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Computer Simulation of the Acoustic Impedance of Modern Orchestral Horns

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This paper outlines the development of a computational tool for modelling the acoustic impedance of modern orchestral (French) horns. The acoustic behaviour of an orchestral horn differs significantly from other brasswind instruments because of the presence of the players right hand in the bell of the instrument. We propose to model the acoustic wave propagation in the complex horn/hand geometry using finite-difference techniques, and we explain how the use of a high-level parallel programming library allows us to parallelise the resulting, processor intensive, computation.

Keywords: horn, brasswind, acoustic impedance, finite-difference, high-level parallel library, parallel application.

1. Introduction

The sound propagation in an enclosed space depends on a variety of closely coupled and nonlinear parameters and is thus often a complex subject. This is typically the case for musical instruments. The advent of easily accessible computational tools includes the development of acoustic models, constructed in order to make the problems of design and analysis of instrument performance more tractable. These models invariably involve abstractions and simplifications depending on the basis of the particular model. The abstraction and simplification of some of the features in the model can however result in a significant difference between modelled output and observed behaviour for a particular instrument design.

We focus in this paper on the study of brasswind instruments, more specifically orchestral horns. The complex behaviour of these instruments offers an interesting challenge both for acousticians and computer scientists.

A number of studies have been performed to simulate the acoustic input impedance of such instruments resulting from a given bore profile. The input impedance is normally regarded as the principal characteristic for determining the playing attributes of a brass instrument. However, such studies have so far been largely limited to trumpets and trombones since the bore profile is independent of the player for these instruments. The french horn offers an additional challenge for computer modelers due to the presence of the player's hand in the bell. This has a significant impact on the acoustic impedance and should not be ignored in modelling work. Having the player's hand partially inserted into the bell of the instrument has two significant consequences for the modeller: first, the problem may no longer be regarded as axisymmetric, and a three-dimensional model may be needed to provide an adequate solution; secondly, the playing characteristics of the instrument are now more closely coupled to the player through his/her hand position. This latter problem is outside the scope of this paper but is part of an ongoing project at the University of Edinburgh.

We thus propose to model the impedance of a horn taking into account the presence of a hand in the bell. The acoustic wave propagation in the complex horn/hand geometry is modelled using conventional finite-difference techniques, and the computations are parallelised in order to make the highly computer intensive simulations feasible for the instrument designer, i.e. there is an acceptably short run time. Although many models have been proposed for brasswind instruments, to the best of our knowledge none has been developed to take into account the effects of the hand and reflect the complexity of the instrument/player coupling in this context.

Structure of the paper

The next section provides further motivation for this work, showing, with the aid of experimental measurements, the lack of agreement between the standard transmission line models and measured data for the case of the french horn. We present the one dimensional transmission line theory and show that the results may not be satisfactory for modelling the impedance of orchestral horns. Section 3 proposes a model of the wave propagation in the complex geometry resulting from the hand in the bell. Since this model is highly processor intensive, we propose a suitable regime for parallelising these computations. To facilitate the process, tools and techniques from high level parallel programming are used. Finally, we conclude and detail future work in Section 4.

2. Acoustic impedance of brass instruments and the horn

Our work is largely motivated by our experiences of standard models of acoustic impedance of brass instruments not providing satisfactory results for the case of the horn, typically because of the presence of the player's hand in the bell of the instrument, and the rapidly flaring bell section in general. We briefly outline in the next section the classical one dimensional transmission line (1-D TL) theory and how we model it using MATLAB [3]. Section 2.2 compares the model analysis with experimentally measured data, and illustrates some of the deficiencies of using this approach.

2.1. 1-D Transmission line theory

A number of computational models of wind instruments have been developed from one dimensional transmission line (1-D TL) theory as discussed by Benade and Jansson [4], Keefe [8], and van Walstijn [14]. These models provide an excellent first estimate of the acoustic impedance of the instrument but their accuracy is somewhat limited in the region of rapidly flaring bell sections. Noreland [10,11] presents a composite model using conventional 1-D TL analysis for the narrow, slowly tapering sections, and couples this to an axisymmetric finite-difference model of the rapidly flaring bell section, with results to good effect.

