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Design and manufacturing of an artificial marine conch by bore optimisation

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The marine conch is a traditional instrument of the brass family. The resonator is made of the inner shape of the shell, with which the lips of the player interact by the way of a hole pierced in the extremity of the shell. Several notes can be played with this instrument. Unfortunately, the marine conch becomes nowadays very rare and expensive.
In order to build an artificial conch (by injection moulding), we studied the acoustics property of a natural conch. This paper is dedicated to the description of the measurements we made and to the presentation of the method used to redesign the bore. First, the input impedance of a natural conch was measured, and the size of the bore was assessed by the way of pictures and image processing tools. From these measurements, an initial bore of the artificial conch was designed with a CAD software, by taking into account manufacturing constraints. Second, the artificial bore was optimized, to improve the harmonicity of the impedance peaks. Finally, an artificial conch was next manufactured by rapid prototyping. As a result, we noticed that the conch manufactured could clearly be used as an interesting musical instrument.

1 Introduction

The marine conch is used since several centuries as a musical instrument. The purpose of this paper is first to study the acoustics properties of this natural instrument. For this, the input impedance of a marine conch was measured. Second, in order to design an artificial conch with equivalent acoustical properties, we carried out bore measurements, impedance calculation and bore optimisation. For the design of the artificial conch, manufacturing constraints were taken into account for the optimisation of the bore.

We describe in this paper the process we followed for the design of the bore of the artificial conch. The results presented here were mainly carried out during a master's thesis [1]. This work has been realised in parallel of a project concerning the manufacturing of artificial conchs (made by injection moulding). Artificial conchs were manufactured according to the results of our optimisation, and were played and tested by musicians.

In section 2, a brief description of the conch is presented (description, functioning). Section 3 is dedicated to the impedance measurements and impedance calculations. In section 4, the optimisation process for the design of the bore is explained. Conclusions and perspectives are drawn in section 5.

2 Description of the natural conch

2.1 A "brass" musical instrument

The marine conch (termed Antsiva in Madagascar, or Horagai in Japan) is a marine gastropod. Several types of conch can be found all over the world. Its use as a musical instrument is very ancient, and several culture and civilisation used it in India, Africa, Japan, the Caribbean islands …
It belongs to the aerophone family. Concerning the mechanism of sound production, it can be considered as an instrument of the brass family: indeed, the lips of the player, by the way of a hole pierced in the extremity, or by the adjunction of a mouthpiece, interact with the resonator and produce an oscillation regime in the instrument [2].
Two or three notes (partials) can be played, and the player has also the possibility to modify the height and the timber of the notes by placing the hand inside the bell. The musical possibilities of this instrument can appear at first sight limited, but the "magie" of the timber makes it interesting and attractive. In addition to its use in traditional music, several musicians in modern and world music are specialists of this instrument (Steve Turre, Les Chevals …).

The conch studied in this paper is a particular shell called Charonia Tritonis (Fig.1).

Fig.1: picture of Charonia Tritonis (dextral). The model below has a mouthpiece

2.2 Geometry of the bore

The internal geometry of the bore is rather complex. A longitudinal section of the conch shows that the inner shape is coiled on a conic helix[1], and has an increasing section

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[1] This disposition is for example used in a particular brass called the "trompe de Lorraine". A large length bore is obtained in a very short instrument by winding round the bore in two opposite helixes inserted one in each other. This instrument produces several partials, and is surprisingly low relatively to its size.

from the extremity to the "bell" (Fig.2). The most widespread sense of the coiling in the nature is dextral.

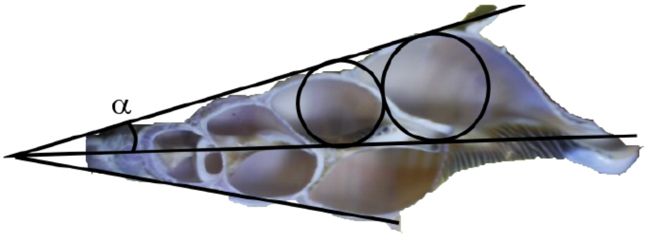

Fig.2: longitudinal section of the conch.

