Investigation of bassoon embouchures with an artificial mouth

Timo Grothe

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Technische Universität Dresden, Marschner Str. 32, 01307 Dresden, Germany
timo.grothe@tu-dresden.de

Playing double-reed woodwinds in tune requires individual embouchure adjustments for each fingering. By pressing his lips to the opposing reed blades, the musician can fine-tune the intensity and fundamental frequency of oscillation, which is only roughly set by the air column. For a controlled study under realistic conditions, an artificial mouth with adjustable lips has been constructed, which enables the measurement of the force exerted to the reed while playing.
Experimental results on a synthetic bassoon double-reed are presented. The reed's resonance frequency and damping are estimated based on acoustic impedance measurements from the reed's outflow end. In the quasi-stationary regime, flow characteristics were recorded with respect to lip force and position on the double-reed. Parameters corresponding to realistic embouchures can be deduced for a lumped reed model. In the dynamic regime, the monitored values of lip force and blowing pressure allow to relate the operation point of the artifical mouth to a quasistatic embouchure configuration.
On a bassoon, blowing experiments with the artificial mouth were carried out covering the full pitch range ($f_0 = 58 - 600$ Hz). The investigation reveals that, with the constraint of correct tuning, the lip force adjustments of a bassonist to play adjacent notes equally loud is in some cases comparable to the adjustment needed to reduce the sound intensity from *forte* to *piano* on the same note.

1 Introduction

The double-reed mouthpiece behaves like a highly nonlinear valve, which interacts with a resonating air column when the musician plays the instrument. In the past, simplified physical models describing the pressure-controlled motion of the single-reed tip [1] as well as measurement techniques to obtain the model parameters for real reeds [2] have been developed. Both techniques were used to characterize double-reeds [3].
In woodwind performance, the player controls the instrument through modifications of the structural and fluid mechanical characteristics of the mouthpiece by adjusting lip-force and blowing pressure. These adjustments determine the interaction of reed, lip, and mouth of the musician and are described by the term *embouchure*, which is known to be a key issue of musical expression among woodwind instruments players. The present study investigates the influence of the embouchure on the sounding frequency on several bassoon notes with the help of an artificial mouth.
First, realistic embouchure configurations are characterized by means of lumped model parameters obtained from experiments. Second, ranges for lip-force and blowing pressure have been explored for playing regimes in which the sound is in tune.

2 Materials and Methods

2.1 Analytical model of the double-reed

The basic model of the single reed is a discrete model in which the reed tip displacement x is the only degree of freedom [1]. The equation of motion for the reed tip as a function of the pressures and forces acting on it writes

$$F(t) + p_m(t)\, S_r = m\, \ddot{x}(t) + d\, \dot{x}(t) + k\, x(t) + p_r(t)\, S_r, \qquad (1)$$

where m, d, and k are constants for mass, damping and stiffness of a reed equivalent lumped model. The variables p_m and p_r are pressures in the mouth and in the reed acting on the reed blade's effective surface S_r. The displacement x ranges from 0 to $h/2$, where h is the reed slit height, which, in case of double-reeds is the maximum distance between the opposing reed blades. The external force $F = k\, x_\infty$ pre-displaces the reed-tip to the position x_∞. For $x = h/2$ the reed is closed.
In the absence of pressure, assuming that the force F is time-invariant, a harmonic solution is given in terms of the reed displacement amplitude in the frequency domain $\hat{x} = |x(f)|$ by

$$\hat{x} = \frac{\hat{p}_r\, \frac{1}{K}}{1 - \left(\frac{f}{f_r}\right)^2 + j\left(\frac{f}{f_r}\right)\frac{1}{Q_r}} \qquad (2)$$

where $f_r = 1/(2\pi)\, \sqrt{k/m}$ is the reed's natural frequency, $K = k/S_r$ is the equivalent reed stiffness per unit area, and $Q_r = (m\, 2\, \pi\, f_r)/d$ is the quality factor of the reed resonance.
In the quasi-stationary regime $(\cdot)_0$, the steady solution of Eq. (1) for the rest position x_0 reads

