ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 96 (2010) 138 – 167

DOI 10.3813/AAA.918265

Directivities of Symphony Orchestra Instruments

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Summary
The sound radiation patterns of musical instruments represent a considerable part of the perceived room acoustics. The directivities of fourteen common symphony orchestra instruments and a soprano singer during performance are investigated. For this purpose, each instrument was recorded with the musician in an anechoic room with 22 microphones distributed around the player. As the result, directivities of the strings and woodwind instruments are noticed to change with the played tone while the brass instruments radiate constantly in the direction of the bell. Playing dynamics was not found to affect the directivity although the spectrum of the sound changes considerably in particular with the brass instruments. The results can be utilized with source modeling in room acoustics simulation and in research on musical acoustics.

PACS no. 43.75.-z, 43.55.Ka, 43.58.Ta

1. Introduction

The physics of musical instruments has been a subject of thorough studying for centuries. Although the sound radiation has received some interest in a more recent time frame, still, much less research has been done on the characteristics of the instrument directivity. Much of the published research has concentrated on the physical properties of the instruments, and various mechanical devices have been utilized to play the instruments. Such measurements provide accurate results, but the contribution of the musician to the directivity pattern is absent.

Possibly the best known publication covering the subject of this paper has been written already 30 years ago by Meyer [1], who discussed the sound and directivity of the symphony orchestra instruments. Unfortunately, the description of the measurement method in detail is not available. The physics of musical instruments have been extensively researched by both Fletcher [2] and Rossing [3], but the directivities are only slightly covered. Other notable papers on instrument directivity have been published by Vigeant *et al*. [4], Causse *et al*. [5], Cook and Trueman [6], Jacques *et al.* [7]. However, different methods have been applied in different research, which makes the comparison of the results challenging.

In the design of concert halls, auralization is utilized to simulate the acoustics based on a computer model of the space [8, 9, 10, 11]. In such models the directivity properties of the sound source have to be defined. As the acoustical modeling is usually employed for larger music performance spaces, the ideal sound source is a symphony orchestra with correct directivities. This paper presents the directivities of all the most common instruments of a symphony orchestra. Moreover, the purpose for the research is to gather comprehensive data for modeling symphony orchestra instruments as sound sources which can then be applied in acoustical models. Therefore, this article is more balanced toward room acoustics modeling and auralization rather than strictly musical acoustics.

All recordings were performed in an anechoic chamber and the same microphone configuration was used with all instruments. This ensures the comparability of different instruments. The effect of the player to the radiation is also taken into account. Otondo and Rindel [12, 13] have reported a comparable technique in anechoic measurements of a selection of wind instruments. However, the number of used microphones was smaller, and the microphones were at closer distance from the instruments. More recently, Pollow *et al.* [14] have utilized a comparable spherical array for directivity measurements, although comprehensive results have not been published.

All instruments were played by professional orchestra musicians. The recordings were accomplished at the same time with the anechoic symphony orchestra recordings [15]. Therefore the bass clarinet, the contrabassoon, and the English horn, often used in symphony orchestras, are not presented in this paper, as parts for these instruments were not written in the recorded excerpts.

This paper is organized as follows. First, the arrangements related to the anechoic chamber, microphones, calibration, and the measurement method are presented. Then, the applied visualization methods are illustrated. The results from the measurements are presented in instrument groups following the conventional order of musical scores, beginning with the woodwinds and brass, and followed by the percussions, soprano, and the strings. Each instrument

Received 3 March 2009,
accepted 3 November 2009.

is introduced by a brief discussion on the principal physical properties and related previous research. The results are compared with the previously published research in the end of each instrument. The overall analysis and observations on each major instrument group is summarized at the end of each section.

2. Recording setup

Instruments were recorded with professional musicians in a cubical anechoic chamber having a distance of 4.2 meters between the wedge tips. The chamber is assumed to be anechoic at frequencies above 100 Hz. Twenty two large-diaphragm condenser microphones were installed in the recording space for capturing the instrument directivity in those directions. Twenty of the microphones were positioned in a dodecahedron shape, similarly to the ISO 3745 standard for sound power measurement in free field [16]. In addition, two microphones were positioned directly in front and above the musician. The average distance of the microphones from the center of the room was 2.13 meters. The microphone angles are listet in Table I.

The recordings for directivity analysis were done as part of the project in which anechoic symphony music for auralization studies was recorded. Thus, the full documentation of the recording setup has been reported earlier [15].

Two ambiguous issues related to the position and orientation are present in directivity measurements. First, the instruments are of largely differing sizes and they radiate sound from different parts. Hence, it is impossible to define the acoustical center for the instruments with musicians. Therefore, the position of the musician's head was defined as the center position. For the large string instruments, the directivities were compensated for the lower instrument position.

The second issue is the definition of the front direction (0 azimuth, 0 elevation). Musicians have usually different habits while playing, e.g., violinists exhibit more or less movement, and the wind instrument players tend to point the instrument straight forward or slightly downward. In this study the musicians were told that the conductor would be in the front direction and they were advised to play in this direction as they would play in a concert situation. Hence, the direction of sight is constant with all recorded instruments. For instance, the violinist played in such a way that the neck of the violin points to the front-left.

The calibration of the microphones was carefully performed with the help of a reference microphone and a high quality loudspeaker. The details of the calibration process are reported by Pätynen *et al.* [15] and they conclude that the frequency response of all microphones was within a 1 dB range between 500 and 10000 Hz and within a 2 dB range from 60 to 20000 Hz.

3. Analysing method

In order to obtain comparable results from different instruments, the recordings were performed as follows. The musicians were instructed to play two octaves of A major chord tones in the native playing range of the instrument separately with constant speed. The seven A major tones were recorded in three different dynamics, namely *piano, forte*, and *fortissimo*. Thus, for all instruments the gathered data is by nature five-dimensional: directivity on a spherical surface is a function of frequency, played tone, and dynamics. Such data is challenging to present clearly with as much information as possible. In musical acoustics, the frequency domain is usually presented in great detail. However, here the frequency domain is condensed into octave and one-third octave bands, which is also the conventional accuracy for the directivity information in room acoustics. For illustrating the recorded data, the following two ways of plotting directivities are applied.

Table I. Positions of the 22 microphones around the musician.

Mic nos.	elevation [deg.]	azimuths [deg.]
1–5	+53	0, 72, 144, −144, −72
6–10	+11	0, 72, 144, −144, −72
11–15	−11	36, 108, 180, −108, −36
16–20	−53	36, 108, 180, −108, −36
21	0	0
22	90	0

The first plotting method illustrates the overall directivity of the analyzed instrument at significant octave bands, see Figure 1. Here only one octave band is shown for clarity. It consists of three cross sections of the spherical space around the player. The first figure can be seen as watching the player from the left side. The middle figure shows the cross section of the horizontal plane, where both microphone levels in elevation angles of 10.8 and −10.8 degrees appear in turns. The microphone at front is at 10.8 degrees elevation. The leftmost figure shows the transverse vertical plane, which goes through the sides of the player. In the bottom part of Figure 1, each polar plot is illustrated with the microphone positions in 3D. The line types are the same as in the three polar plots. Microphones nos. 3 and 10 shown previously in Figure 2 are marked with numbers.

Some interpolations are necessary to do with this plotting technique, as there were not microphones at all the positions required for the three planes. In the leftmost figure values in elevations 11 and 53 degrees in the front and −11 and −53 degrees at the back are averaged from the two nearest microphone signals. In the rightmost figure the sound pressure levels are linearly interpolated from the two nearest microphones in all directions except for the top position, since there were no microphones on the exact transverse vertical plane. In each figure every octave band is normalized to 0 dB in the strongest direction. Values lower than −10 dB are not shown here, therefore gaps can appear at certain plotted octave bands with instruments having strong directivity. It is important to notice that the plots are not shown for more omnidirectional octave bands where the average value is above −3 dB. Therefore every octave band is not necessarily visible in each plane.

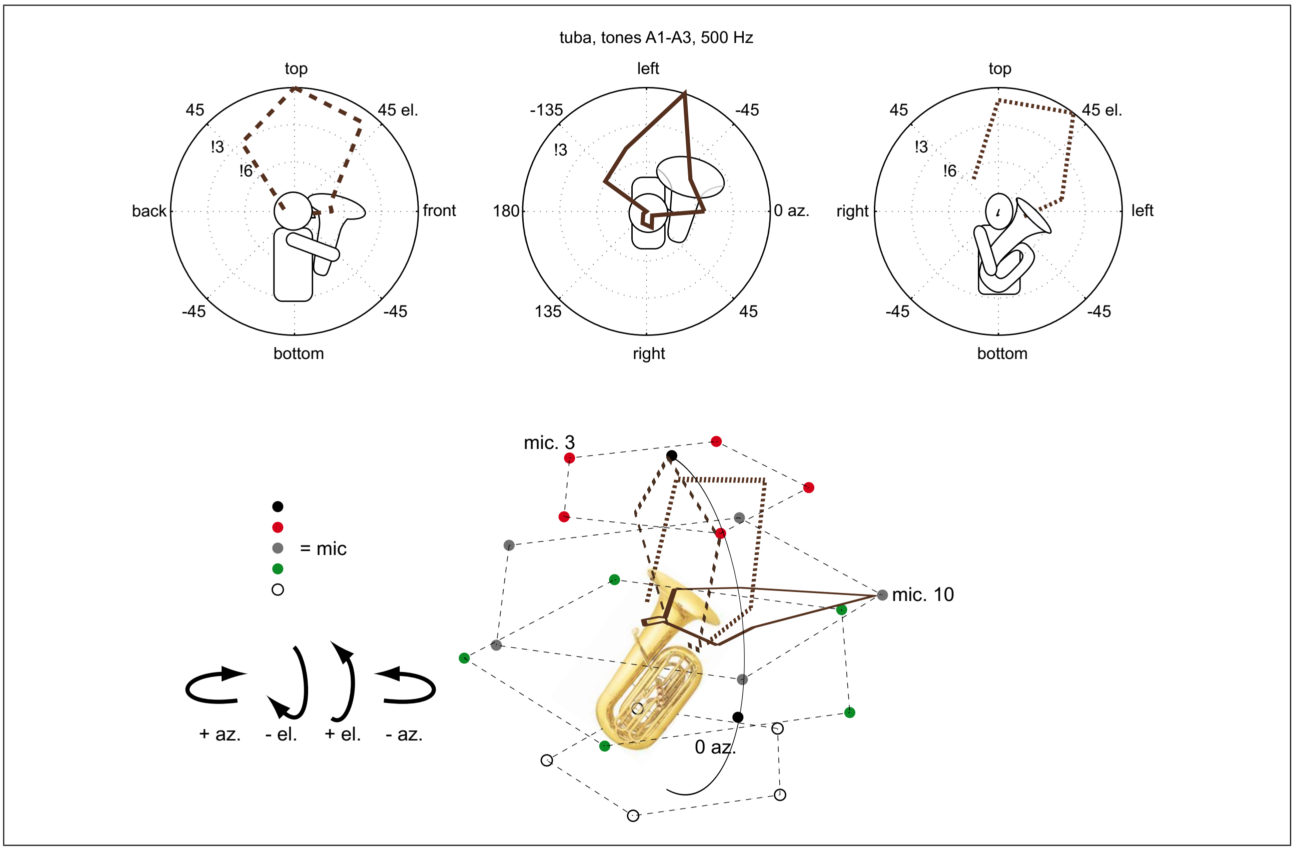

Figure 1. Illustration of the polar representation. The three polar plots are as seen from the left of the player (median plane, dashed line), from above the player (lateral plane, solid line), and from the front of the player (transverse vertical plane, dotted line). In the lower part each plane is depicted in perspective with the microphone positions. The front direction is shown with an arc.

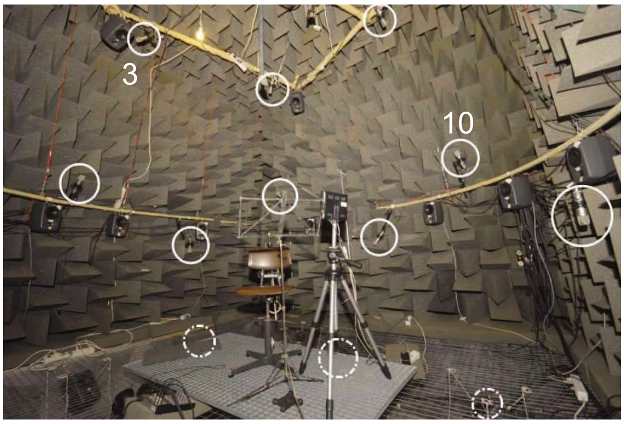

Figure 2. The recording configuration in an anechoic chamber. Microphone positions in the field of view are circled, and microphones nos. 3 and 10 are numbered.

The second plotting method shows more detailed sound pressure levels in one-third octave bands (see Figure 3). These figures contain the four elevation levels from the upmost to the downmost, each having five microphones. Individual azimuth and elevation angles of each microphone are shown on the y-axis. The increasing brightness of the contours indicate a higher magnitude where the contour limits follow the values shown in the colorbar. Thus, the direction and frequency within $0 \ldots -3$ dB and below -30 dB are the brightest and the darkest colors, respectively. In this representation the two microphones at 180 degrees azimuth appear twice in the two lowest elevations so that the plot is symmetrical. Hence, the front direction is located between -36 and 36 azimuth angles. Microphones nos. 3 and 10 are shown also here with numbers.

Two versions of this figure type are used, where in the first one each one-third octave band is normalized to 0 dB, as in Figure 3. Such figures titled as 'normalized view' are in most cases used to show the average instrument directivity. Solid lines appearing in part of the normalized plots in the maximum areas are due to the Matlab function `contourf` with linear interpolation. In the second type the data is plotted without frequency band normalization, thus showing the radiated spectrum. Such figures are generally used to illustrate the radiation with single tones. The appearance of harmonic frequencies in these plots can be slightly shifted due to the one-third octave filtering.

4. Woodwind instrument directivities

The woodwind group is different from other instrument types in many respects. Most importantly, the mechanism of sound production varies between woodwind instruments. Flutes incorporate an air jet hitting a sharp edge and thus creating oscillations in the pipe. The clarinet uses

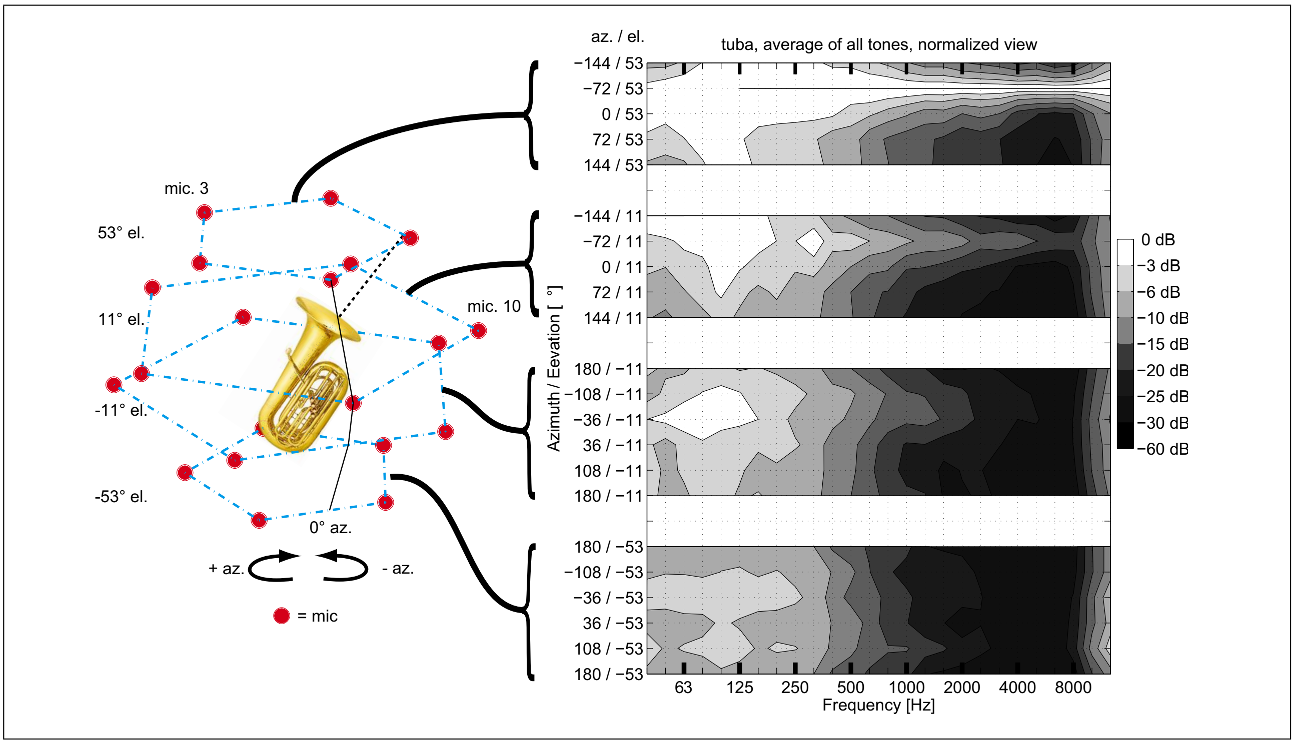

Figure 3. Illustration of the one-third octave band representation of an instrument radiation with normalization.

a single vibrating reed, while the oboe and the bassoon have a double reed to produce sound. In each case the pitch is altered by changing the effective length of the pipe by opening and closing tone holes.

In the next sections, directivities of the woodwind instruments most commonly appearing in a symphony orchestra are presented with a brief description of the physics of each instrument.

4.1. Flute and piccolo

The modern transverse flute is a cylindrical pipe with open ends and an overall length of approx. 660 mm and a diameter of approx. 19 mm. In a common symphony orchestra the flute and the piccolo are the only instruments in which the sound is produced by forming a Helmholtz resonator between the air jet in the embouchure hole and the closed end of the pipe [17]. A comprehensive study of the flute physics has been conducted by Wolfe *et al.* [18, 19] and Verge *et al.* [20]. On the other hand, flute performance technique with dynamics, harmonic structure and blowing pressure have been studied by Fletcher [21]. A specific technique called overblowing is used with the flute for playing tones above the fundamentals that are available by opening the tone holes. Here, the lowest sounding frequency is forced to the second harmonic. Hence, the tone sounds one octave higher [19].

The transverse and piccolo flutes have a considerable source of sound radiation at the mouthpiece unlike single or double reed instruments [1]. The open, far end of the flute as well as open finger holes function as radiation sources which are in phase at odd harmonics and in opposite phase at even harmonics when all finger holes are closed. Open finger holes present considerable radiation at middle frequencies, which makes the total radiation complex [2]. At high frequencies the open end radiates most of the sound.

The overall directivity of the flute is presented in Figure 4. The plotted data is averaged from tones A4–A6 in *piano, forte*, and *fortissimo*. The orientation is such that the player faces in the front direction, thus the open end of the instrument points to the right. Data in the 500 Hz octave band consists of the fundamental frequencies of the three lowest recorded tones. Seen from the left side of the player, the strongest radiation between 0 ... −3 dB is concentrated to the front downward direction. Seen from above the player, the strongest directions are on both sides of the front direction as well as behind the player. However, the sound pressure level is lower on the left side. In the transverse vertical plane the radiation is concentrated to the right. Again, radiation to the left is lower than in other directions.

Compared to 500 Hz, higher analyzed octave bands also contain overtones. Here, the directivity is partially divided into separate regions. At 2 and 4 kHz, the front and right directions are emphasized considerably, while the 2 kHz band has the most directivity in separate directions. On the other hand, the 1 kHz band features a more evenly distributed radiation pattern to the front, above, and the approximate axis of the instrument.

