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High resolution 3D radiation measurements on the bassoon

Timo GROTHE and Malte KOB

Hochschule für Musik Detmold, Germany, grothe@hfm-detmold.de

Abstract

Musical wind instruments with tone-holes have complex radiation patterns. Since openings act as sound sources, depending on their relative distance and phase soundwave superposition can lead to boosts or cancellations at different observation points. These phenomena are particularly prominent in the bassoon, as a multitude of differently sized tone-holes are distributed irregularly across a long, bent corpus. To extend our knowledge on pitch-related directivity patterns of such complex instruments the bassoon was chosen as a test case measurement object for a high resolution radiation measurement in 3D, using a repeatable, artificial excitation and a 2 axis turntable. We compare the radiation patterns of four different tonehole configurations, and discuss implications for simultaneous measurements with a microphone array.

Keywords: Sound, Music, Acoustics

1 INTRODUCTION

The bassoon has a long bent corpus with many toneholes of different size and opening direction distributed across it. Like in other large wind instruments, the position of the player holding the instrument has important influence on the radiation. Being a sound source of large geometrical irregularity, the bassoon/player combination is assumed here to be a good test case for a complex musical instrument radiator.

Tonmeisters, who record the bassoon sound for music production, experience an imbalanced sound, especially when placing spot microphones in the vicinity of the instrument. Besides obvious sound disturbances like keywork noise and level variations due to the varying position of the first open tone hole with respect to the microphone, also the timbre appears imbalanced between notes [5].

The purpose of this work is to study how the radiation pattern of the bassoon without player changes due to variations in the fingering.

After the pioneering works of Jürgen Meyer [6], who was the first to unravel the directions of the bassoon's main radiation lobes with 3 dB dynamics (Fig. 5), very few systematic attempts to measure the radiation of the bassoon have been reported - to the knowledge of the authors.

Among these are the works of Pollow *et al.*, who recorded the bassoon (among a broad variety of musical instruments) in anechoic conditions with a spherical array of 32 microphones in an truncated icosahedric arrangement of 4.2 m diameter [8, 9]. The data of these measurements is now publicly available [11]. In a similar fashion, Paetynen and Lokki [7] recorded the bassoon (among other instruments) using an array of 22 microphones in pentagonic arrangement at 6 height levels. The angular resolution of the microphone arrays in these studies is near to 36 and 72 degrees, respectively.

In contrast to these studies, Grothe and Kob employed an artificial player for continuous blowing of the bassoon and derived 2D directivity pattern from continuous measurements with the turntable method. In the horizontal and a vertical plane polar pattern of the bassoon radiation without player are rendered in 1 degree resolution [4].

Using a repeated capture measurement scheme with a musician playing notes and a rotated microphone arc, Bodon measured the 3D directivity of the bassoon (among other instruments) in 5 degree resolution [2]. Most recently, Ackermann *et al.* analyzed variations in bassoon radiation patterns using spherical harmonic (SH) representations of the data recorded by Pollow *et al.* [9, 11]. With this interpolation technique, 3D radiation pattern of 1 1 degree resolution were produced, at SH order 4 [1].

As a complement to these earlier studies, the purpose of this paper is to present a 3D directivity data set of the bassoon without player, with a high spatial resolution of 5 degrees in the measurement.

2 MATERIALS AND METHODS

For a repeated measurement scheme in acoustical radiation experiments, a precise positioning system and a stable excitation of the measurement object is vital. For the excitation, an impulsive sound source has been used. It provides sufficient excitation level for radiation measurements from a few Hz to about 1.5 kHz (Fig. 1).