$$x_0 = x_\infty + \frac{\Delta p_0}{K}, \qquad (3)$$

where $\Delta p_0 = p_m - p_r$ is the pressure difference across the reed. For convenience the displacement x_0 is replaced by the slit height $h_0 = h - 2\, x_0$. The steady response Eq. (3) in terms of the intake cross section $S_0 = h_0\, \bar{w}$ writes

$$S_0 = S_\infty \left(1 - \frac{\Delta p_0}{p_M}\right) \qquad (4)$$

where p_M is the mouth pressure needed to completely close the reed; $\bar{w}$ is the effective reed width, which is the width of an equivalent rectangular reed channel; quantities $(\cdot)_\infty$ describe the initial configuration in absence of pressure with a lip force applied. The interaction of the pressure induced reed deflection and the flow-rate is included by means of the Bernoulli equation $\Delta p_0 = \rho\, q^2/(2\, S_0^2)$. Inserting into Eq. (4) and rearranging yields an expression for the quasi-stationary flow q through the reed channel

$$q = q_A \left(1 - \frac{\Delta p}{p_M}\right) \sqrt{\frac{\Delta p}{p_M}}, \qquad (5)$$

where $q_A = S_\infty \sqrt{2\, p_M/\rho}$ is a constant proportional to the maximum flow rate $q_{max} = 2/(3\sqrt{3})\, q_A$. With the above equations single ($\bar{w} = w$) and double-reeds ($\bar{w} = 2/3\, w$) with a physical reed channel width w have been modeled [2, 3].
The unknowns in the above equations are referred to as reed parameters. In summary, the independent parameters characterizing a single or double reed are:

- f_r : Fundamental resonance frequency [1/s]
- Q_r : Quality factor of this resonance [-]
- q_A : Flow parameter [m^3/s]
- p_M : Pressure to close the reed [Pa]

Two experiments have been carried out from which these parameters were determined experimentally with a bassoon double-reed in various embouchure configurations.

2.2 Experimental setup

To investigate the reed in realistic embouchure situations, an artificial mouth has been constructed. The key feature of this device is the possibility to precisely adjust the artificial lip relative to a rigidly fixed double-reed mouthpiece. The lip fixture can be positioned along the longitudinal axis of the double-reed and perpendicular to it by use of micrometer screws (Fig. 1). The lip is mounted on a load cell such that the integral force exerted to the lip can be measured. For optical access to the reed blades, the lip fixture is mounted in a housing made of acrylic glass.
In double-reed embouchures, the player "bites" the reed by

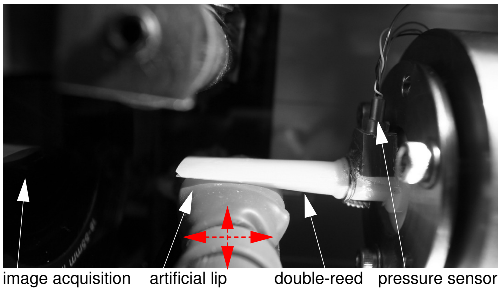

Figure 1: Photograph of the artificial mouth with axial and vertical lip position adjustment. The upper lip was retracted from the blade in the experiments.

pressing his teeth into the lips, which rest on the reed blades. To mimic this situation, a three component artificial lip has been constructed. It consists of a rigid rib imitating the teeth, which is sheathed by a piece of 3 mm cellular rubber. On top of this, at the contact surface to the reed blade, a glycerin filled air balloon is overlaid, which reported to have damping characteristics similar to human lips [4].
In an experimental situation, the housing is pressurized and the pressure is controlled manually by a precision diaphragm pressure regulator without constant bleed. The resulting pressures in the artificial mouth and inside the reed are measured with piezoresistive transducers (Kulite XCQ-093, Leonia, USA), the flow into the artificial mouth is measured by a thermal mass-flow meter (Voegtlin GSM-D9TA, Aesch, Switzerland). The housing of the setup has the outer dimensions 200 x 180 x 80 mm^3 and has been proven to be airtight up to a pressure difference of 20 kPa.
Owed to the precise lip adjustment, the artificial mouth cavity is excessively large compared to that of a musician. Although the vocal tract resonances are used in advanced single-reed performance techniques [5], this parameter is considered as minor here compared to the interaction of reed and lips. Except for the mouth cavity volume, the setup can be used to reproduce realistic configurations of lips relative to the double-reed which will be called embouchures in the following.