The 1-D transmission line model described here is based on a piecewise solution to the linearised lossless wave equation as described in [14]:

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \qquad (1)$$

where p is the acoustic pressure, c is the wave velocity, and ∇^2 is the Laplacian operator for a cartesian coordinate system. For plane waves propagating in one dimension, the wave equation reduces to:

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \qquad (2)$$

Corrections can be made to Equation (1) and Equation (2) to account for visco-thermal losses at the boundary surfaces of the horn.

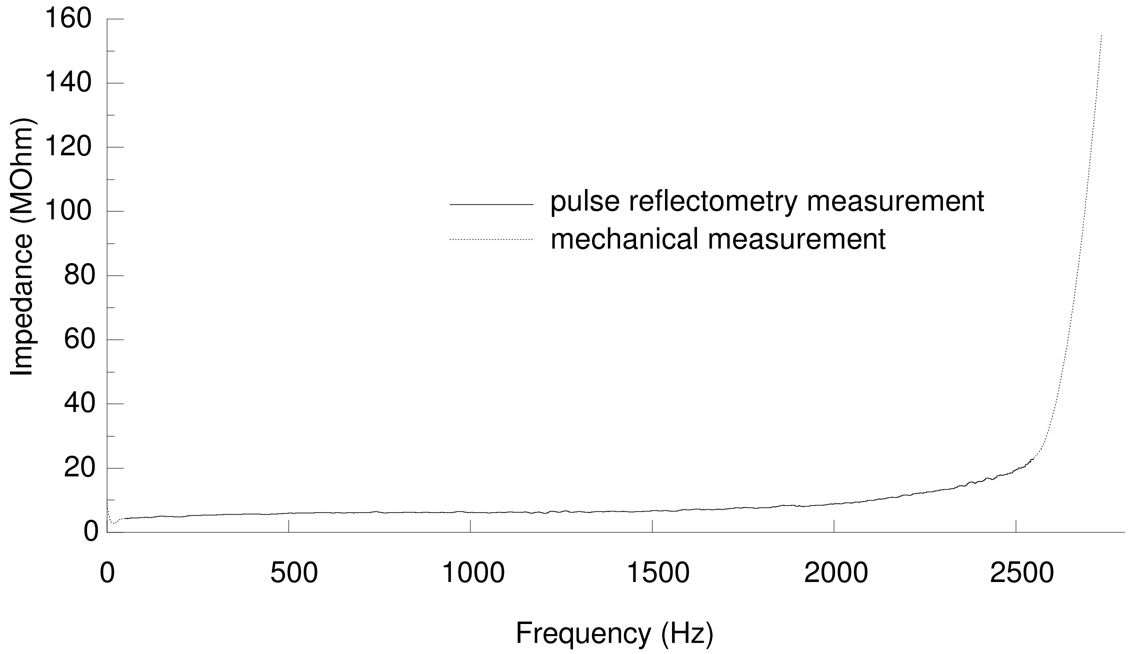

Figure 1. Measurement of the internal bore profile of the open B♭ tubing of a Paxman model 40 B♭/f-alto horn.

There are no analytic solutions for the general case of horns of varying cross section, but a lumped parameter or piecewise solution, in which the horn is modelled as a series of short cylindrical or conical sections, yields good results for horns with only moderately flaring bell profiles. The classical method of piecewise modelling of wind instruments is described by Plitnik and Strong [13]. Solutions are usually expressed in terms of acoustic impedance, $Z(\omega)$, defined as the ratio of the acoustic pressure $p(\omega)$ and the acoustic volume velocity $U(\omega)$ measured at the input plane of the instrument for a sinusoidal input signal of angular frequency ω. These 1-D transmission line models become less effective in the region of rapidly flaring bell sections principally due to the excitation of higher order modes.

The MATLAB model used here reads in a text file containing information about the bore profile: axial distances from the mouthpiece and corresponding bore radii. The model outputs frequency and acoustic impedance.

A comparative study between output from the transmission line model and measured data for a modern orchestral horn highlights this weakness. The bore profile of an instrument (including mouthpiece) was measured using a combination of acoustic reflectometry and traditional mechanical measurements. Pulse reflectometry measurements were obtained using apparatus developed at the University of Edinburgh by Kemp [9]. This technique has proved useful in obtaining accurate bore profile data of brass instruments up to (but so far not including) the final rapidly flaring region of the bell. The bell and mouthpiece were measured using conventional mechanical techniques. The instrument studied here is the open B♭ tubing of a Paxman model 40, B♭/f-alto horn. The bore profile is shown in Figure 1.