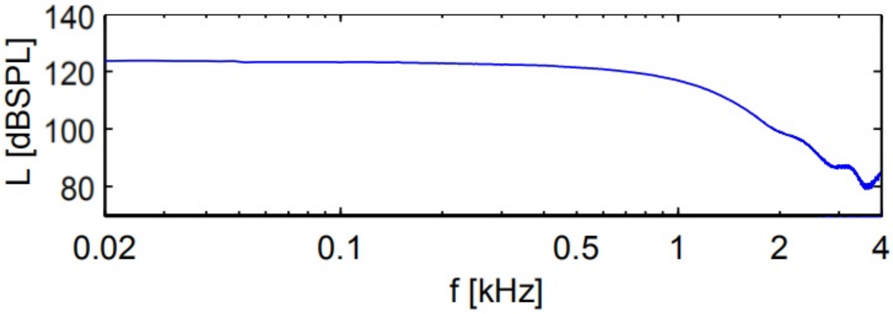

Figure 1. Frequency response of the excitation mechanism

Experimental setup Bassoon and excitation mechanism were mounted on a frame of metal tubing with 16-20 mm diameter. This frame was mounted on a 2 axis turntable (ELF, fouraudio, Herzogenrath, Germany) such that the bassoon's longitudinal axis matched the vertical rotation axis of the turntable (*y* in Fig. 2). A measurement microphone (Type 4190, Brüel and Kjær, Naerum, Denmark) was positioned in the horizontal plane, in negative *x*-direction in a distance *D*=2 m (Fig. 2). The setup was placed in an anechoic chamber with a cutoff frequency of about 200 Hz.

During a measurement series, the turntable was rotated clockwise

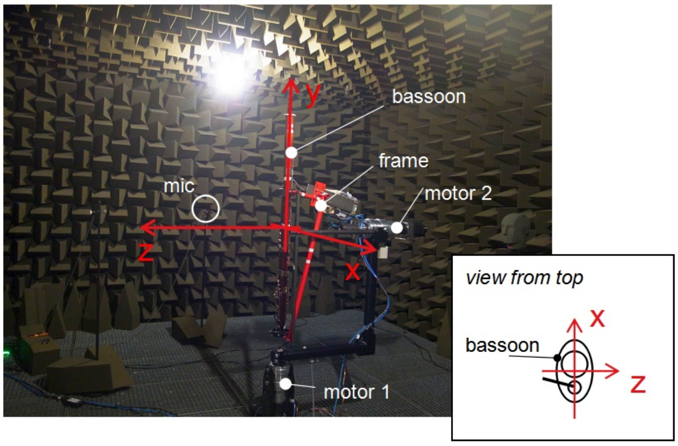

Figure 2. Setup and coordinate system for the bassoon radiation measurement with a 2 axis turntable.

- about the vertical axis (motor 1), by angle H (perpendicular to the horizontal plane);
- about the pivoted horizontal axis (motor 2), by angle V (perpendicular to a vertical plane).

Figure 2 shows the initial state of the setup ($H = V = 0$). For this setup, the microphone position $\vec{m}$ in a bassoon centered coordinate system $(x|y|z)$ as a function of turntable rotation angles H and V writes

$$\vec{m} = (-\cos(V)\cos(H)D, \sin(V) - \cos(H)D, \sin(H)D)^T. \qquad (1)$$

Signal processing Aiming at comparable results, the postprocessing followed the procedures described in the earlier studies [2], and [10]:
The position dependent levels $L(H,V,f^n_{0,nom})$ shown in the following are calculated from the absolute values of the fft-coefficients at $f^n_{0,nom}$. The latter are the fft-lines closest to the frequencies of the harmonic series $n\,f_0$, where n is the ordinal number of the harmonics and and f_0 is the fundamental pitch of the respective fingering. Pitches are referenced to equally tempered tuning at A4 = 440 Hz. For the signal processing, an open toolbox[1] for MATLAB® [3] has been used.
To generate frequency dependent balloon plots from the spectral level data, the position of the microphone $\vec{m}(V,H)$ was converted to azimuth and elevation angle with respect to the bassoon centered coordinate system (Fig. 2), and the level of the corresponding measurement is displayed as radius.

Repeatability The combination of excitation mechanism and 2-axis turntable shows a good repeatability. A full rotation series in 5 ° resolution in both angles H and V, with 3 repetitions in each position took about 28 h. The average difference between the first ((V|H) = (0 °|0 °)) and the last ((V|H) = (360 °|360 °)) measurement is < 1 dB between 150 Hz and 1.5 kHz, maximum difference < 1.5 dB.