2.3 Measurement of reed parameters

A synthetic bassoon double-reed (Selmer Premium Plastic Medium 270M, Elkhart, USA) has been used to exclude the dependence of the mechanical properties of the reed blade upon the moisture content of the air.
Preliminary experiments evaluating the sounding frequency and the dynamic level of the blown reed suggested that it is insignificant if the reed is "bitten" by one or two lips, as the initial reed slit height seemed to be the determining factor. The following experiments were carried out in an asymmetrical configuration, where an artificial lip was pressed to one reed-blade, while the other was left free. The distance of the lip's axis relative to the reed tip has been fixed at 10.75 mm, which is an intermediate value for the position of the lower lip when playing the bassoon.
For each of several embouchures with varying lip force, two experiments have been carried out to identify the double-reed parameters. The parameter representing the embouchure is the initial reed slit height h_∞.

Dynamic reed parameters The reed's dynamical properties f_r and Q_r can be estimated from the acoustic impedance measured at the downstream end of the double-reed [6]. While a reed blade motion is excited acoustically by a swept-sine pressure signal from the impedance head, the input impedance spectrum measured at the downstream end of the reed has a dip near the mechanical resonance frequency of the double-reed assembly. The dip corresponds to an admittance maximum of the reed assembly and can be clearly detected in the spectrum when comparing two configurations with free and strongly damped reed blades.
From successive measurements with increasing lip force this dip can be traced (Fig. 2). Considering the asymmetrical embouchure, this technique may be rather vague in estimating eigenfrequencies of the reed-blade. With regard to the lumped model, however, it gives a qualitative idea of the increase in resonance frequency and damping of the reed-lip assembly as the lip force on the reed blade is increased.

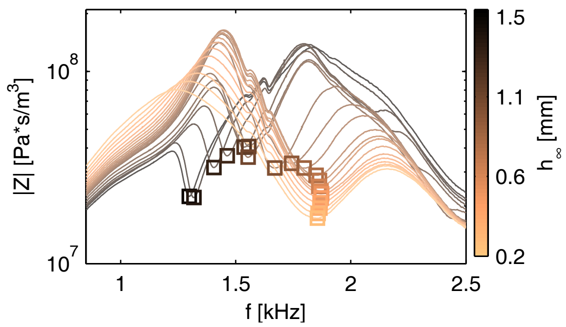

Figure 2: Acoustic impedance spectra measured at the downstream end of a bassoon double-reed in several embouchure configurations. The color indicates the initial reed slit height h_∞. The squares mark the impedance dips associated to the resonance frequencies f_r of the reed assembly.

Quasi-stationary reed parameters The flow-related reed parameters p_M and q_A can be obtained from a measurement of the reed's non-linear pressure flow characteristic, which is a plot of flow-rate versus the corresponding differential pressure between mouth and reed channel for a non-beating reed [2]. The pressure p_M to close the reed and the maximum flow q_{max} are indicated in the graph.
In the present setup, the flow-rate has been measured upstream of the reed, at the intake of the artificial mouth. In contrast to other experimental setups with a diaphragm at the outlet of the reed to measure the flow [2, 3], the configuration is identical to the playing situation: Bocal and bassoon

were attached to the reed during the experiments. Because of the large volume of the artificial mouth, the measurement procedure required to adjust several steady-state regimes of constant mouth pressure by use of a pressure regulator. To prevent the reed from auto-oscillations, a piece of plasticine was attached to the free reed blade and the openings of the resonator were loosely stuffed with foam, additionally.
The curves obtained from connecting the measurement points are scaled along the q- and Δp-axis by the initial reed slit height h_∞, which characterizes the embouchure configuration (Fig. 3).

