding to delays of around 50 ms). This paper has rather considered an orchestra in an 'infinite space', and thus focused on the earliest arriving sound, which is arguably the most important sound for musicians.

6. CONCLUSIONS

This paper has demonstrated how boundary element method may be used to assess the validity of taking measurements on empty or only partly furnished stages, and added to the body of work suggesting measurements on empty stages cannot be considered valid. An initial analysis has examined sensitivity of stage sound fields to the exact configuration of the orchestra and found minor changes to the onstage sound field patterns occurred due to random perturbations. This paper has also focused on validating BEM model attenuation values, for a simple setup of seated musicians, with published full scale and scale model data, which has indicated that BEM model shows reasonable agreement with real conditions onstage.

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