The average directivity is presented in Figure 6. Around 500 Hz the sound is radiated to the front region, while a substantial attenuation is found on the left side. Above 600 Hz the directivity begins to concentrate on the right side. Very pronounced directivity is noticed below 4 kHz

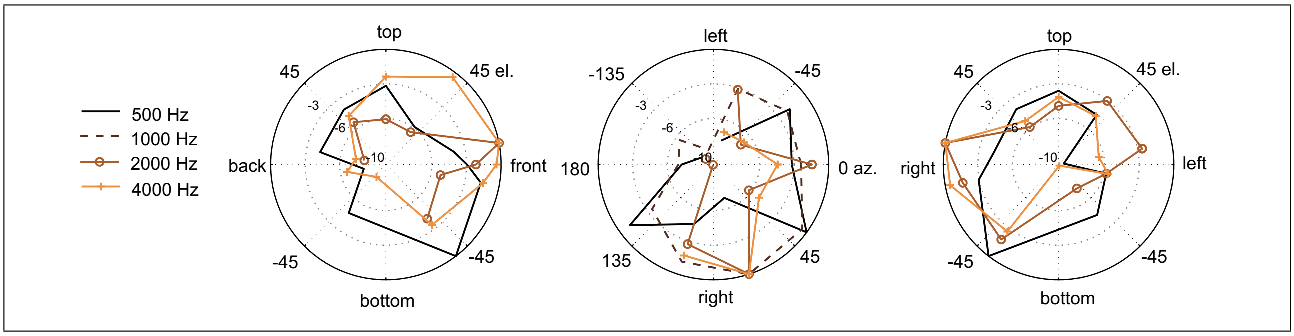

Figure 4. Overall directivity of the flute in the median, lateral, and transverse planes.

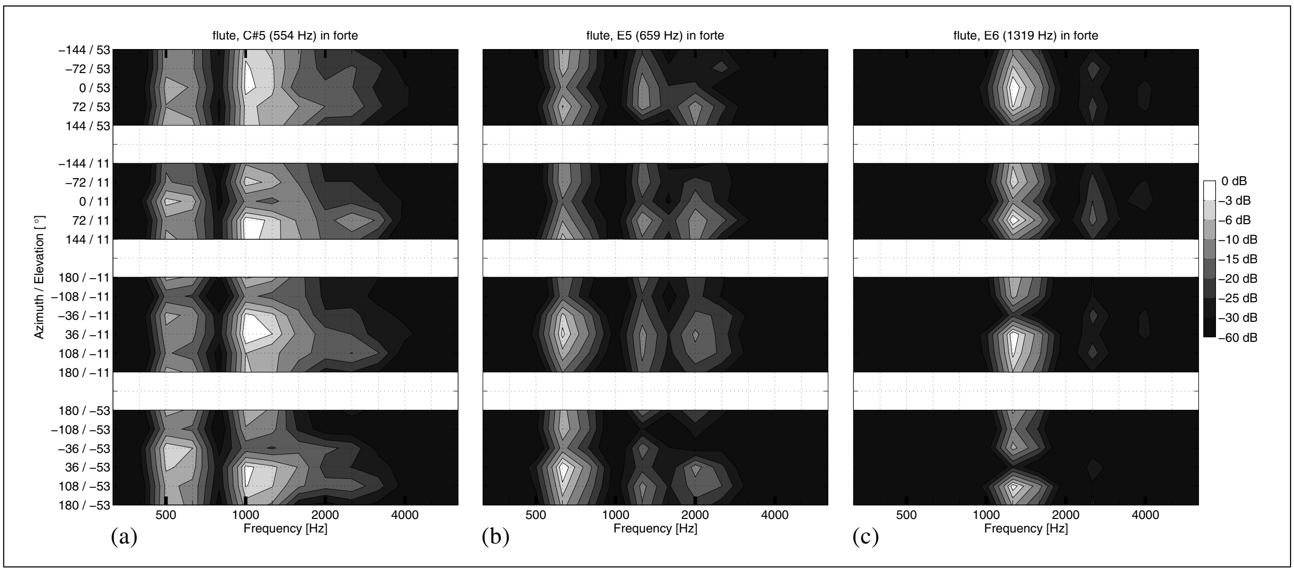

Figure 5. Flute radiation with different tones in *forte*. a: C♯5, b: E5, c: E6.

in the direction of the open end. The average sound pressure is very low above 5 kHz.

The effect of the played tone on the directivity is two-folded. First, the radiation patterns of single tones change with respect to different fingerings. A comparison between two tones is shown in Figures 5a and 5b. The fundamentals radiate in substantially differing directions. Second, the radiation of the harmonics is similar with tones having the same fingering. This results from the overblowing technique, as the same tone holes remain open. This is noticed with all tones where the tone one octave higher is overblown, which is in relation to the flute directivity discussed by Meyer [1]. Moreover, similar behavior is noticed also with tones having nearly similar fingering. An example is given with tone E6 in Figure 5c where a pressure node is formed in the pipe with opened tone holes compared to tone E5 [19]. As seen in Figures 5b–5c, the first harmonic of the higher tone radiates very similarly as the second harmonic of the lower tone.

Playing dynamics has a small effect on the directivity with a slight dependency on the playing technique used for a specific tone. The directivity of the fundamental is changed with tones E6 in *fortissimo* and A6 in *forte*. However, the strongest directions of the second harmonics remain at the same regions independent on the dynamics. On the other hand, the radiation patterns with two of the three recorded dynamics are close to each other with the particular tones. While this phenomenon cannot be explained accurately, possible reasons for the changes could be inadvertently changed fingering or small player movement despite the instructions. The same phenomenon did not occur with the high piccolo tones. Otherwise the directivity at all harmonics remains constant except for the emphasis of the higher frequencies.

The flute directivity by Meyer is only presented in the lateral plane. Here the most distinct similarity compared to those results is the change of the radiation pattern on the right side of the player between 500–1000 Hz, where the cancellation of the low-register fundamentals radiating from separate sources change to emphasized radiation at higher frequencies [1]. While a remark by Benade cites the flute directivity not being omnidirectional at any point, the average radiation from all recorded tones is the most even around the 1000 Hz one-third octave band [22].

The piccolo is approximately half of the length of the flute. Thus, the sounding range is one octave higher. Corresponding tones on octaves A5–A7 were recorded with the piccolo. In general, the piccolo shows characteristics

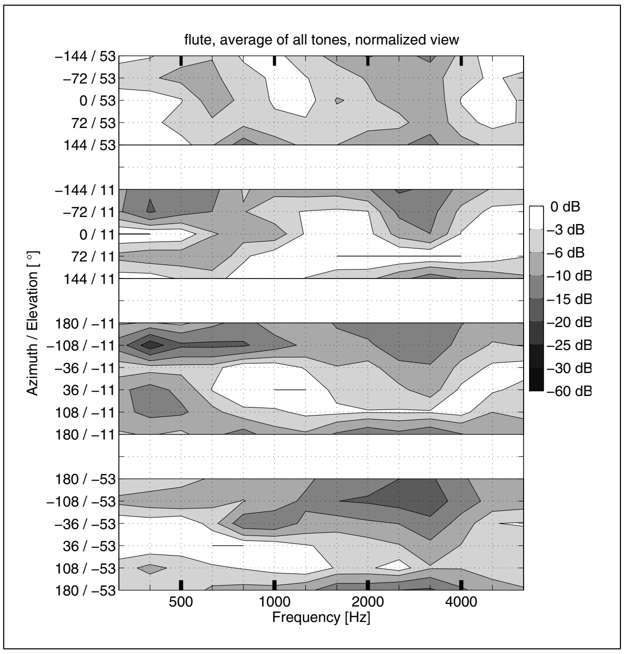

Figure 6. Flute sound radiation averaged from all recorded tones.

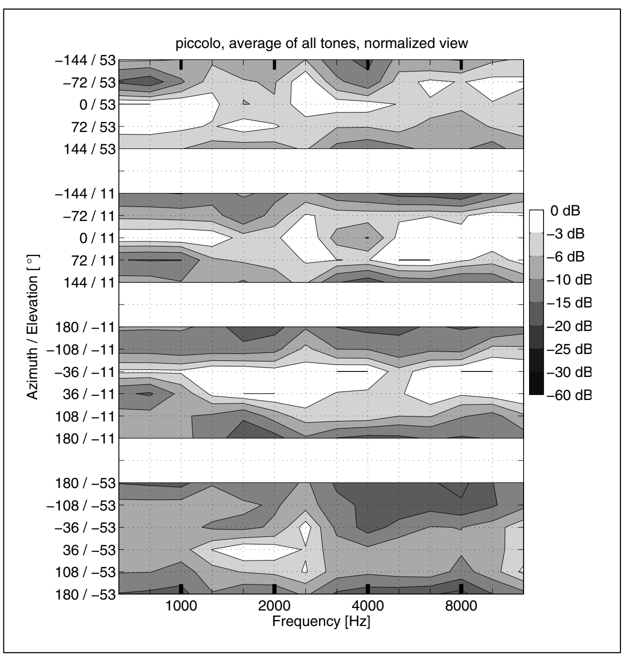

Figure 7. Average radiation of the piccolo.

comparable to the flute. The magnitude of the overtones decreases above A6 for all measured dynamics.

The average directivity of the piccolo is shown in Figure 7. Compared to the flute average (see Figure 6), there are some common features as well as major differences. For both instruments the lowest frequencies are radiated in the same directions. The strongest directions of the fundamental frequencies are found at the front in the middle elevations with all tones. Around 1 kHz, the flute directivity is balanced on the right side of the player, while around 2 kHz the piccolo exhibits a fairly strong radiation at the front. Above 4 kHz the piccolo radiation is emphasized on the right side less than with the flute above 2 kHz.

4.2. Oboe

The sound of the oboe is produced by a pair of reeds which causes the air column to oscillate in the pipe. The acoustical length of the air column is determined by the open finger holes. The oboe forms a pipe with one closed end at the mouthpiece, and thus it works as a quarter-wave resonator. The pipe has a slightly conical cross section. As with the cylindrical flute with open ends, the closed conical pipe of the oboe creates a complete harmonic overtone series [3].

The overall directivity is not dependent on the vibration generating reed as in the case of the flute embouchure. Instead, the finger holes and the open end are considered the main radiation sources. The division into the radiation between the first two open holes and further openings is reported to be determined by the distance between the finger holes and the harmonic frequencies of the played tone [2]. 1500 Hz is seen as the cutoff frequency for the oboe [23, 22], where the frequencies below the cutoff are radiated from the first open holes. Above the cutoff frequency the sound is mostly radiated from the further open tone holes and the open end. In addition, radiation from the open tone holes is nearly isotropic [2]. Warusfel *et al.* [24] have used computational models to simulate the directivity pattern of the oboe. The relation between the played tone and the blowing pressure has been discussed by Fuks and Sundberg [25].

Fingerings for the tones in the lowest octaves are similar, and the octave changed with a tone hole. Therefore the oboe fingering system is somewhat comparable to the flute. In this relation the change of oboe directivity in different octaves is presumed similar as in the observations on the flute. Due to the playing range of the instrument the lowest recorded tone is C♯4. Otherwise the tones follow the notes of A major chord, thus the highest recorded tone is A5.

While only the fundamentals of the two lowest tones are within the 250 Hz octave band, the average sound pressure level of the omnidirectional pattern in all planes is above −3 dB. Octave bands above 500 Hz have an increasing radiation in the lower directions, and the 4 kHz octave band exhibit strong radiation downward (see Figure 8). On the other hand, the contribution of the shadowing player is not known.

Like the other recorded woodwind instruments, the oboe has a highly alternating directivity which depends mainly on the played tone. As expected from the playing position, the directivity in the lateral plane is more symmetrical with regard to the front than with the flute.

Examples of the effect of the played tone to the directivity are given in Figures 9a–9c. The fundamental of the tone C♯4 has mostly omnidirectional radiation. The second harmonic around 550 Hz is directed strongly in the forward direction while the maximum sound pressure is received at the fourth harmonic in the lower front region.

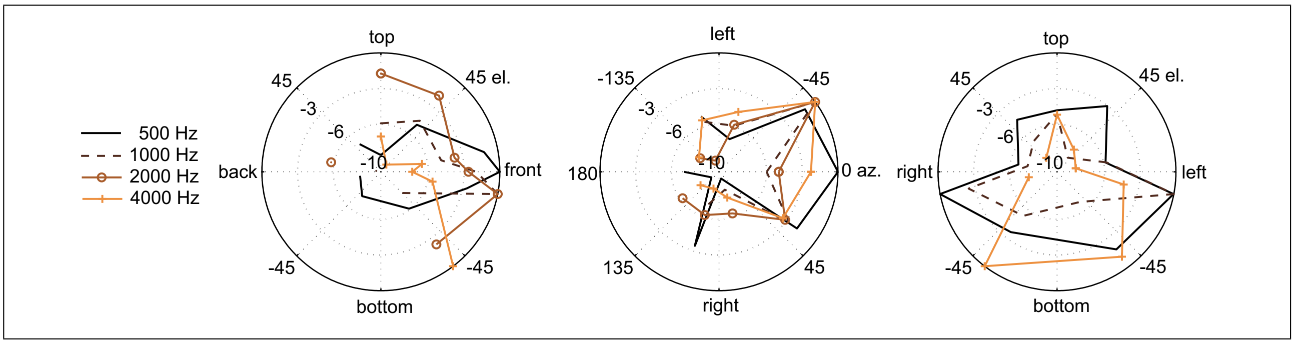

Figure 8. Overall directivity of the oboe in the median, lateral, and transverse planes.

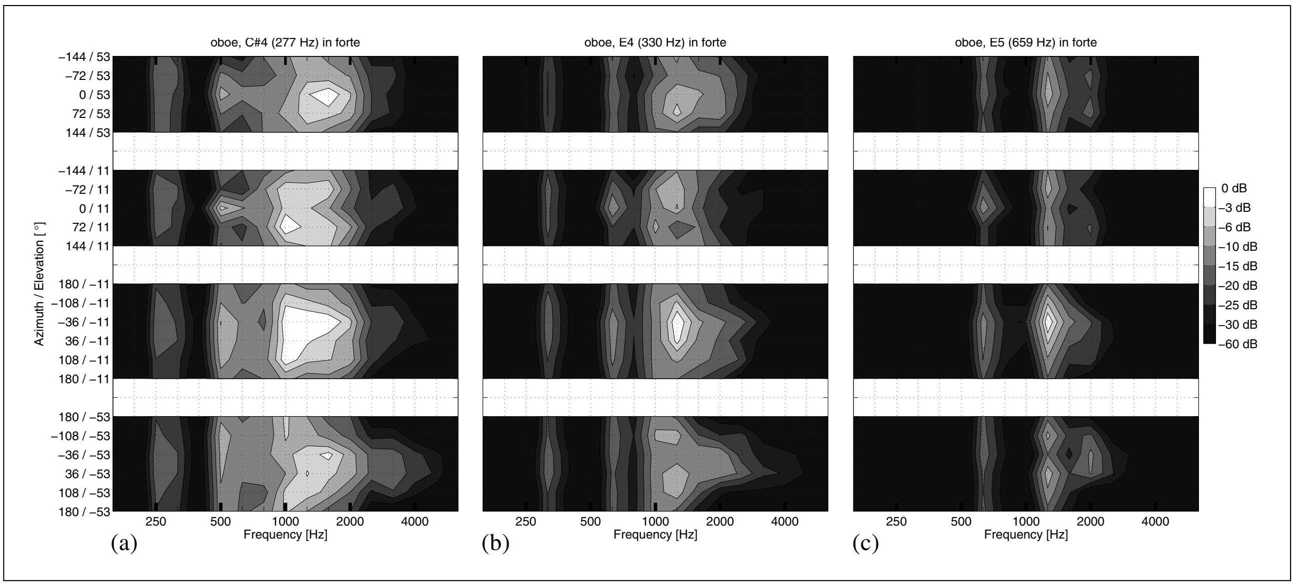

Figure 9. Oboe radiation at different tones in *forte*. a: C♯4, b: E4, c: E5.

At E4 the radiation is fairly similar, as maximum is in the same direction at the same frequency band. The first two harmonics are also radiated in the same directions. In addition to these tones, directivity at the 1250 Hz one-third octave band is similar with all recorded tones where harmonics are located in this frequency band.

With A4 and the tones above that the fundamental is not radiated omnidirectionally. An example is given in Figure 9c with tone E5 where the fundamental radiates to the front. It is noticeable that the radiation at E5 follows closely the radiation of the even harmonics of tone E4. Similar relation is found with other tones as well. In general, directivity of the oboe at higher tones is comparable to the tones one octave lower due to the similar fingerings. Therefore the radiation of the harmonics at higher tones can be approximated by observing the even harmonics of lower tones up to 2 kHz.

The average directivity of the oboe in the contour representation can be generalized by a more omnidirectional pattern in the lower hemisphere below 400 Hz and a narrowing beam in the bell direction above 1000 Hz, as seen in Figure 10. These observations are roughly in line with the 1.5 kHz cutoff frequency. However, a truly omnidirectional behavior was only found much below the cutoff frequency compared to the isotropic radiation discussed in the literature. In relation to the directivity presented by Benade [22], the back side of the player is found to attenuate gradually above 500 Hz beginning from higher elevations.

The average attenuation observed here in the bell direction between 1–2 kHz is prominently similar to the analysis by Meyer [1]. In addition, the symmetrical radiation on the sides is present in Meyer's observations. The sound pressure level difference of over 12 dB between the front and back of the player above 1 kHz is of the same magnitude than shown by Meyer (see Figure 10, −11 degree elevation). The results in the left plot in Figure 8 give a suggestion of the strong, narrow lobes appearing both at the back and above the player around 2 kHz in the median plane (see [1] p. 85).

4.3. Clarinet

The clarinet resembles closely the oboe by its physical appearance. However, there are two fundamental differences between these instruments. First, the shape of the clarinet is cylindrical in contrast to the conical oboe. Therefore the even harmonics are attenuated. Moreover, this results in

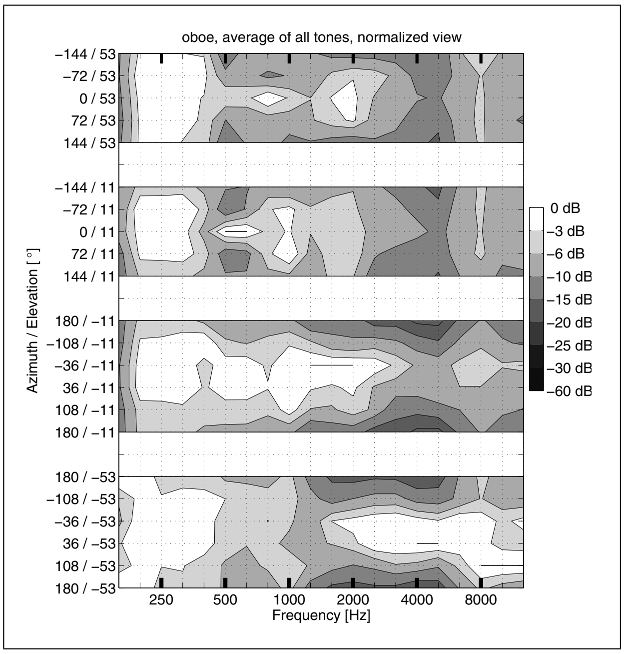

Figure 10. Oboe sound radiation averaged from all recorded tones.

modes of musical twelfth. Second, the method of sound generation is different. While the oboe uses a double reed excitation, the clarinet mouthpiece contains only a single reed which vibrates close to a rigid edge. The vibrating reed regulates the air flow in the pipe. Although the pitch can be altered only with blowing technique, the tone is mainly adjusted by opening and closing the finger holes which alter the effective length of the pipe [2, 3]. In addition, the bell of the clarinet is more flared compared to the oboe. The reported cutoff frequency of 1500 Hz for the radiation from the tone holes is the same as with the oboe [23]. Meyer [1] states the clarinet directivity to be similar to the oboe below 2000 Hz. While the bass clarinet is not investigated here, the directivity is predicted to be different due to larger dimensions and the bell pointing upward.

