Embracing the Digital in Instrument Making: Towards a Musician-tailored Mouthpiece by 3D Printing

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ABSTRACT

At present, the manufacturing of musical instruments still strongly relies on the tacit knowledge of experienced handcrafts while is commonly based on standard machining or casting techniques. This limits the musician-tailoredness to a small group of players, while others take compromises by employing stock parts.

The present article describes a new methodology for the design and production of woodwind instruments mouthpieces. By embracing digital modeling and manufacturing, this methodology encompasses four phases, which can be cut short when necessary. The aim of the presented methodology is to link the geometry of the mouthpiece to tone properties. Based on 3D printing, the inside geometry can be altered to complex and reproducible detail to obtain the desired acoustic features - eventually leading to mouthpiece geometries tailored to the player's sound and playability requirements.

The results of aerodynamic investigations together with the subjective experience of saxophone players have been used to design mouthpieces with modified inside geometries of both baffle and chamber. Prototypes have been produced at the Delft University of Technology (TU Delft) using several 3D printing technologies and different materials. Both professional and amateur saxophone players tested these at the Royal Conservatoire of The Hague and at the North Sea Jazz festival (Rotterdam 2012). Based on the judgment of the players, specific geometrical features were revealed to emphasize specific tone characteristics. A number of professional players are actively performing with our mouthpieces.

The application and further development of the methodology will lead to a better empirical basis to reason about acoustics and playability, and can be applied to other instruments as well. Future work includes additional measurements and developing a parameterized database of 3D models.

1. INTRODUCTION

It is widely recognized among wind instrument players that the inside geometry of the mouthpiece has a strong influence on the response, timbre, and intonation of a woodwind instrument.

Mouthpiece manufacturing nowadays still often relies on the knowledge of experienced handcrafts and is commonly based on lathe work or casting techniques. In the last decades several mouthpiece manufacturers have adopted computer-aided design systems and computer numerical control (CNC) machines for the production of saxophone and trumpet mouthpieces. The use of 3D printing however, compared to the other manufacturing techniques offers advantages in terms of reducing production costs and allowing the construction of inside geometries that are hardly achievable by machining.

Our methodology, presented in this paper, focuses on modifications of the mouthpiece inside geometry, which influence the flow structures and turbulence level inside it. The aim is to improve the acoustic properties of a mouthpiece according to specific sound requirements, in a controlled, measured and reproducible way, by exploiting the capabilities of 3D printing.

2. BACKGROUND

2.1 Mouthpiece performance

Due to the complexity of the mouthpiece functioning principle, it is hard to directly relate its internal geometry to the sound quality of the coupled mouthpiece-instrument system.

First attempts to identify such a connection dealt with variations of the chamber volume and shape. The work of Benade [1] revealed that a short and open mouthpiece chamber is associated with a dark tone quality, while a long and narrow chamber is associated with a relatively brighter tone quality. A variation of cavity size effects the lowest resonances in equal proportions and does not alter their ratios. At higher frequencies, however, the mouthpiece length correction becomes frequency dependent and can have important consequence on tuning and tone color.

Wynman [2] performed acoustic measurements on five different geometrical-types of alto saxophone mouthpiece models. He found that changes in the acoustic spectrum due to mouthpiece chamber modifications depend on the dynamic level of playing. Wynman also stressed that the amount of brightness in the tone is primarily controlled by the baffle shape and that a small baffle-to-reed angle tends to promote a bright tone.

An interesting overview of mouthpiece investigations can be found in the PHD dissertation of Scavone [3], which describes the modeling of single-reed wind instruments based on acoustic principles in the digital waveguides domain. Scavone also stresses the influence of the bore shape (conical and cylindrical) on the reed behavior, which strongly affects the harmonic distribution of the sound spectrum.

The study of Hasbrook [4] provides a large database of measurements on different saxophone and mouthpiece combinations. The analysis primarily focuses on mouthpiece pitch and compares a traditional ”classical” sound versus a traditional ”jazz” sound. An observation was that the tip opening usually increases from classical to jazz mouthpieces, as the length of the lays.