Studied fingerings In total, four fingerings, namely B♭1, E♭3, E♭3$_{aux}$, and F3 were studied. The fingerings B♭1 (f_0=58.3 Hz) and F3 (f_0=174.6 Hz) mark the extremes of all holes being closed, and no keys pressed, respectively (Fig. 3: top, and bottom). The fingering E♭3 (f_0=155.6 Hz) is a so-called fork fingering. It is identical as for the neighboring note E3 (f_0=164.8 Hz), except the next tone-hole is closed[2] (Fig. 3, upper mid). The fingerings E♭3 and E♭3$_{aux}$ (f_0=155.6 Hz) differ only in one hole additionally opened (approx. at x =1.75 m (Fig. 3, lower mid)). This very common auxiliary fingering for E♭3 is known among bassoonists not only to stabilize the tone production and slightly flatten the pitch, but also to produce a significant change in timbre. For the fingering F3 (f_0=174.6 Hz), by lifting the fork, three closely spaced finger holes in the region $0.52m < x < 0.6m$ are open (Fig. 3: bottom), instead of only one as in E♭3.

3 RESULTS

The observed complex radiation patterns of the bassoon are the result of a superposition of single point sources that contribute with individual phase and amplitude to the measured sound pressure level at the microphone position. For the relation of wavelength and open tone-hole distances the following basic acoustic relations apply: For very low frequencies the sound radiation of a wind instrument with multiple sound sources can be described as omnidirectional when the overall size of the instrument is small, e.g. 1/4, compared to the wavelength λ. In this case, the radiation of all instruments' openings is more or less in phase. For the bassoon this is never the case since the lowest fundamental produced at B♭1 is 58 Hz, and with a waveguide length of 2.5 m the associated frequency for $\lambda/4$ would be 34 Hz. However, for the lowest fundamental the radiation pattern is mostly omnidirectional (see pattern marked with + in Fig. 4) because only one opening, the passive end, radiates sound. For other tones, the fundamentals and all partials of the contributing sound sources are therefore not in phase, and superpose with amplitudes and phases that are individual for each fingering. The effect of the fingering is shown in Fig. 4. The fundamental E♭3 (155.6 Hz) is realised with two different

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[1] http://www.ita-toolbox.org/index.php

[2] downstream of the active tone-hole at approximately x =0.6 m

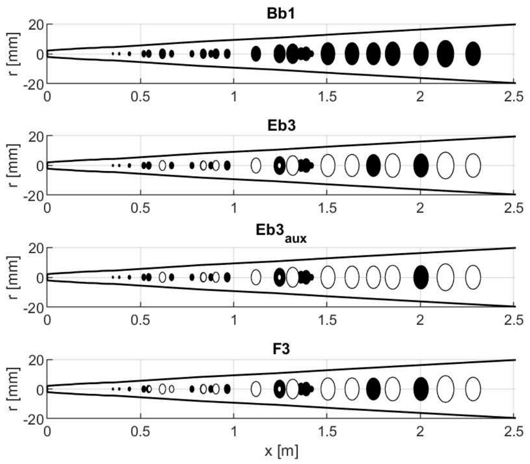
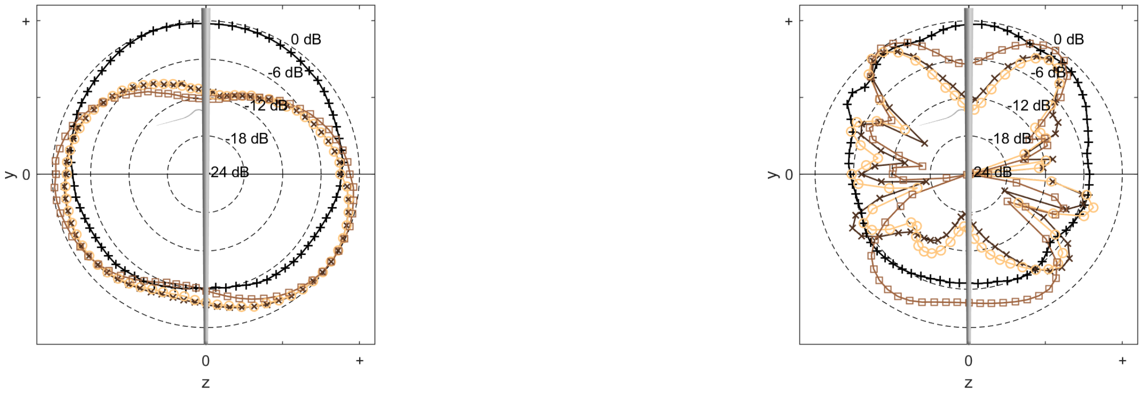