The overall directivity of the clarinet is shown in Figure 11. The clarinet radiates at the 250 Hz octave band to the front hemisphere with a small emphasis at lower elevations. Similar behavior can be noticed at the 500 Hz octave band. The lateral plane in the middle figure shows more pronounced radiation on the left of the player.

At the higher octave bands the directivity is clearer. Sound radiation at the 1000 Hz band is the strongest at the front. The most apparent directivity occurs at the 2 kHz octave band where the sound is radiated in the direction of the bell in median plane. In the lateral plane the front-left direction is the strongest. The 4 kHz octave band is radiated more evenly in all planes, although the bottom-right is the most apparent individual direction. According to the plots, radiation to the low elevations is pronounced above the 1500 Hz cutoff frequency.

A more detailed representation of the average directivity of the clarinet is depicted in Figure 12. Here the normalized radiation below 1 kHz can be generalized as a hemisphere which is slightly tilted down toward the axis of the instrument. The maximum sound pressure is received in the front of the player mainly in the two middle elevations. However, at the octave bands containing only the harmonics of the recorded tones the directivity is focused to the lowest elevation near the axis of the instrument. This is visible especially around 2 kHz (see Figure 11).

Since the results for the flute and the oboe have shown that the directivities of the harmonics are comparable with two tones one octave apart, it is plausible to assume that the same behavior applies to the clarinet as well. However, the even harmonics are absent from the clarinet spectrum with low tones, and the fingerings are similar with tones a musical twelfth apart. Therefore the compared tones should have the corresponding interval.

The averaged directivities with tones A3 and E5 are presented in Figures 13a and 13b where the similarity between the harmonics can be observed. The first harmonic of tone E5 resembles strongly the second harmonic of A3. Although the higher harmonics with A3 are not visible separately, the corresponding relation applies at second and third harmonics of tone E5 as well. Notably the second harmonic is also visible at E5 unlike at A3. This is related to the registers of the clarinet, as sounding tones above A♭4 are played with an open register hole, thus providing overtones at all harmonics [3].

Albeit other perfect twelfths are not available in the recorded data, the radiation of the harmonics can be compared with other tones having harmonics at the same frequency band. Of the recorded tones, the third harmonic of A4 (see Figure 13c) and the second harmonic of E5 have nearly the same frequencies. Although the radiation patterns at the 1250 Hz one-third octave band are not identical, they are still similar compared to the radiation of other harmonics. The third and second overtones of A4 and A5, respectively, are also noticed to have radiation in the corresponding directions. The relation between other tones is more difficult to analyze as the harmonics at higher frequencies are closely distributed. Regardless, the clarinet exhibits the same phenomenon observed with the flute and the oboe.

The playing dynamics do not have a substantial effect to the clarinet directivity. As expected, the strength of the overtones becomes higher as the dynamics is increased. In Figures 14a and 14b tone C♯4 is shown as an example of different dynamics. In *piano*, the sound pressure level of the higher harmonics in the direction of the bell stays above −30 dB up to 2.5 kHz. In *fortissimo*, similar levels span up to 5 kHz. The strongest regions remain in the same directions independent of the dynamics with the lower register tones. In the higher register the second harmonic is visible with quiet playing, but with increased dynamics it is attenuated. The average directivity shown in Figure 14c is closest to the radiation in *forte*. The peaks in the radiation below 1 kHz are emphasized in *piano*, and in *fortissimo* the only region above −3 dB sound pressure level at the 1–2 kHz frequencies is in the direction of the bell.

Meyer notes the radiation pattern to be close to spherical below 500 Hz with the player. While the results indicate

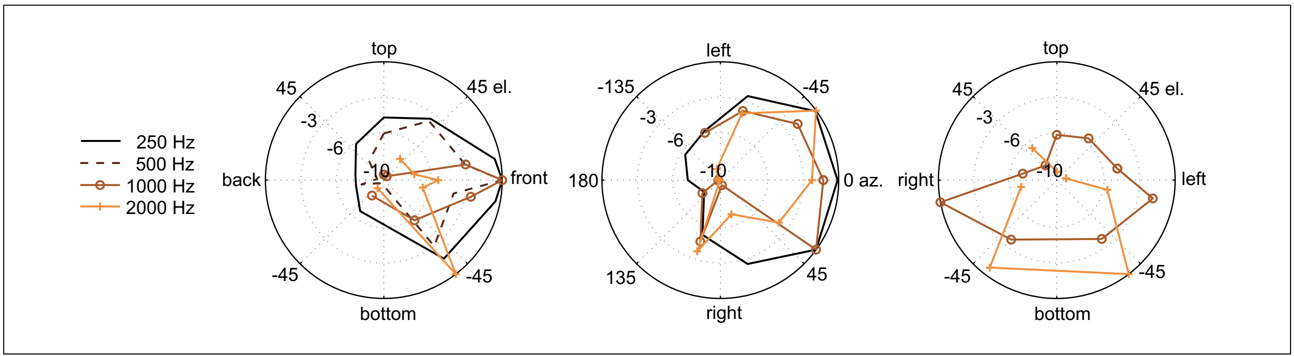

Figure 11. Overall directivity of the clarinet in the median, lateral, and transverse planes.

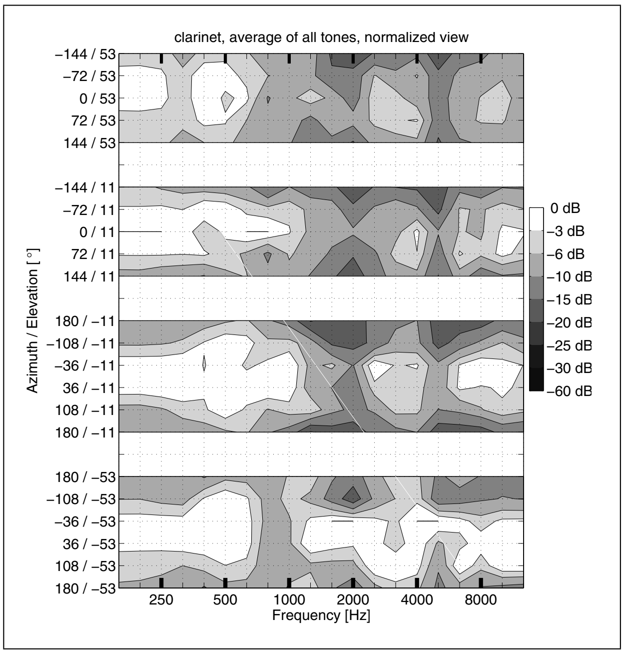

Figure 12. Clarinet sound radiation averaged from all recorded tones.

that the radiation is lower at the back of the player below 500 Hz, it is clearly visible here that the overall pattern becomes narrower at increasing frequencies. One prominent difference between the oboe and the clarinet is mentioned to be the absent emphasis at the top and back with the latter instrument. Correspondingly, such emphasis are not visible in the leftmost plot in Figure 11, unlike with the oboe. The attenuation of around −13 dB behind the player in relation to the front at −11 degrees elevation is much similar to the values presented by Meyer [1]. Otondo and Rindel have obtained rather even directivity results in the horizontal and median planes at 1 kHz octave band, while here the radiation at 1 kHz is found to be more irregular.

4.4. Bassoon

The bassoon sound is excited by a double reed similarly to the oboe. The length of the folded pipe (approximately 2.6 m) provides the lowest playing range compared to the other reed instruments [3]. The smaller angle of the bore, the metal tube connecting the reed to the pipe, and the long finger hole chimneys in the lower joint are considered to produce the distinct bassoon sound [2]. The reported cut-off frequency related to the sound radiation from the finger holes is around 400–500 Hz [2] which is considerably lower than with the oboe or the clarinet. Noticeable formants have been found at 440–500 and 1220–1280 Hz [26].

The fingerings of the bassoon tones are generally more complex than with the oboe or the clarinet. Similar fingerings with tones in octave intervals can be found between F♯2–F3 and F♯3–F4. The tones A2–A4 were recorded with the bassoon, and the total compass of the instruments extends to about an octave lower and a fourth higher than the recorded range.

At the 125 Hz octave band the radiation is omnidirectional in all planes, and the sound level is slightly below −3 dB only on the left of the player. The directivity at the 250 Hz octave band is similar seen from the left and above of the player with the exception of slight attenuations at the back and on the left side.

The bassoon directivity is the most pronounced between 1–2 kHz (see Figure 15). The 1 kHz band is strongly radiated in the direction of the bell. The most prominent directions at the 2 kHz octave band follow the radiation at 1 kHz. The 2 kHz band in the rightmost plot shows a particular diagonal directivity following the instrument axis. Another observation of the 2 kHz octave band is the radiation pattern of a cardioid shape in the lateral plane. The overall sound level beyond the 2 kHz octave band is very low.

A common attribute to the octave bands above 500 Hz is the small amount of radiation to the back compared to the lower frequencies. In the ordinary playing position most of the tone holes in the middle section of the bassoon are in front of the player. The lowest section, the boot joint, is visible to the back, and the open finger holes function as separate sound sources below the approximate cutoff frequency. Without different measurement approach the effect of the player cannot be confirmed, but the position of the instrument is suggested as a possible cause for the high-frequency attenuation at the back.

In Figure 16, similar conclusions can be drawn. The lowest frequencies are radiated more to a wider area in the

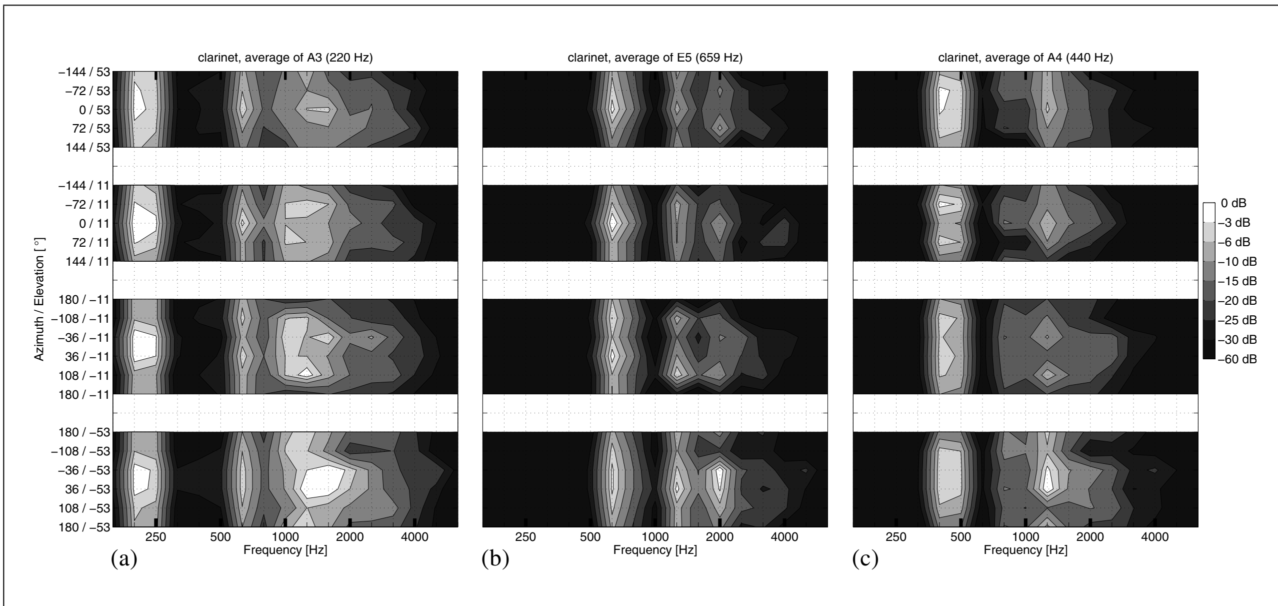

Figure 13. Average radiation of different clarinet tones. a: A3, b: E5, c: A4.

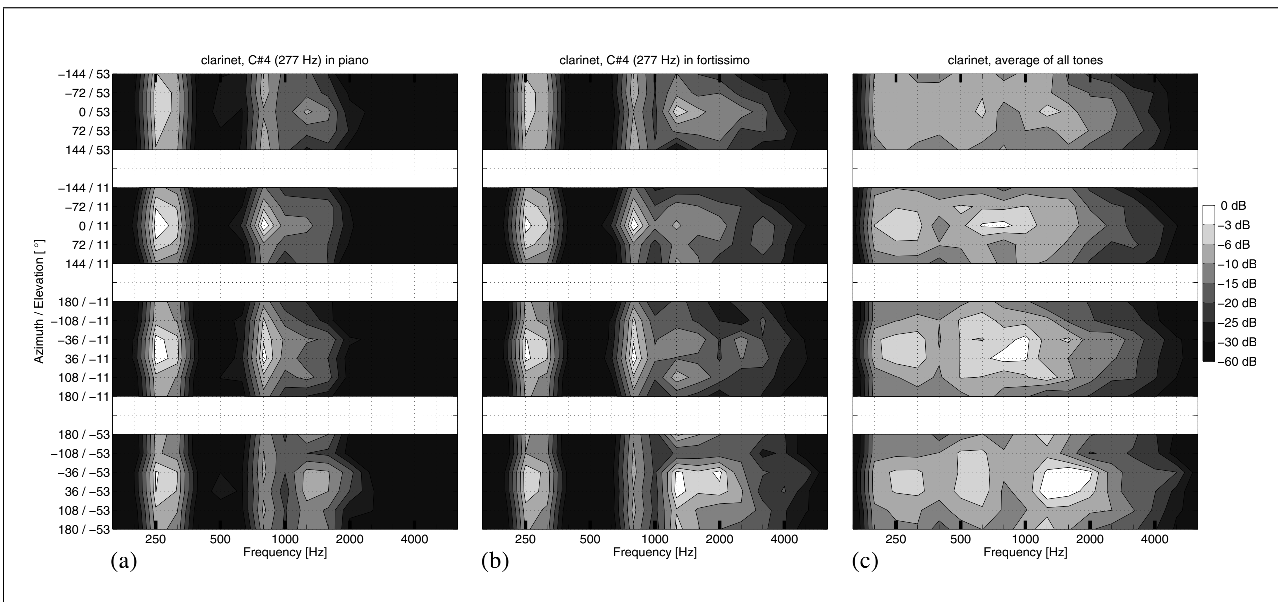

Figure 14. Clarinet sound radiation. a: C♯4 in *piano*, b: C♯4 in *fortissimo*, c: Average of all tones.

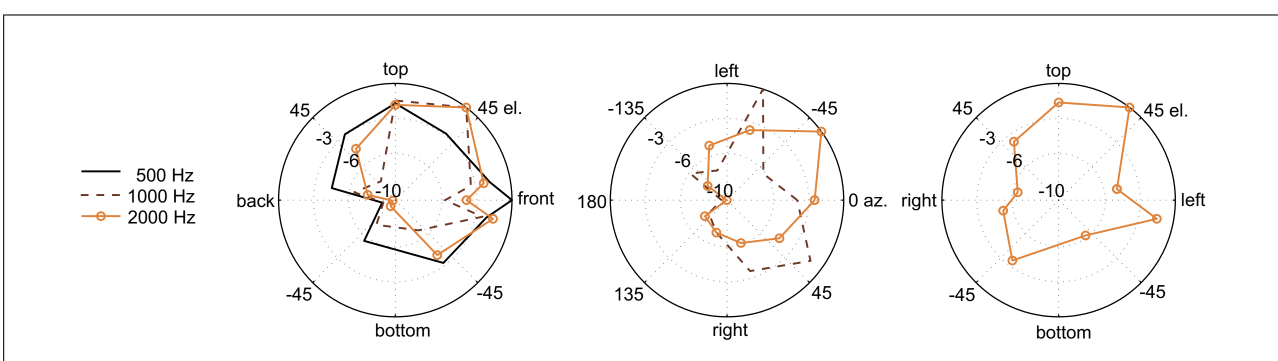

Figure 15. Overall directivity of the bassoon in the median, lateral, and transverse planes.

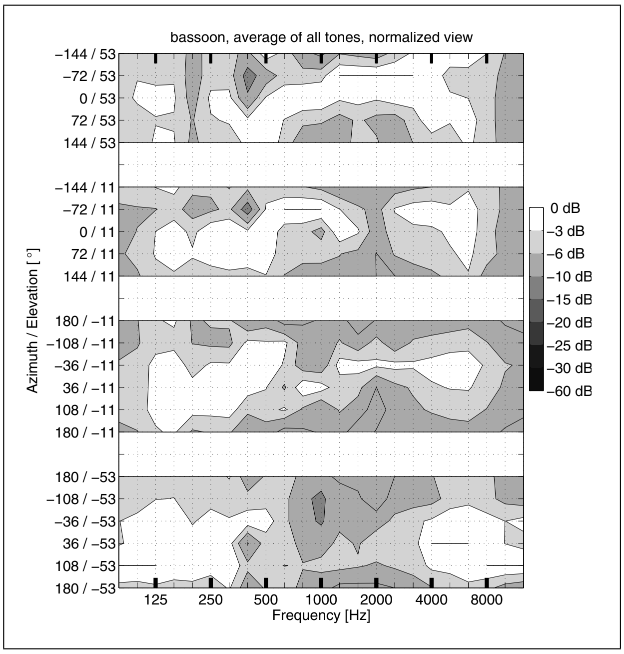

Figure 16. Bassoon sound radiation averaged from all recorded tones.

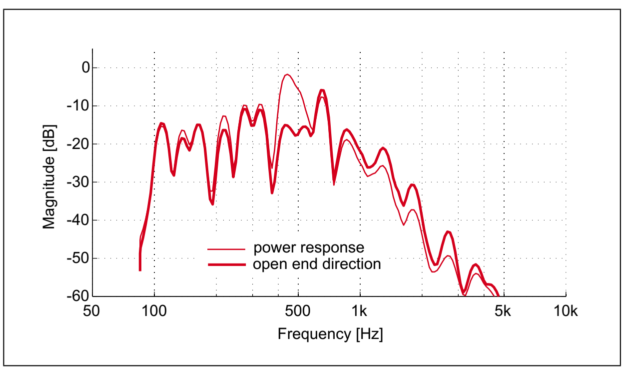

Figure 17. Power and magnitude responses of the bassoon. The magnitude response is recorded in the direction of the open end. The curves are one-third octave smoothed.

-53 and −11 degrees elevations. Above 500 Hz the two highest elevation levels are stronger, and beyond 1000 Hz the direction of the instrument axis is prominent. The overall sound level above 3 kHz approaches the noise level, and the directivity cannot be reliably observed. It is also noticeable that the direction closest to the bell receives a considerably low sound pressure level at overtones around 400–500 Hz. This is also visible without normalization and can also be seen in Figure 17. Here the power response thus, the average radiation, is remarkably higher compared to the magnitude response in the direction of the open end. Moreover, the first formant noticed by Lehman [26] lies at this specific frequency band. The weaker format at 1220–1280 Hz, however, is not visible in the directivity figures.

The radiation characteristics of the bassoon on selected tones are presented in Figure 18. Tone C♯3 in Figure 18a is given as an example of the following common properties observed with separate tones. The maximum magnitude is seen at the third harmonic at tones C♯3–A3. Additionally, this overtone is radiated strongly to the sides at all elevation levels. Lower harmonics are directed slightly to the right front, which is common for tones up to E4. The divided directivity around 500 Hz at the −11 degrees elevation level is characteristic to most recorded tones except A2.

A corresponding method was applied with the bassoon tones as with other woodwinds in order to find similarities in the directivity of single frequency bands.

A comparison of tones C♯3 and C♯4 is shown in Figures 18a–18b. The fundamental of C♯4 is radiated to same regions as the second harmonic of C♯3. In addition, the first harmonic of A4 (see Figure 18c) has somewhat similar directivity as the third harmonic of C♯3 and the second harmonic of A3. In general, the sound radiation is found to be similar at common frequency bands appearing with multiple tones. Hence, somewhat corresponding behavior is found in the bassoon sound radiation as with the other woodwinds.

