PARAMETER RANGES FOR ARTIFICIAL BASSOON PLAYING

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ABSTRACT

This contribution presents bassoon blowing experiments with an artificial mouth. Given the precise adjustability of lip position and blowing pressure, the challenge in the presented experiment is to find those parameter combinations, that produce ”reasonable” sustained sounds. In a large set of blowing experiments, artifical mouth adjustment parameters are identified, for which sounding pitch is within af few Cents deviation from the nominal pitch expected for that fingering. For those musically relevant regimes, an overview on the steady-state parameters of bassoon playing is given. The overview comprises artificial mouth parameters (lip force, blowing pressure, time-averaged flow-rate, RMS reed pressure, and reed pressure shape parameters) and sound related parameters (harmonic spectral centroid, formant frequencies, and loudness). The experiments were carried out with one and the same synthetic bassoon reed on five modern german bassoons and cover the complete playing range in frequency (notes) and dynamics (loudness). The observed variability between the five instruments is relatively small. Yet the comparison of the steady-state parameters with acoustic impedance curves provides some insight into the resonator-reed interaction in the bassoon.

1. INTRODUCTION

When a reed wind instrument produces a sound, the periodic closing of the reed valve is triggered by reflections of pressure waves from the air column. The range of possible oscillatory states is very broad; depending on the player's interaction with the reed, many different sounds can be produced for one and the same air column.

Here, the aim is to investigate sustained notes in the usual playing range of the bassoon. While it is relatively intuitive even for a completely untrained person to start and maintain single notes on a bassoon, it is problematic to imitate this process with an artificial mouth: Even if such a device provides control over the relevant parameters, it is still demanding to determine ranges of these parameters, for which the blowing machine produces a musical sound at the expected pitch on the instrument.

One systematic approach to study the operating regimes is to keep one playing parameter constant, while varying others. Scanning through the parameters in this way, the broad range of oscillatory and non-oscillatory states are explored, and the limits of the working range of the reed can be found [1]. The parameter, that was kept constant here was not an adjustment parameter, but the fundamental frequency f_0 of the produced sound. Parameter pairs of lip force and blowing pressure were indentified, to play sustained notes in tune. Similar to the requirements that musicians must meet, the tolerated pitch deviation was only ± 5 Cent. The fact that the blowing machine could be operated successfully at reasonable levels with the required pitch accuracy suggests, that the parameters obtained from ”artifical” bassoon playing are also meaningful for the real musical performance.

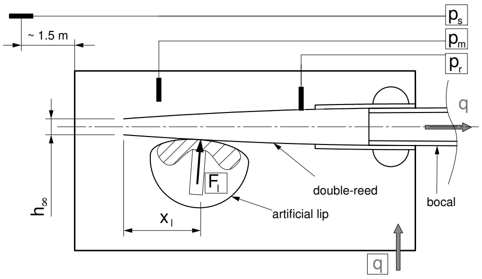


Figure 1: Sketch of the experimental setup. Measured quantities in boxes (p_m, p_r, F_{lip}, q, p_s) are recorded instantaneously during the experiment.

2. MATERIAL AND METHODS

2.1. Experimental setup

To measure the performance characteristics of the bassoon, a self-built artificial mouth has been used that facilitates precise lip adjustment (Figure 1). The main component of the device is a synthetic bassoon double-reed (270M, Conn-Selmer Inc., Elkhart, Indiana, U.S.A.) which is rigidly mounted at its rear end in the mouth pressure cavity. An artificial lip can be moved towards the reed. The lip assembly consists of a rigid rib, imitating the teeth, which is sheathed by a piece of cellular rubber. On top of this, a glycerin filled air balloon is overlayed imitating the dynamic properties of human lips. The lip is mounted onto a precision load cell that can be positioned by two micrometer screws parallel and normal to the longitudinal axis of the reed. The pressure inside the reed is measured 30 mm downstream of the reed tip. The mouth cavity is air-tight and the flow-rate into the box is measured with a thermal mass-flow meter. The external microphone was placed about 1.5 m from the large end of the bassoon perpendicular to the longitudinal axis. Details of the setup are given in [2].