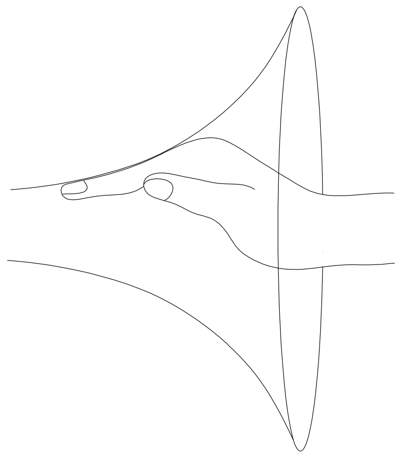

Figure 2. Typical position of a player's hand in the bell of a French horn.

2.2. Specific issues of horn technique

Unlike other members of the brasswind family of musical instruments, the horn is played with the player's hand partially inserted into the bell of the instrument as shown in Figure 2. This is a legacy of historical practise developed prior to the invention of the valve. Where, by varying the level of obstruction of the bell throat by the hand, the pitch of an "open" note may be manipulated to provide notes that would not otherwise be available on a fixed length of tubing. By modifying the termination impedance of the horn the presence of the hand in the bell also extends the range of resonant modes in the upper register of the instrument, typically from B♭4 and above. Without the presence of the hand in the bell, the high register becomes difficult or impossible to play. Thus, the player's hand forms an integral part of the instrument, and it is difficult to assess the quality of a particular instrument without accounting for this.

Figure 3 illustrates measured impedance curves taken from the open tubing of a B♭ horn with the hand positions of two different players, and without the hand in the bell. The playing response and intonation of the instrument is very strongly dependant on the frequencies and magnitudes of the local impedance maxima.

This first experiment clearly shows the impact of the hand position in the bell and its effect on the acoustic impedance. Further investigation illustrates how the 1-D TL model may not be acceptable when applied to a study of the acoustic impedance of the horn. The curves in Figure 4 show the difference between the 1-D TL model prediction of Section 2.1 and the measurements for the same instrument, and we can see that there is a clear difference between those curves, particularly in the high register.

3. Numerical modelling of the bell/hand geometry

Section 2.2 clearly illustrated the need for any model whose function is to calculate the acoustic impedance of the horn to take into account the player's hand, its shape and position in the bell. Thus, the model needs to be more sophisticated than the standard 1-D TL model. In this section we describe some features of how to model the bell/hand geometry, and present a user friendly design tool for instrument makers, based on this model.