The directivity changes very little with different playing dynamics and the differences are caused by the emphasized overtones with higher dynamics. Therefore the harmonics at higher frequencies can be distinguished more easily. The normalized directivity plot remains practically unchanged below 1000 Hz for the different dynamics. The average directivity shown in Figure 16 represents best the directivity in *forte*.

In light of analyzing individual tones the most prominent attribute is the strongly changing directivity around the cutoff frequency. In the middle elevations, most recorded tones have a divided radiation pattern in alternating directions. The sound level in the open pipe direction is comparably low between 400–500 Hz. In addition, the strong formant of the bassoon sound lies in the same one-third octave band [26]. The sound radiation in the direction of the bell is prominent at over 1250 Hz.

Compared to the bassoon directivity in the literature, the omnidirectional behavior at low frequencies, as well as the prominent attenuation around the bell direction starting near 500 Hz, is reported by Meyer [1]. On the other hand, the directivity on the instrument axis above 1 kHz is presented by Meyer as a narrowing dip in amplitude, as opposed to the observation here on a stronger region. In contrast to the weak radiation to the back of the player discussed earlier, Meyer cites only a neglible shadowing effect.

4.5. Discussion on woodwinds

The analysis on the woodwinds resulted in a conclusion of a directivity with low predictability. Due to the physical properties and multiple sound sources in the instrument the directivity changes with the played tone. Overall, the high frequencies are radiated in the direction of the bell while low frequencies are more or less omnidirectional.

The directivity remained nearly constant with different playing dynamics with all woodwinds. Obviously the relative strength changes between the harmonics in relation to

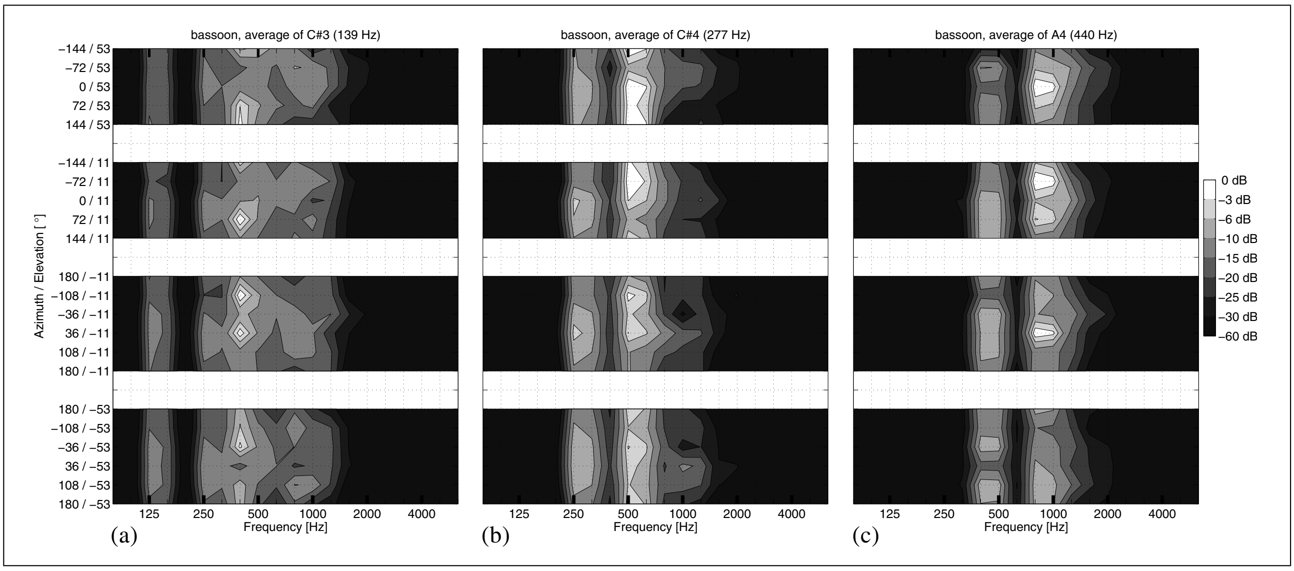

Figure 18. Bassoon sound radiation at selected tones. a: C♯3, b: C♯4, c: A4.

the blowing pressure, which can be seen in figures without normalization. Example given in Figures 14a and 14b is therefore applicable to most cases with the woodwinds.

On average the oboe and clarinet directivities were noticed to be somewhat similar, and they both radiate mainly to the front hemisphere at frequencies below 500 Hz. With the oboe, the strongest region changes gradually to the bell direction between 1–2 kHz. The clarinet radiates strongly downward above 1250 Hz. The harmonics of the oboe tones have similar directivity with tones one octave apart and a twelfth apart with the clarinet tones.

The bassoon exhibits the most evenly spread average radiation, and the normalized sound pressure is between $0 \ldots -10$ dB in nearly all directions with few exceptions. An observation on the particularly low sound level in the bell direction is noticed to be related with the formant at 400–500 Hz. Similarly to the oboe, the sound radiation of the bassoon changes from omnidirectional toward the bell direction at higher frequencies.

The results are in many regards comparable to the directivity characteristics by Meyer [1]. However, direct comparisons are complicated due to the difference between the coordinate orientations.

5. Brass instrument directivities

The sound generation of the brass instruments is rather different from the woodwinds. The lip vibration in the constricted mouthpiece induces oscillations of the air column in the instrument. The lip vibration is then amplified by the tube, which for one can be seen as a pipe nearly closed in the mouthpiece, resulting in a series of odd harmonic frequencies. The shape and flare of the bell, the mouthpiece as well as the bore of the pipe change the resonance frequencies to an approximately complete harmonic series [2, 3]. The flared bell increases the efficiency of the sound radiation, and more importantly, increases the directivity of the instrument. In practice, the brass instruments are assumed to radiate sound only from the open end [3].

Except for the trombone, specific valves are used to change the effective length of the pipe by connecting extensions to the piping. In addition to the three valves, modern French horns often have a fourth one which alters the tuning more dramatically by adding a portion of a considerable length to the actual pipe. The case with the trombone is more straightforward where a slide is used to incorporate the change in the pipe length. This feature requires obviously a cylindrical bore for the slide section. Also the bore of the trumpet is mainly cylindrical. The tuba is conical, while the French horn has a small cylindrical portion [2, 3, 27].

Research on the directivity of the brass instruments with documented measurements have been recently published by Otondo and Rindel on the French horn and the trumpet [12]. Early research by Martin presents the cornet and the French horn measurements in horizontal plane [28]. Directivity measurements on a loudspeaker-driven trombone for simulation purposes have been performed by Warusfel *et al.* [24]. Comprehensive directivity information on orchestra brass instruments is presented by Meyer [1]. In the light of these references, the brass instruments are expected to exhibit high directivity at frequencies where the wave length is small in relation to the size of the bell.

5.1. French horn

The modern French horns are double horns having two separate pipes sharing the same mouthpiece and bell. An auxiliary valve is used to choose the tuning in addition to the valves affecting to the lengths of the both pipes. The instrument used in the recordings had F- and B♭-tuning. The common length of the F-tuned horn is approximately 3.75 m. [3]

The compass of the horn is wide, spanning approximately three octaves up to sounding F5 [3]. The directivity

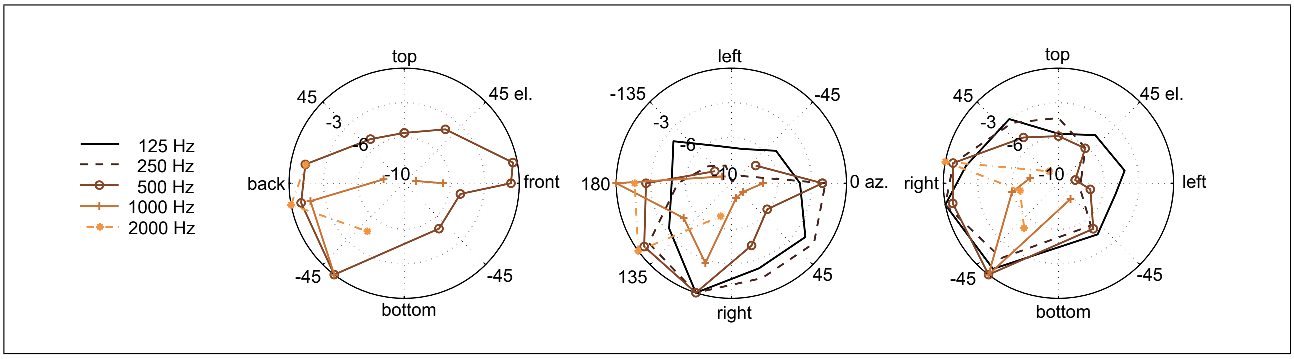

Figure 19. Overall directivity of the French horn in the median, lateral, and transverse planes.

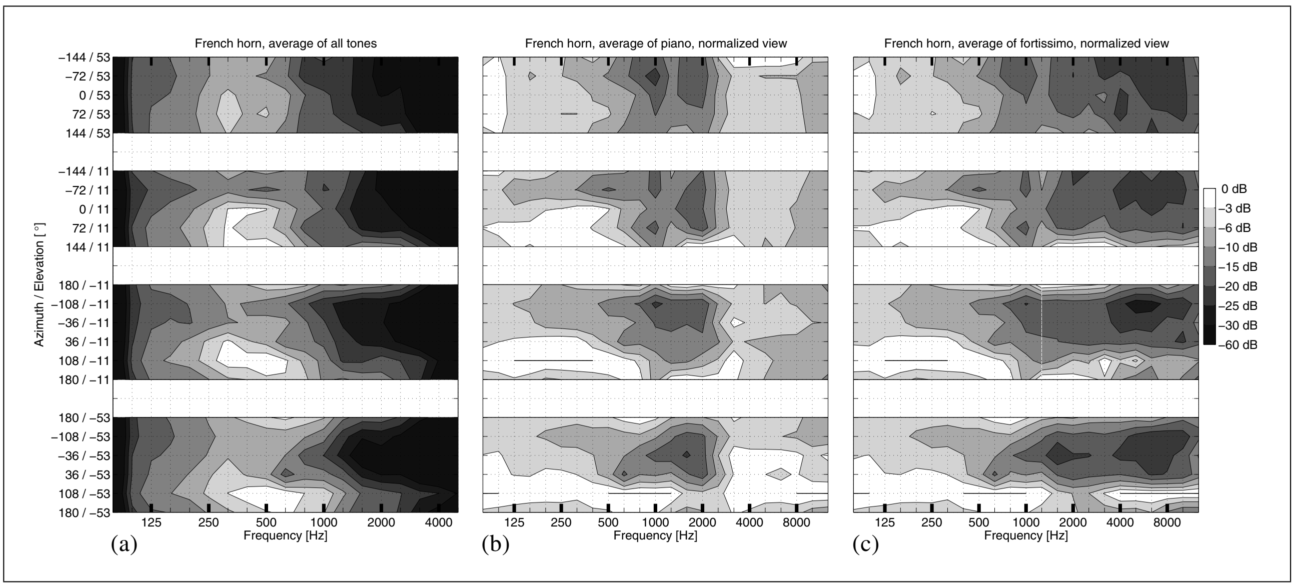

Figure 20. Average sound radiation of the French horn. a: all tones without normalization, b: in *piano*, c: in *fortissimo*.

was recorded with tones A2–A4 which cover the usable playing range fairly well excluding the highest tones. The playing position characteristic for the horn results in a very different radiation pattern in relation to the front direction of the player as the instrument bell points to the back on the right side. Besides the body of the player being close to the bell, the common playing technique also consists of inserting the right hand to the bell opening. These matters are predicted to result in a more complex directivity compared to other brass instruments.

The average directivity of the French horn is shown in Figure 19. The radiation in the median plane is fairly omnidirectional at the lowest octave bands. In the middle and right plots the 125 Hz octave band shows considerable decrease in the sound pressure in the direction opposite to the bell. In median plane the directivity is even up to 500 Hz.

Below 1 kHz the lateral plane shows slightly varying radiation pattern with prominent bias on the right side. The same behavior is noticed in the rightmost plot. At the 1 kHz octave band the bell direction is slightly attenuated. Above 1 kHz the directivity is limited in the bell direction.

An overview of the average sound radiation is seen in Figure 20a. Here the dominant radiation from the bell is apparent above 500 Hz. At the frequencies below 250 Hz the directivity is more even.

The played tone is not noticed to present any considerable change in the sound radiation above 630 Hz. The strongest direction up to 1 kHz and above 4 kHz remains in the far right at the bottom elevation level. At the 11 degrees elevation the directivity is slightly divided into the 0 and 144 degrees azimuth angles near the 500 Hz one-third octave band. This is best noticed with tone A4 where the fundamental lies at this frequency band. The difference in the sound pressure levels between the 72 degrees azimuth and the adjacent microphone positions is circa 2 dB.

The playing dynamics affects to the overall timbre of the sound a great deal. Higher playing intensity emphasizes noticeably the high frequencies, which results from the nonlinear propagation of the sound waves [2]. This can be seen in Figures 20b and 20c. The directivity can be resolved only up to the 2.5 kHz one-third octave band in *piano*, but to over 12.5 kHz in *fortissimo* due to the increased sound pressure at high frequencies.

More details in the directivity can be seen in Figure 20c. Between 1250 and 4000 Hz the radiation maximum changes to the middle elevation levels, and above

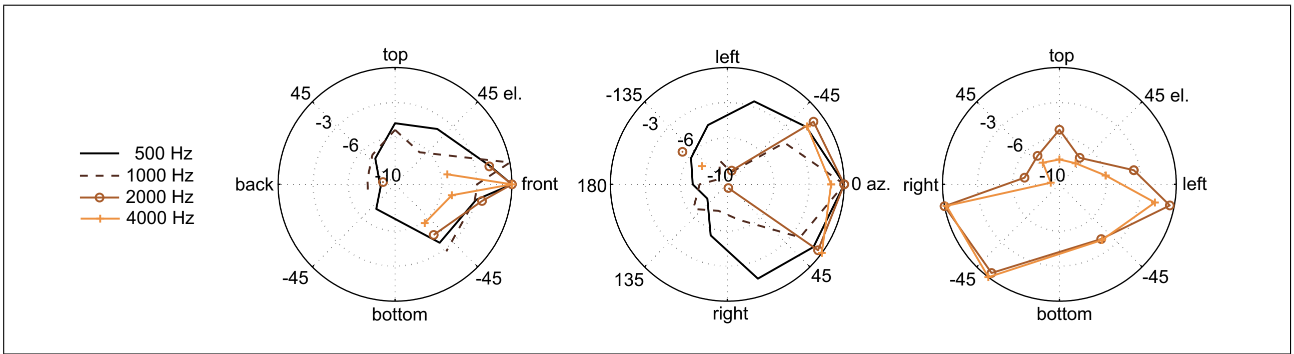

Figure 21. Overall directivity of the trumpet in the median, lateral, and transverse planes.

4 kHz the bottom elevation is again dominant. This change is plausibly caused by the right hand held at the bell opening. This reduces the radiation to higher elevations compared to a situation with unobstructed bell.

In the literature Meyer [1] as well as Otondo and Rindel [12] have presented visualizations regarding the French horn directivity. The results presented above are rather well in line with the Meyer's findings, particularly about the directivity in the lateral plane at lower frequency bands. At higher frequencies the concentrated radiation is obvious. However, in the vertical planes the directivity differs from the results shown by Meyer, where the overall radiation is indicated at somewhat higher elevations in relation to the bell axis. Compared to the figures at the 1 kHz octave band by Otondo and Rindel the values on the attenuation at the opposite from the bell direction appear to be similar.

The sound radiation was further investigated from the constantly declining part of the average power responses. The results for different dynamics were −21 dB/oct. in *piano*, −13 dB/oct. in *forte*, and -9 dB/oct. in *fortissimo* above 800 Hz. Luce and Clark [29] have stated a rolloff rate of −15 dB/oct. for the French horn.

5.2. Trumpet

The trumpet has the shortest length of the tubing of the common brass instruments, and the total length is approximately 1.4 m. This results in range of three octaves above sounding E2 with B♭ tuning [30, 3]. The playable overtone series is transposed to lower frequencies by three valves, although four valve constructions are also found.

The recorded tones comprised of octaves A3–A5 with a B♭-tuned instrument. However, due to the recording devices in the same space, a reflection occurred at back-left top elevation microphone during the recording. Unfortunately, this was not noticed prior to the analysis. According to the calculations on the time delays between the microphone signals, the reflection is assumed to have been caused by the small flat screen used for the conductor video (see Figure 2 in Pätynen *et al.* [15]). This is visible as unusually high sound levels above 2 kHz in this particular direction, as the trumpet sound at this frequency band is radiated to a narrow frontal area. The reflection has been compensated in the following figures by interpolating the affected frequencies from channels 3 and 5, unless notified otherwise. A portion of the total radiated sound in the forward region is therefore lost with the compensation. However, the effect on the visualized directivity in the front area is small.

The overall trumpet directivity is depicted in Figure 21. The radiation patterns at separate octave bands are particularly symmetrical with regard to the instrument axis. The median plane shows the least directivity at the lowest octave bands. At 1 kHz and above the directivity is increased in the front direction. In the lateral plane the case is very similar, although the 500 Hz octave band presents more even distribution of the radiation in the front half-plane. Above 1 kHz all octave bands show very comparable characteristics. Slight biasing to the right side is visible at higher frequencies in the rightmost figure. On the other hand, it should be noticed that comparably little sound energy is received in the microphone positions used in this figure at such frequencies.

Figure 22a shows the overall normalized directivity of the instrument without correction of the occurred reflection. The effect is noticed in the topmost row of the plot where the high frequencies are unnaturally strong. In the following figures the reflection has been compensated by averaging data from adjacent positions.

As seen previously in Figure 21, the directivity becomes narrower as the frequency increases. Here the radiation remains within −6 dB of the maximum in most directions at frequencies below 400 Hz. Above the 1 kHz one-third octave band the directivity changes rapidly and the most prominent directions in the instrument axis are clearly noticeable. The apparent cutoff frequency of 1 kHz is consistent with the values in the literature presented by Fletcher and Tarnopolsky [31]. At high frequencies the sound level differences are as high as 15 dB between adjacent microphones. The main direction of the radiation is seen at two angles at the two lowest elevation levels as opposed to the 11 degrees elevation due to the geometry of the microphone positions.

The sound radiation between individual tones does not present any noticeable differences. However, C♯5 were noticed to exhibit particularly omnidirectional behavior at its fundamental frequency (554 Hz) compared to slightly

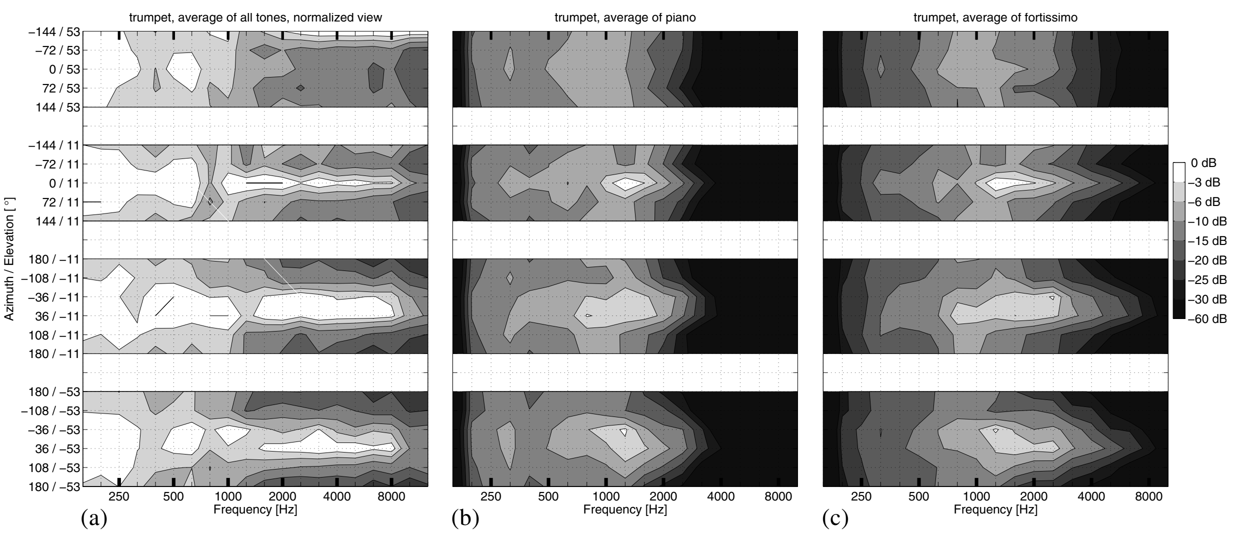

Figure 22. Average sound radiation of the trumpet. a: all tones with normalization, uncorrected, b: in *piano*, c: in *fortissimo*.

lower tones, such as E4 or A4. At C♯5 the sound pressure levels in different directions were only within −6 dB of the maximum, and the directivity was prominent starting from the second harmonic.