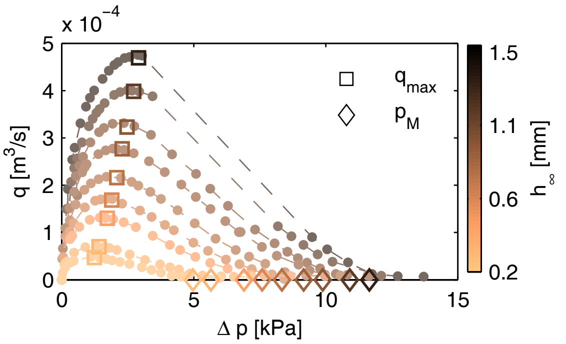

Figure 3: Quasi-stationary pressure-flow characteristic of a bassoon double-reed in several embouchure configurations. The color indicates the initial reed slit height h_∞.

3 Results

3.1 Reed parameters for realistic embouchures

The whole range of embouchure configurations has been covered with the axial lip position chosen in the above measurements. The initial reed slit height has been adjusted between 1.4 mm, which is the distance of the reed blades in the absence of lip force and pressure difference, and 0.2 mm, the minimal slit height at which it was possible to sound a note.
From the characteristics measurements (Figs. 2 and 3) the model parameters have been determined as follows: The reed's resonance frequency f_r and quality factor Q_r are obtained from fitting the transfer function of a damped oscillator to the characteristic dips in the acoustic input impedance spectra shown in Fig. 2. The parameters p_M and q_{max} related to steady flow are directly read from the non-linear reed characteristics shown in Fig. 3. Assuming the linear relation of differential pressure and intake cross section Eq. (4), the flow parameter q_A is calculated by $q_A = 3/2\sqrt{3}\, q_{max}$.
Concerning the reed's resonance frequency, Almeida provides values of 2.7 and 2.4 kHz on dry bassoon reeds from natural cane and 1.9 kHz on a plastic reed without embouchure interaction [3]. Vibrational analyses conducted by Pinard *et al.* on freely vibrating clarinet reeds showed that the resonance frequencies of wet clarinet reeds are reduced by 25 % to 1.7 kHz compared to 2.3 kHz for dry reeds [7]. The effect of the embouchure on the resonance frequency has been studied by Thompson on a clarinet reed, who was able to shift the resonance frequency between 2 and 3 kHz, in extreme cases between 1.8 and 3.4 kHz [8].
Concerning the parameters of steady flow, a similar study has recently been conducted for a synthetic clarinet reed by Dalmont *et al.*, who provided values for p_M and q_A, measuring several embouchure configurations [2]. The reed parameters