The effect of mouthpiece chamber modifications on the sound produced by saxophone has been the main focus of the ensablished mouthpiece manufacturer François Louis. Some of the design concepts are provided by François Louis himself in a web seminar masterclass [5].

A similar investigation on the effect of the mouthpiece depth modification on the sound of the trumpet was carried out by Poirson *et al.* in [6]. It was found that increasing the depth of the mouthpiece chamber tends to produce a more ”dark” sound as revealed by both measurements with an artificial blowing device and measurements on real players. They concluded that the influence of the musician on the produced sound is comparable to the variations of the mouthpiece geometries and therefore it is important to use an artificial blowing device to determine the qualities of a wind instrument for design and validation of the modeling tools.

2.2 3D printing

3D Printing is a collection of production technologies also known as Additive Manufacturing (AM). Although there are differences between different AM technologies, they all fabricate physical objects directly from a 3D computer file by adding material layer upon layer. Originally these technologies were used for prototyping, but improvements in speed, price and material properties have caused an ever increasing application of 3D printing for the production of end-products.

Compared to traditional manufacturing, such as machining and (injection) moulding, AM offers unprecedented freedom in shape complexity and custom geometry. Ref. [7] provides a literature overview of proposed methods to utilize this geometrical complexity. Combined with a high reproducibility and low costs for custom fabrication, 3D printing has a large potential for the production of customized musical instruments, as emerging from recent applications on a fully 3D printed flute (http://youtu.be /zwHg szH0aqI) and a fully 3D printed violin (http://www.wired.c o.uk /news /a rchive /2011).

In earlier work we have explored the use of four different 3D printing technologies for the production of saxophone mouthpieces [8]. The technologies included: PolyJet , Fused Deposition Modeling, Selective Laser Sintering and Selective Laser Melting. Both the PolyJet and Fused Deposition Modeling machines are available in-house at the TU Delft. For the Selective Laser Sintering and Selective Laser Melting we have used the services of AM service bureaus.

Figure 1 shows some of the prototype models produced at TU Delft using the above mentioned techniques. The materials used for the shown mouthpieces are (from left to right): ABS, Titanium, Objet VeroBlue plastic, Polyamide.

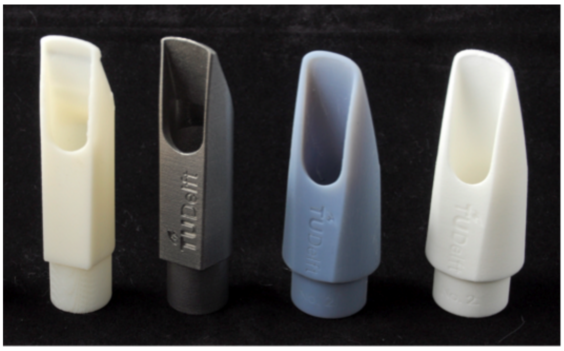


Figure 1: Preliminary mouthpiece models produced using different 3D printing technologies and materials.

The mouthpieces used for the tests described in Section 4 were produced using the PolyJet technology. Based on the ASTM categorization for AM technologies http://ww w.astm.org /COMMITTEE /F42.htm , the PolyJet technology belongs to the category Material Jetting. While moving over two axis (X and Y) an inkjet head deposits a layer of a liquid UV curable resin. After the deposition of the layer, a UV lamp cures the resin into a solid polymer. Once a layer is complete, the build tray lowers (Z axis) and the jetting of a new layer is initiated. This process is repeated until the entire model is created. A schematic illustration of the working principle of a PolyJet machine is shown in Figure 2 . We found that the PolyJet technology, produced by Objet® (now Stratasys, http://objet.com) is suitable for producing high quality mouthpieces that do not require post processing.

