Effect of the structural dynamics of the bocal on the sound spectrum of a bassoon

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Introduction

The bocal of a bassoon is a thin curved metal tube to which a double-reed mouthpiece is attached. When the instrument is played, the reed acts as a pressure controlled valve and due to the pulsating flow the bocal starts to vibrate. The outer contour of the bocal has a major influence on the modal shapes of the structural modes and the relation between the eigenfrequencies. The matter of interest in this investigation is the interaction of the structural dynamics of the bocal and the reed.

In an previous study [1], investigations on the structural dynamics of the bocal, both experimentally and numerically were performed. It could be shown, that straightening the curvature of a bassoon-bocal leads to a shift in the modal frequencies above 2 kHz. The in-plane bending modes produce a rigid-body-motion of the reed towards the players lips. Consequently, LDV - measurements of the motion of the bocal tip in playing conditions showed changes of harmonic components above 1 kHz for the "straight" bocal. The displacement amplitudes about $30 \cdot 10^{-6}$ m. By means of a numerical model of the bassoon without a reed it was stated, that the pressure fluctuations inside the bocal causes a displacement of the bocal tip.

We present an experimental study including playing experiments with a musician and and artifical mouth. The aim of the investigation is to clarify, whether a distinct change of the bocals structural dynamics leads to measurable changes in the sound spectrum.

Artificial Mouth

In order to perform repeatable experiments, an artificial mouth was built. Two air-filled silicon tubes act as lips, similar to the embouchure of a player. Like in a real playing situation, the bocal is clamped at the upper end by the artifical lips clasping the reed and at the lower end by the plug connection to the wing joint of the bassoon. Thus, the reed's rigid body motion is only affected by the forces at the bocal tip and by the lips' properties of the articifial mouth, which can be kept constant during the experiments. The reed was manufactured from a synthetic material whose properties were assumed to be invariant during the measurements. No humidification of the supplied air is necessary to play a note. The airflow is regulated by a directional control valve, with a limiting frequency of 125 Hz. To initiate self-sustained oscillations of the reed, both lip pressure and mouth pressure are increased by a trigger impulse. The device is well suitable for a realistic and repeatable excitation of the bassoon.

Experimental Setup

One bocal (Heckel, Type CC 1) was prepared in order to add mass locally to it. An adaptor made from a light polyurethan-based material ($\rho = 270$ kg/m^3, $E = 300$ MPa, $m = 12$ g) was positioned at a deflection antinode of the bocals 5th in-plane bending mode, which was detected at 1.95 kHz in an experimental modal analysis. To this adaptor up to four pieces of additional mass (each $m = 28$ g) can be attached by a bolt connection without removing the reed from the artificial mouth.

Throughout all experiments that were carried out in this investigation, the bassoon was mounted in a stand in a position that it could be played by a musician as well as by the artificial mouth. The recordings were performed in a room that was designed to match musicians needs ($4.7 \times 3.2 \times 2.9 m^3$, reverberation time approx. 0.6 seconds 0.13 - 4 kHz). A free-field microphone (B&K, Type 4190) was placed in a distance of 1.8 m to the instrument, pointing horizontally to it in a height of 1.2 m. For all acoustic measurements in this study, this was the reference recording situation.

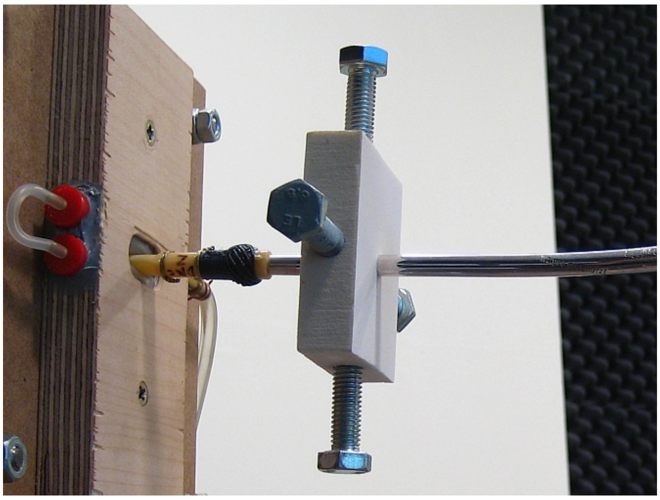

Figure 1: Artificial mouth used for the excitation of the bassoon. The doublereed-mouthpiece is clasped by silicon tubes and the bocals structural dynamics can be systematically influenced by locally attaching additional mass to it.

Each note was performed 6 times per run, then the setup was changed, i.e. mass was added or removed. Each run was repeated six times, so that from each configuration 36 sound samples were recorded. The raw data are exemplary shown for the note F2 (87.3 Hz) in fig 2.