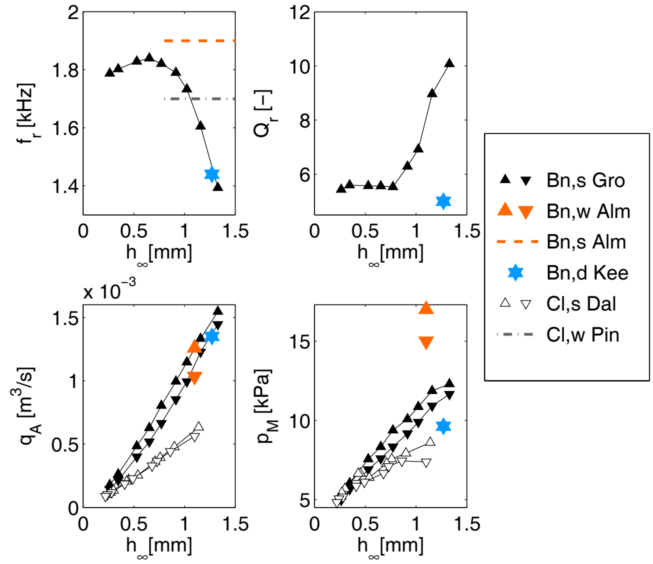

Figure 4: Parameters of a lumped element reed model of bassoon double-reed as a function of the initial reed slit height h_∞, for increasing (△) and decreasing (▽) pressure. Comparison of own measurements (Gro) with literature data (Alm [3], Kee [6], Dal [2], Pin [7]) from bassoon (Bn) and clarinet (Cl) reeds in wet (w) and dry (d) conditions and reeds made from synthetic materials (s).

from the present study are juxtaposed in Fig. 4 to values from the literature for bassoon and clarinet reeds.
The other parameters for the basic single-reed model can be calculated from the ones given above for any embouchure situation characterized by an initial reed slit height h_∞ as

$$\begin{aligned} K_s &= \frac{p_M}{q_A}\sqrt{\frac{2\,p_M}{\rho}} \;; & S_\infty &= \frac{p_M}{K_s} \;; \\ \bar{w} &= \frac{S_\infty}{h} \;; & K &= 2\,K_s\,\bar{w} \;. \end{aligned} \qquad (6)$$

3.2 Lip force in playing regimes

The artificial mouth (Sec. 2.2) allows to carry out blowing experiments in the same setting as in the previous experiments, without disconnecting the resonator from the mouthpiece. On a bassoon, the device is able to generate a sound for any note within the usual playing range (B♭1, $f_0 = 58$ Hz to d", $f_0 = 591$ Hz).
In all subsequently reported experiments, the embouchure parameters were adjusted such that the respective notes sounded in tune according to the standard equal tempered scale (reference a': $f_0 = 443$ Hz).

Embouchure parameter ranges To investigate the embouchure parameter ranges on one specific modern German bassoon, all notes have been played using the standard fingerings according to the fingerchart[1] of the International Double Reed Society (IDRS). The same synthetic bassoon reed, which was characterized in the previous experiments has been used with the asymmetrical embouchure configuration described above. The experimental procedure was as follows: After initiating the tone, the blowing pressure in the mouth and the lip force were carefully balanced to play the note in tune at the softest possible dynamic level. Subsequently, the blowing pressure was increased followed by a readjustment

[1] http://www.idrs.org/resources/BSNFING/BsnFingerings.pdf last viewed 2012/02/20

of the lip force to maintain the tuning. The parameter ranges for blowing pressure p_m and lip force F for which the notes on the instrument could be sounded in tune, are shown in Fig. 5.
For each note the experiment was ended if the reed overblew (a sudden jump into a new stable regime with higher pitch), switched to another mode (a smooth and reversible turnover to a higher or lower pitch as the pressure is increased) or produced a multiphonic sound (a mutual sounding of two enharmonic notes). In rare cases, p_M was reached (the reed stayed closed, d') or the lip was completely retracted from the reed blade (C, h'). In the lowest register, the experiment predominantly ended in overblowing. The “short fingerings” (notes in the upper first register to be fingered with the left hand only) tended to mode switches rather than to overblowing. Multiphonics and persistent reed closure occurred only in the higher registers. Here, some notes on the instrument could be sounded in tune at very high blowing pressures $p_m > 12$ kPa. However, the plot in Fig. 5 is restricted to the normal range of blowing pressures in bassoon playing which is 1 kPa $< p_m <$ 9 kPa [9].
In the present experiments, the sound pressures measured approximately 2 m from the instrument were in the range of 70 to 98 dB SPL.