In order to estimate the size of the bore of the conch, we made a section of a conch (Fig. 2) and we estimated the area of the different sections with basic image processing tools. We made the following simplifications for the setting up of a geometrical model of the conch's bore:

- The directrix of the surface is a conical helix, with a constant thread
- The generatrix of the surface is circular
- The increasing of the area of the generatrix is constant (according to the distance to the vertex of the cone).

According to these assumptions, the equations describing the surface of the bore are (Eq.1):

$$\begin{cases} x = (a + b\cos v)\exp kt \cos t \\ y = (a + b\cos v)\exp kt \sin t \\ z = (a\cot\alpha + b\sin v)\exp kt \end{cases} \quad (1)$$

Measurements of the geometry of the conch showed that approximately, $\alpha = \pi/12$ (half-opening angle of the cone), $n = 3.5$ (number of turns of the helix), R_i = 7mm (input radius at the extremity of the conch). With these values, the geometry of the model of the bore is given Fig. 3.

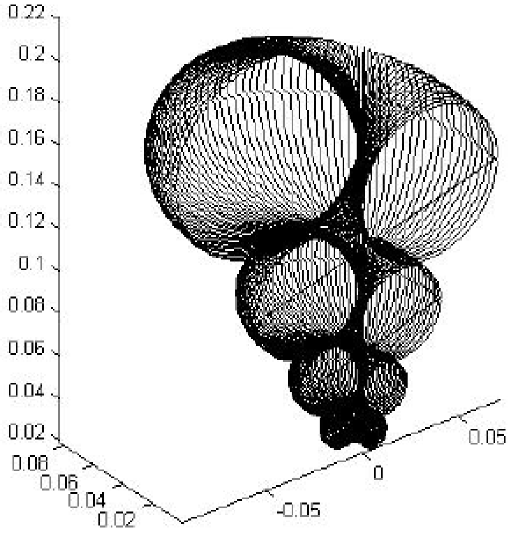

Fig.3: geometry of the model of the natural conch's bore

With the geometrical model, the length l of the uncoiled helix was computed by integration (l = 462.3mm). This length will be useful in the next section for the impedance calculation.

3 Input impedance of the conch

3.1 Input impedance measurement

Brass wind instruments are traditionally characterized by their acoustic impedance $\mathbf{Z_{in}}$, the transfer function between the acoustic flow **Ue** and the acoustic pressure **Pe**, which depends on the frequency. This quantity can be calculated or measured [3, 4]. The impedance of the natural conch was measured at the LAUM (Laboratoire d'Acoustique de l'Université du Maine) (Fig.4). The measurements were made without mouthpiece.

Fig.4: input impedance measurement of the conch

The impedance of the conch presents several peaks, the partials of the resonator (Fig.5).

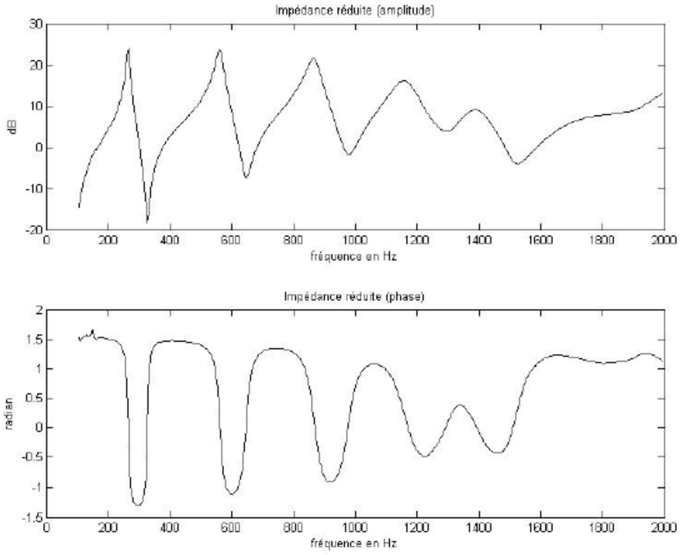

Fig.5: measured input impedance (relative) versus frequency for the natural conch (magnitude and phase).

