Impact of Excitation and Acoustic Conditions on the Accuracy of Directivity Measurements

M. Kob
University of Music Detmold, Neustadt 22, 32756 Detmold, Germany
kob@hfm-detmold.de

Directivity measurements of music instruments produce qualitative and quantitative information about the spatial distribution of sound energy. This information can be used for improved microphone placement during recording sessions but also serves as radiation characteristics for virtual instrument synthesis. Many directivity measurements have been performed in anechoic rooms, using a human or artificial player. However, the perceived sound of an instrument strongly depends on the playing technique, the room acoustics, the distance from the instrument and other conditions. This contribution points out potential consequences of different excitation techniques, microphone distance and acoustic boundary conditions on the accuracy of directivity measurements.

Introduction

Musical instruments can be categorised according to various aspects. Among these are their excitation mechanism and their radiation characteristics or directivity. It is well known that directivity of musical instruments is frequency-dependent. This indicates that their structural properties allow more than one mode of oscillation or the dimensions of radiating surfaces are comparable to the wave length of the musical sound. Consequently, the radiation of complex instruments becomes complex as well and cannot easily be described with basic acoustic sources such as a point source or a dipole.

An empirical approach to determine the radiation characteristics of musical instruments is the measurement of radiated sound pressure in a constant distance but in various directions. These measurements are part of the manufacturers' data sheet for loudspeakers and give valuable information about their performance in different use cases. Three representations are often used: two-dimensional diagrams such as polar plots or isobar/dispersion plots, and three-dimensional diagrams such as balloons. Polar plots use one line in polar coordinates for each frequency and orientation that can easily be interpreted (see figure 6). Isobar plots are a coloured map of either horizontal or vertical orientation and require a colour bar for interpretation (see figure 3). Balloons are a convenient way to display three-dimensional radiation characteristics for selected frequencies.

For musicians and sound engineers the radiation of musical instruments is of major interest. A comprehensive collection of directivity patterns for most orchestra instruments has been published by Jürgen Meyer in the book "Acoustics and the Performance of Music" [Mey09]. In this book the directivity patterns are given for each instrument for several frequency ranges. They represent a special version of the polar plots and indicate the radiated sound pressure level in a range from maximum to -3 dB to indicate 50 % of radiated energy, or to -10 dB which corresponds to 50 % of the loudness. This overview is very valuable to determine optimal recording positions that include the desired frequencies of the instrument.

In live playing situations – concerts, rehearsals, studios – a number of aspects could cause alterations of the directivity obtained under laboratory conditions. Some of these are due to the player, some due to the design of the instrument, and some are caused by room acoustical conditions.

This article shall point out potential sources of influence on the radiation of musical instruments and indicate conditions how directivity measurements can be performed and optimised for various purposes.

Theoretical/acoustical considerations

For practical reasons it would be nice to define "the" directivity of an instrument that would be representative in most cases. Does this approach make sense or not? What consequences does such a simplification have? General statements such as "trumpets are very directive" and "kettle drums radiate omnidirectional" are correct, because they focus on the main characteristics of the instruments and their behaviour in that characteristic conditions. This would be the bright sound of a trumpet and the rather low pitch of a kettle drum. A consideration of the sound generation principle can explain why this generalisation is possible. A simple model of the trumpet would be an exponential horn with one sound wave output at the open end. For frequencies above 2 kHz, that correspond to the bright sound components, the radiated sound wave approximates a plane wave which is highly directive in direction of the bell. A model for the kettle drum would be a circular membrane that is orientated such that almost all vibrational modes contribute to a horizontal radiation towards the audience.

There are, however, a number of instruments that do not exhibit these unique model characteristics but rather show a complex and highly variable directivity. What are the reasons for this complexity? Within the signal chain: source – filter – radiation – room – microphone all elements contribute to the directivity pattern in different ways. Source, filter and radiation are essentially forming the directivity pattern whereas room acoustics, microphone characteristics and recording distance can introduce artefacts to the measurements (see sections and). The source-filter model has been used since long to distinguish between two functions that can be used as separate functions to model a musical instrument. Despite the feedback between these function – which is essential for the generation of musical sounds – the source-filter model can serve to illustrate the generation of directivity. The source is considered as a player-controlled energy support that provides an initial broad-band velocity or pressure input to the musical instrument. The input is then formed by an acoustic resonator such that a sound wave is produced, and certain frequencies are enhanced, others are damped. Musical sounds mostly build sound waves that have a strong harmonic series of frequencies. This sound is then radiated by constrained openings of the instrument body, or by vibrating membranes or plates, with individual radiation impedances that result in the overall directivity. Thus, directivity is the product of all previous components, which contribute to its complexity.