Embouchure corrections for sound intensity Sounding a note in tune on the bassoon does not only depend on the fingering, but also on the desired dynamic level. If a sequence of notes has to be played at a the same level, the musician might have to change its embouchure significantly from note to note.
To report the required embouchure corrections, values of mouth pressure and lip force are provided in Fig. 5. These notes were played with the artificial mouth at the same dynamic level, which was given in terms of the RMS-value of the reed pressure. This scalar might not be proportional neither to the radiated sound nor to the perceived loudness, but it is suited to compare the embouchures of adjacent notes and is independent of the room acoustics.

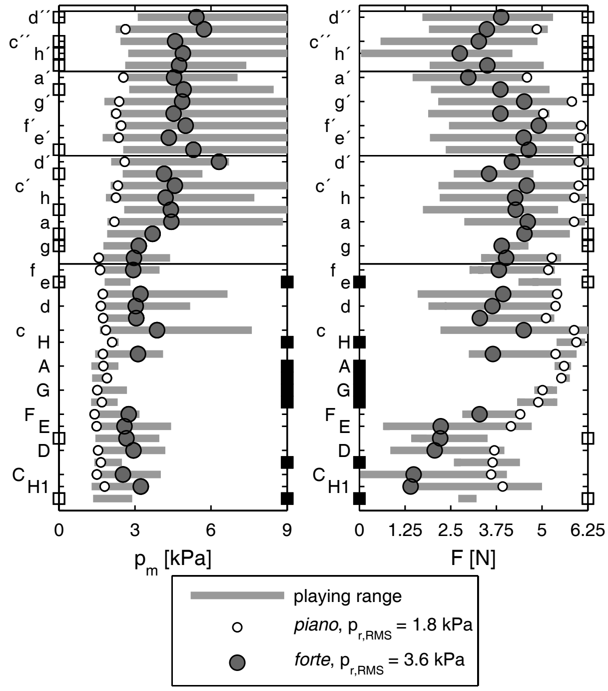

Figure 5: Time-averaged mouth pressure p_m and lip force F in an artificial mouth during bassoon playing.
Thick grey lines depict the parameter ranges of playing in tune. Circles mark values corresponding to two given RMS reed pressures for soft (*piano*) and loud (*forte*) playing. Squares mark notes that could not be played at these levels (*piano*:□, *forte*:■). Horizontal black lines mark the register borders [10].

4 Discussion

Experimental setup The asymmetrical embouchure situation chosen for the experiments might look improper at first glance. A real bassoon embouchure, however, is not so far from this situation: Bassoonists usually have an overbite on the reed. The upper teeth and lip are used as a support against the action of jaw and lip on the double-reed. The overbite results in a parallel offset which provides a finer control on the reed slit at the tip.
In the artificial mouth, this support is provided by means of the rigid fixture of the reed at its rear end (Fig. 1): The force application point is shifted about 25 mm downstream compared to players upper lip. Thus, a well defined reed configuration can be adjusted by only one lip. The fact that all notes were actually playable at reasonable sound pressure levels confirms that this is a proper way to imitate a real double-reed embouchure. The usage of an upper lip will provide additional damping, which may be important in fine-tuning the sound color.

Dynamic properties The dynamic measurements presented in Fig. 4 clearly show a strong dependence of the embouchure on the reed's resonance frequency. The range, in which the resonance frequency was shifted by tightening the embouchure was about 30 % (1.4 to 1.8 kHz). This is somewhat smaller than the range observed by Thompson on a clarinet reed with a similar measurement technique [8].
The resonance frequency of the reed is far above the actual sounding frequency, but it might cooperate with higher modes of the resonator in the playing regime. Experiments and calculations on the bassoon have shown, that higher mode coupling is important in many fingerings [6, 11]. Especially in the upper registers, where higher mode fingerings with irregularly spaced resonances are used, it might be useful for the player to tune the reed's resonance such that the regime of oscillation is stabilized. The need for such stabilization is apparent in the light of the broad variety of auxiliary fingerings that especially bassoon players are urged to experiment with [6, 11]. For a further investigation, direct measurements of the reed-tip displacement as reported by Almeida [3] should be carried out to provide detailed insights into the structural mechanical behavior of the reed lip assembly.