The experimental procedure was as follows: After initiating the tone, the blowing pressure p_m in the mouth and the lip force F_{lip} were carefully balanced to play the note in tune at the softest possible dynamic level. Having adjusted the correct pitch, the blowing pressure was increased, followed by a readjustment of the lip force to maintain the tuning. This procedure was repeated to explore the complete parameter range for blowing pressure p_m and lip force F_{lip} for which this note on the instrument could be sounded in tune. The blowing pressures were in normal range reported for bassoon playing $1\ \text{kPa} < p_m < 9$ kPa [3], and standard fingerings [4]. The study was restricted to sounds at the expected pitches for the respective fingerings, multiphonics and other unusual sounds were excluded.

In this way, the complete musically relevant dynamical range of a note, available for the specific fingering at a fixed lip position, has been obtained experimentally.

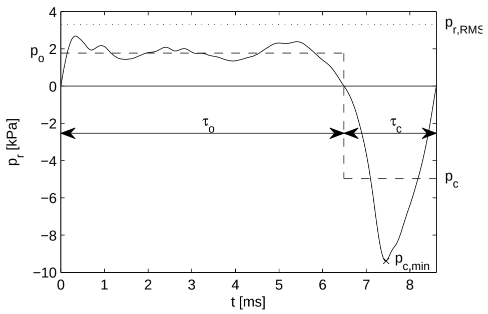


Figure 2: Reed pressure (solid) and the corresponding simplified Helmholtz-pattern (dashed), and integral mean reed pressure $\bar{p_r} > 0$, for the note B2 ($f_0 = 116$ Hz).

2.2. Directly measured quantities

During the experiments, several quantities are directly measured (see Fig. 1). Considering the instrument as a black box, the measured quantities can be divided into input and output parameters.

Artificial mouth adjustment parameters

x_l the position of the lip along the reed

F_l the force of the lip

p_m the blowing pressure in the "mouth" cavity.

Together with these adjustment parameters, the resulting output data characterize the

Working point of the reed

p_r the unsteady reed pressure in the reed,

p_s the sound pressure in the surrounding of the setup

q the mean volume flow-rate through the reed

At a fixed position of the lip, for a given resonator, the experimental situation is completely defined with these five measures. The setup is rugged enough to swap the resonator parts (i.e. bassoon and bocal) without changing the embouchure.

2.3. Derived parameters

Additional features have been extracted from the raw data recordings in the time and frequency domain. Time averaged values of lip force F_{lip} and blowing pressure p_m have been used to link the experimental situations to an analytical two-parameter model for the reed.

Reed pressure waveform parameters

In the normal playing regimes on the bassoon, the reed fully closes once per period and performs a two-step motion. During one part of the period (duration τ_o), the reed remains open, $p_r > 0$; in the subsequent part (duration τ_c) the reed is closed $p_r < 0$. The subscripts $(.)_o$ and $(.)_c$ mark the open and closed period during one cycle. For a typical bassoon reed configuration, the measured reed pressure waveform (p_r) is shown in Fig. 2. Within the two episodes of the pressure waveform p_r which are determined by the zero crossing of the reed pressure signal, the integral mean pressures are p_o and p_c, respectively.
Another measure that can be read from the pressure waveform is the RMS values of the reed pressure. This excitation sound level is related to the dynamic playing level of the instrument. As an additional parameter the maximum underpressure during the closed episode of the reed p_c, min is given.
In summary, the following six time-domain parameters are used to describe the operation point of the bassoon reed:

$\tau_{o,c}$ the duration of reed opening and closure during one cycle,

$p_{o,c}$ the integral mean pressure in the reed during the opened and closed episode,