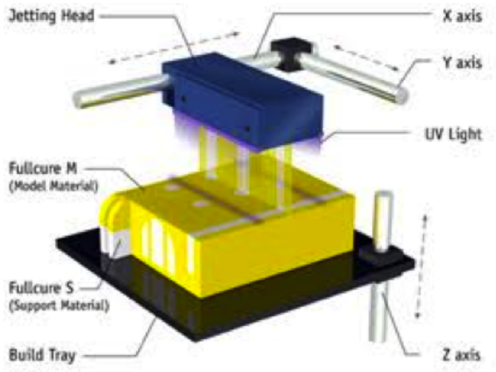


Figure 2: PolyJet 3D printer machine.

3. METHODOLOGY FOR MOUTHPIECE DESIGN

The proposed methodology consists of four phases and it is sketched in Figure 3

In the first phase mouthpieces with specific geometrical features are produced using 3D printing. The geometric

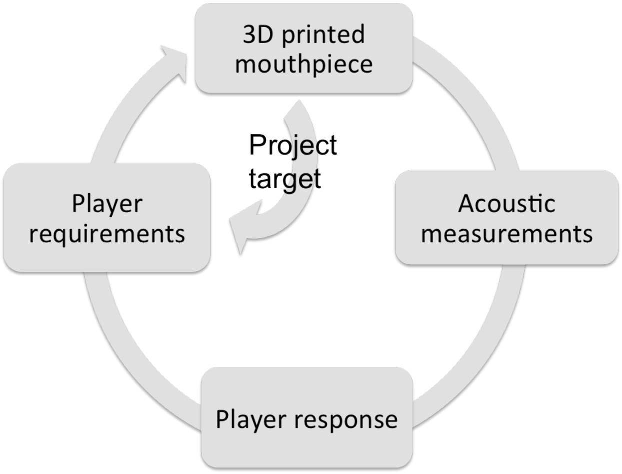


Figure 3: Sketch of the methodology for mouthpiece design.

characteristics of the mouthpiece are varied according to specific acoustic targets. The inputs can derive from either previous experiments or innovative design ideas. Some of the saxophone mouthpiece designs produced at TU Delft in the first tests, were based on the results of the aerodynamic measurements described in Section 4.1.

As second step acoustic tests are carried out on the mouthpieces in an anechoic environment by means of an artificial blowing device (artificial mouth) and microphones. This step is needed to objectively and quantitatively determine the spectral characteristics of the designed mouthpieces, without the influence of the player. The objective characterization of the spectra compared to the musician response would shed light on the timbre characteristics of each design. In general, it is difficult to discuss musical tone quality without using subjective terms such as: ”dark”, ”mellow”, ”focused”, ”bright”, ”compact”, etc. These tests would elucidate some of the above definitions often used by musicians to describe an instrument timbre , from a more scientific point of view. Aerodynamic visualization or computational fluid-dynamics simulations could also be performed in this phase to investigate the flow features associated to each geometry.

Once the spectra of the different mouthpieces have been objectively analyzed, the next crucial phase of the method consists of tests with real players. These would enable to link the measured acoustic spectra to the player-based characteristics.

An extensive investigation on different saxophone models and mouthpieces have been performed by Talley [9]. The scope of the latter work was to identify the tone fingerprints of different musicians, which is the distinctive tone quality of every player. The analysis of Hasbrook [4] demonstrates how the internal voicing of a player can dramatically alter the tone quality, independently of mouthpiece choice. From the above studies it seems not possible, in a first stage, to define the quality of a mouthpiece without considering its effect on the player.

Performing the same tests on several musician would allow to statistically link the measured spectra of each mouthpiece to the response on the player. Characteristics found by several players would be considered to belong to the specific design. The ease-of-play could also be inferred, which is not directly detected from measurements on artificial blowing devices. Furthermore such analysis will indicate the sensitivity of the musician to modifications of the mouthpiece geometry.

By knowing what a geometric modification would cause on the spectral characteristics of the sound and also knowing the response of musicians to it, one could systematically alter the mouthpiece shape in a ”controlled” and ”reproducible” way, using the 3D printing technology, directly obtaining timbre characteristics that satisfy the player’s requirements. This represents the main target of this project.

