BORE RECONSTRUCTION BASED ON INPUT IMPEDANCE MEASUREMENT: APPLICATION TO THE BASSOON CROOK

Marthe Curtit, Fazli Yahaya [a], Jean Pierre Dalmont, Joël Gilbert [b], Olivier Cottet [c]

[a] Pôle d'innovation des métiers de la musique,
Institut technologique européen des métiers de la musique, Le Mans, France
[b] Laboratoire d'acoustique de l'université du Maine, UMR CNRS, Le Mans, France
[c] Bassoon and Oboe maker, Boutigny-Prouais, France
marthe.curtit@itemm.fr

ABSTRACT

The bore profile of a wind instrument has an important influence on its acoustical characteristics. Specifically, playing frequencies are close to the resonance frequencies of the tube constituted by the bore of an instrument. Several methods were developed to obtain bore dimensions, such as pulse-reflectometry, or radiography techniques. The method investigated here is based on tube input impedance measurement, which provides us with an alternative way to estimate the bore profile. Accuracy of the method is 2% of the diameter dimensions for measured ducts. In collaboration with the oboe and bassoon maker Olivier Cottet, this method has been applied to the case of a bassoon crook, at two different stages of fabrication. For two measured crooks, the average difference between mandrels dimensions and straight crooks is below 1.1 % of diameter dimensions. After the bending stage this difference is about 2.5 %. Comparison of reconstructed bores for crooks made with metal sheets of different thicknesses is presented. No link is established between the thickness of the metal sheet used and the bore profile of the crook after the bending stage. However, some differences appear for a crook made by metal sheet of varying thickness. Those modifications of the bore profile might explain differences perceived by the maker in the sound produced.

1. INTRODUCTION

Bore reconstruction from reflection function is a convenient approach which can be applied in many technical fields. The mathematical resolution used is the so-called "Layer Peeling" algorithm. Its development for a discrete conical and lossy model has been proposed in [1].

Other measurement techniques have already been applied to reconstruct bore dimensions, such as pulse-reflectometry technique [2], [3]. Impedance measurements are used in [4] with a different method, which propose an optimization procedure based on successive modifications of a starting geometry, in order to mach the input impedance curve measured. In the present paper, the reflection function is deduced from measured input impedance.

This method is applied to a bassoon crook at different stages of fabrication. The bassoon is a double reed wind instrument, with an air column of approximately 2.6 m length. Its structure is composed of 5 parts: the crook, the wing joint, the butt joint, the long joint and the bell. The crook, first and slender part of the air column is known (amongst makers) for its incidence on the bassoon sound. Prior studies concerning the role of the crook on produced sound can be cited. Firstly, studies on dynamic motion of crook structure during the playing [5] shows that the crook curvature might be a parameter capable of influencing the sound produced. Other type of studies concern the inner bore profile of the crook and its relation to the sound produced. In [2], many historical crooks have been connected to a same bassoon to observe differences on its input impedance. So far, no univocal link between inner crooks bore profile and sound produced by the instrument has been determined.

This paper is divided in three sections. Section 2 describes the non-invasive technique used to measure the internal profile of various crooks, based on input impedance measurements. Section 3 concentrates on measuring crook's inner bore profiles at different stages of fabrication. The crooks measured are made using sheets of different thickness.

2. ACOUSTIC METHOD FOR BORE ESTIMATION

To determine bore profile on a tube, an alternative to pulse-reflectometry technique [3], [6] is used. The method is based on an input impedance measurement. In the past few years, a Z sensor for this specific measurement was developed [7]. This sensor consists of two microphones, a piezoelectric speaker, a digital signal conditioner, an amplifier, an acquisition device and an interface program installed on a PC for signal processing and swept-sine signal generation.

Data from the two microphones allows the computing of the pressure and volume flow at the input in the frequency domain, so that reduced input impedance $Z'_i(f)$ can be calculated.

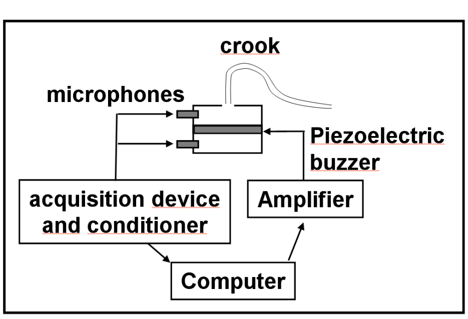

Figure 1 – Schematic diagram of Z sensor

The algorithm used in bore reconstruction is the "Layer peeling" algorithm [1]. Knowing the dimension of the input section of a tube, the method uses the reflection of sound waves occurring at every section's change to estimate the sections in the interior profile iteratively. In our case, the reflection coefficient $R(f)$ in the frequency domain is obtained from the tube input impedance $Z_i(f)$, (equation 1) :

$$R(f) = \frac{Z_i(f) - 1}{Z_i(f) + 1} \qquad (1)$$

The reflection function in the time domain is obtained by using the inverse Fourier transform. Propagation losses are taken in account at each iteration in the algorithm via an appropriate filter for the calculation of the propagated wave pressure in a portion of cone [1].