$p_{c,min}$ the minimum pressure during the closed episode,

$p_{r,RMS}$ the RMS value of the reed pressure

Timbral spectral parameters

Characteristics of the spectrum of a sound are correlated with the perception of timbre. Many acoustical parameters and "features" of sounds have been suggested as descriptors of timbre. Only very few, purely spectral parameters will be used here, based on the widely accepted algorithms from the ISO Standard ISO/IEC 15938 (MPEG-7) [5], the phonetics software `praat` [10], and the German standard DIN 45631.
The MPEG-7 description standard defines among many others, three purely spectral parameters for timbre characterization. The three parameters are called the *harmonic spectral centroid* (hsc) in Hertz, *the harmonic spectral spread* (hss) and the *harmonic spectral deviation* (hsd). They are defined as the amplitude-weighted mean of the harmonic peaks of the spectrum (hsc), and the amplitude-weighted standard deviation of the harmonic peaks divided by the harmonic spectral centroid hsc (hss). The harmonic spectral deviation (hsd) is a measure for the deviation of the amplitudes of the partials from a global (smoothed) spectral envelope [5].
The parameters have been calculated with freely available code `TimbreToolbox` [5] from the developers of the standard.
A similar timbre characterisation method in the frequency domain is the formant analysis. Formants are broad peaks in the spectral envelope of a sound [6]. Although "formant" is a term from voice analysis, formants are not only found in sounds of singers, but also in the sound of conical wind instruments [7, 8]. In contrast to the spectral centroid it based on analyzing a number of local maxima in the spectrum. Their relative positions on the frequency axis are relevant for the impression of timbre. Each formant is characterized by a center frequency F_i and a bandwidth B_{Fi}, where i is the ordinal number of the formant. Formant analysis is attractive here, because the formant frequencies detected in bassoon sounds were largely insensitive to the sound recording position in non-ideal room acoustics [9].
In this study the Burg-Algorithm in `praat` [10] has been used to detect four formants for frequencies up to 5 kHz with the Burg-Algorithm from the recorded time-domain data of one second duration. These spectral timbral descriptors are calculated for both the pressure inside the reed and the sound pressure in the surrounding of the instrument. In psychoacoustics a number of approaches are suggested to assign a metric to a sound that describes its perceived loudness. These loudness models take spectral and temporal characteristics of the sound pressure into account, with respect to the capabilities of the human auditory system. Here, the first standardized loudness model of Zwicker (DIN 45631) has been used to assign a scalar loudness value N in the dimension Sone to the sound recorded in approximately 1.5 m distance from the instrument.
In summary, the following ten frequency-domain parameters are used to describe the operation point of the bassoon reed and the sound radiated from the instrument. The subscripts $(.)_r$ and $(.)_s$ indicate whether the property was derived from the sound spectrum measured inside (reed pressure) or outside

(sound pressure) of the instrument.

$hsc_{r,s}$ the harmonic spectral centroid

hss_s the harmonic spectral spread,

hsd_s the harmonic spectral deviation,

$F_{i\,r,s}$ ($i = 1..4$), the center frequencies of the first four formants

$B_{Fi\,s}$ ($i = i..4$), the band widths of the first four formants

N_s the psychoacoustical loudness

Quasistatic reed model parameters

The quasistatic reed model [11] predicts the flow-rate through the pressure dependent reed slit opening as

$$q = q_A \left(1 - \frac{\Delta p}{p_M}\right) \sqrt{\frac{\Delta p}{p_M}} \quad (1)$$

where $\Delta p = p_r - p_m$ is the pressure difference between the pressure p_r inside the reed and the pressure p_m in the mouth cavity; q_A and p_M are model parameters in dimensions of volume-flow rate and pressure. The function given by Eq. 1 has a maximum $q_{\max}$ at the so called saturation pressure $p_{m,s}$. Reading these two values from measured curves, the model parameters can be determined as

$$q_A = \frac{3}{2}\sqrt{3}\, q_{\max}, \quad p_M = 3\, p_{m,s} \quad (2)$$

For details see [11, 12] Especially p_M and q_A are important, as they can be used to characterize the working point with respect to an analytic model [11, 13]. The non-dimensional blowing pressure γ and non-dimensional embouchure parameter ζ are defined as

$$\gamma = \frac{p_m}{p_M}, \quad \zeta = Z_c \frac{q_A}{p_M}, \quad (3)$$

where Z_c is the characteristic impedance of the air in the cross section at the bocal tip, where the reed is attached to the resonator.

The applicability of this analytic single-reed model to the case of the double-reed has been proven [12]. From p_M and q_A a reed equivalent stiffness K_s per unit area can be deduced as

$$K_s = \frac{p_M}{q_A} \sqrt{\frac{2\, p_M}{\rho}}, \quad (4)$$

where ρ is the air density.

These parameters depend upon the initial slit height of the reed, which is closely related to the lip force applied to the reed blade. Measuring lip force during performance allows to link any quasi-static working point of the reed to these model parameters [14, 2].