Five impedance peaks were extracted of these input impedance measurement (frequency – magnitude), by detecting the maximum of impedance magnitude.

3.2 Input impedance calculation

The calculation of the input impedance has been made by a theoretical approach based on the transmission line modelling [3]. For the geometry of the bore corresponding to our model (Fig.3), the uncoiled bore is finally a simple cone of input radius Ri = 7mm, $\alpha = \pi/12$, and length l = 462.3mm.

In order to verify if our geometrical model was not too simple, we calculated the fit of the calculated impedance on the measured impedance. This fit was not very good, in particular the frequency of the first peak was rather different. For this reason, we decided to correct the length of our model, by determining the length of the cone, whose frequency of the first peak corresponds to those of the measured impedance. The value of the length is in this case l_2 = 506 mm. With this new length, the calculated impedance (of the geometrical model) and the measured impedance (of the natural conch) are plotted on Fig.6.

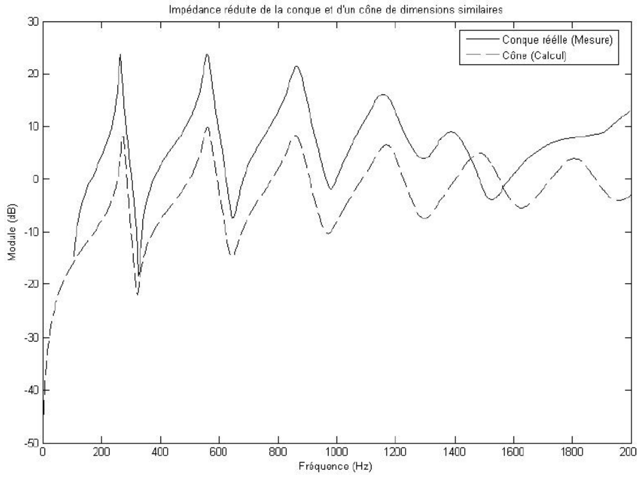

Fig.6: magnitude (in dB) of the measured input impedance (continuous line) and calculated impedance (dotted line) .vs. frequency.

Differences are noticeable between the measurement and the calculation, but the frequency of the 4 first peaks are remarkably very close. This result confirmed that our geometrical model was not so bad. Furthermore, these results gave indication for the design of a bore, namely to be close of a cone.

4 Design and optimisation of the bore

4.1 Initial design of the bore

The objective of the project was to "design an artificial conch that sounds similar to the natural one". After a study of the sound production in the conch, this problem can be transformed in: "design an artificial conch whose bore is similar to those of the natural one".

However, manufacturing constraints must be taken into account at this level, because the making of complex inner shapes (conical helix) is rather a complex task. The starting point of the design of the conch was to have an instrument as easy as possible to manufacture.

The first constraint was to have a conch made of two parts, two half shells clamped according to the mating surface (sticking). The second constraint was to produce each half shell by plastic injection moulding. Due to manufacturing constraints, it was not possible to reproduce the shape of the bore of the natural conch (conical helix). Indeed, the demoulding of such a part is not possible due to the existence of back drafts. The third constraint was to keep up the external form of the natural conch, in order to preserve the external visual aspect of the instrument.

The problem was to design a large length bore in a relative small space. A CAD model was used to generate the inner shape of the bore. After several propositions, an initial shape of the bore has been proposed (Fig.7).