The different playing dynamics were not found to cause any changes to the trumpet directivity. The spectrum changes in the front so that the frequencies above 2 kHz are emphasized with louder playing. This is presented in Figures 22b and 22c.

Compared to the directivity values in the literature, the observed behavior is in line with results by Meyer [1], reporting that the omnidirectional pattern extends up to 1100 Hz with 10 dB attenuation or less. On the other hand, entirely omnidirectional frequency bands are not found, while Meyer states that the radiation level below 500 Hz is between 0 . . . −3 dB. Here, radiation low frequencies is noticed to be between 0 . . . −6 dB. Both Meyer and Martin [28] (for cornet) describe narrow fluctuations or side lobes at middle frequencies. Unfortunately such effects cannot be reliably observed with the used measuring setup.

The recorded playing dynamics were also analyzed with regard to the declining slope of the power responses, which resulted in −21 dB/oct. in *piano*, −20 dB/oct. in *forte*, and −13 dB/oct. in *fortissimo* above 1.5 kHz. Such values are in line with −15 – −25 dB/octave values presented by Fletcher and Rossing [2].

5.3. Trombone

The general sound production of the trombone is similar to the other brass instruments. The overall length of 2.75 m is twice that of the trumpet, which results in a playing range of an octave lower. In some trombones a separate valve is used to connect additional length to the tubing, providing a lower playing range. Both tenor and bass trombones are common in symphony orchestra works where parts have been written for trombone in general. As the construction in both versions is closely similar, only the tenor trombone is investigated here. The bass trombone is expected to perform comparably, only scaled to lower frequencies due to the larger bell. The bell diameter in tenor trombones is around 18 cm and corresponding measure for bass trombone is approximately one-third higher [3].

Tones A2–A4 were recorded, which gives a good representation of the playing range of the tenor trombone. The 125 and 250 Hz octave bands radiate far more omnidirectionally in all planes than with the trumpet at one octave higher. The front region is emphasized beginning from 500 Hz. At the 1 kHz and higher octave bands the directivity is highly concentrated in the bell direction. The directivity at the 4 and 8 kHz octave bands does not considerably differ from the pattern at 2 kHz.

Normalized directivity is depicted in Figure 23a, where one can notice the similarity to the trumpet directivity. During the recording the playing direction was slightly turned on the left side, which results in biasing of the high frequency radiation on the front left. The radiation remains over −6 dB of the maximum in all directions up to 400 Hz, while most directions are strong until the 630 Hz one-third octave band. At higher frequencies the direction of the radiation is straightforward until the noise floor is reached at above 8000 Hz. In Figure 23b the data is presented without one-third octave normalization, where the radiated spectrum is close to the average of the tones in *forte*. The sound pressure decreases rather rapidly even in the direction of the bell after 630 Hz, suggesting the instrument cutoff frequency.

Of the individual tones, the average of tone A3 is given as an example in Figure 23c. Here the relative sound level differences between harmonic frequencies are visible. The overtones near to 1 kHz have the highest sound pressure level with tones up to C♯4. The fundamental is radiated at the level equal to the overtones only with tone A4.

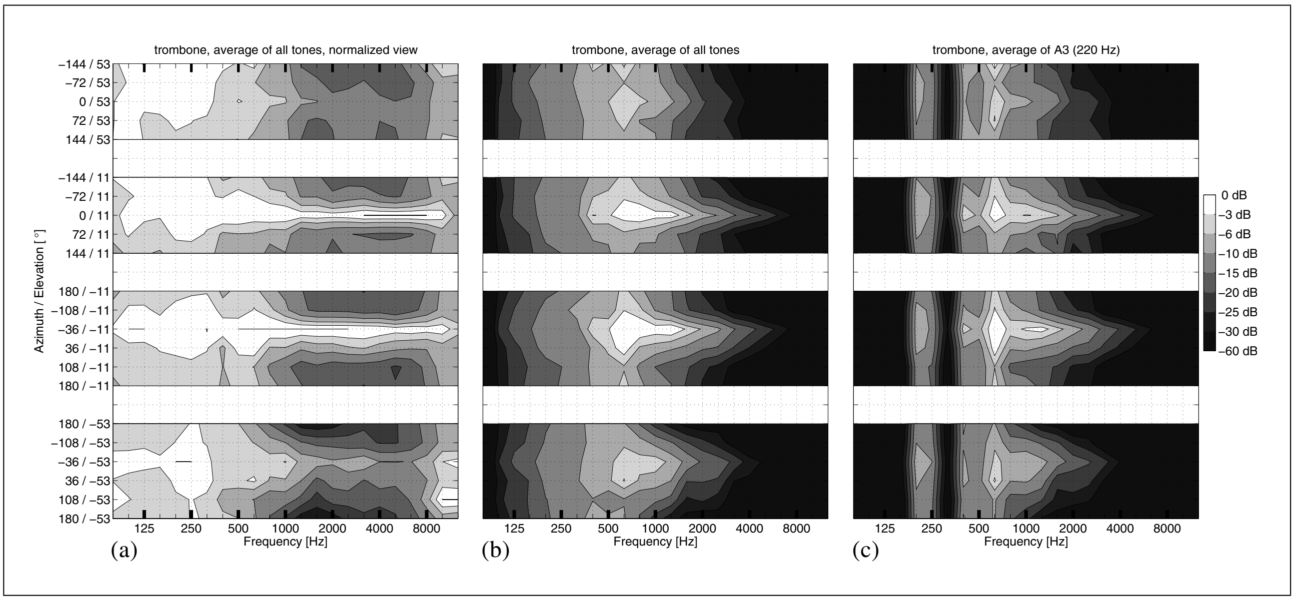

Figure 23. Average sound radiation of the trombone. a: all tones with normalization, b: all tones, c: average of A3.

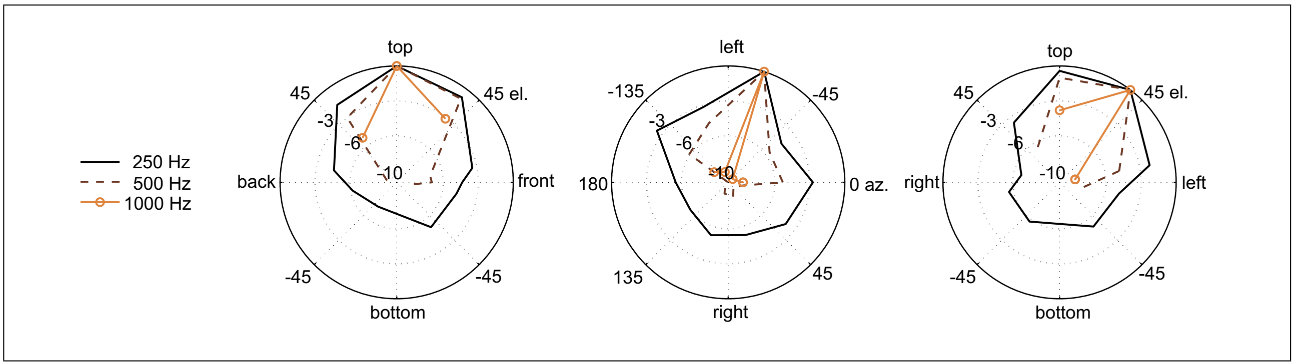

Figure 24. Overall directivity of the tuba in the median, lateral, and transverse planes.

Meyer reports omnidirectional pattern between 0 and −3 dB up to 400 Hz [1]. Similarly to the trumpet, here the corresponding region of the frequency range stays above −6 dB. The angle of the radiation becomes quickly narrower, and a level difference of 18 dB is mentioned between the front and side near 1500 Hz. In Figure 23a the corresponding difference is near to that value, around 16 dB at the 1250 and 1600 Hz bands.

With different dynamics, average slopes above the maximum of the power response were estimated at −15 dB/oct. in *piano* and −11 dB/oct. in *forte*, and −10 dB/oct. in *fortissimo* above 1000 Hz.

5.4. Tuba

The contrabass tuba or simply, tuba, is the largest of the orchestra brass instruments. The name tuba can refer to several similar instruments, but here the instrument used for playing the contrabass tuba parts in orchestral works is discussed. A comparably high conical portion of the tubing is characteristic for the tuba, as the total length of over 5 m is reported to be almost entirely conical [3]. This length refers to the B♭0-tuned tuba, although higher tunings exist as well. The bell diameter is the largest of the brass instruments.

A C1 tuba was used in the measurement, and other instruments with adjacent tunings are assumed to exhibit comparable results. The recorded tones spanned the range A1–A3, which results in the lowest fundamental frequency of 55 Hz. In this case it should be reminded that the used measurement environment does not provide totally anechoic conditions at such low frequencies. Therefore the results below 100 Hz should be considered approximate. With the knowledge on previously discussed brass instruments and the shape of the tuba, the results can be considered self-explanatory. Low frequencies below 250 Hz are radiated somewhat omnidirectionally with up to 6 dB attenuation in the opposite direction from the bell. At higher frequencies the directivity is very strongly concentrated on the axis of the bell. The directivity at significant octave bands is presented in Figure 24. In this case the rightmost plot showing the transverse vertical plane describes the radiation pattern particularly well. The directivity above 1 kHz would be visible only as single points in these plots. A more detailed view on the average tuba radiation is shown in Figure 25. Here the directivity is the most obvious compared to the previous figures. As a reference, the fundamental of the highest recorded tone lies at 220 Hz.

The radiation does not present any considerable change neither with the playing dynamics or the played tones. Due to the fairly smoothly narrowing directivity, a specific cutoff frequency cannot be determined similarly to the other brass instruments. The maximum average sound pressure level suggesting the cutoff frequency was at around 400 Hz. Depending on the playing dynamics, descending slopes for the average sound level at higher frequencies were estimated at −18 dB/oct. in *piano*, −12 dB/oct. in *forte*, and −10 dB/oct. in *fortissimo* above 500 Hz.

The region of omnidirectional radiation above −10 dB is reported to extend up to 400 Hz by Meyer [1]. The 500 Hz plots in Figure 24 suggest similar behavior, although none of the observed planes are positioned in relation to the tuba principal axis. At 1000 Hz the principal radiation region spans an angle of 90 degrees above −10 dB in results by Meyer. Correspondingly a −10 dB difference between adjacent microphones is exceeded here at the 1000 Hz one-third octave band in top elevation (see Figure 25).

5.5. Discussion on brass

In the previous sections, the directivities of the common brass instruments of a symphony orchestra have been presented. The directivity was seen to remain constant, thus not depending on the played tone. In general, the brass instruments exhibit a much more straightforward radiation compared to the woodwinds. This results from the lack of tone holes and from the flared horn with a point source-like radiation.

All brass instruments presented close to omnidirectional radiation at low frequencies, as the bell does not effectively direct the sound at long wavelengths. Compared to the instrument properties discussed by Rossing [3], the observed limits of omnidirectional radiation are noticed to be closely proportional to the inverse of the cited bell diameter.

The spectrum of the brass instrument changes strongly with the dynamics, as playing in *fortissimo* excites a lot more overtones than moderate playing. This was visible with all the recorded brass, while the most noticeable difference in the slope between *piano* and *fortissimo* was 12 dB/oct. with the French horn.

During performance, brass players tend to play sometimes toward the music stand. This has a major impact on the effective directivity, as the high frequencies are efficiently reflected from a solid plate. Although the music stand used in our recordings was of a lightweight type, a comparable phenomenon occurred with the small LCD screen used for following the conductor. This resulted in an unwanted reflection with the trumpet. In addition to regular playing, mutes are sometimes used with brass instruments to change or attenuate the produced tone. While the effect on the directivity can be large, the mutes are not studied in this paper.

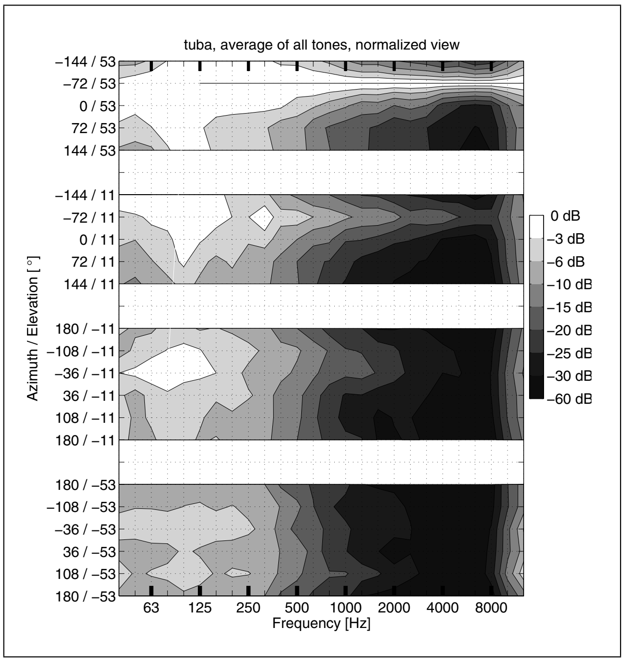

Figure 25. Average sound radiation of the tuba.

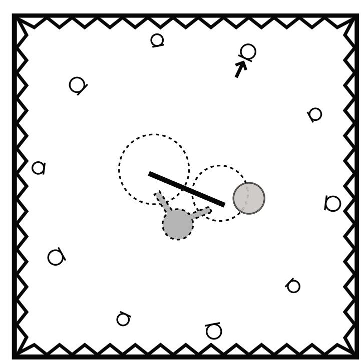

Figure 26. Positions of the timpani, tamtam and bass drum. Dashed circles: the timpani; solid line: plane of the tamtam and the bass drum axis. Gray symbols indicate the percussionist position. The arrow points to the mic no. 6 in the front (see Pätynen *et al.* [15] Figure 3).

6. Percussion instrument directivities

The common percussion instruments are basically vibrating membranes, bars, or tubes excited with a mallet strike. The vibrational modes are determined by the shape and material of the particular instrument. The modal properties of related shapes are studied in detail in the music acoustics literature, e.g. by Fletcher and Rossing [2], Rossing [3] and Rossing *et al.* [32], and recently by Tronchin [33]. Meyer has presented some percussion directivities based on calculations or experiments [1]. However, comprehensive real-world measurements on the percussion directivities are not widely available, which makes comparing the results difficult. In the following sections, investi-

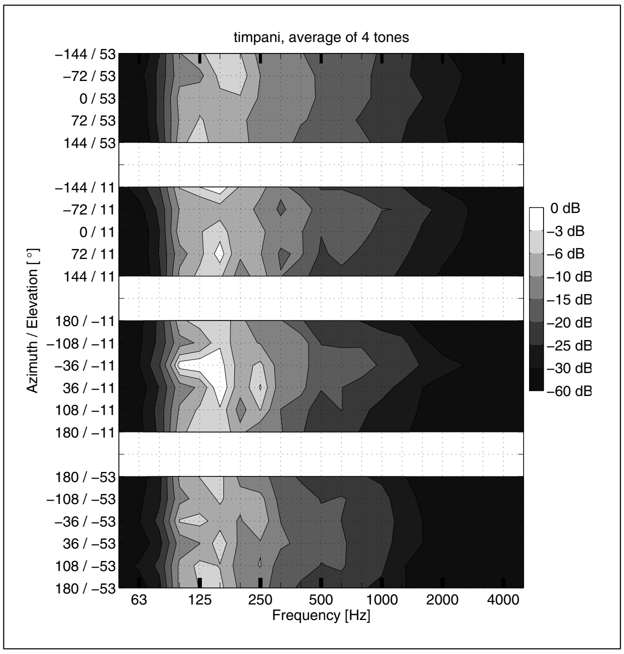

Figure 27. Average sound radiation of two timpani.

gations with various percussion instrument recordings are discussed briefly.

The instruments as well as the player were positioned more freely compared to other instruments in order to accommodate the instruments closer to the room center. The orientation of the large percussions is illustrated in Figure 26 with the player position denoted with gray circles with corresponding line type. It should be reminded that the recordings with large percussions, such as the timpani and the bass drum, are considered approximate due to the near positioning to the microphones. The directivities are shown with the figures without normalization, as the scale of tones is small (timpani) or nonexistent (other percussions).

6.1. Timpani

The timpani are likely the percussion instruments appearing the most frequently in orchestral works. Unlike many other drum-like instruments, the timpani are tuned to a perceivable pitch corresponding with the tones of prominent chords in the key of the composition. Therefore the instrument is used in parallel in larger groups. The tuning is made possible mainly by the radial modes forming a harmonic overtone series. The diameters of the two recorded timpani were 73 and 63 cm.

The directivity was measured by using a passage from Beethoven's Symphony no. 7, I movement, bars 15–18, where tones A2 and E3 are each played twice in different dynamics with an ample pause in between. The average directivity is shown in Figure 27. The overall radiation is divided mainly into the both sides at different elevation levels, which results from the measurement configuration. Tone A2, which was played with the drum on the player's left side, exhibits strong radiation at the 100–150 Hz one-third octave bands in −36 az. / −11 el. degrees directions, while the higher tone E3 on the right radiates to 36 az. / −11 el. and 72 az. / 11 el. degrees directions. In the latter case the two first harmonics are distinguishable at the lower elevation level. Hence, the averaged Figure 27 represents the individual tones fairly well.

Playing with *tremolo* was also studied, but major differences were not found compared to a single tone. The radiation of the fundamental frequency was similar in both cases, and the second harmonic was slightly attenuated in *tremolo* at the two highest elevation levels.

Meyer has cited variations down to −18 dB at the frequency of the first radial mode, while values between −14 ... −18 dB were observed here with individual tones in *forte* at corresponding one-third octave bands. On the other hand, higher variation than the cited 3 dB between radiation regions was found at the first radial mode [1].

6.2. Other percussions

Other recorded percussions, namely bass drum, cymbals, and tamtam are discussed in a single section. All these instruments sound without a definite pitch.

The orchestral bass drum with two drumheads was positioned in the middle of the recording chamber in a rack so that the axis of the rack was perpendicular to the front direction (see Figure 26). In addition, the drum was tilted in 45 degrees angle, similarly as the instrument is often found during performances. Thus, the normal of the upper drumhead was pointing nearest to the 72 degrees azimuth angle at the top elevation level. The diameter and depth of the drum were 92 cm and 40 cm, respectively. The directivity is investigated with nine separate drum hits in our recording of the bars 1–85 from the fourth movement of Mahler's first symphony.

Most of the sound energy produced by the bass drum was recorded at frequencies below 100 Hz. The averaged directivity over nine hits is presented in Figure 28a. The most prominent regions of the sound radiation are located on the lower left side near the axis of the lower, resonating drumhead. However, radiation in the above direction on the same axis is not nearly as strong. Hence, such a large sound source radiates sound with unexpectedly narrow characteristics. The difference between individual tones was not large, although stronger hits were seen to produce more distinguishable peaks at the mode frequencies.

The cymbal directivity was measured by striking two 48 cm diameter cymbal plates together at the chest level of the standing player, and the strike occurred close to the intended center of the room. Similarly to the bass drum, cymbal hits from the Mahler recording were investigated. Seven cymbal hits with the described playing style were recorded, and one crescendo played with a suspended cymbal and mallets was disregarded in this context. Four hits were allowed to decay freely, while three were damped. Two of the damped hits sounded only for 0.5 s. In the longer sounding hits the movement of the cymbals is often an essential part of the playing technique. In our recording the movement was only moderate.