Some Gibbs phenomenon can appear as 'ripples' in the reflection function and also in the reconstructed bores, due to the finite frequency range. Various methods can be used to avoid such oscillations on the data, such as "zero padding", "additional length" or simply by averaging two following points in the reconstructed bore. This last solution has been used in this paper.

Input impedance measurements are done with a frequency range of 100-6000 Hz. At low frequencies, missing data are obtained from a linear extrapolation of the measured reduced input impedance Z'_i. Because of the inverse Fourier transform, the reflection function is discretised in the time domain. This leads to a resolution length □x in the bore reconstruction, given by equation 2 :

$$\Delta x = \frac{c}{4 \times f_{max}} \qquad (2)$$

where f_{max} is the upper limit of measured frequency range and c is the speed of sound.

With f_{max}=6000Hz this lead to a resolution of 1.4 cm in the space domain. For a bassoon crook 326 mm long, this gives 24 data points along the reconstructed bore. A condition to the application of the layer peeling algorithm is to respect the plane wave approximation. That supposes a maximum diameter of 5 cm for the objects measured. The widest section of the crook is approximately 9 mm in diameter; well within limits. An application of this reconstruction method is used below to investigate the bore profiles of a selection of crooks.
The reliability of the method for a simple cone showed that the error between real and reconstructed dimensions is 2% maximum.

3. CROOK BORE PROFILE AND STAGE OF FABRICATION

Instruments such as calipers are generally used by makers to determine the bore profile of historical instruments. But they suppose a sufficiently wide bore to allow measurements to be taken. In the case of a bassoon crook, such measurements are not possible, and the only readily available way to control the bore profile is by measuring the dimensions of the mandrel used to produce the crook or to measure its external radius at the end of the fabrication process.
The process of crook fabrication consists of 4 steps: a sheet of metal is first cut in a trapezoidal shape and both oblique edges are welded together. The formed cone is then hammered on a mandrel until it is perfectly adjusted to it. The crook is then filled with alloy and after a period of cooling down, bent using a wooden shaper to get an appropriate curvature. Later on, the assembly is heated again to evacuate the alloy.

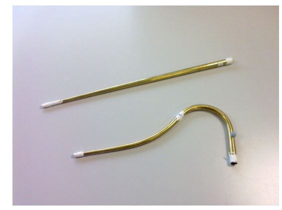

Figure 2 – Two crooks before (up) and after (down) the bending stage.

The aforementioned method is used to measure bores before and after crooks have been curved. The set studied comprises various crooks made with metal sheets of different thicknesses. The dimensions of the reconstructed bores are compared to that of the mandrel used to produce them.

3.1. Straights crooks and mandrel

Bore reconstruction is first applied to straight crooks, before bending. Crooks are made of sheets with two different thicknesses which are 0.5 mm and 0.6 mm. Obtained reconstruction results are plotted on figure 3 :

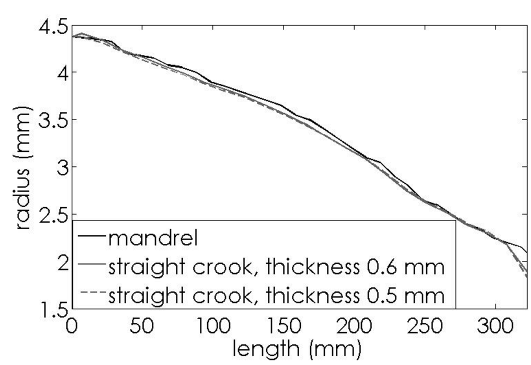

Figure 3 – Bore reconstruction results for two straights crooks (before being bent) and mandrel dimensions.

Results show that the error on the last point is much larger than for the other points. So, for all the averages presented below, this last point is not considered.

The average diameter difference between mandrels and crook dimensions is 0.076 mm and 0.068 mm, respectively for crooks made with 0.5 mm and 0.6 mm thick sheets (figure 4). Relatively to the mandrel dimensions, the corresponding diameter variation is 1.1 % maximum. During fabrication, the precision expected by the maker on the diameter is about 0.1 mm. Values obtained here are within this precision interval.