Figure 3. Tonehole-pattern of the studied fingerings

fingerings (○: normal fingering, ×: auxiliary fingering). The tone-hole openings only differ in the fifth hole from the passive far end of the bassoon bore which is open in case of the auxiliary fingering (Fig. 3). The effect on radiation is shown in the radiation analysis of the 2^{nd} partial near 300 Hz (Fig. 3 (a), left) and of the 5^{th} partial near 700 Hz (Fig. 3 (b), right). Whereas the overall shape of the polar pattern is similar, at 700 Hz the details exhibit differences of up to 3 dB for the side-lobes which – when played in temporal proximity – would produce a perceivable timbre change.



(a) $n f_0 \approx 300$ Hz

(b) $n f_0 \approx 700$ Hz

Figure 4. Single-partial radiation pattern in the frontal plane. Comparison of 4 different bassoon fingerings
+: B♭1 ($f_0 = 58.3$ Hz (a): n=6, (b): n = 12; Fig. 3 top);
×: E♭3,($f_0 = 155.6$ Hz (a): n=2, (b): n = 5; Fig. 3 upper mid)
○: E♭3$_{aux}$ ($f_0 = 155.6$ Hz (a): n=2, (b): n = 5); Fig. 3 lower mid)
□: F3 ($f_0 = 174.6$ Hz, (a): n=2, (b): n = 4; Fig. 3 bottom)

Even small musical differences in melody such as a diatonic interval from E♭3 to F3 can produce large level differences of more than 12 dB as shown in the comparison of the patterns with circle markers (E♭3) and square markers (F3), respectively. Not only the location but also the number of lobes vary strongly around the instrument. As shown in Fig. 3, the only difference between F3 and the regular fingering of E♭3 are two more open toneholes (5^{th} and 7^{th} from the bocal).
These results, produced with a technical broadband excitation mechanism, are in good agreement with an earlier study of the authors on a bassoon blown with an artificial mouth [4]. The measured data can be compared to a model of the radiation characteristics of the bassoon with spherical harmonics (SH) of order 4, generated with data from a database of anechoic microphone array measurements [11]. This comparison is shown in Fig. 6 (b) vs. (c) and Fig. 7.

4 DISCUSSION

Whereas measurements from our study match well with earlier investigations [6, 4, 2], they do not resemble order 4 SH-based interpolations of directivity pattern recently published [1, 11]. Reasons for this is the low resolution of their microphone array (approximately 36° degree [8]) with respect to the complexity of the sound source.