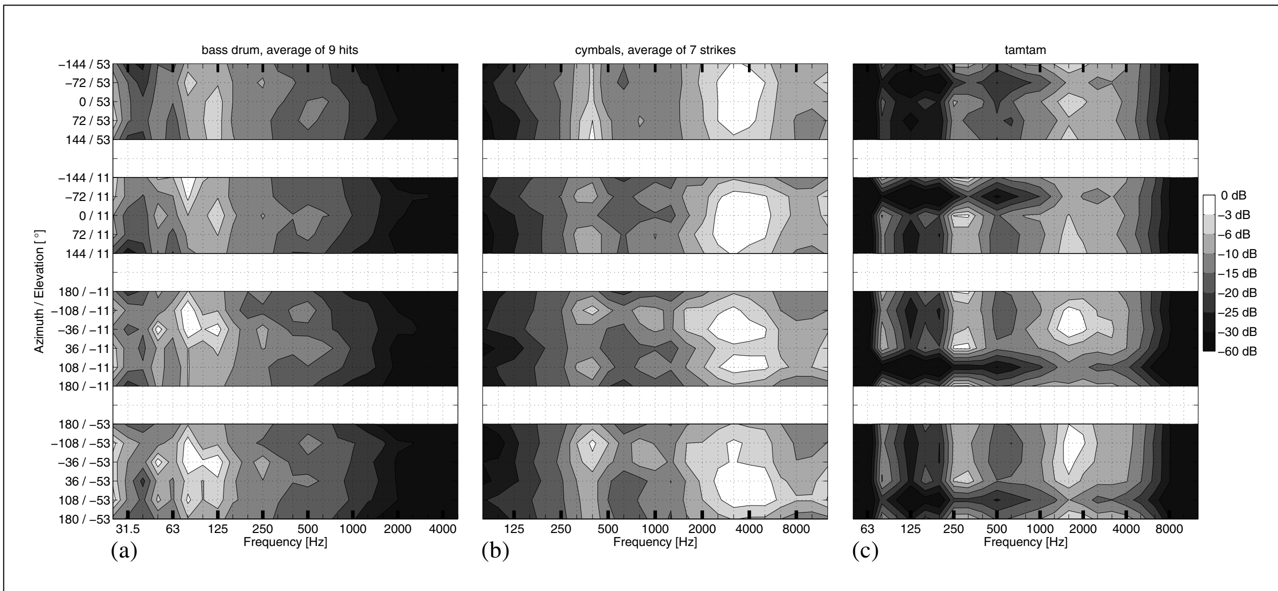

Figure 28. Average sound radiation of percussion instruments. a: Bass drum, b: Cymbals, c: Tamtam.

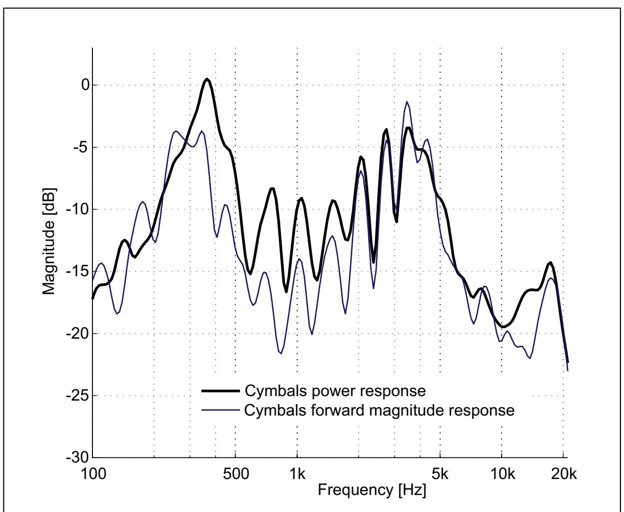

Figure 29. Front and average magnitude responses of the strongest cymbal hit.

The average of all seven hits is depicted in Figure 28b, where the directivity is concentrated in the front region at the most prominent frequency range of 2–8 kHz. Around 400 Hz the radiation is split on the both sides of the player. This is visible due to the more rapid attenuation of the specific frequencies in the weaker directions. In addition, the playing technique in the undamped cases included rotating the cymbals to face to the front, as seen in orchestra performances. The sound energy in the front direction is increased above the highest analyzed one-third octave band at 17 kHz. A similar emphasis is visible also in the response averaged over all directions. This can be seen with the strongest cymbal hit magnitude response (see Figure 29), which represents well the average of all hits. The directivity is not seen to change considerably depending on the duration of the ringing. The most noticeable difference is found at the 3–4 kHz, where the directivity is not as contiguous as with longer sounding hits. This results from the moved cymbals during longer ringing.

The tamtam is a large, round metal plate suspended from a supporting frame, and it is played by striking with a soft mallet. Tamtams differ from gongs by not having a bulge in the center and being thinner. Unlike gongs, the tamtam does not have a perceivable pitch, and the timbre develops slowly to brighter when struck hard enough. The tamtam with 66 cm diameter was positioned facing to the front direction with the player on the right side (see Figure 26). The radiation was analyzed from the first 6 s period of a strong, undamped strike. In this time the sound pressure level in the front direction was attenuated approximately 20 dB. The result is shown in Figure 28c. The rather unusual radiation pattern has maxima in the front and left areas depending on the elevation, but also two minima on the upper and lower elevation levels. This results from the relative positions of the microphones around the instrument, where the microphones nearest to the plane of the tamtam have received the least sound pressure.

7. Vocal directivity

The system for recording anechoic symphonic music was used to record also a soprano aria. Soprano passages were analyzed using the same methods as the orchestral instruments. However, tones of A major chord were not studied. Instead, four consecutive excerpts were investigated from the beginning of Mozart's aria of Donna Elvira from the opera Don Giovanni [15]. Since sung vowels have different formants, a set of short passages were seen to represent better the average of soprano spectra. The downside with this choice is that the results are not directly comparable with the presented orchestra instruments.

Related research on the human voice directivity is found from several authors using artificial or real sources [34, 35,

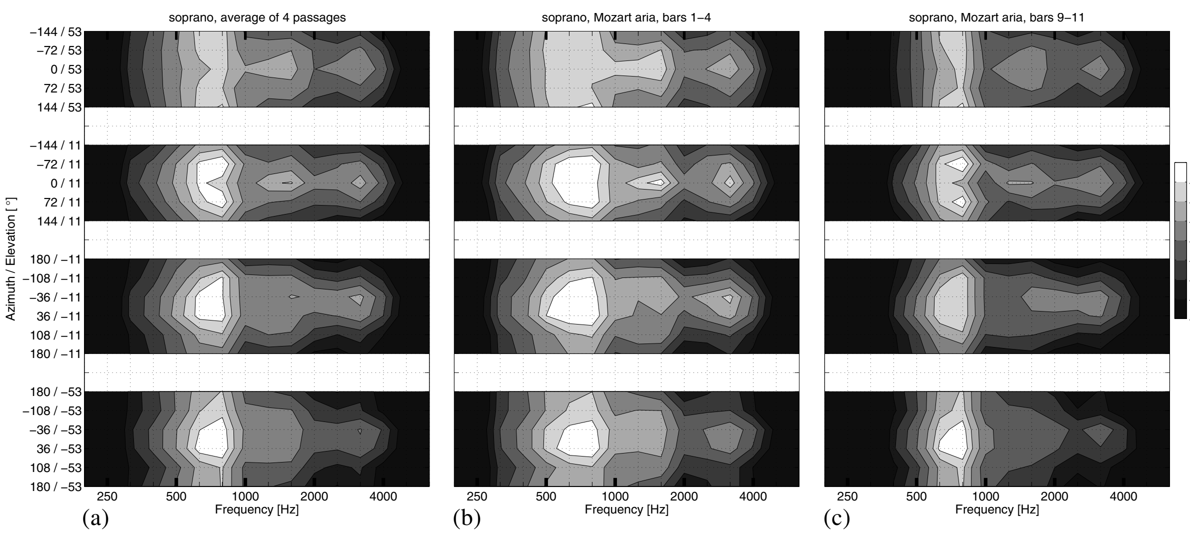

Figure 30. Measured radiation patterns of a soprano singer. a: average of four passages, b: bars 1–4 (first passage), c: bars 9–11 (third passage).

36], while comparable analysis method using long-term spectrum has been utilized by Cabrera *et al.* [37]. The head position of the standing singer was 30 cm above the center of the room. The change in the distances to the microphones causes at most 1 dB errors in the sound pressure levels according to the $1/r$-law.

The first 15 measures of the aria was divided into four passages containing bars 1–4, 5–8, 9–11 and 12–15. The tones in each passage were between B♭4–G5 extending down to F4 in bar no. 3 and up to A♭5 in bars 9, 12 and 13. Hence, the fundamental frequencies are most prominently between 470–780 Hz. The averaged radiation from the four passages is presented in Figure 30a. Directivity at the fundamental frequencies is concentrated in the front hemispehere in the elevations directly in front or below the head. This can be noticed even more so from the first passage depicted in Figure 30b, where range of tones was wide and contiguous from F4 to G5. The emphasis around 1600 Hz results from the strong formants at certain vowel, in this case with the word *'quell'*, appearing twice. The other peak at 3150 Hz one-third octave band can be also seen to be a higher formant for the sounding vowel. Formant frequencies for the corresponding vowel with woman singers has been reported in the literature at 1750 and 3250 Hz, respectively [3].

A representation of the third passage is shown in Figure 30c. Although the range of tones is comparable to the other passages, the formants above 1 kHz are much less noticeable. The region of 800 – 1000 Hz has a divided directivity on the sides, while less energy is received directly in the front area. A similar phenomenon is also seen in the second passage where the directivity is not entirely contiguous in the front direction.

The long-time average responses of the first 15 bars of the aria are shown in Figure 31. The change of the directivity at higher frequencies and formants is visible as an

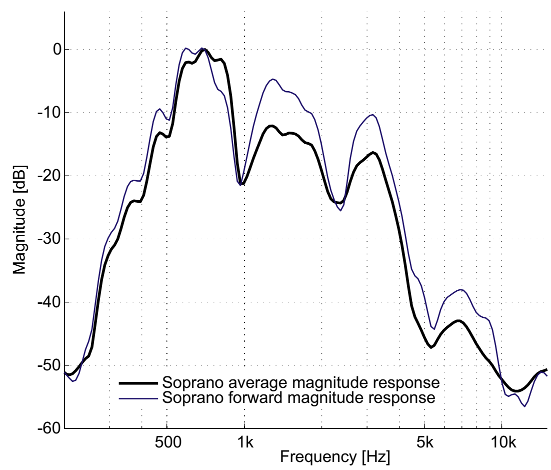

Figure 31. Front and average magnitude responses of the soprano.

increased difference between the front and average directions. Again, the average sound pressure level near 800 Hz is higher than in the front of the singer.

The attenuation of the front direction between 800 – 1000 Hz seen Figure 30c has also been reported by Katz and d'Alessandro especially with vowel /o/ [34]. Kob and Jers have obtained partially similar results at this frequency range. Particularly at 800 Hz both sides receive stronger radiation than the front direction with female singer and vowel /a/ [36]. Cabrera *et al.* have also attained comparable results indicating attenuated front direction around 650 – 1000 Hz [37]. In this case our results indicate a difference of approximately 5 dB between the front and ±72 degree angles in the 11 degree elevation. Measurements by Marshall and Meyer indicate a decrease of sound pressure of comparable magnitude in the front of the singer in relation to the both sides. However, this phenomenon is found at higher frequencies around 2 kHz [38].

8. String instrument directivities

The bowed string instruments form the most substantial part of the complement of a contemporary symphony orchestra. Large orchestras may have more strings than the woodwinds and brass players together. Additionally, string players are positioned to the foreground of the stage with the least acoustical obstructions.

The sound of the bowed string instruments is generated by a complex mechanism. The moving bow causes a triangular displacement to the string with an alternating action of slipping and sliding. The string vibration alone does not contribute much to the radiated sound. The excited vibration is coupled to the body of the instrument with the bridge. The top and back plates of the instrument work as vibrating plates having their own set of modal frequencies that change between individual instruments. In addition to the side walls, or *ribs*, the instrument plates are connected by the sound post, which provides support under the bridge. Moreover, the bass bar strengthens the top plate in order to withstand the tension of the strings. [2, 3, 39, 40]

The sound radiation from the string instruments differs greatly from the previously discussed instruments due to the absence of particular shape directing the sound as in wind instruments, such as the clarinet or the trumpet. Directivity studies on the violin have been presented thoroughly by Cremer [39]. Monopole and dipole characteristics as well as the varying radiation in two directions with regard to the excited frequency have been studied by Weinreich [41, 42]. Meyer has published directivities more related to performance situation [1].

8.1. Violin

The four strings of the violin are commonly tuned with intervals of perfect fifths, beginning from G3 (approximately 196 Hz). Tones around A7 can be played ordinarily, and even higher tones are playable through harmonics.

Studies in the literature have shown that the violin body has three principal types of different vibrational modes. The modes are often referred as A (air or f-hole modes), T (top plate) and C (body, or *corpus*). The A_0 and T_1 modes have been reported to cause considerable air motion in and out from the violin body through the f-holes in the top plate and introduce noticeable sound radiation [43, 44, 45]. These modes are in relation to the motion of the top plate. The C modes express the motion of the violin body where both plates have similar vibration characteristics [46]. The f-hole mode is mentioned to be occurring consistently at 260–300 Hz in studies consisting of multiple violins [3]. This mode is also known to form a major part of the low frequency spectrum of the violin with the T_1 mode occurring around 460 Hz [47]. These modes are usually within

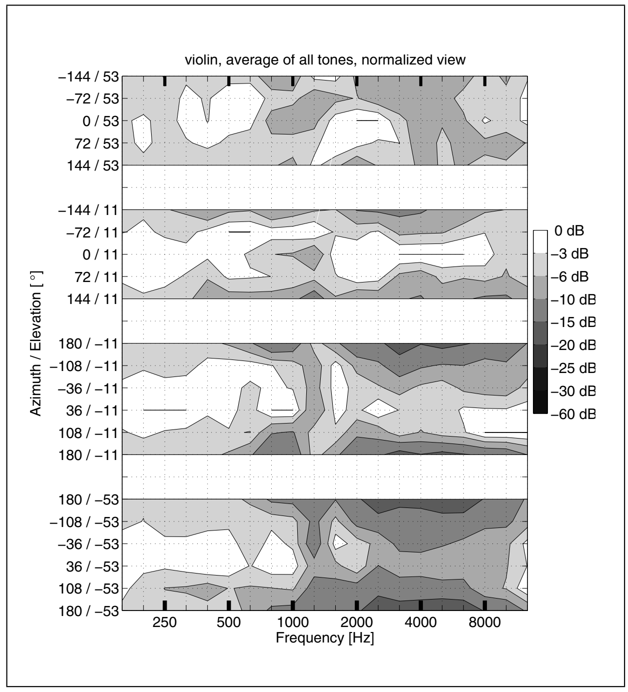

Figure 32. Violin sound radiation averaged from all measured tones.

a half semitone from the frequencies of freely vibrating D and A strings. While the lowest body modes C_1 and C_2 at approximately 185 and 405 Hz are not reported to have considerable effect on the sound radiation, modes C_3 and C_4 produce noticeable resonance peaks around 530 and 700 Hz, respectively [43]. Above 1 kHz the density of individual modes is high. Strong resonances of the bridge have been measured at 3 and 6 kHz, of which the former occurs at a dense peak of the body resonances [2].

Since the tones above the pitch of an open string can be played on lower strings, there are numerous possibilities to play a single tone. The measured tones A3–A5 were played in the first position, using G, D, A, and E strings for tones A3–C♯4, E4, A4–E5, and A5, respectively. The four strings have varying vibrational characteristics due to their different mass and structure, but the authors are not familiar with studies on the exact effect of the differences between played strings - besides the obvious change in the overall timbre.

It is important to notice in the following that the direction of the zero degree azimuth is positioned in the front of the player. Hence, the neck of the instrument points in the direction between 0 and -72 degrees azimuth. In general, there is some variation in the playing position between players, and practically all violinists are assumed to move more or less while playing in a performance. In the directivity measurements the violinist was instructed to stay as still as possible.

The average sound radiation of the violin is presented in Figure 32. The overall directivity below 500 Hz is rather omnidirectional, while at 2–6.3 kHz the sound is radiated in the front direction. Sound pressure level at that frequency range is considerably lower in bottom elevations.

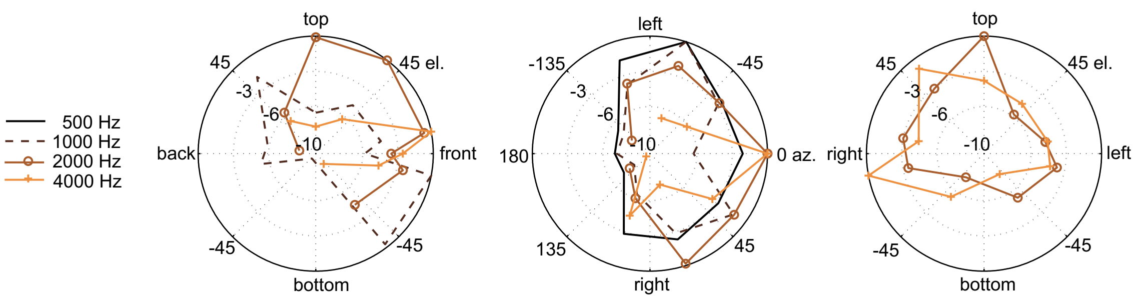

Figure 33. Overall directivity of the violin in the median, lateral, and transverse planes.

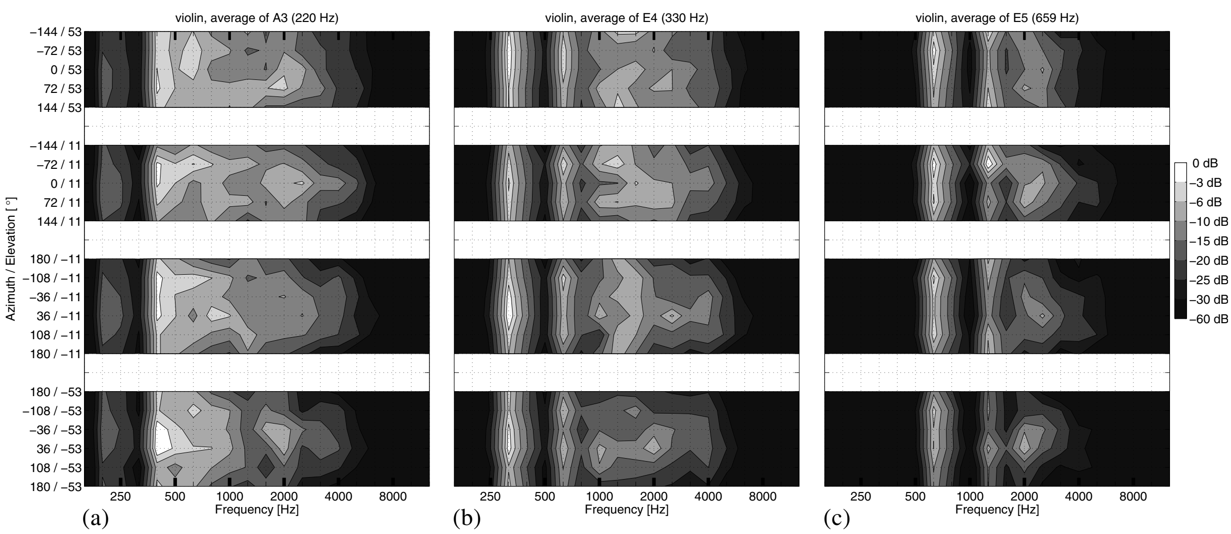

Figure 34. Average sound radiation on selected violin tones. a: *A3*, b: *E4*, c: *E5*.