Source normalisation

Directivity patterns are usually evaluated by SPL measurements in different directions from the source.

Source properties will have a major impact on the SPL values of the directivity assessment. This information might be interesting to compare the sound level among instruments, but is not very useful In most representations the directivity is normalised to the maximum value which is often organised such that it corresponds to 0 azimuth, 0 elevation.

Frequency-dependent evaluation

Since most musical instruments exhibit a frequency-dependent directivity the values are evaluated by subsequent filtering in frequency bands. The bandwidth is variable, and can be chosen according to the desired resolution of the evaluation but also according to the source and filter characteristics. Musical sounds contain a harmonic series, noise components and other components, and the directivity potentially can vary rapidly due to a high modal density. Consequently, the radiation might vary from harmonics to harmonics. This fact contradicts the wish for a general radiation characteristics. A broader bandwidth – such as 1/3 octave filtered plots – would integrate the contributions from several components, resulting in effects that are described in following section. A semitone-resolution would be able to distinguish directivity patterns associated with approximately the first 10 harmonics. However, this bandwidth would yield a huge data set and is not needed for simple instruments.

Multiple sources

In the case of instruments with more than one or a segmented radiating area, multiple areas might radiate simultaneously, resulting in multipole characteristics. Some instruments contain several oscillators that operate in one case, e.g. organs or pianos. In case of flutes both ends have opposite phase, resulting in a dipole characteristics. Strong effects of these multipole instruments are expected when the openings contain coherent signals, i.e. are fed from the same source, and are of similar amplitude and either same or opposite phase. The interference of two such coherent sources can cause SPL values at the microphone from $-\infty$ (opposite phase) to +6 dB (same phase).

The interference can also occur from early reflections, i.e. neighboured objects with a reflection factor of unity, and electro-acoustic reinforcement systems.

Another aspect that causes complex directivity patterns is the origin of secondary sound sources along the instrument body. These might be tone holes of wind instruments that potentially radiate at more than one or two openings. String instruments also can radiate from vibrating shells and openings in the instrument's body, such as f holes in violins. A prediction of the actual configuration is difficult since the location of potential radiating objects depends on the operating deflection shapes of the structure and the relative position of openings and modal antinodes of the enclosed air column.

Source/filter vs. radiation

The radiated SPL depends on the source/filter characteristics. Polar diagrams are therefore very often normalised with respect to the SPL in 0° direction or another assumed main radiation direction. The effect is – among the desired relative SPL values a reduction of the source/filter properties. This can easily cause strange directivity patterns when the source strength is insufficient at that frequency band and/or in the 0° direction.

An interesting question is whether the linear source-filter-radiation approach really holds for the use of a normalised directivity. If so, the radiation pattern of an instrument should be the same for any source and filter signal. An investigation of Katz & Alessandro shows that this is the case for low and high components of the singing voice but not at frequencies from approximately 1 to 3 kHz [Kd07]. The reason for this deviation can be explained by the variation of the mouth opening shape and area for different phonemes. In this case the instrument modifies its radiation impedance and directivity as a consequence of a filter adjustment.

Human player excitation

Directivity measurements of real instruments of instrument groups cannot be easily performed on a turntable with constant excitation of the musical instrument(s). Whereas a turntable for one or more musicians can be manufactured, a repeatable excitation of an instrument for many subsequent and potentially identical sounds is not possible for a human player. There are two solutions to this problem: either a simultaneous recording of all directions must be performed, or the excitation level of the instrument must be used as a normalisation parameter that compensates for variable source power. The massive multichannel recording of sound has become somewhat easier with the availability of MADI and IP-based audio transfer concepts such as DANTE or Ravenna. However, the calibration procedure and financial implications for such a set-up must be considered.

The player can have impact on the energy support, i.e. a scaling of the source level, and – in most instruments – determine the properties of the resonator(s), e.g. by modification of an air column or string length. The radiation of instruments can be changed by movement of the whole instrument or by obstruction of propagation by the player's body.

The fact that she or he serves as an effective sound absorber and diffraction element for the radiated sound as well as for reflected sound waves deserves some more consideration. In anechoic environments, this effect is rather weak for instruments that project the sound towards the listener, such as trumpets. Instruments that radiate close to the player, such as flutes or violins, are strongly affected by the presence of the player. Also instruments with multiple radiation sources will be affected by the presence of the player (see section).

Measurements with humans also require a controlled, repeatable excitation. If no simultaneous recording is possible (see [KJ99]) this results in long sessions with sung sweeps. For the upper hemisphere with 10° resolution this results in $37 \cdot 9 = 325$ sweeps (the 360° measurement should be equal to that at 0°, the 90° measurements should all be identical). When each sweep takes 5 seconds and adjustment of the height would take one minute the whole session would last about 40 minutes.