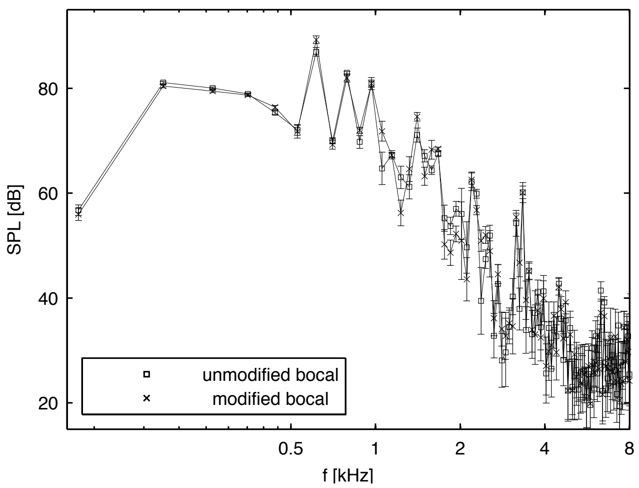

Figure 2: Comparison of the sound spectra played on the unmodified and modified bocal by the artificial mouth, played note F2 ($f_0 = 87$ Hz)

Analysis

From the quasi-stationary part of each time series segments with the length τ were cut out. τ was calculated by counting zero-crossings and subsequent resampling using polynomial cubic interpolation. The discrete fourier transform from the i^{th} period-synchronized sample is the harmonic spectrum $P_i(f_j)$, where $f_j = j \cdot f_0$, $j = 1 \ldots k$ and $f_0 = 1/\tau$ is the fundamental frequency. The concatenation of n magnitude spectra from from multiple measurements is a data matrix of size $(n \times k)$, where n is the overall number of spectra observed from the measurements, k is the number of the partials. In this study, n was 3000, i.e. 36 repetitions of the same note, each with 83 periods analyzed. For F2 and a sampling frequency of 35.635 kHz k is 183, respectively.
In order to depict overtones or frequency bands that change significantly due a variation of the experimental situation, pairs of these data matrices were analyzed by linear discriminant analysis (LDA) [2].
LDA is a multivariate statistical technique to separate a set of observations on dependent variables into predefined classes. Here, the dependent variables are the harmonic frequencies f_j. The aim of LDA is to determine corresponding coefficients c_j in order to maximise the expression in eq. 2 for linear combinations y_i of the measurement data given by eq. 1. To compare two states of one variable parameter, we used a two-class model with classes A and B; the separation of all observations y_i into y_A and y_A are therefore predefined by the experimental setup.

$$y_i = c_j \cdot P_{j,i} \tag{1}$$

$$\Gamma = \frac{\sigma^2_{between}}{\sigma^2_{within}} \tag{2}$$

where

$$\begin{array}{ll} \sigma^2_{between} & n_A(\mu_A - \mu) + n_B(\mu_B - \mu) \\ \sigma^2_{within} & \sum_{p=1}^{n_A} (y_{A,i} - \mu_A)^2 + \sum_{q=1}^{n_B} (y_{B,i} - \mu_B)^2 \\ & y_A, y_B : n_A, n_B \text{ observations in group } A, B \\ & \mu_A, \mu_B : \text{group means} \\ & n = n_A + n_B \\ & \mu\text{: overall mean} \end{array} \tag{3}$$

Preliminary to LDA, a principal components analysis (PCA) was performed in order to remove outliers from the data set. A measurement was stated to be an outlier if its score on the first principal component was out of the range $\mu \pm 3.5 \times \sigma$. The overall rate of outliers was less than 1% for the notes performed with the artificial mouth, and less than 4% for the notes performed by a musician. Outliers are caused by severe spectrotemporal changes during the measurement time. The pre-allocation of the observations into two classes, was done by the k-means clustering algorithm. The training data set for the subsequent LDA, consisted only of those observations which were pre-classified correctly. These were at least 65% for the sound spectra from a musician and 85% for the sound spectra measured using the artificial mouth. The discriminant function thus obtained was used to classify all observations in the following.
A way to judge the substantive utility of the discriminant function obtained is by examining the Λ, the ratio of the variance within classes to the total variance [3]. For the case that n observations x with the mean μ are classified into two classes A and B with the means μ_A and μ_B and $n = (n_A + n_B)$ Λ is given by eq. 4:

$$\Lambda = \frac{\sum_{n_A}(y_{n_A} - \mu_A)^2 + \sum_{n_B}(y_{n_B} - \mu_B)^2}{\sum_n (y_n - \mu)^2} \tag{4}$$

The size of the effect represented by the discriminant function is expressed by $Cohens'd$ from eq. 5:

$$d = \frac{(\mu_A - \mu_B)}{\sqrt{\frac{(n_A-1)\cdot\sigma_A^2 + (n_B-1)\cdot\sigma_B^2}{n_A+n_B}}} \tag{5}$$

The denominator of this term is the pooled standard deviation of n observations x, σ_A^2, σ_B^2 are the variances within classes A and B with the observations x_A and x_B, as specified above. Hence, d quantifies the extent, to which the sound spectrum of a bassoon note is affected by the variation of a single parameter.