4. FIRST APPLICATION

A first application of the proposed methodology is described in this Section.

4.1 Preliminary aerodynamic measurements

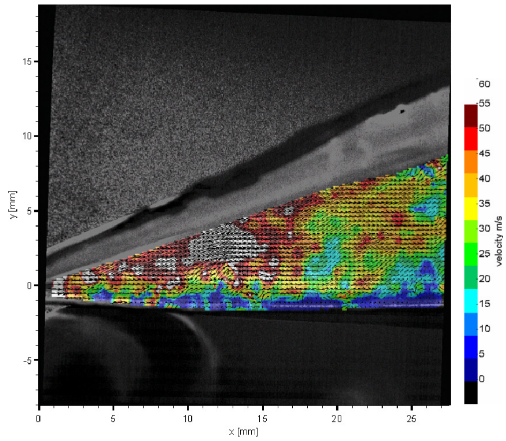
Aerodynamic tests on a saxophone mouthpiece have been performed at the aerospace faculty of TU Delft using the particle image velocimetry (PIV) experimental technique. The mouthpiece was connected to a real tenor saxophone and blown by an artificial mouth. Experimental setup and detailed results of the flow field measurements can be found in ref. [10]. Contours of the velocity field inside the mouthpiece baffle are shown in Figure 4 .

The instantaneous velocity contours of Figure 4(a) revealed that the flow velocity features maxima of over 60 m/s, mainly localized on the upper lay of the baffle when the reed is approaching closure. Figure 4(b) shows the mean velocity contours calculated over about 300 reed opening/closing cycles. These indicate that the mean velocity across a reed cycle has maxima localized on the upper surface of the baffle at a distance of about 6 reed apertures (at rest) downstream of the tip (12-13 mm in this case) and that about 11 reed apertures downstream of the tip flow recirculation occurs, starting in the vicinity of the reed.

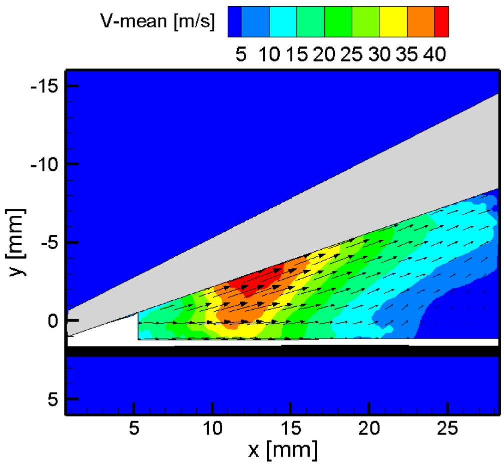
The first part of the baffle roof has been identified as the most influential on the sound production and it was believed that slight modifications of such a region might have a strong impact on the reorganization of the flow structures in the mouthpiece and therefore on the sound properties of the instrument. This seems to be in line with the findings of Wynman [2] and the experience of mouthpiece manufactures and handcrafts.

These aerodynamic results have served as input for geometric modifications of standard mouthpieces and led to the design of eleven different prototypes, three of which are shown in Figure 6 in Section 4.

The use of 3D printing might improve future PIV experiments by producing mouthpiece models with flat external sides. This would increase the optical accessibility through the mouthpiece and overcome some of the experimental issues reported by Lorenzoni and Ragni in [10].



(a) Instantaneous velocity snapshot



(b) Mean velocity

Figure 4: Flow visualizations inside the mouthpiece by particle image velocimetry.

4.2 3D printed mouthpiece

Since the first target user of our mouthpiece design method was David Liebman, one of the mouthpiece models normally used by him was chosen as reference for the geometrical modifications and a 3D scan of it was made at TU Delft using a ”Phoenix Nanotom S” CT scanner (http://www.ge-mcs.com /en /radiography-x-ray /ct-computed-tomography /nanotom-s.html). This mouthpiece was a ”Jazz Chamber” Lebayle® soprano mouthpiece of aperture 8.