Artificial player excitation

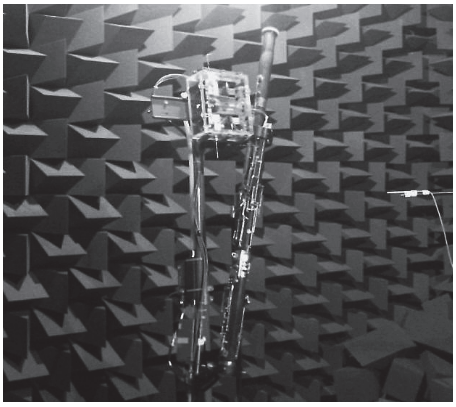

Figure 1: Set-up for bassoon measurements using an artificial player

Artificial players can be useful to study the behaviour of musical instruments without the human factor. There are a number of advantages but also some problems associated with this approach. Among the advantages is a potential total control of all physical and environmental parameters and the chance to analyse stationary signals. On the other hand, these conditions are quite far from artistic use of the instrument. Another problem is the gap in the feedback loop that musicians fill. The auditory process that makes the player adjust important physical and musical parameters – such as pressures, tensions, velocities, pitch and timbre – is missing, and the artificial player needs to be carefully adjusted to achieve favourable conditions for the production of musical sounds. The machine control of musical instruments has been a challenging topic in the last decade [SMC14] and is beyond the scope of this article.

For investigations of directivity usually rather basic playing techniques are used, and an artificial player can provide the adjustment of the corresponding physical parameters. For wind instruments this would be the air and lip pressure plus the closure of tone holes (if any). Exemplary the bassoon directivity measurements using an artificial player have been investigated [GK13]. A comparison of an human and an artificial singer using both excitation techniques can be found in [Kob02].

Example for reflections

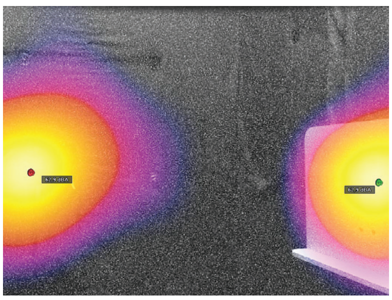

Figure 2: Reflection from a music stand

It is well known that directivity measurements shall be performed under anechoic conditions. However, these conditions cannot be expected when musicians perform on stage, and even in studios reflections are likely to occur. An example is the presence of a music stand in the studio. In figure 2 the reflection of filtered noise from 2 to 2.5 kHz is shown using an acoustic camera (VISOR, HEAD Acoustics). At that frequencies the SPL values of both, the loudspeaker and the music stand, are the same. The resulting isobar plot of a 6-channel loudspeaker (Globesource, Outline) with and without reflections due to a wooden music stand are shown in figures 3 and 4. It can be seen that the omnidirectional

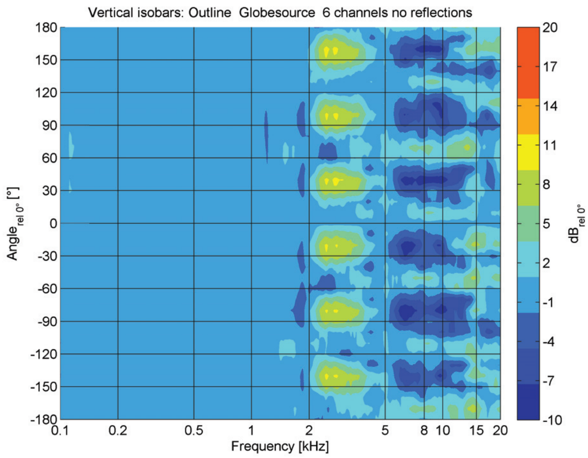

Figure 3: Isobar plots of a dodekaeder loudspeaker with equal phase signals on the 6 horizontal loudspeakers

characteristic is not disturbed below 1 kHz, because the wavelength of the sound is larger than the dimensions of the stand. From 2 to 5 kHz the interferences of the individual