On the other hand, radiation to the top elevation level is more evenly distributed, as the normalized sound level remains above −10 dB of the maximum. A substantial fluctuation in the radiation pattern is seen around the 1250 Hz one-third octave band. This results from a strong local radiation on the left of the player. A direct explanation for this is not found, as the major modes are commonly located at much lower frequencies.

The polar representation of the average violin directivity is shown in Figure 33. At the 500 Hz octave band the sound is radiated in the lateral half plane. The octave bands above 1000 Hz show irregular radiation patterns. In the leftmost plot the directivity maxima are diagonally in the low front and above-back of the player at 1 kHz. The lateral plane shows divided radiation into the both sides of the player. At the 2 kHz octave band sound radiates to the front above region. Seen from the left side, the 4 kHz octave band shows highly concentrated forward directivity, and only the front direction is within −3 dB of the maximum. Although not shown in the plots, the 8 kHz octave band is fairly similar to the 4 kHz band.

The average directivities of three selected tones are presented in Figures 34a–34c. By first comparing Figures 34b and 34c, one can notice that the violin radiation presents similar behavior as observed previously with woodwinds, e.g. the flute and the oboe. With tone E4 the directivity of even harmonics is comparable to the first harmonics of E5. Such a quality is noticed at all applicable octave pairs, although at C♯4–C♯5 this is visible only with the two lowest harmonics. This property is not entirely restricted to the octave intervals. Similarities can be found in the location of the magnitude peaks between A3–E4 and A3–E5 at 630, 1250, and 2000 Hz in Figure 34a. This observation is in relation to the effect of directional tone color, as the radiation remains constant with regard to the frequency [42].

The violin playing dynamics has very little effect on the directivity. Only small differences can be seen in between average of all tones in *piano* and *forte*. Of single tones, the difference between dynamics is the most visible at A4 (see Figures 35a and 35b), which was recorded on freely sounding A string. The harmonics of high order are emphasized in the spectrum in *forte*. Obviously, the directions of the radiation peaks do not change. The average spatial spectrum shown in Figure 35c represents accurately also the average radiated sound in *forte*.

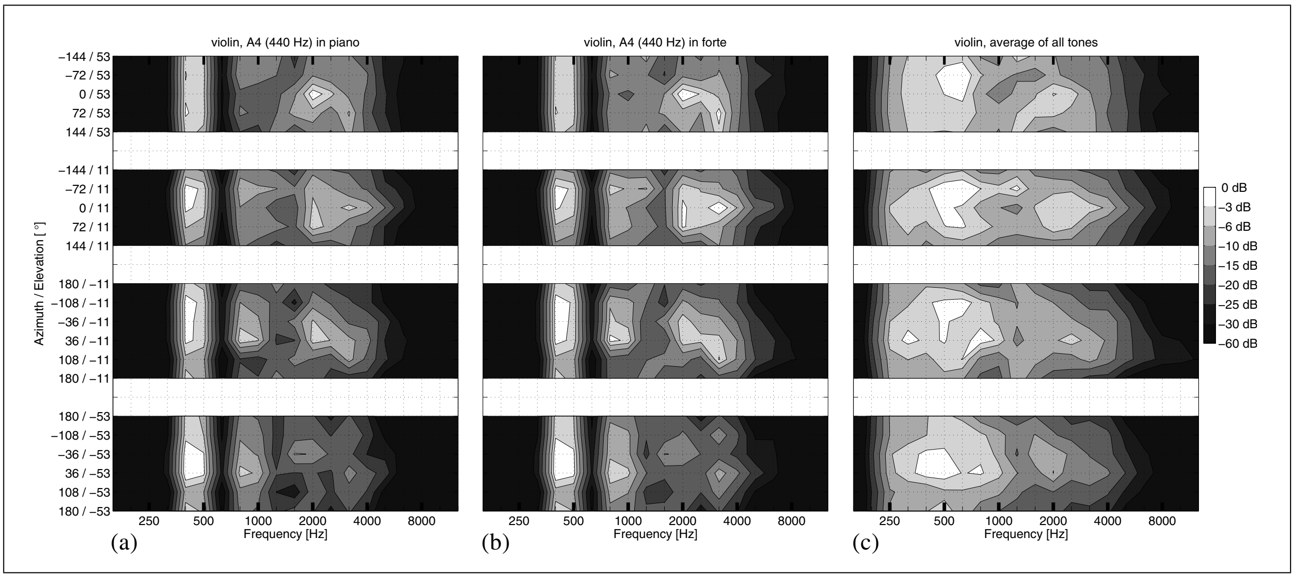

Figure 35. Violin sound radiation at different dynamics. tones. a: A4 in *piano*, b: A4 in *forte*, c: All tones.

Meyer has stated the violin to be omnidirectional up to 600 Hz within −10 dB, and above that the sides and the back are attenuated gradually [1]. Also a divided radiation to both sides is mentioned at 550–700 Hz. Around 1000–1500 Hz and 4000–4500 Hz strong concentrations occur in the front region, while at 2000 Hz more distributed behavior is reported. Some similarities to these values can be noticed here: the radiation is above −10 dB until the 630 Hz octave band, and at 800 Hz signs of divided pattern are present in middle elevations. Concentrated directivity is observed at 1250 Hz in the lateral plane but more on the left side compared to the representation by Meyer.

After Meyer, Cremer has cited studies where two major lobes appear in the plane of the violin bridge near 2300 and 3100 Hz [39]. Weinreich has reported of monopole radiation below the air mode (circa 280 Hz) at which frequency the violin radiates as a dipole [41]. However, references of such effects were not found here with the one-third octave analysis.

8.2. Viola

The authors are aware of only a little research on the viola compared to the violin, despite the structure of the viola being close to the violin. In general, the effective phenomena are same in both instruments. The larger size is the most obvious difference. The size varies between individual instruments, but generally violas are approximately 5 cm longer than violins. Fletcher and Rossing [2] have stated the viola has 15% greater dimensions compared to the violins. The strings of the viola are tuned a perfect fifth lower, thus at approximately one third lower frequencies than those of the violin. Resonances are not shifted proportionally to the tuning, and the principal resonances are 20–40% lower than with the violin. Perhaps most prominently, the main air resonance is positioned less than one-third lower. This results in a frequency above the second lowest string and far from the lowest playable tones. As a result, the sound of the viola has its distinctive, somewhat hollow timbre [3].

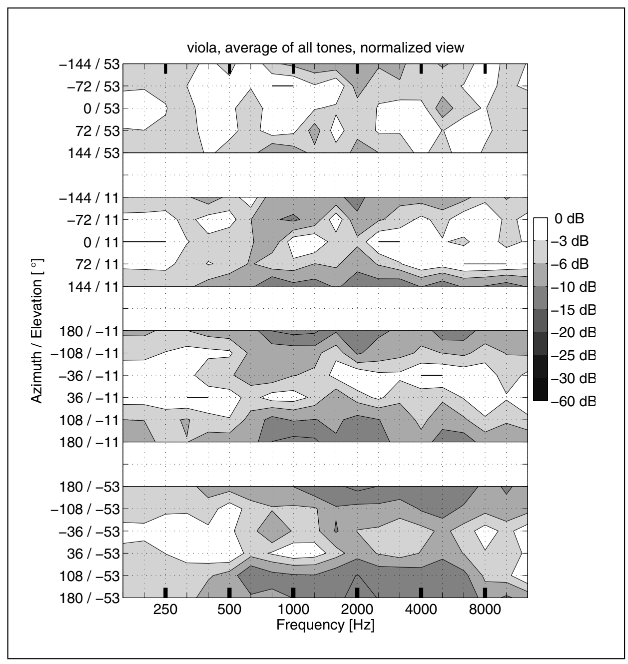

Figure 36. Average sound radiation of the viola.

The sound radiation of the viola is investigated with the same tones as the violin, which enables us to have an analysis of a more comparative nature. The overall directivity of all recorded tones with the one-third octave band normalization is presented in Figure 36. The impression on the forward directing radiation is similar to Figure 32. Two boundaries in the directivity can be noticed with the viola, similarly to the 1000–1250 Hz region in the violin directivity. With the viola the lower boundary at 630 Hz is located considerably lower. Below this frequency band the radiation is evenly distributed in most directions. At

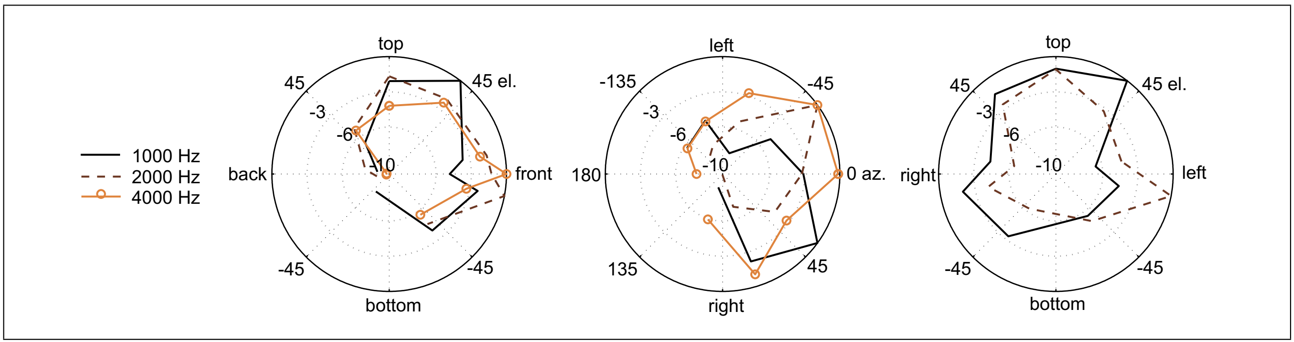

Figure 37. Overall directivity of the viola in the median, lateral, and transverse planes.

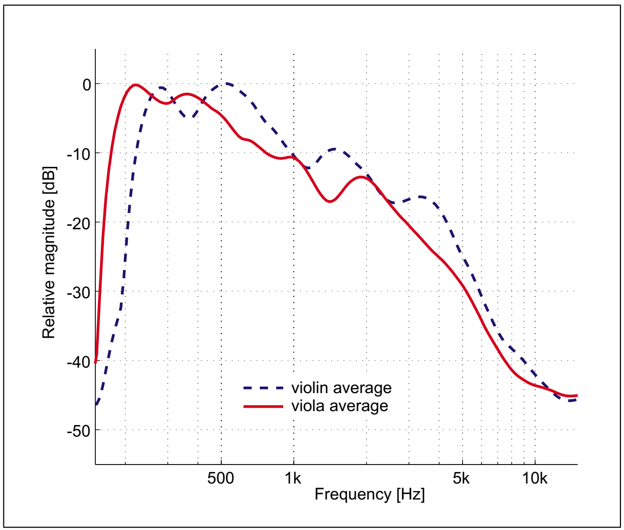

Figure 38. Long-term spectrum of the measured tones on the viola and the violin averaged in all directions. The curves are octave smoothed.

higher frequencies the directivity is more concentrated at the front. The region between the 500 and 800 Hz one-third octave bands presents strong variations in the directivity also with individual tones. In addition, a second, although not as prominent fluctuation in the sound radiation is present around 2 kHz where the radiation is concentrated in the direction of $-36/-11$ (az./el.) degrees. Above 2 kHz the directivity remains constant.

The viola directivity is depicted in three planes in Figure 37. In overall the viola exhibits less directivity than the violin. The plotted octave bands in the median plane show a pattern resembling to the violin at 2 kHz. In the lateral plane the 1 and 2 kHz octave bands have pronounced directivity in the front-right and front-left directions, respectively. Overall directivity in the transverse vertical plane shares a similar shape with the violin.

The relative differences in the average radiated sound between the viola and the violin is seen in Figure 38, where the long-term magnitude responses averaged over signals from the dodecahedron microphones (nos. 1–20) are shown for both instruments. Both curves have similar shapes, while the peaks of the viola power response lie at lower frequencies. By comparing the frequencies of the peaks, we can approximate differences in the resonances of the recorded instruments, since the same tones were recorded. Four peaks can be noticed in the violin power response at approximately 290, 530, 1500, and 3350 Hz whereas for the viola the third peak is somewhat absent. The peaks with the viola are located 23, 31, 35, and 44 percent lower than with the violin, respectively. Similar calculation for the two noticeable notches results in 18 and 47% lower frequencies. These results are in line with values of 20–40% lower resonances reported by Fletcher and Rossing [2]. The results correspond also with a previously published value for the declining slope of the overall sound radiation at higher frequencies. For bowed violins, a slope of approximately -15 dB/octave has been cited for frequencies above 3 kHz [2]. In Figure 38 both the violin and the viola responses follow roughly such a slope.

The directivity with individual tones appear to alternate strongly. By observing the radiation at specific one-third octave bands with different tones, the same phenomenon of similarly radiated harmonics is noticed as with the violin.

Examples of the similar directivities are given in Figure 39. First we observe the region of the third and fourth harmonics with tone C♯4 and the third harmonic of E4 in Figures 39a and 39b. The magnitude peaks at the 1 kHz one-third octave band appear in the same positions with both tones. The higher harmonics around 2 kHz share also a small resemblance. On the other hand, notably the second harmonic of E4 is radiated differently from the C♯4, as they fall into adjacent analyzed one-third octave bands.

With the tone pair E4–E5 in Figures 39b–39c the effect is seen better with the second and the first harmonics, respectively. The fundamental of E5 produces very similar pattern as the second harmonic of E4 at the 630 Hz one-third octave band. One can similarly observe the peaks around 2 kHz. Although the fourth harmonic of E4 is not clearly visible, corresponding one-third octave band with the second harmonic of E5 has also somewhat similar pattern.

The same relation in the radiation of the harmonics is present with other recorded tone pairs having discernible peaks. The effect is the strongest with tones one octave apart. Tones C♯4 and C♯5 make an exception with the second and first harmonics, as the radiation at the two highest

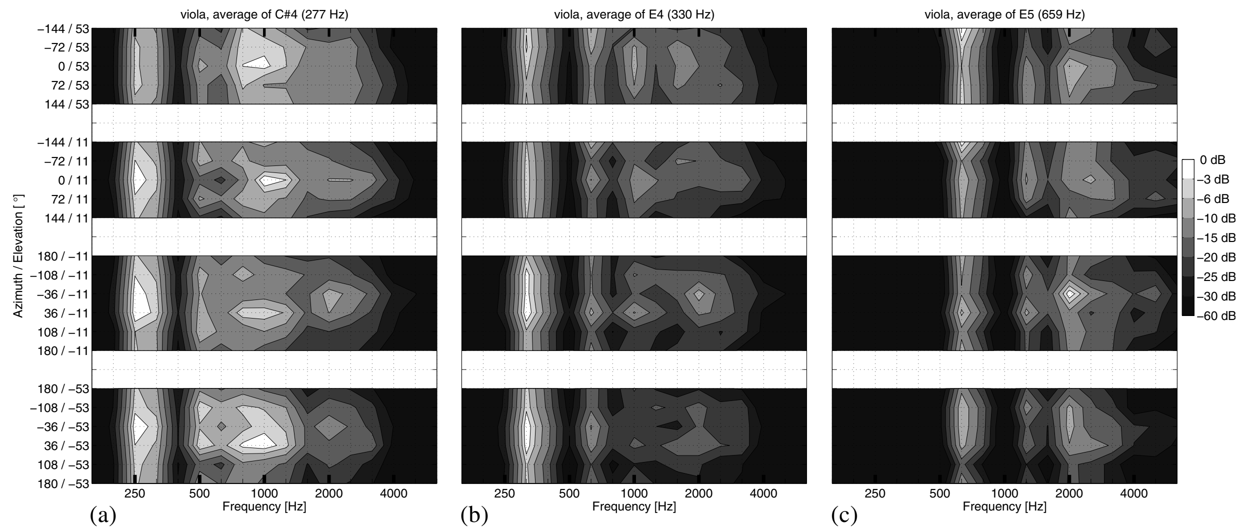

Figure 39. Average viola sound radiation on different tones. a: *C♯4*, b: E4, c: E5.

elevations are different. On the other hand, higher harmonics have corresponding directivities.

The viola directivity does not change much with different playing dynamics. The overall spectrum of measured tones in all directions remains unchanged near 1000 Hz. With increased dynamics the regions around peaks are more pronounced but the locations of the peaks remain unchanged.

Compared to the findings on the viola by Meyer, the most prominent resemblance here is the behavior near 600 Hz. Meyer has stated a strongly concentrated radiation in the direction of the instrument back plate in the horizontal plane with all instruments. The same phenomenon can be observed at far left of the player in Figure 36 at middle elevations. As shown also by Meyer, lower frequencies are noticed to be mostly omnidirectional.

8.3. Violoncello

The violoncello, or cello, is the second largest of the ordinary bowed string instruments. Due to the differences in individual instruments, exact size measures cannot be given. The scale of the other cello dimensions apart from the rib height is approximately double of that of the violin. The ribs are roughly four times higher than in the violin [2].

Similarly to the viola, research on the cello acoustics is scarcely found. Measurements on both the cello and the contrabass can be found in some studies. Besides Fletcher and Rossing [3], Askenfelt [48] and Brown [49] have presented input admittance and resonance measurements on different celli and basses.

The strings of the cello are an octave lower than with the viola. The principal air mode A_0 has been cited to be found near 104 Hz, near the second lowest open string [48]. Overall frequencies of the other modes are reported to be approximately 40% of the corresponding violin modes, which renders the modes slightly higher with regard to the string tuning than with the violin [2]. Studies on the cello directivity in performance have been published by Meyer [1].

In the recording calibration an assumption was originally made that the acoustical center of the instrument is positioned near the musicians's head, which again is at the center of the measurement chamber. The acoustical center of the cello cannot be accurately defined in practice, and the contact point of the bow to the strings was approximately 0.4 m lower and 0.2 m in front of the intended head position. Unless stated otherwise, all following figures have been compensated by estimating the error in the sound pressure levels in each microphone according to $1/r$-law. Calculated with values in Table I, the compensation produces largest change in microphone no. 20, where the sound pressure level is reduced by 1.9 dB. For reference, Pollow *et al.* have utilized phase information for correcting the source displacement in directivity measurements. While suitable for point-like sources, this approach is not directly applicable for volumetric sources that exhibit phase differences.

The average directivity of the cello is presented in Figure 40 in three planes. In the median plane the 500 Hz octave band radiates strongly to the front, while at higher octave bands the radiation corresponds more with the length axis of the instrument. This effect is noticed particularly in the rightmost plot, where only the 2 kHz octave band has a non-uniform pattern. While the 500 Hz and 1000 Hz octave bands exhibit higher variation in the lateral plane, at 2 kHz the radiation is even in the front half-plane. Octave bands below 500 Hz are nearly omnidirectional in all planes, and the attenuation at the back of the player is noticeable above 500 Hz.

The overall directivity of the cello with normalized one-third octave bands is shown in Figure 41. In Figures 41a and 41b the difference between the directivity results with

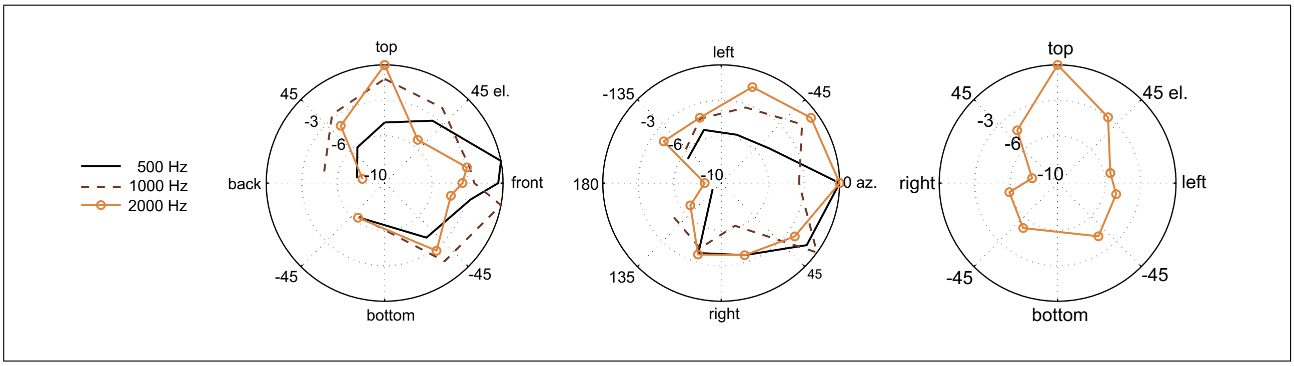

Figure 40. Overall directivity of the cello in the median, lateral, and transverse planes.

