Exposé - Master Thesis

The sound radiation of musical instruments at the transition from near field to far field

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Abstract

Musical instruments have complex radiation patterns that vary at different points of observation relative to the source. Usually directivity patterns are measured at one specific distance in the far field. Although in practice musical instruments are often recorded with very close positioned microphones, there is very little data on their radiation patterns in the near field as the interferences of sound waves are very complex. To gather more data in the near-field and investigate the transition from near to far field, magnitude spectra of four different instruments playing single notes recorded at various distances with a multi-channel microphone line array in an anechoic room are analyzed.

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Introduction

In a live concert listeners might observe that the perceived sound of musical instruments can change depending on the position of observation [1], not just in loudness but also in timbre [2]. This phenomenon does not only depend on the acoustical features of the performance space as a medium or microphones and amplification used in the signal chain, but also on the characteristics of the musical instruments as ‘dry’ sources themselves. Instruments have several areas radiating sound concurrently and therefore are complex sound sources with multipole characteristics [3].

How a source radiates sound is specified by its directivity or radiation pattern, which by definition describes the amplitude and phase of sound waves radiated into a particular direction.

Radiation patterns of musical instruments are essential in the field of augmented reality, for attaining an authentic synthesis of instruments as sound sources and being able to implement them into virtual acoustic simulations and auralizations. [4, 5, 6].

Specifically in recording and live music situations information on the directivity of a musical instrument is crucial to achieve a desired sound result. The positioning of the instruments in the room and relative to each other, as well as the microphone placement in relation to the instruments are important factors to be considered [7]. Still most microphone placement techniques are based on empirical research and follow aesthetical guidelines [8, 9].

So far musical instruments as sound sources have mostly been researched from one specific distance, but rarely in close proximities with near field conditions.

Observing the directivity of a sound source at various distances, the second far field criteria has to be considered, which is dependent on the frequency and source dimensions. In the far field the magnitude spectrum of a sound source at one specific angle is uniform and the radiated sound power decays with increasing distance of observation. E.g. for an ideal point source the radiated sound pressure decays by 6 dB with doubling the distance. In the near field interferences occur due to complex phases and result in different magnitude spectra. Therefore within the near field the directivity of a sound source in one particular direction also varies at different distances of observation. The transition from near to far field can be calculated theoretically, still in practice some questions remain unanswered: Is the transition exactly at the point defined by the criteria? Is it an abrupt transition or rather smooth? How does the directivity of a musical instrument behave at different distances within the near field, is it complex or can it be described by a function?
Current State of Research

Musical instruments have been researched intensely regarding their physics and different principles of tone production [10]. Sound generation of an instrument depends on the principle of the type of excitation through energy transmission via broad-band velocity or pressure input, filtered in a resonance body, resulting in a fundamental frequency with a specific manifestation of harmonic overtones and how the resulting sound is radiated by openings at the instrument corpus, plates or vibrating membranes with individual impedance. All these factors can result in a highly complex directivity pattern that give a musical instrument its unique character.

Laying the foundation for the field of acoustic radiation pattern analysis of musical instruments, in 1972 Meyer [11] discussed the sound characteristics and directivity of symphony orchestra instruments. The measuring method was not described in detail, however it is mentioned that the measurements were made in an anechoic chamber with a distance of 3.5m.

Since then, several studies have investigated the directional behaviour of various musical instruments using different measuring setups using the advantage of multi-channel recording to capture a sound source simultaneously from different angles.

Otondo and Rindel [12] investigated three different classical wind instruments using an array of 13 microphones at 45° degree intervals in the horizontal and vertical planes at a distance of 1.5m above and around the sources. A study by Pätynen and Lokki [13] measured 14 of the most common symphony orchestra instruments using a dodecahedron shaped microphone array with an average distance of 2.13m from the instrument. With an even larger setup Hohl [14] used 64 microphones arranged on a spherical microphone array to measure three groups of instruments strings, of the wind instrument family, both brass and woodwind, to allow a data representation using spherical harmonics [15, 5, 1]. In a large scale work Shabtai et al. [6] collected directivity data of 41 musicals instruments, recorded with a surrounding spherical microphone array recorded in an anechoic chamber. At a measuring distance of 2.1m 32 microphones positioned on the faces of a truncated icosahedron [16].

All of the above mentioned studies used human excitation of the instruments, which bears the problem of reproducibility since musicians adapt their playing to what they hear and also that they themselves serve as sound deflecting, absorbing and reflecting elements [3].

To compensate these factors, several studies have used artificial excitation of instruments to guarantee stationary signals. The violin as part of the family of string instruments has been subject to many different artificial excitation methods, including exciting the strings electromagnetically or with forced hammers [17], driving the bridge with electromechanical shakers and utilizing loudspeakers to stimulate vibrations on the instrument corpus among
others. To achieve more authentic results more recent research about the directivity of violins has focused on using bowing machines [18, 19].

Comparing the pros and cons of artificial versus human excitation of the bassoon has been investigated by Kob [3]. Standing out from the above mentioned studies, it was observed that the measured directivity was different at the two distances of observation, one at 1.2m in the near field and one at 3.5m from the instrument in the far field.