In summary, the five parameters that were derived from the artificial mouth adjustment parameters and the describing the embouchure under playing conditions are the following:

p_M pressure parameter,

q_A volume-flow parameter,

K_s reed stiffness per unit area,

γ non-dimensional blowing pressure

ζ embouchure parameter

2.4. Bassoons and bocals used in the experiment

The tested bassoons were modern German Bassoons from the manufacturers Adler, Hüller, and Heckel. From the latter manufacturer, a student model and a professional model have been used. The bocal were type CD0 and CC1 of Fa. Heckel (Wiesbaden, Germany) and type N6 of Fa. Wolf (Kronach, Germany). The N6 bocal used here has the same length as Heckels CC1; CD0 is about 5 mm shorter. One of the bassoons has been measured with both N6 and CD0.

3. RESULTS

3.1. Parameter ranges

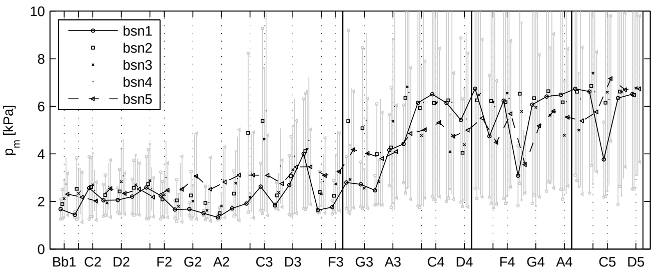
For the parameters described above, characteristical values are given in Table 1. These values have been obtained from blowing experiments with an artificial mouth, obtained with one and the same synthetic bassoon reed on five different bassoon-bocal combinations. For all instruments and notes played, the lip was in the same intermediate position x_l = 10.75 mm from the reed tip.

Table 1: Typical values for parameters in artificial mouth blowing experiments on a modern German bassoon. The values are given as a range $(\cdot)_{min} \ldots (\cdot)_{max}$ or as a mean value $\bar{(\cdot)} \pm \sigma$ (σ: standard deviation).

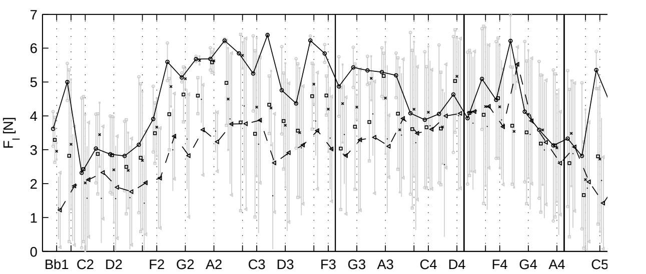
		Symbol	Unit	Range
artificial mouth adjustment parameters	directly measured	p_m	[kPa]	$1.1 \ldots 12$
		F_{lip}	[N]	$0 \ldots 7$
		x_l	[mm]	$0 \ldots 15$
working point of the reed		q	[l/s]	$0.02 \ldots 0.42$
		$p_r(t)$	[kPa]	$-24 \cdots +8$
		$p_s(t)$	[Pa]	arbitrary
	derived parameters	f_0	[Hz]	$58 \ldots 592$
		$p_{r,RMS}$	[kPa]	$1 \ldots 9$
		$p_{s,RMS}$	[dB SPL]	$72 \ldots 95$
		hsc_r	[Hz]	$380 \ldots 1000$
reed pressure waveform parameters		τ_c	[ms]	$2.8 \ldots 0.75$
		τ_c/τ	[-]	$0.1 \ldots 0.45$
		p_o	[kPa]	$0.2 \ldots 8$
		p_c	[kPa]	$-12 \cdots -2$
		$p_{c,min}$	[kPa]	$-24 \cdots -5$
		$\lvert p_c/p_o \rvert$	[-]	$1 \ldots 7$
timbral spectral parameters		hsc_s	[Hz]	$580 \ldots 1500$
		hss_s	[-]	$0.2 \ldots 0.7$
		hsd_s	[-]	$0.1 \ldots 0.3$
		F_1	[Hz]	540 ± 110
		F_2	[kHz]	1.2 ± 0.18
		F_3	[kHz]	1.9 ± 0.2
		F_4	[kHz]	3.1 ± 0.6
		B_{F1}	[Hz]	220 ± 160
		B_{F2}	[Hz]	470 ± 280
		B_{F3}	[Hz]	730 ± 450
		B_{F4}	[Hz]	890 ± 470
		N_s	[Sone]	44 ± 12
quasistatic reed model parameters		p_M	[kPa]	7.4 ± 1.8
		q_A	[m^3/s]	$(0.6 \pm 0.3)\, 10^{-3}$
		K_s	[Pa/m^2]	$(1.6 \pm 0.35)\, 10^9$
		γ	[-]	$0.16 \ldots 1.4$
		ζ	[-]	$0.6 \ldots 2.7$

