Experimental investigation of high-resolution measurements of directivity patterns

Andrea Corcuera Marruffo, Alexander Mayer, Alex Hofmann, Vasileios Chatziioannou, Wilfried Kausel
Department of Music Acoustics - Wiener Klangstil (IWK), Austria, Email: corcuera-marruffo@mdw.ac.at

Introduction

Measuring and modelling the directivity characteristics of sound sources is a long-standing challenge in acoustics that has received increased attention in recent years. Knowing the directional properties of sound sources is important in several applications such as in the design of new auditoriums, virtual sound environments and in the manufacture of musical instruments.

Musical instruments are sound sources that create sound fields with complex directivity patterns which are frequency dependent and may also vary depending on the dynamics. Due to the difficulties in providing an accurate repeatable excitation, the directivity patterns of musical instruments are often measured for all angles simultaneously using large surrounding spherical microphone arrays. While the use of this method allows to measure the directivity characteristics of an instrument that is excited in a natural manner, the spatial resolution of the measurements is limited by aliasing as a consequence of the spatial sampling strategy. On the other hand, a repeated capture system makes it possible to acquire higher resolution directivity patterns at the expense of obtaining patterns that do not include the influence of a player.

After the early works of Meyer [1], several notable studies have been published on the capturing of directivities of musical instruments. Otondo and Rindel [3] used 13 microphones at 45°intervals placed in the horizontal and vertical planes to measure a clarinet, a trumpet and a French horn. Pollow *et al.* [4] measured the directivity characteristics of 41 symphonic orchestral instruments using a 32-microphone array in the shape of a truncated icosahedron and Pätynen and Lokki [2] measured a similar set of instruments, including different playing dynamics, with an array of 22 microphones. More recently, researchers have measured instrument directivities using a repeated capture system, like Bodon [5] who measured 3D directivity patterns of several musical instruments with 5°resolution both in azimuth and elevation with musicians, using a rotating microphone arc. Other recent studies have used artificial excitation techniques, such as Grothe and Kob [8] who used a turntable and an artificial continuous blowing player to obtain three-dimensional directivity patterns of a bassoon.

This paper presents high-angular resolution directivity patterns of a trumpet measured under anechoic conditions in three different 2D planes. The goal of this study is to explore the inaccuracies caused by spatial subsampling and frequency smoothing that are common in directivity modelling. To this end, high angular resolution directivity data of a trumpet without a player are presented and used as a reference grid that allow to study possible lower resolution patterns. The measurements are compared with existing data, and a case study with a lower spatial and frequency resolution is conducted.

Method

Measurement setup

The directional characteristics of a B_b trumpet were measured in the anechoic chamber of the Department of Music Acoustics - Wiener Klangstil, at the University of Music and Performing Arts Vienna (see Figure 1). The trumpet was excited artificially using a horn driver (*PA horn driver MRD-120*) that was attached to the mouthpiece using a custom-made holder. A stepped logarithmic sine sweep from 150 Hz to 10000 Hz was used to measure the directivity signals. The amplitude of the input signal was modified to avoid the saturation of the measurement microphones. The trumpet was mounted on an automated turntable that was rotated by 0.5°, from 0°to 360°, resulting in a total of 721 measurement points per plane. The measurements were done in three different planes, namely the horizontal, vertical and median planes of the instrument. To this end, the setup was manually modified by rotating the trumpet in order to modify the measured plane. The directivity signals were captured using a microphone that remained static, at a distance of 1 meter. The height of the microphones was determined with a laser pointer targeting the centre of the instrument's bell. Each full rotation took approximately 12.5 hours.

Figure 1: Setup used for the measurement of the sound radiation of a trumpet, with a turntable, two microphones, and a horn driver employed for the excitation of the instrument.

Excitation and response measurement

The radiation at 1 meter was measured with a *ROGA Type RG-50 1/4* Inch measurement microphone, with a linear frequency response (+/-1.5dB) up to 20000Hz. The microphone was calibrated, and suitable recording levels were found empirically. The excitation of the trumpet was measured with a pressure microphone (*ENDEVCO Model 8507C-2*) placed inside the mouthpiece of the instrument.

The Turntable Hardware

The turntable hardware used is based on the former construction designed by Lahmer and Mayer [7]. The main component of the turntable is a heavy-duty ball bearing on which all superstructures can be stably mounted. The rotary motion is transmitted directly to the bearing via a gear train. To achieve high angular resolution and accuracy, the drive technology was changed from stepper motors to a closed-loop-controlled DC-motor drive. This update achieves an angular position accuracy of 0.0012°. Further deviations may occur due to slight out-of-roundness of the pivot bearing, which have not yet been determined. However, these deviations would be reproducible due to the toothed drive.