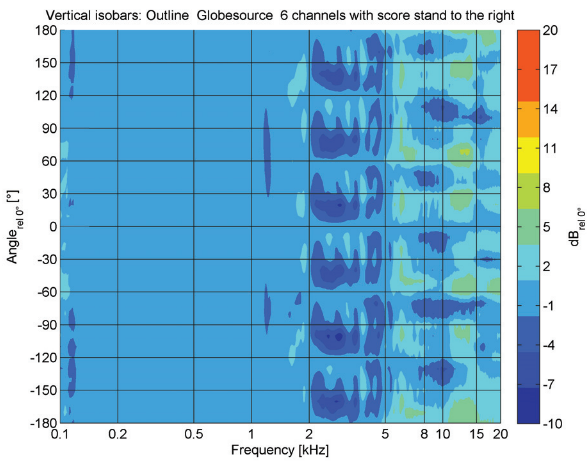

Figure 4: Isobar plots with the same configuration as before but with a wooden music stand to the right

loudspeakers cause significant level reduction in the case without music stand and a level increase in this range with music stand. At higher frequencies the stand causes more pronounced level reduction. For a microphone recording this effect would result in significant timbre coloration of the recordings. A movement of the musician would change the phase relation and cause individual timbre modulation in that frequency range.

A similar effect – but within a different frequency range – would be observed by reflections by objects with other size or shape such as walls, floors or furniture. A larger diffuse field component would reduce the effect.

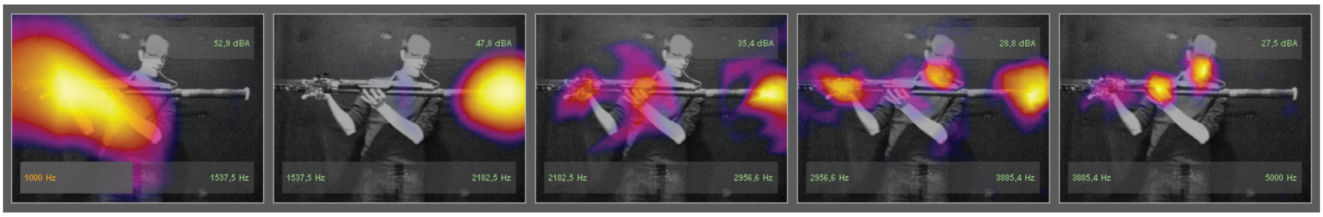

Figure 5: Radiation from a bassoon. The images correspond to these frequencies (from left to right): 1000..1500 Hz; 1500..2200 Hz; 2200..3000 Hz; 3000..3900 Hz; 3900..5000 Hz.

Example for multiple radiation sources

Wind instruments with tone holes can have rather complex radiation patterns. In case of the bassoon the directivity varies significantly with frequency. Whereas this can be expected from oboes, clarinets and similar instruments as well, the bassoon exhibits an even more complex pattern (see figure 5). Two reasons can explain the presence of such a variable radiation: first, the instrument is folded, i.e. the length of the active air column does not correspond to the distance from the mouthpiece. Second, the traditional instrument has a large number of keys that open/close remote tone holes. Often, these are needed to correct the impedance and thus improve intonation and/or playability of the instrument. Therefore, the individual fingering will lead to a variation in open tone hole configurations that contribute to the radiation. This effect is especially significant at higher frequencies.

Distance of microphone position

As a consequence of the multiple radiation sources of wind instruments the complex radiation pattern does not only change significantly with frequency but also with distance of the measurement microphone. This effect has been observed during directivity measurements of a bassoon and was presented at SMAC 2013 [GK13]. In figure 6 the polar plot of a high note b', corresponding to a fundamental frequency of 470 Hz, is shown for two distances. Whereas

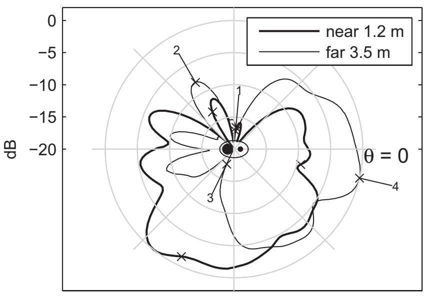

Figure 6: Measurement of bassoon directivity in two distances (from [GK13])

in most directions the overall directivity is similar but less expressed in the smaller distance, at one direction (marked '3') the SPL is maximum in the smaller distance but almost negligible in the far distance. This effect can be explained by the superposition of two or more coherent sources that constructively interfere in one case but cancel out in the other distance ($\lambda/2$ difference in path length). A visual proof is given in [GK13]. The effect of less expressed minima in the nearer distance can be explained by the pressure distribution in the near field of sound sources with reactive power radiation.

Conclusions and outlook

A number of factors have been identified for complex radiation patterns of musical instruments. Some of them are inherent properties of the instrument such as multi-pole radiation sources or variable mouth openings. Others are due to the measurement set-up such as the microphone distance or reflections from objects near the instrument. For optimised measurement procedures the impact of these factors can be estimated using tools such as acoustic cameras. Future investigations could address the quantitative assessment of errors when neglecting ideal conditions for directivity measurements.

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