Experiments and Results

Firstly, an experiment with the modified and unmodified bocal was performed with the artificial mouth. The results are shown in fig. 3.

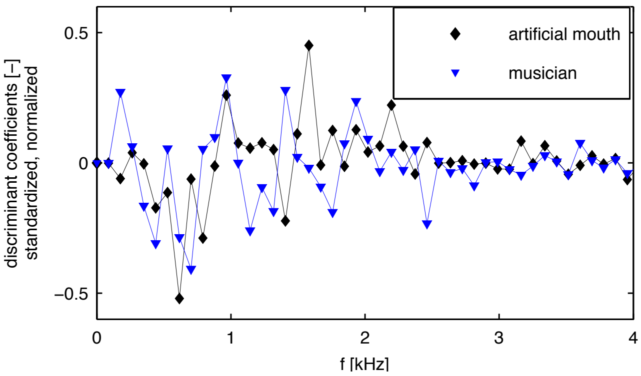

Figure 3: Discriminant functions from the sound spectra obtained with modified and unmodified bocal (played note F2 $f_0 = 87$ Hz).

A second experiment was carried out, both with the artificial mouth and a musician. In this case also two different bocals as well as two different bassoons were used. The statistical values for the discriminant functions obtained are listed in Table 1. The difference of the means has been proven to be significant by a two-sided t-test for the classification results of every experiment.

parameter	mass		bocal type		bassoon	
	Λ	d	Λ	d	Λ	d
musician	0.690	1.3	0.056	8.2	0.039	10.0
artif. mouth	0.278	3.2	0.001	111	0.000	184

Table 1: Statistical parameters of the discriminant functions obtained from the experiments with additional mass attached to the bocal, using two different bocal types and two different bassoons. Λ is the ratio of the residual variance after classification to the total variance, d is a measure of the size of the effect observed.

The third experiment was a perceptional pilot-experiment that was carried out with one professional bassoonist. Here, the bocal was hidden behind a black cloth hung up between player and bassoon, with a hole in it for the reed. The test person could not see the bocal and was informed that he would be testing 6 different types of bocals, although in each experiment only the additional mass was changed, while the bocal never was removed from the bassoon. The test person was asked to repeat the three notes Bb1, F2 and F3. The results are shown in fig. 4.

Throughout the experiment, the test person reported perceptional differences between all 6 bocals that he believed he was testing. In a repetition of the experiment, the person reported to recognize some bocals from the previous experiment, but his predications were not consistent.
For the second experiment about a week later, the design of the test was simplified. The same test person was asked to play three different bocals: the unmodified bocal, the modified bocal and a completely different bocal (Heckel CD 1). Again, the bocals were hidden, but in the first run, the test person was informed about the order of presentation. Subsequently the order was randomized and the player was asked to reassign the right order. This experiment was repeated six times, and again the responses were not consistent.

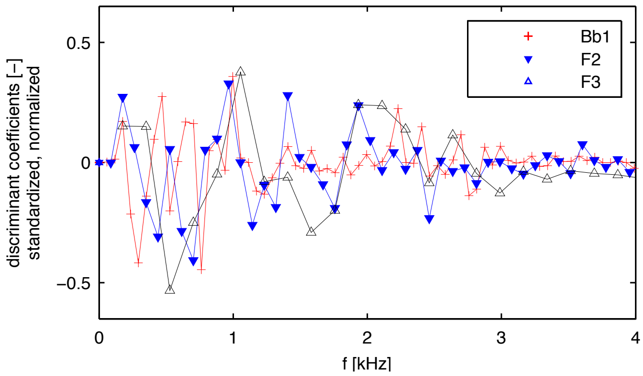

Figure 4: Discriminant function that separates the sound spectra of the notes Bb1, F2 and F3 played by an professional bassoonist using the unmodified and modified bocal

Discussion

In this experimental study, the effect of a variable parameter on the sound of a bassoon note was obtained from multiple sound spectra of sustained notes by means of Linear Discriminant Analysis (LDA). By the use of an artificial mouth we could show, that a manipulation of the mass distribution of the bocal leads to measurable changes in the sound spectrum. Mass that was additionally attached close to the bocal tip damped partials around 1 kHz (see fig. 2,3). This effect could be confirmed by playing experiment with a musician who performed for several notes (see fig. 4). However, a perceptional pilot-test showed clearly, that the induced changes are close to the perceptional threshold.
The statistical parameters of the LDA in Table 1 show, that the observed effect is rather small, compared to changes in other parameters (e.g. bocal type, bassoon). Obviously, the artificial mouth constructed for this study allows reproducible experiments. In combination with LDA it is an appropriate tool to identify subtle changes in the sound spectrum due to geometrical modifications of the musical instrument.

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