The scanned model was reconstructed in SolidWorks® and modifications have then been made to the baffle and chamber of the original mouthpiece shape, according to the findings described in Section 4.1.

For producing these mouthpieces we used an Objet Eden 260 machine. The machine is able to produce objects up to the size of 600 x 252 x 200 mm at a resolution of 600dpi and layer thickness of 16 micrometer. The material we have used is a biocompatible resin marketed by Objet as MED610. It is a rigid transparent material developed and approved for prolonged contact with human tissue (http://objet.com /3d-printing-materials /bio-compatible). Using this machine allowed us to fabricate one mouthpiece in approximately one hour, or a batch of 10 unique mouthpieces in less than 4 hours.

There is no general agreement on the effect of the material on the sound characteristics of a mouthpiece. According to Larry Teal [11] the material by which the mouthpiece is constructed has little influence on the tone quality. This seems to disagree with what reported by David Liebman [12], who instead states that each material offers a unique response and that especially metal mouthpieces have a more brilliant and compact sound. A wide range of modern mouthpieces are produced in vulcanized rubber which offers a good compromise between flexibility and hardness.

3D printing offers a wide range of possible materials and it will be used to further investigate the effect of the material on the sound characteristics.

4.3 Acoustic measurements

The acoustic properties of each mouthpiece geometry still need to be assessed. As also stressed by Poirson *et al.* in [6], the use of an artificial blowing device is an essential requirement for the determination of the objective qualities of a wind instrument.

An artificial mouth was produced by students at TU Delft and is shown in Figure 5.

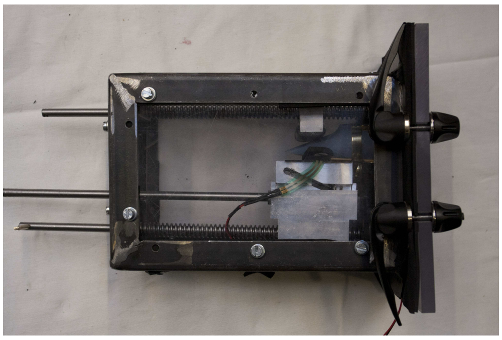


Figure 5: Artificial mouth produced at TU Delft for mouthpiece acoustic tests.

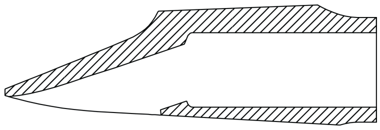
The artificial mouth in Figure 5 has been produced following the indications of the group of Gazengel [13] and features improvements compared to the model used by Lorenzoni and Ragni in [10]. This is a 5 mm thick Plexiglas® box reinforced with a steal frame. The side where the mouthpiece is installed is fixed to the rest by quick-release fasteners, which allow to easily interchange the mouthpiece inside the box. A metal support is placed underneath the mouthpiece and artificial lips of silicon-like material are installed on it. The position of the support can be adjusted both horizontally and vertically. An extra support is placed above the mouthpiece to simulate the teeth and to hold the mouthpiece in place during the tests. The pressure inside the box is controlled by a feedback system which allows to keep the level steady during the tests.

Acoustic tests using this device are planned in Delft in September 2013. The test set-up will consist of acoustic radiation measurements by means of microphones at the bell end and acoustic impedance measurements on the mouthpiece alone using an impedance probe.

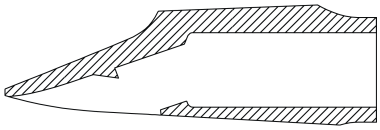
4.4 Player response

Eleven different 3D printed mouthpiece geometries were produced using the Objet Eden 260 machine and the Objet® MED610 material. This material is also used for medical prothesis, it is safe for the user and provides good strength and stiffness for the present purpose.