Analysis

The analysis of the signal was done in the time domain. First, the time-domain response signals were delay-compensated. The delay corresponding to the distance of 1 meter was removed, equivalent to 146 samples at 50 kHz sampling rate. Then, the response signals were divided in blocks of 5000 samples (equal to the duration of each frequency point in the stepped sweep), windowed using a Hanning window ($L = 5000$) and band-pass filtered with a filter whose cut-off frequency corresponded to the current excitation frequency of the signal. This was done with the aim to guarantee the analysis of steady and clean signals, independent of unwanted influences, like harmonic distortions. Finally, the signals were normalized with respect to the reference signal that was recorded inside the mouthpiece. The normalized data were converted to dB and plotted in a polar plot. Negative levels are artificially set to 0 dB for plotting purposes.

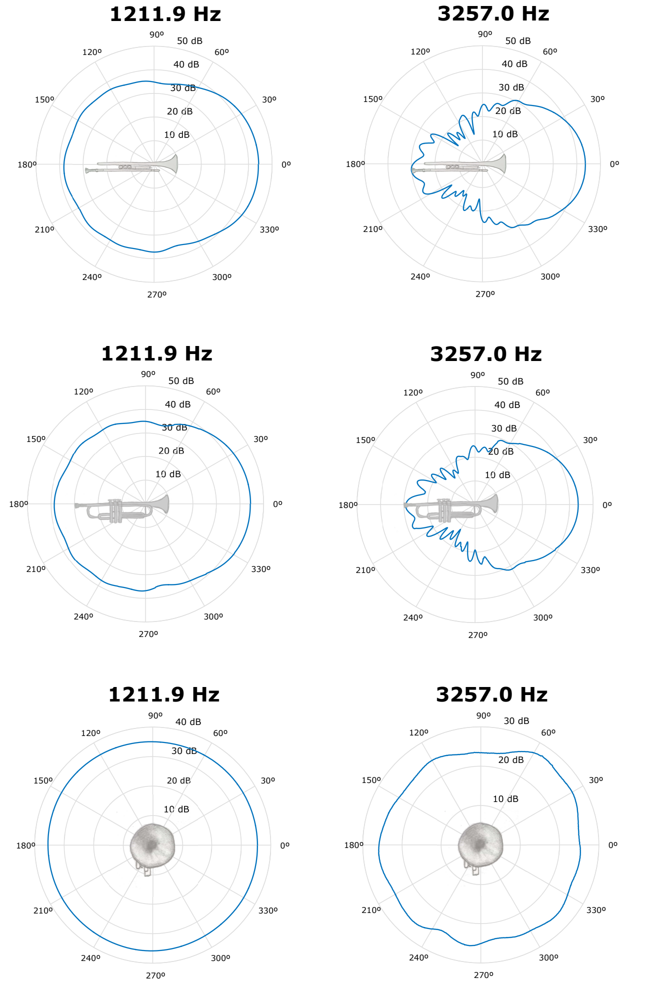

Figure 2: Directivity of the trumpet in the horizontal, median, and frontal planes for two arbitrary frequencies (1211.9 Hz and 3257.0 Hz).

Results

The polar representation of the trumpet directivity is shown in three planes in Figure 2. In general, the trumpet shows a uniform radiation at lower frequencies. At 1000 Hz and above, the width of the pattern becomes narrower and more directional towards the bell. The directivity patterns obtained from the high resolution measurements are consistent with the results found in literature. The sound radiation is close to omnidirectional at frequencies below 1000 Hz, suggesting a cut-off frequency around this value, which is in line with results by Pätynen and Lokki [2] and Meyer [1]. From about 2000 Hz, Meyer described secondary lobes whose number increases with frequency. These features can be clearly observed in Figure 2 (right column, top and middle plot).

Interpolation

As the pressure information is only determined over the given measurement points, interpolation is necessary to approximate the radiation pattern in positions between the available grid locations. This is a recurrent problem in the measurement of sources using microphone arrays, in which spatial interpolation is needed for visualization or for its use in acoustic simulations. Points between discrete angles are usually approximated by linear interpolation, but other numerical methods can be used, like splines. Another option would be to decompose the sound radiation into a finite set of spherical harmonics.

The present measurements done at very closely spaced locations provide a reference grid with high angular resolution that allows the study of data interpolation using lower resolution sampling schemes. The lower resolution schemes can be obtained by subsampling the high resolution measurements. The chosen interpolation methods may then be evaluated by comparing with respect to the reference.