3.2. Comparison of five instruments

The mouth pressures p_m range from 1.5 kPa to more than 10 kPa (Fig. 3(a)). Blowing pressures larger than 10 kPa are unrealistically high [3]. Therefore, the vertical axis in Fig. 3(a) is cropped

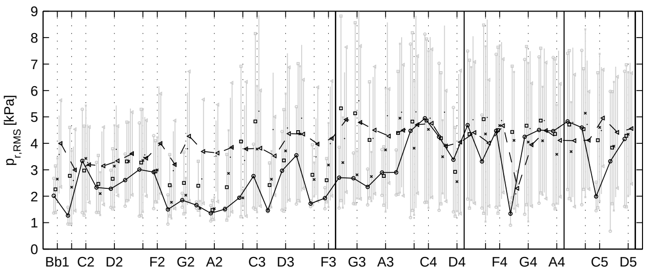


(a) Mouth pressure

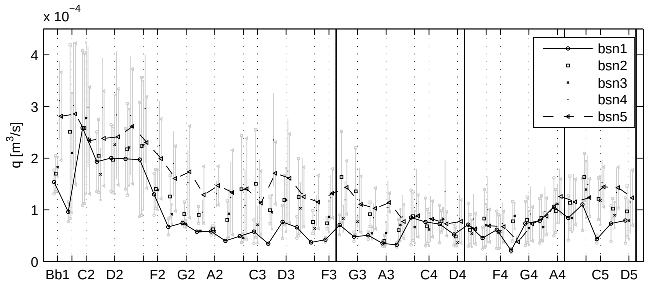


(b) Lip force

Figure 3: Input parameters p_m and F_{lip}



(a) Root-Mean-Square of the reed pressure



(b) Time averaged flow-rate

Figure 4: Output parameters $p_{r,RMS}$ and q

at this value, although notes could be played for even higher mouth pressures.
Ascending the scale, the minimum mouth pressure to sound a note in tune increases approximately linear with log-frequency: Lower notes require less blowing pressure than higher notes.
In general, two regions can be identified in Fig. 3(a): The lower notes (from B♭1 to A3) offer a smaller blowing pressure range (1 kPa$<\Delta p_m<$5.5 kPa) and are played at lower mean value of $\bar{p_m}\approx 2.5$ kPa; the higher notes (A3-D5) have a larger blowing pressure range (4.5 kPa$<\Delta p_m<$9 kPa) and a higher blowing pressure offset. Compared to the mouth pressure, the lip force characteristics to sound the notes in tune is irregular, no simple dependence on the log-frequency scale can be observed (Fig. 3(b)). Very generally speaking, the mean values $\bar{F_l}$ are smaller at the lower and upper limit of the tonal range, and larger in between. Adjacent notes may require a very different F_{lip} offset. For each single note, the lip force range ΔF_{lip} indicates the adjustments needed to compensate for tuning when changing the dynamic level. This value reaches up to several Newtons and largely depends on the tuning properties of each instrument, and, naturally, on the position x_l of the lip on the reed, which was constant in all measurements presented here. Apparently the bassoon-bocal combination *bsn1* (open circles in the graphs) was tuned too low and required globally a higher lip force, whereas for the combination *bsn5* (triangles in the graphs) the opposite trend is observed in Fig. 3(b).
For each note, the oscillatory regime established for a combination of p_m and F_{lip} is characterized by the output parameters RMS-value of the reed pressure $p_{r,RMS}$ and the time-averaged volume flow-rate q. These may be called primary output parameters, because they are distinct measures at the operating reed, directly measurable without further analysis.
The RMS reed pressure $p_{r,RMS}$ for musically relevant regimes ranges from 1 to 9 kPa, equivalent to 154 to 173 dB SPL (Fig. 4(a)). The minimum value for the softest regimes is $\bar{p}_{m,min}=2\pm 0.5$ kPa, the differences on one note comparing between instruments exceed 1 kPa. This observation is largely influenced by the tuning of the instrument. Ascending the scale, the mean RMS reed pressure $p_{r,RMS}$ tends to increase slightly. The notes of the lower register have a large fluctuation in $\bar{p}_{r,RMS}$ across the log-frequency axis. This fluctuation is decreased for higher notes; apart from some outliers, $\bar{p}_{r,RMS}$ is here around 4.2 kPa.
The time-averaged volume flow-rate q ranges from up to 4.5×10^{-4} m^3/s for C2 at the lower end of the tonal range, to less than a tenth of this value at F4 in the medium high register (0.25×10^{-4} m^3/s). The notes B♭1 to E2 require the most volume flow ($\bar{q}$ = 2×10^{-4} m^3/s). From F2 to G4, the mean flow $\bar{q}$ decreases from 2 to 1×10^{-4} m^3/s. From A4 upwards in the note scale $\bar{q}$ tends to increase again (Fig. 4(b)). These general trends in the flow-characteristics resemble the inverted lip force characteristics (Fig. 3(b)). The flow-rate tends to be increased for notes which are played at lower lip forces.