Quasi-stationary properties Compared to the clarinet reed, the hysteresis between the characteristics recorded at increasing and decreasing pressures is larger for the bassoon double-reed. As the synthetic bassoon reed used here behaved similar as wetted double-reeds of natural cane [3], it can be hypothesized that the greater hysteresis compared to single reeds is due to the double-reed design. In the quasistatic deformation, this encounters dry friction in the contact area where the curved reed blades are tied together and internal friction in the material. In dynamical regimes, viscous effects of the fluid may become important.

Performance characteristics The results form the blowing experiment give some insight into the actions required from a player in *quasi-stationary* playing. It can be seen in Fig. 5 that the parameter ranges of some notes (e.g. G♯, H, e), are considerably small compared to their neighbors. To a player, these notes may appear to be out of tune, as they cannot be played loudly without changing their pitch. In the higher registers, notes are found which cannot be played softly (e.g. g, c'♯, h') at the right pitch. Generally, the plot of lip forces indicates that the notes in the low register have smaller and more demarcated ranges of playing parameters, compared to higher notes, whose pitch is more easy to bend as musicians report.

Another intuitive aspect of woodwind performance is confirmed by the results depicted in Figure 5: Loud notes are played with high blowing pressures p_m and a "loose embouchure" (small F), whereas soft notes require a "tight embouchure". A general trend can be seen that high notes require a larger blowing pressure than low notes, independently of the dynamic level. Ascending in the scale, the lip force increases up to the third register and decreases again in the highest register. Therefore upwards octave jumps may require a remarkable tightening (e.g. H1-H, D-d) or loosening of (e.g. a-a', h-h') of the embouchure.

Although the lip force characteristics look similar for soft and loud playing in principle, it differs in details. This indicates the need of incessant embouchure corrections not only between adjacent notes (e.g. E-F, c-c♯, c'-c'♯, f'-f'♯), but also between different dynamic levels played on the same note.

As articulation and speed are excluded in this experiment, it can be guessed that in a real musical performance the proper dynamic adjustment of the embouchure is even more complicated.

5 Conclusion

The ability of a precise lip adjustment and lip force measurement in an artificial mouth reveals insights into the interaction of reed and player.

Realistic bassoon embouchures have initial reed slit heights ranging from 1.4 down to 0.2 mm and can be characterized by means of dynamic and quasistatic experiments. Parameters for a lumped model of the reed are obtained from these experiments. In the playing regime, the operation point of the artificial mouth is determined by the monitored values of lip force and blowing pressure. It can be related to a quasistatic initial slit height and, thus, to the reed model parameters describing the actual embouchure configuration. With these configurations, it is possible to play notes on a modern German bassoon across the full pitch range. The scattering of lip force and blowing pressure playing different notes under the constraint of correct tuning provide insights in the instant embouchure adjustments of basson players. Each note requires individual fine-tuning depending on the fingering and desired dynamic level. The measurements reveal that a bassoonist has to increase its lip force on the reed by about 40 % to reduce dynamic level from *forte* to *piano*. The lip force adjustment to play adjacent notes in tune at the same dynamic level is very irregular throughout the registers, and ranges from −30 % to +50 %, (average ± 10 %). These adjustments likely correspond to the subjective perception of intonation quality. An instrument requiring only smoothly changing lip force adjustments in tone production through the registers will be comfortable to play.

The reed model parameters corresponding to realistic embouchures and the values of blowing pressure for relevant playing regimes of the bassoon provide a basis for further investigations of the interaction of reed and air column by use of either experiments or physical models.

Acknowledgments

The author wishes to thank Johannes Baumgart, Roger Grundmann, Mico Hirschberg, and Cornelis Nederveen for valuable discussions and suggestions. Douglas Keefe kindly provided unpublished supplementary data on a previous study [6]. The present work is part of the research program KF2229603-MF9 supported by the German Federal Ministry of Economics and Technology (BMWi).

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