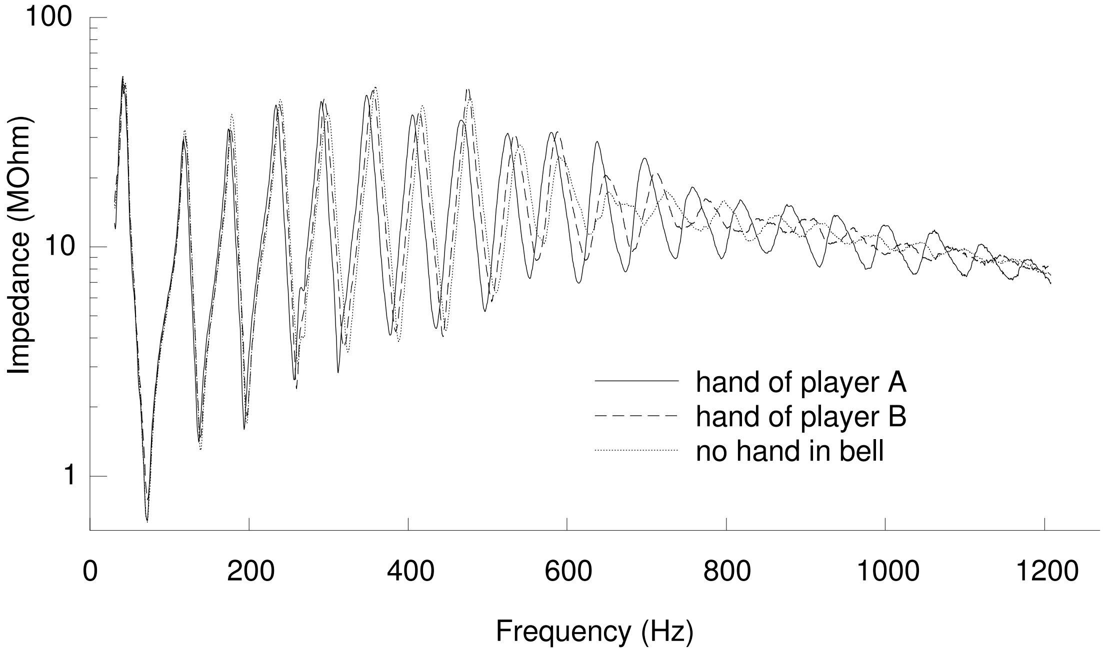

Figure 3. Impedance curves taken from the open B♭ tubing of an Alexander model 103 F/B♭ horn for different player's hand positions.

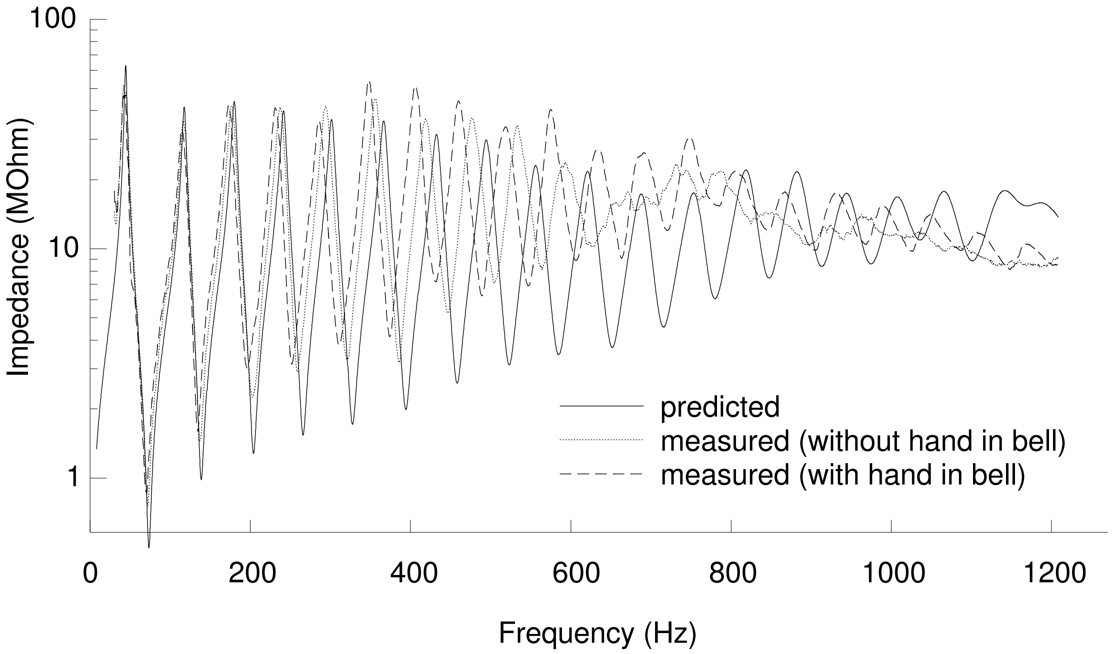

Figure 4. Impedance curves taken from the open B♭ tubing of a Paxman 40 B♭/f-alto horn, with and without hand, and 1-D TL model curve.

3.1. Basics of the model and tool prototype

To the authors' knowledge no computational study has been conducted which includes the effects of the presence of the player's hand in the bell of an orchestral horn. The solution proposed by Noreland [10,11] for rapidly flaring axisymmetric bell sections provides an excellent starting point and may be adapted for this purpose by modelling the bell/hand geometry using a 3-D finite-difference scheme.

Modelling wave propagation in the complex geometry produced by the hand in the bell is highly processor intensive and can result in long run times. For this reason, the modelled domain is decomposed into a number of subdomains, for each of which the wave equation may be solved using conventional finite-difference techniques.

As part of an ongoing project to develop a user friendly design tool for instrument makers, we propose to parallelise the problem solution as detailed in the next section. This parallelised routine is at the heart of a linked suite of computer programmes currently under development. The prototype of our tool is displayed in Figure 5.

The main component of the suite is *ProCAIB* (**Pro**gram for **C**alculating the **A**coustic **I**mpedance of **B**rasswinds). Input to *ProCAIB* is generated by running the preprocessor application, *ProGIG* (**Pro**gram for **G**enerating the **I**nstrument **G**eometry files).