3.3. Relation with resonator acoustics

To experimentally determine the number of relevant air-column modes n_{modes} for a real bassoon and to show its change with the fingering, a rescaling of the magnitude of the input impedance curve is helpful. When the reed is beating, it is locked as a non-linear exciter to a linear resonator. For a qualitative description of this mode-locking phenomenon, Fletcher gave several qualitative criteria for both system components [15]. He postulated that i) air column modes must be strong and ii) nearly harmonically related to participate in a mode-locked regime of oscillation. In the present study, measured input impedance curves of the bassoon have been analyzed with respect to these criteria. For each fingering, a selection of modes has been made in order to meet Fletchers criteria. To meet criterion i), the impedance peaks -6 dB lower than the maximum peak were neglected. To meet criterion ii) all modes which are more than 100 Cent (one semitone) off the nearby harmonic frequency were excluded. Summing up the remaining modes yielded the number of *supporting* air column modes n_{modes}. The comparison of $|p_c/p_o|$ from blowing experiments and n_{modes} obtained from the above

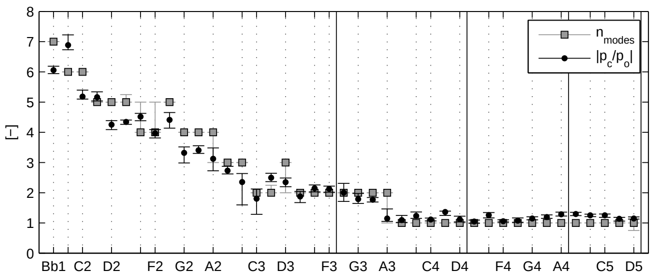


Figure 5: Relation between the mouthpiece pressure waveform ($|p_c/p_o|$) and the number of supporting resonator modes (n_{modes}).

analysis, shows their close relationship (Fig. 5). This very good agreement with the theoretical predictions [16, 17] indicates the proper choice of the thresholds ± 100 Cent for the harmonicity and -6 dB for the impedance magnitude, to determine the number of relevant air-column modes.

4. DISCUSSION

With an experimental apparatus it is possible to "artificially" play the bassoon and to investigate its acoustical behaviour under realistic playing conditions. The possibility to precisely adjust the artificial lip is very important to being able to carry out blowing experiments covering the full tonal and dynamical range of this instrument. A large set of benchmarking data describing the bassoon under quasi-stationary operation conditions is presented, including the time-averaged volume flow during playing. In particular, the measurements include the time-averaged volume flow and lip force during playing. The measured lip forces and blowing pressures for each note allow insights into the intonation corrections, that musicians have to do in fine-tuning the pitch.

The mean lip force during a sustained note can be used to link the steady-state operating parameters of the reed with the classical model of quasi-static flow through a reed channel. A reasonable applicability of this model for the case of the bassoon has been shown elsewhere [2]. This makes it possible to "translate" artificial mouth adjustment parameters characterizing realistic embouchure configurations into reed model parameters in relevant playing regimes.

Furthermore, attempts have been made to relate aspects of the bassoon performance to the resonance properties of the air column. The presented experimental data confirms for the practical case of the bassoon that the reed pressure waveform is largely determined by the number of supporting air column modes of the resonator which ranges up to seven for the lowest notes.