Figure 3 shows two interpolation methods at frequencies of 3257 Hz and 7042.9 Hz, for two case studies with resolution of 5°and 45°, and two different interpolation methods, linear and splines. At low frequencies, having few measurement points is not a problem, since the near omnidirectional directivity patterns can be reconstructed from a few points. However, at higher frequencies it can be observed that the reconstructed patterns are smoothed. The interpolation error increases with raising frequency, as shown in Figure 4. This error is calculated as the Euclidean distance between the interpolated values and the normalized reference values in dB.

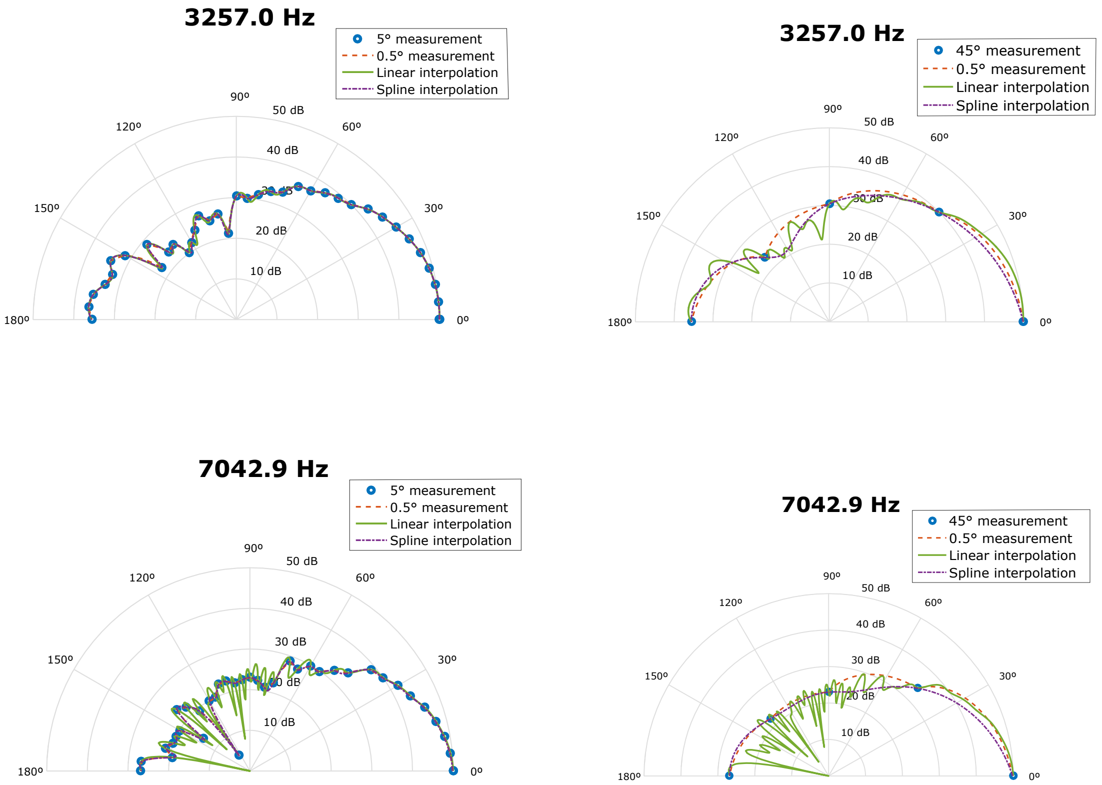

Figure 3: Interpolation of the directivity pattern of a trumpet in the horizontal plane at two frequencies (3257 Hz in the upper row and 7042.9 Hz in the lower row). Two spatial resolutions are studied, 5°(as in the setup of [5]), and 45°resolution (as in [3]). For better visualization, only half plane is shown, the pattern is normalized to the maximum value and a range of 50 dB is used.

The overall error is larger for the case with less measurement points (blue curve). In particular the fine side lobes that are noticeable in the high-resolution patterns are lost, resulting in patterns with smoothed shapes that differ from the reference, as observed in Figure 3 (lower row). Nevertheless, the practical implications of such spatial undersampling remain to be studied.

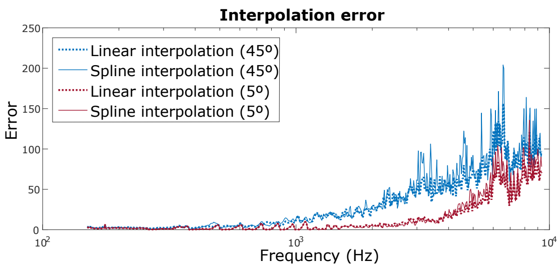

Figure 4: Interpolation error per frequency for 45°resolution (blue) and 5°resolution (red).