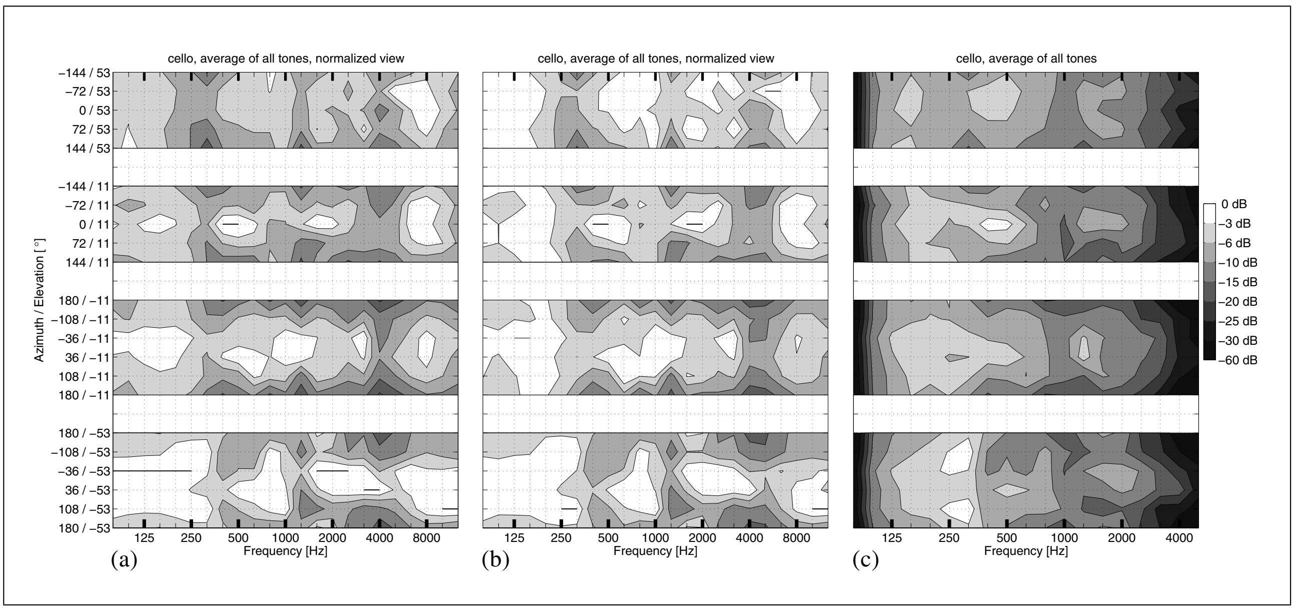

Figure 41. Average sound radiation of the cello. a: without compensation, b: with compensation, c: with compensation, without normalizing.

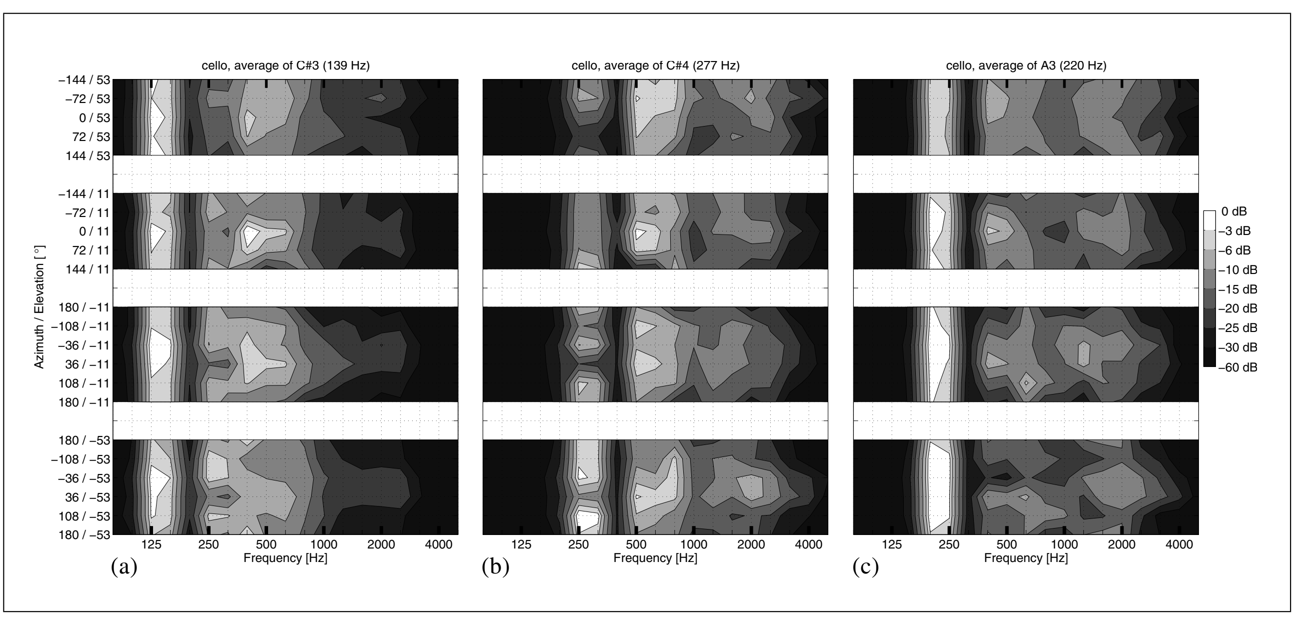

Figure 42. Average sound radiation of the cello on selected tones. a: *C♯3*, b: *C♯4*, c: *A3*.

uncompensated and compensated center point is shown. The compensation reduces the level of the low elevation directions.

Characteristic to the violin and the viola, the overall directivity of the cello has two noticeable frequency bands of pronounced radiation. First, below 300 Hz the sound pressure level is above −6 dB in all directions. At the 315 Hz one-third octave band most of the sound is directed to the both sides at the bottom elevation. Second, at the 1250 Hz one-third octave band the sound radiation is concentrated to the front region at the −11 degree elevation level (see Figure 41c).

The radiation characteristics of the harmonics are investigated similarly as with the violin and the viola. References to similar behavior were found with individual cello tones as well, although not quite as distinctly. An example of the similarity of the directivity at harmonics is shown in Figures 42a and 42b. With the exception of the left hand side at the 11 degrees elevation, the regions of the radiation peaks and minima are corresponding at the 250 Hz one-third octave band. The areas of the most prominent directions, particularly the peak at the center of the 11 degrees elevation, can be perceived also at the 500 Hz band despite the harmonics being densely located. The most substantial peaks with tone A3 in Figure 42c are also located at the strong regions of tone C♯4. Some individual tones were also found to have particularly corresponding radiation patterns. The first common harmonics with tones A3 and A4 have radiation patterns very much alike. Moreover, the bottom elevation maxima at the 315 Hz one-third octave band visible in Figure 41c are very noticeable with both the tones A2 (third harmonic) and E3 (fundamental).

With different dynamics the overall directivity does not present any considerable change. Above 1 kHz more sound is radiated in the top-left direction and the sound pressure levels above 2 kHz are generally increased with higher dynamics.

Meyer has reported omnidirectional radiation below 200 Hz, which is lower than observed here [1]. The radiation from pronounced plate resonances around 250–300 Hz described by Meyer can be noticed in Figure 41c, where the radiation is concentrated to both sides at 250–315 Hz especially in the bottom elevation. Also the concentrated directivity in the front at 500 Hz and 2000 Hz is visible in Figures 41b and 41c. The front-back ratio is cited to first exceed 10 dB at around 500 Hz, which corresponds roughly to the 400–500 Hz observed here.

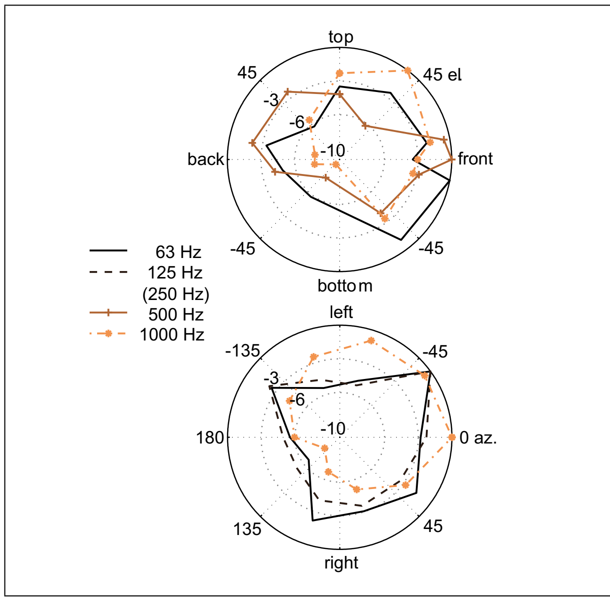

Figure 43. Overall directivity of the contrabass in the median and lateral planes.

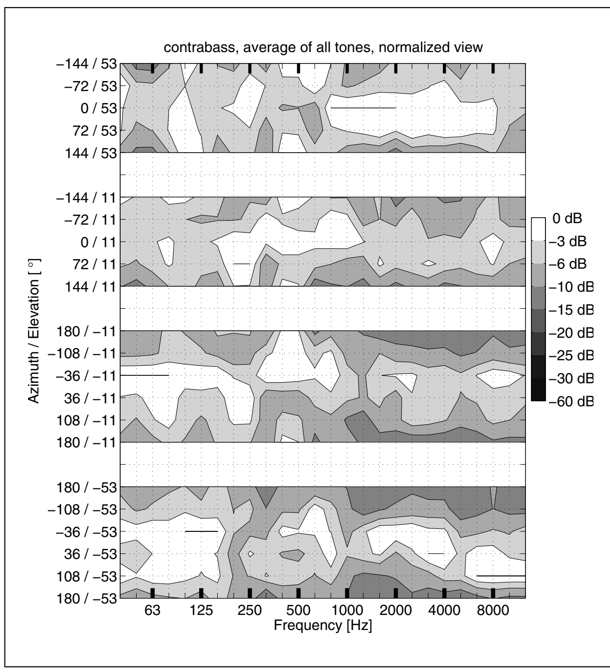

Figure 44. Average radiation of the contrabass with one-third octave normalization.

8.4. Contrabass

The largest of the common bowed strings, contrabass, or double bass, differs from the rest of the string family with its flat back and carved shoulders. The four strings are commonly tuned in perfect fourths instead of fifths from E1 up to G2, although configurations having more strings are possible but rarer.

As with the cello, only limited research specifically on the contrabass is published. A comprehensive analysis of the vibrational modes with a comparison to the cello has been reported by Askenfelt [48]. An extensive study of the contrabass sound regarding the structural properties of the back plate has been more recently carried out by Brown [49]. The instrument used in our studies featured a flat back plate. Compared to the cello, Askenfelt has noticed prominent similarities between the body vibration modes on the two instruments. A_0 resonance frequency of quality contrabasses has been found around 60 Hz, while the first top plate resonance T_1 can be found approximately at 100 Hz [48]. These values suggest a relative resonance placement of 60% of the corresponding cello resonances.

A major chord tones A1-A3 were recorded with the contrabass. Due to the limited anechoic conditions, the results on frequencies below 100 Hz are considered approximate. Additionally, the size of the instrument caused problems with the consistent instrument positioning during the recordings as discussed earlier with the cello. The contact point of the bow to the strings was approximately 0.5 m below and 0.2 m in front of the center of the chamber. The sound pressure levels are compensated due to the changed distance to the microphones. The largest compensation is an attenuation of 2.3 dB in the direction of 36 degrees azimuth in the bottom elevation.

The averaged contrabass directivity with compensated levels is shown in Figure 43. The most notable is the even radiation in the transverse vertical plane, therefore only the two leftmost plots are presented. Also the 250 Hz octave band exhibits small variation, thus it is not shown. The sound radiation in the median plane at the 63 Hz octave band is the strongest in front below direction. The above-front direction presents the most noticeable changes depending on the inspected frequency band. The 500 Hz octave band has a pattern slightly resembling a figure-of-eight in both front and back.

In the lateral plane the radiation is slightly biased on the front-left. Otherwise the radiation shows less variation than with other string instruments. A strong similarity to the cello directivity can be observed here. With the cello a cardioid-shaped pattern was noticed at 2 kHz (see Figure 40). One octave lower, the contrabass shows similar cardioid pattern.

The one-third octave band directivity in the forward direction can be characterized in three regions in Figure 44. First, below 200 Hz the sound pressure level is the highest in the lowest elevation levels. Second, the 11 degrees elevation is dominant between 200–750 Hz. Third, the front-above direction is the strongest above 750 Hz. In addition, the back side of the instrument shows considerable sound levels around 500 Hz.

The directivity at harmonic frequencies that are common between two tones are found to be similar. The overtones of the recorded contrabass tones were relatively weak compared to other string instruments. Therefore only the couple first harmonics could be compared. The peaks in the average directivity in Figure 45 represent well the strongest regions with individual recorded tones.

The effect of different dynamics is small, and the sound radiation at frequencies below 250 Hz remains unchanged. Radiation to the back is found to be emphasized with increased playing dynamic at 500 Hz.

With the smaller string instruments, a certain frequency limit of omnidirectional radiation could be found. However, with the contrabass this frequency is more ambiguous. At the lowest elevation levels the directivity changes around the 160 Hz and 250 Hz one-third octave bands (see Figure 44). On the other hand, the two highest elevations exhibit slight changes at 200 Hz. Therefore the directivity is changed more substantially the first time around 200 Hz.

These general observations are fairly well in line with the behavior reported by Meyer [1], where even the low

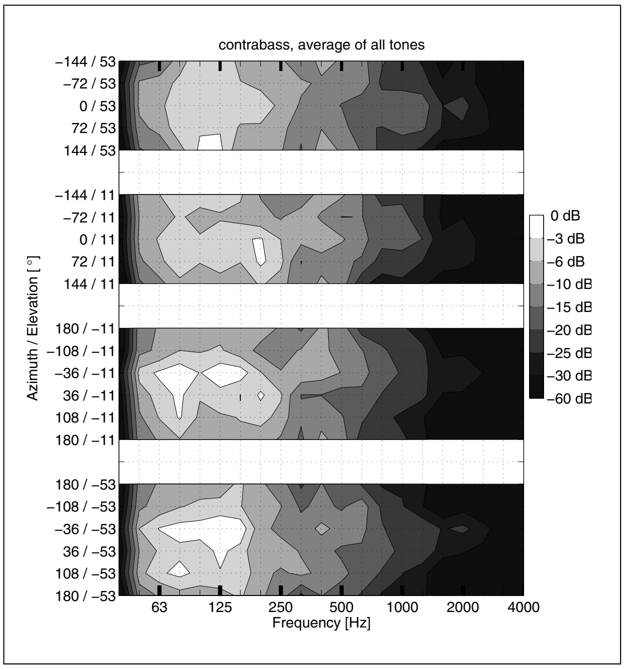

Figure 45. Average radiation of the contrabass.

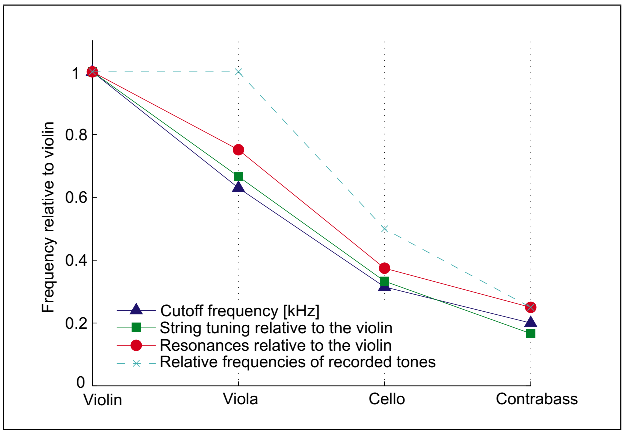

Figure 46. Comparison of measured frequency properties of the string instruments. Physical values are from Fletcher and Rossing [2] and Hutchins [50].

frequencies are found to have pronounced radiation. The radiation is reported to be more omnidirectional only around 100 Hz. The lateral directivity to the front half-plane at 1000 Hz is also illustrated by Meyer. Increased radiation to the back at 400–500 Hz occurs at higher frequencies than suggested by Meyer.

8.5. Discussion on string instruments

Analysis on the string instruments provided results showing a more complex overall directivity compared to the wind instruments. However, with the set of recorded tones the radiation at one-third octave bands was found to remain fairly constant independent of the played tone. The similarities in the radiation pattern was noticeable especially with two tones with one octave interval, where the even harmonics of the lower tone radiate similarly to the first harmonics of the higher tone. This was most prominently observed with the violin and the viola.

The string instruments were also noticed to exhibit one or two frequency bands dividing the contiguous regions of the radiation patterns. One or two of such frequencies were found depending on the instrument. This was seen as an emphasized radiation peak in a single or multiple constant directions at specific one-third octave bands. Additionally, these peaks were found to be present with several individual tones. Moreover, the sound radiation is more omnidirectional below the lowest peak frequency with the violin, the viola and the violoncello. Thus, this can be conceived as a type of a cutoff frequency.

The frequencies discussed in the sections of individual instruments are plotted in Figure 46 with other physical and acoustical values in relation to the violin. While the resonance placement of the instrument is predicted to reflect the change in the cutoff frequency, the string tuning is noticed to correspond better with the found upper limit of the omnidirectional radiation.

With the string instruments, the directivity does not change substantially with the playing dynamics. However, a change in the frequency spectrum was obvious especially with the viola.

Directivities of single musicians were investigated in these studies. A violin part, for example, can be played by over a dozen violists in an orchestra. While Meyer has discussed thoroughly on the effect of the seating order of the players, the contribution to the overall directivity by other players in a string section is unknown. Such investigations would improve the knowledge on the radiated sound from orchestras.

9. Conclusions

The directivity of the symphony orchestra instruments have been presented. Each instrument was recorded in an anechoic chamber with evenly spaced microphones, and the instruments were played by professional musicians. The results have been analyzed with various methods in order to investigate the effect of different tones and playing dynamics to the sound radiation around the player. Short introductions to each instrument family were also presented. The observed directivities were compared to the results presented in the literature, mainly to the book by Meyer.

The results for the brass instruments showed predictable and constant directivity in the direction of the bell, while the width of the pattern is decreased with increasing frequency. Regarding the auralization, applying the directivities with filtering functions is therefore suitable.

The sound radiation from the woodwinds and the string instruments were found to have common properties with partially constant directivity. Woodwinds tones in different registers were noticed to radiate similarly, and with the strings the harmonic frequencies common for two tones tend to have directivities very much alike. While it is possible to apply the directivities in auralization with more complex functions compared to the brass instruments, the use of multi-channel sources would reproduce the effect of directional tone color more accurately.

Further research on this topic includes utilizing achieved results in the field of auralization and concert hall studies. In addition, one-third octave data with a user interface used in the analysis is made available as supporting material at http://auralization.tkk.fi.

Acknowledgements

The research leading to these results has received funding from the Academy of Finland, project no. [119092] and the European Research Council under the European Community's Seventh Framework Programme (FP7/2007–2013) / ERC grant agreement no. 203636. J. Pätynen wishes to thank the Finnish Foundation for Technology Promotion for funding.

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