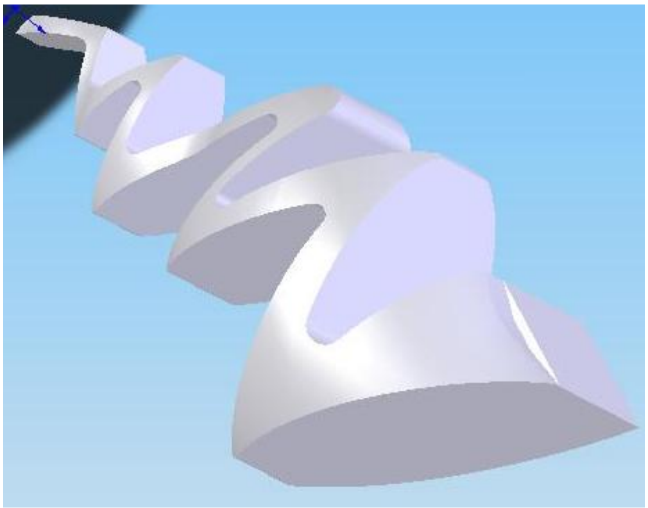

Fig.7: Virtual representation of the initial form of the bore (represented with a CAD-3D software).

This bore is not coiled on a helix, but makes several bends (eight) to increase its length. The section increases progressively from the input to the end. This shape was considered as the initial solution to optimise. A mouthpiece has been added to the instrument.

To build the acoustical model, this initial form has first been uncoiled. Second, each section of the bore has been replaced by the corresponding circular equivalent section. The geometry was simplified and finally represented by the juxtaposition of several conical parts (Fig. 8). Impedance calculation of this bore showed that the inharmonicity of this instrument was very important and that it had great chance to be a "poor" instrument.

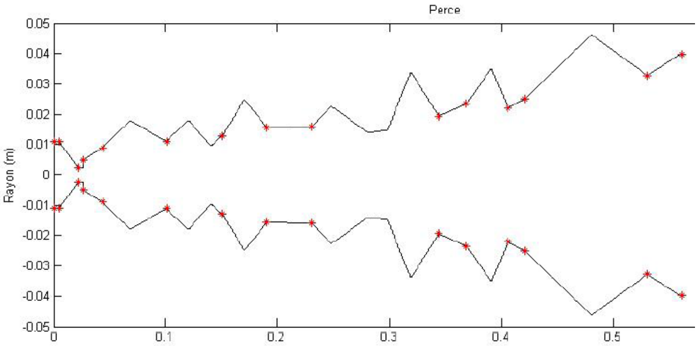

Fig.8: Geometrical model of the initial bore for the calculation of the impedance. Evolution of the radius of the bore .vs. the distance to the mouthpiece

4.2 Definition of the optimization problems

Optimisation in mechanical design is a very widely used technique. Several papers deal with bore optimisation in musical acoustics, using calculus-based method [5, 6] or genetic algorithms [7]. The main elements necessary to formulate the problem are the definition of the optimisation criteria, the definition of the design variables and the algorithm for the iterative process.

The bore of the conch was split into N conical elements (Fig.8), defined by their input and output radii, and their length. To parameterise the optimisation problem, the variables were the input radius R_{ej} of the j-th element and the output radius of the last element R_{sN}. A continuity constraint was added for the definition of the bore ($R_{s(j+1)}=R_{ej}$). An example of the parameterisation for N=4 elements is given Fig.9.

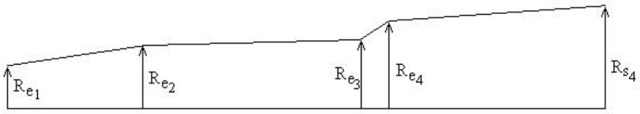

Fig.9: example of parameterisation of the bore

Among the (N+1) variables which define the bore, some of them have been considered as fixed. Two main reasons justify this choice:

- To limit the size of the optimisation problem, and limit the convergence time
- To preserve the external shape of the conch. Indeed, due to geometrical constraints, certain variables must remain fixed, in particular in the "bend" of the bore.

Among the (N+1) variables, the variables which are fixed are represented with a star "*" in Fig.8. In particular, the mouthpiece and the output of the bell are remain fixed and are not concerned by the optimisation. Finally, only M=10 design variables were considered for the optimisation. The optimisation variables are defined by the vector $X(R_{ei}, R_{ej}, ..., R_{ek})$ of dimension M.