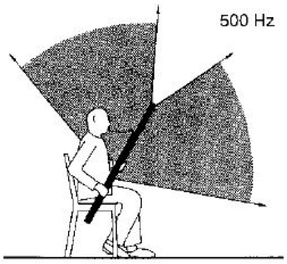
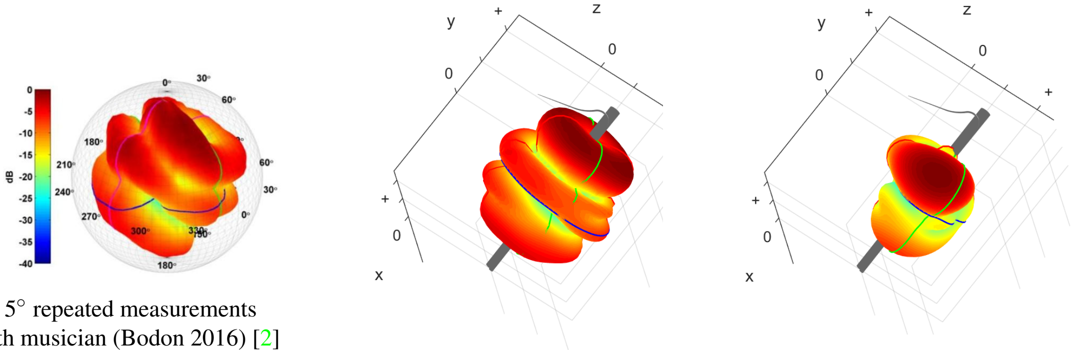


Figure 5. Directivity plot of the Bassoon (Meyer 1972) [6], reprinted with kind permission of the author.

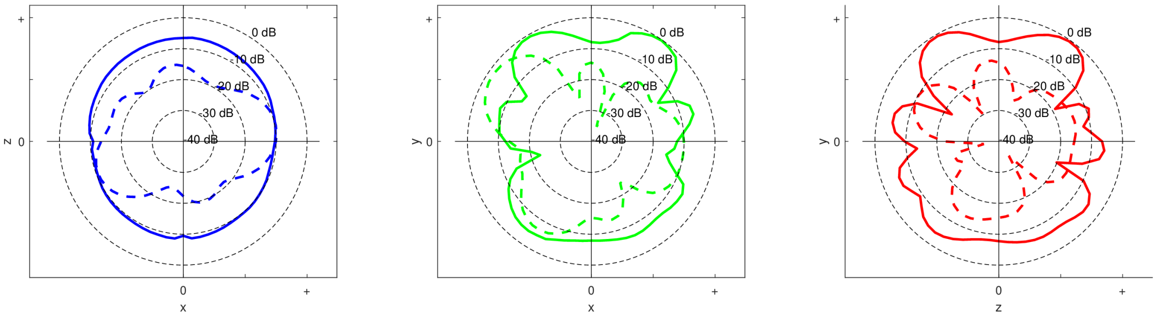


(a) 5° repeated measurements with musician (Bodon 2016) [2]

(b) 5° repeated measurements without musician (this study)

(c) 4^{th} order SH-based interpolation 32 ch. spherical array measurement with musician [1, 8, 11]

Figure 6. Bassoon directivies in 5°-resolution near 600 Hz
(a): 4^{th} harmonic frequency of D3 $f_0 = 146.8$ Hz.
(b),(c) : 4^{th} harmonic frequency E♭3, $f_0 = 155.6$ Hz.
Figure (a) is shown here for comparison, reprinted from [2] with kind permission of the author.



(a) horizontal plane (b) median plane (c) frontal plane

Figure 7. Polar plots of the bassoon directivity pattern in 5° resolution.
solid line: measured (this study); dashed line: 4^{th} order SH-based interpolation of a 32 ch. spherical array measurement [1, 8, 11].

The validity of single-center SH-based interpolations computed from measurement data with low spatial resolution depends critically upon the question if the object under study can be considered as a single, centered source.

In contrast to the approach of calculating a virtual center for a given array measurement [10], it might be interesting for muscial auralization purposes to model multi-pole radiation of one instrument as a superposition of low-SH-order-sources, i.e. to decompose 3D data into multiple sources with known positions. The data from this study is well suited for such attempts, and might also serve as benchmark to estimate the complexity of the source in terms of SH-order and design a suitable microphone array. However, for the case of the bassoon, we conclude from our measurement data that at 5° resolution spatial aliasing occurs already from 1 kHz.

If a high spatial resolution in a musical instrument radiation measurement is required, repeated capture measurements with technical excitation have many advantages over array measurements.

Future work should include a listening test with auralizations of variable SH-order basing on even higher resolution measurement data to investigate the necessity of precise radiation models of musical instruments with respect to sound perception.

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