Frequency smoothing

Although it is possible to provide source directivity measurements with high frequency resolution, in practice, the directivity information is often presented in frequency bands, such as octave or fractions of an octave, rather than presenting the frequency dependence of the data at high frequency resolution. This is the case for example in room acoustics, where the directivity information is generally presented in one octave or one-third octave frequency bands [9]. Combining directivity patterns into a single pattern within a certain frequency band significantly reduces the amount of data stored and represented, providing a general overview of the behaviour of the instrument, but it might also average out the particular directivity patterns corresponding to individual frequencies of the instrument.

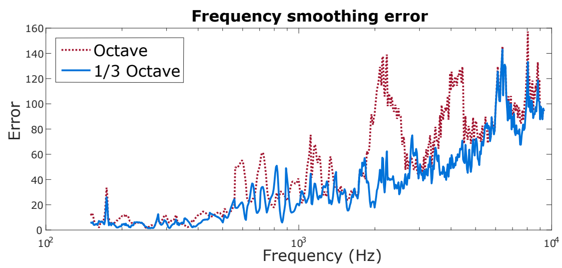

Figure 5: Frequency smoothing error for one octave (dotted red) and one third octave (blue solid) band smoothing.

As seen in Figure 6, the directivity patterns averaged in one-third octave bands and, especially, in one octave band, show a smoother behaviour that differs considerably from the original data. As shown in Figure 5, the frequency smoothing error shows a similar trend as the

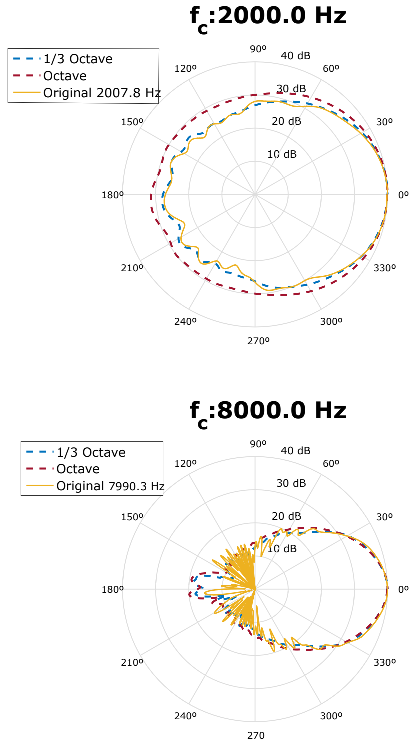

Figure 6: Directivity patterns for frequencies 2007.8 Hz and 7990.3 Hz (yellow), and averaged in one third octave (dashed blue) and one octave (dotted red) bands, with respective center frequencies (f_c) of 2000 Hz and 8000 Hz.

interpolation error, increasing with frequency. This error is computed similarly to the interpolation error, by calculating the Euclidian distance between the band-averaged values and the normalized reference values in dB. It can be seen that, in general, the error is greater for the one octave band than for the one-third octave band. Therefore, the frequency domain must also be carefully handled in order not to lose information, which might be acoustically significant.

Discussion

This study presented high resolution measurements of a trumpet, measured at half degree resolution and using artificial excitation. The directivity patterns obtained are consistent with the results found in the literature, showing an omnidirectional pattern in all planes at frequencies below 1000 Hz, and a more directional pattern towards the bell of the instrument above this value. At mid frequencies, side lobes appear that are more numerous and pronounced as the frequency increases. These narrow lobes could be assessed thanks to the high resolution of the measurements as they would have otherwise been overlooked.

Attention was given to the angular interpolation of some patterns with low angular resolution, obtained by subsampling the high-resolution measurements. Pattern reconstruction at low frequencies can be performed by interpolating between a few measurement points due to the omnidirectional behaviour of the instrument. However, for mid and high frequencies, more data points are needed to match the high resolution pattern, used as a reference. This effect is expected to be more prominent for distributed sound sources with more complex directivity patterns.

Furthermore, it could be observed that a significant amount of information is lost when condensing the frequency data into octave or one-third octave bands, conventionally used in room acoustics. Thus, one needs to be cautious when post-processing the obtained data as otherwise valuable information may be lost.

Nevertheless, it remains to be studied whether these high spectral and spatial resolution patterns are perceptually beneficial. Hence, future work aims to study various angular and frequency resolutions to understand the perceptual implications and thresholds of source directivity.

Acknowledgments

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