Two optimisation criteria were chosen. The first one (c1 – Eq.2), represents the relative "distance" of the artificial conch to the natural one. The second one (c2 – Eq.3), represents the "inharmonicity" of the instrument.

$$c_1 = \sum_{i=2}^{5} \left(\frac{f_i}{f_1} - \frac{f_{iref}}{f_{1ref}}\right)^2 \qquad (2)$$

$$c_2 = \sum_{i=2}^{5} \left(\frac{f_i}{f_1} - i\right)^2 \qquad (3)$$

(with f_i, frequency of the i-th impedance peak – f_{iref} for the natural conch).

The optimisation problem can be stated as follows (Eq.4):

$$X^* = \arg\min_{X\in R^M} .c(X) \qquad (4)$$

The optimisation procedure was programmed in matlab using the Levenberg-Marquardt algorithm [8]. This algorithm is based on the quasi-newton method and is particularly robust for the definition of an optimum.

4.3 Results

With the initial bore as input, several optimisations were carried out. For the best solutions, the frequency ratios of the impedance peaks are given in table 1.

Frequency ratio	f_2/f_1	f_3/f_1	f_4/f_1	f_5/f_1
Natural conch	2.13	3.30	4.42	5.31
Optimization c1	2.16	3.29	4.49	5.70
Optimization c2	2.15	2.98	4.08	5.0

Table 1: frequency ratios of the natural conch and the different optimizations

For the design of the conch and the suite of the project, we decided to consider the results of the optimisation according to the criteria c1. For the playability of the instrument, we considered, as for the brass instruments, that the harmonicity of the impedance peaks is a very important characteristic. The geometry of the optimised bore, corresponding to the optimisation of c1, is given Fig. 10.

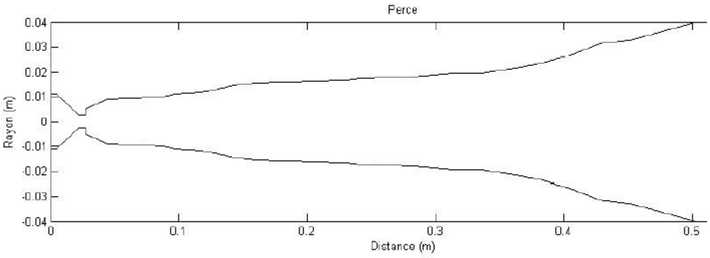

Fig.10: geometry of the optimised bore for criteria c1. Evolution of the radius of the bore .vs. the distance to the mouthpiece for the.

5 Discussion – Conclusions

A prototype of a conch, with a geometry corresponding to those of Fig.10, was made with rapid prototyping techniques (Fig.11). Tests showed that the instrument was playable and produced an interesting sound. The note corresponding to the first impedance peak is stable and sounds full. The second partial is less marked and is less stable, as for the natural conch. The differences between the natural conch and the artificial are rather thin. The main difference is that the changing of the note by placing the hand in the bell is less efficient with the artificial conch than with the natural. A special work on the bell of the artificial conch has to be made.

In conclusion, we presented in this paper a study of the marine conch. A study of the inner geometry of the conch showed that the form is complex (conical helix, with variable section). We proposed a simplified model of the geometry. Measurements of the input impedance of the conch showed that more than four impedance peaks can be extracted, corresponding roughly to a harmonic series. We presented next the optimisation of the bore of an artificial conch. Manufacturing constraints were taken into account for the definition of the initial form of the bore. The optimisation leaded to an improvement of the harmonicity of the artificial conch. Finally, artificial conchs are now manufactured in injection moulding, with the results of our optimisation. The continuation of this work will be to design conchs of different size.

Fig.11: picture of the two parts of the artificial conch, made in rapid prototyping. The inner shape of the bore is visible in the two half-parts.

Acknowledgments

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