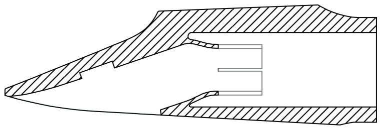
Liebman evaluated the eleven mouthpieces, during a workshop at the music conservatory in The Hague. The musician gave our team positive feedback and provided us with a first user-based characterization of the mouthpieces from the point of view of an experienced musician. Three of the eleven soprano mouthpieces tested by Liebman are shown in Figure 6



(a) Number #1: Original geometry:



(b) Number #9: Baffle ramp:



(c) Number #11: Baffle cavity and neck connection

Figure 6: Three of the mouthpiece designs tested by David Liebman at the music conservatory in The Hague.

The comments by Dave Liebman about the three mouthpieces are the following:

Number #1: Original geometry *"As good as the original"*

Number #9: Baffle roof ramp *"By far the best. Better ability for dynamics: full, round with color"*

Number #11: Baffle roof cavity and neck connection *"Mellow sound, pleasant. Does not have expansion. Not bad but nasal. Not as warm"...*

Number #1 is a close reproduction of the original geometry, the only significant difference is the material used. The inside geometries of the number # 9 and number #11 are based on the aerodynamic results of Section 4.1 and with respect to the number #1 both have a modified baffle roof geometry, which is the region where the flow speed was shown to have a maximum.

In particular number #9 features a small ramp which induces a flow recirculation and aims at increasing the turbulence level in the chamber. The presence of multiple turbulent flow scales enriches the spectral content of the sound. This would explain the "full" sound mentioned by Liebman.

The mouthpiece number #11 has a cavity in the baffle and a connection to the saxophone neck. The function of the connection is to smoothly converge the flow towards the neck. The flow in this case does not expand in the chamber and is more accelerated toward the neck due to the sectional reduction. Less flow recirculation is expected to occur which implies a spectrum more focused on a specific frequency band, generating what Liebman defined as nasal sound.

By eliminating the sectional area discontinuity, the neck connection revealed to noticeably improve the response of the model, increasing the "ability for dynamics", as mentioned by our test musician.

The geometric modifications applied to the mouthpiece revealed to produce the foreseen effects on the musician response. A more objective characterization of the models will derive from future acoustic measurements. The changes in the flow pattern also need to be assessed by targeted aerodynamic experiments or computational fluid dynamics simulations.

The 3D mouthpiece team has also presented the new mouthpiece at the North Sea Jazz Festival (Rotterdam 2012), where musicians have shown particular interest to the production technique and the good acoustic quality of the mouthpieces. The soprano player Jure Pukl (www.jurepukl.com) tried the mouthpieces at our stand at the North Sea Jazz. He was positively impressed by the sound of the number #9 model and he is currently performing with this mouthpiece.

5. CONCLUSIONS AND FUTURE WORK

A methodology has been presented for the design of new single-reed woodwind instruments mouthpiece geometries based on aerodynamic investigations in combination with acoustic measurements and players' evaluations.

Modified mouthpiece inside geometries were designed based on the results of aerodynamic experiments and innovative design ideas and manufactured using additive manufacturing. Musicians who played on the modified mouthpieces noticed the difference with the standard designs and the judgement seemed to be strictly correlated with the expected flow behavior.

3D printing revealed to be a powerful tool for the production of saxophone mouthpieces. The main advantages reside in the high speed of production, accuracy, large variety of usable materials, low costs and capability of producing complicated shapes compared to standard manufacturing techniques. The firsts feedbacks by the musicians revealed that 3D printing is valuable for the production of actual mouthpieces and that the present method has the potential for improving the design of mouthpieces, towards the production of geometries tailored to the sound requirements of the musicians. Patent application has been made by TU Delft for the application of 3D printing to saxophone mouthpiece design.

Future work will consist of acoustic tests on the eleven mouthpieces evaluated by Liebman, using the above described artificial mouth. Tests are planned to start in September 2013. In a second stage numerical and experimental aerodynamic investigations will also be employed trying to directly relate the acoustic spectrum of the saxophone-mouthpiece system to the flow pattern and turbulence intensity level in mouthpiece baffle and chamber.

Acknowledgments

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