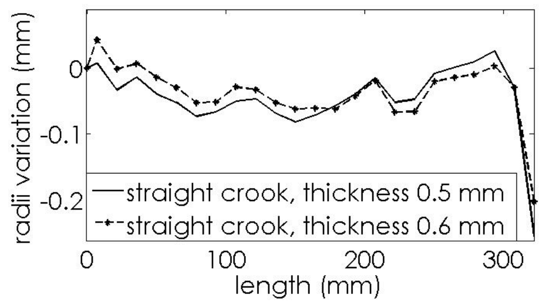

Figure 4 – Difference between mandrel dimensions and bore reconstruction for two straight crooks made with metal sheets of different thicknesses.

Before being bent, crooks made with metal sheets of different thicknesses are shown to have very close dimensions (difference between diameters of the two crooks is less than 1 %), and the bores dimension are also very close to that of the mandrel.

3.2. Bent crooks

The same method is used to determine the bore profiles of five bent crooks. Two crooks are made with 0.5 mm thick sheets. Two others are made with 0.6 mm thick sheets. The last crook is made with a sheet of thickness varying from 0.6 mm at the wide section to 0.5 mm at the reed end (thickness varies linearly along the length). All the crooks are made using the same mandrel.

The measurement of the two previous crooks initially straight show a diameter difference with mandrel of 0.148 mm and 0.166 mm, respectively for crook made of 0.5 mm and 0.6 mm thick sheet (figure 5). The bending operation induces a corresponding mean diameter variation of 0.08 mm and 0.1 mm respectively.

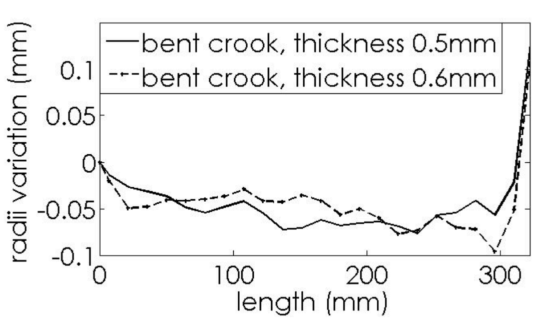

Figure 5: Differences between reconstructed bores of straight and bent crooks.

Two other crooks made with 0.5 mm and 0.6 mm thick sheets have been measured after the bending stage. Similar differences are found between bore and mandrels dimensions, respectively 0.17 mm and 0.112 mm.

The fabrication process affects the diameter of all crooks by an average of 2.15% of mandrels dimensions. Although the crooks are not all equally affected, this variation is slightly larger than the precision of fabrication. It should be noticed that the accuracy of the method used here is comparable to that obtained in [2].

Another crook made with a metal sheet of varying thickness presents a larger variation of its internal radius. Reconstruction of its bore profile is plotted on figure 6. Average difference between its diameter is about 4.6 %, or 0.32 mm. It seems that this crook might (according to the maker) produce a different sound on the bassoon while playing.

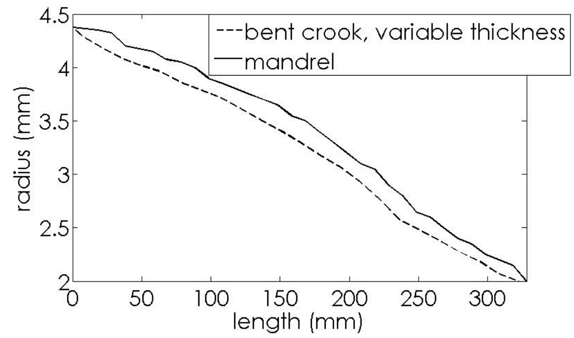

Figure 6: Reconstructed bore of a bent crook made with a metal sheet of varying thickness, and mandrel dimensions.

The fabrication process induces larger bore modifications on the last crook measured, and made of a metal sheet of varying thickness. In order to explain the differences that is felt by the maker on the bassoon's sound, this last crook should be further investigated. A good starting point would be to observe the input impedance of a complete bassoon fitted with different crooks, as done in [2].

4. CONCLUSIONS

Bore reconstruction based on input impedance measurement is an efficient method to obtain bore dimensions of bent ducts for which mechanical measurements are not permitted. The accuracy of this method is estimated to be 2 % of the measured diameter. With uniform metal sheets, results for straight and bent crooks shows that there is no significant difference between input impedances measured, and also between bores and mandrels dimensions. The average diameter variation due to the bending operation is about 0.09 mm, regardless of the thickness of the crooks.

The crook made with a metal sheet of varying thickness presents a bore profile variation which is greater than the others. Corresponding average variation of its diameter is 4.6 %, which is more than 0.3 mm. Bore differences on this crook may be an explanation for the differences perceived by the maker in the bassoon's sound while playing. Further investigations could be done to study the effects of crooks bore variations on the sound of the bassoon.

5. AKNOWLEDGEMENTS

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