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6. REFERENCES

[1] Andre Almeida, David George, John Smith, and Joe Wolfe, "The clarinet: How blowing pressure, lip force, lip position and reed hardness affect pitch, sound level, and spectrum," *The Journal of the Acoustical Society of America*, vol. 134, no. 3, pp. 2247–2255, 2013.

[2] Timo Grothe, *Experimental Investigation of Bassoon Acoustics*, Ph.D. thesis, Technische Universität Dresden, 2014.

[3] Leonardo Fuks and Johan Sundberg, "Blowing pressures in bassoon, clarinet, oboe and saxophone," *Acta Acustica united with Acustica*, vol. 85, pp. 267–277(11), March/April 1999.

[4] Terry Ewell and Lisa Hoyt, "The bassoon-family fingering companion" http://www.idrs.org/resources/BSNFING/BsnFingerings.pdf, last viewed 2015/07/01, 1999.

[5] Geoffroy Peeters, Bruno L. Giordano, Patrick Susini, Nicolas Misdariis, and Stephen McAdams, "The timbre toolbox: Extracting audio descriptors from musical signals," *The Journal of the Acoustical Society of America*, vol. 130, no. 5, pp. 2902–2916, 2011.

[6] Ingo R. Titze, Ronald J. Baken, Kenneth W. Bozeman, Svante Granqvist, Nathalie Henrich, Christian T. Herbst, David M. Howard, Eric J. Hunter, Dean Kaelin, Raymond D. Kent, Jody Kreiman, Malte Kob, Anders Löfqvist, Scott McCoy, Donald G. Miller, Hubert Noé, Ronald C. Scherer, John R. Smith, Brad H. Story, Jan G. Švec, Sten Ternström, and Joe Wolfe, "Toward a consensus on symbolic notation of harmonics, resonances, and formants in vocalization," *The Journal of the Acoustical Society of America*, vol. 137, no. 5, pp. 3005–3007, 2015.

[7] Jürgen Meyer, *Acoustics and the Performance of Music – Manual for Acousticians, Audio Engineers, Musicians, Architects and Musical Instruments Makers*, Springer, 2009.

[8] Wolfgang Voigt, *Untersuchungen zur Formantbildung in Klängen von Fagott und Dulzianen*, Gustav Bosse Verlag, 1975.

[9] Timo Grothe and Peter Wolf, "A study of sound characteristics of a new bassoon as compared to a modern german bassoon," in *Proceedings of the Stockholm Music Acoustics Conference 2013, SMAC 2013, Stockholm, Sweden*, 2013.

[10] Paul Boersma and David Weenink, "Praat: doing phonetics by computer [computer program]. version 5.1.34" retrieved 22 April 2012 from http://www.praat.org/, 2012.

[11] Jean Kergomard, *Elementary Considerations on Reed-Instrument Oscillations*, chapter 6, pp. 230–290, Springer Verlag Wien - New York, 1995.

[12] Andre Almeida, Christophe Vergez, and Rene Causse, "Quasistatic nonlinear characteristics of double-reed instruments," *Journal of the Acoustical Society of America*, vol. 121, no. 1, pp. 536–546, 2007.

[13] Fabrice Silva, Jean Kergomard, Christophe Vergez, and Joël Gilbert, "Interaction of reed and acoustic resonator in clarinetlike systems," *The Journal of the Acoustical Society of America*, vol. 124, no. 5, pp. 3284–3295, 2008.

[14] Timo Grothe, "Investigation of bassoon embouchures with an artificial mouth," in *Program of the 11th Congrès Français d'Acoustique and 2012 IOA annual meeting, Acoustics2012, Nantes*, 2012.

[15] N. H. Fletcher, "Mode locking in nonlinearly excited inharmonic musical oscillators," *The Journal of the Acoustical Society of America*, vol. 64, no. 6, pp. 1566–1569, 1978.

[16] Jean-Pierre Dalmont, Joël Gilbert, and Jean Kergomard, "Reed instruments, from small to large amplitude periodic oscillations and the helmholtz motion analogy," *Acta Acustica united with Acustica*, vol. 86, pp. 671–684(14), July/August 2000.

[17] S. Ollivier, J.-P. Dalmont, and J. Kergomard, "Idealized models of reed woodwinds. part i: Analogy with the bowed string," *Acta Acustica united with Acustica*, vol. 90, no. 6, pp. 1192–1203, 2004.