Most research work observed instruments in an ideally static position, however the musicians movement with the instrument and the resulting spectral fluctuation have also to be considered [20]. The above mentioned research works have covered diverse aspects of measuring radiation patterns of musical instruments, yet there is still scarce data on directivity patterns for various distances, which therefore shall be the focus of this thesis.

Methodology

Following the individual tasks and steps for creating the database of the directivities of musical instruments measured at various distances is presented. Since the implementation of the measurement system using Matlab has been the first step, it will be mentioned at the beginning. Followed by a description of the multichannel measurement setup this chapter concludes with how the data will be represented and evaluated.

Measurement System Implementation in Matlab

![Figure 1: Overview of signal processing of recorded measurements [16]](image)

The multichannel recording will be transferred as wav-files from the Sinus Tornado Multichannel Measurement System into Matlab using the SMT Sinus Measurement Toolbox and then be processed in the following steps:
After the onset of the signal, or in other words the beginning of a recorded single note, the most stationary part is found in the frequency domain using a STFT to extract a windowed steady part in the time domain of the signal. In order to detect the pitch of the individual played note, the discrete fourier transform (DFT) of the signal will be computed, to then apply peak picking in the discrete frequency domain. In this step the fundamental frequency is identified first and compared to a table of theoretical fundamental frequencies tuned to $A_4$ at 443 Hz using the equal temperament tuning system. Then the partials of the measurement signal are identified also by comparison to the theoretical table, that includes the respective partials as part of the overtone series of each fundamental frequency. To assure a correct detection with actual frequency values and assign the musical note name of the fundamental frequency with its overtones, the result is once more double checked and compared with the theoretical table. Subsequently for each channel of the recording the absolute magnitude levels of the detected formants are saved.

Measurement Setup

The measurements will be made in the Anechoic Room of the Technical University Berlin with a room volume of $830m^3$ and a cut-off frequency at 63 Hz. Frequencies below the cut-off can not be analyzed properly and have to be examined specifically.

As observed sources four musical instruments with different principles of sound generation were chosen: Tenor Saxophone as part of the woodwind family, Tenor Trombone as a brass instrument, Classical Guitar as a plucked string instrument and Double Bass as a string instrument that can both be played pizzicato and arco style. Professional musicians will be asked to play long-held single notes separated by pauses in ascending chromatic scales over the instruments entire playable range. For example to cover all 32 notes of the Tenor Saxophone’s range from G#2 to E5, played in chromatically ascending whole notes and separated by whole note pauses at a tempo of 60 bpm, would take four minutes and 16 seconds. This duration could ideally be recorded in one continuous session. The instruments will be fixed steady to one specific spot, to guarantee no change in distance to the microphone line array but still allow the excitation of the instrument in a natural playing position. The line array will consist of a fixated metal rod with drilled holes that allow embedded mounting of multiple Gras 40PL CCP Free-field QC Microphones, ideally 32 or more, depending on how the setup ultimately can be realized. The line array will be adjusted to one specific height, hence the radiating center of the measured musical instruments has to be adjusted to the same height. Ideally beginning at 0.1 m relative to the source, the microphones will be spaced evenly e.g. at 0.1 m to each other within a distance to up to 4 m. Within this distance - according to the second far-field criteria - the transition from near to far field for the frequency range of the observed instruments
is to be expected. Evenly spaced microphones will allow an easier computation of the data, applying the inverse distance law for sound pressure $p \sim 1/r$ radiated by an ideal point source. At distances of $4m < r \leq 8m$ additional microphones could be positioned with a wider spacing of e.g. $1m$ to gather further data in the far field.

All microphones have to be positioned perfectly in line in the horizontal and vertical planes and therefore their placement will be checked using a cross line laser measuring tool. The microphone line array will be recorded by a Class 1 sound level meter Sinus Tornado Multichannel Measurement System. To minimize any possible reflections on the metal floor grating the musicians with their instruments and the line array will be placed on in the anechoic room, absorber foam is used to cover any reflecting surfaces.

![Figure 2: Sketch of the measurement setup with exemplary 16 channels, placed on metal floor grating in an anechoic room](image)

**Analysis**

Using the principle of the second far field criteria the discrepancies of the stationary signal parts of the measured data with a window length of $0.2ms$ are analyzed by comparing the relation of the measured sound pressure levels of the respective fundamental frequency and its overtones at different distances. The second far-field criteria is dependant on the distance $r$, the source dimension $h$ and the frequency $f$ but disregards the phase.

$$r \gg \frac{(h^2 \times f)}{r}$$

Hereby the theoretical transition from near to far field can be calculated and compared to the measured data. Using multiple linear regression the behaviour of sound radiation in
the near field can be analyzed further. Conclusively the measured data will be represented as waterfall diagrams with three axes: frequency, absolute magnitude level and distance.

Figure 3: Waterfall diagram of a directivity pattern including the theoretical far-field transition indicated as red line.

*note: this is just a generated example*

### Time Schedule

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<tr>
<td>Implementation of Measurement System</td>
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<td>Measurement Setup</td>
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Literature