ProGIG is parameterised by a series of easily modifiable generic design templates that the instrument designer can manipulate to his or her needs. In the case of the horn, the hand position is also taken into account and profiled through the preprocessor.

The output of *ProCAIB* consists of the acoustic impedances corresponding to the given bore profiles/hand geometry. A final component in the suite is the post processor *ProANAB* (**Pro**gram for **ANA**lysing **B**rasswinds data). *ProANAB* assists in the interpretation of modelled output, providing feedback to the instrument designer. Typically, instrument design is an iterative process and output from *ProANAB* can be used directly to modify the input to *ProGIG*, taking into account the results from earlier computations to refine the profiling of the instrument.

The main computational part of the problem is in the *ProCAIB* component, for which we propose a parallel algorithm to deal with the numerous parameters.

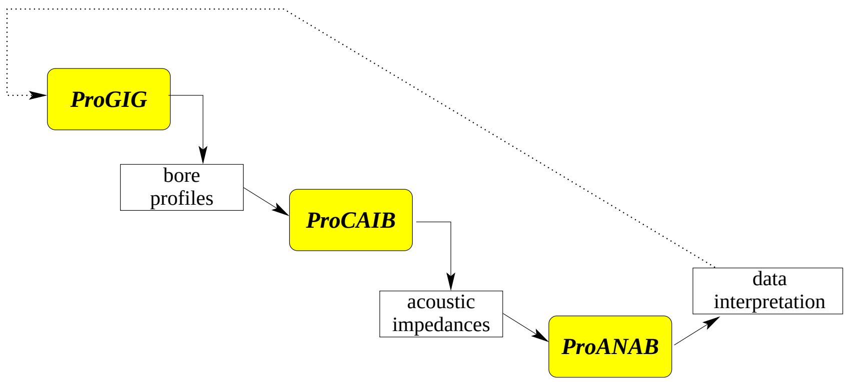

Figure 5. Prototype of a tool for instrument designers.

3.2. Parallelising the model

We propose the development of an ad-hoc solver for the solution to the wave equation, using a high-level parallel programming approach integrating MATLAB [3] numerical algorithms. This allows us to separate the application-specific design from the parallelisation problem. Our goal is to parallelise the *ProCAIB* component.

Several high-level approaches to parallel programming have been documented in the research literature [7,12], based on the fact that many parallel algorithms are following a number of generic patterns (or *skeletons*) of computation and interaction. The skeletal programmers abstract such patterns, and provide them to the application programmer as a library, allowing the programmer to experiment easily with a variety of parallel structures for a given application, without needing to attend to the underlying implementation of the parallel computations and interactions.

Calls to MATLAB functions can be made from a C program through the use of the MATLAB Engine [2]. We therefore propose to perform calls to MATLAB functions from the C/MPI-based skeleton library *eSkel* [5]. In this way, we can have direct control over the interactions between the different parts of the model, using either implicit or explicit interactions [6], and we can refine the parallel scheme of the program.

We propose to parallelise the computation for a given bore profile/hand geometry, since we have identified these to follow a *pipeline* pattern. The model can be decomposed into several sub-domains, and several successive computations must be performed on each of these sub-domains. The pipeline skeleton allows us to associate a state to each pipeline stage, and this state is evolving while processing the successive sub-domains, taking into account the correlations between these computations.

For automated design optimisation work we can add an additional level of parallelism in which several bore profiles may be analysed in order to determine the best design solutions for an instrument within a given design space. In this case, the parallelisation is straightforward and easy to integrate with *eSkel* using the *farm* skeleton to distribute the independent computations on several processors. The MATLAB Distributed Computing Toolbox [1] could be used for the same purpose, since it allows several executions of a MATLAB program to be run in parallel on a cluster of computers. However, our choice is motivated by several arguments:

- the implementation is straightforward because of the facilities offered by high-level parallel programming libraries;
- we can integrate the inner parallelisation of the computation for one single bore profile;
- we have a better control on the allocation of processes onto the available processors and on the parallel behaviour of the program;
- all the parallel software used is a free-software.

4. Conclusions and future work

In this paper, an overview is presented of the complex problem of modelling the bell/hand geometry of an orchestral horn. Some experimental measurements have been done to show the impact of the presence of the hand in the bell on the acoustics of the horn. We have also shown that the classical one dimensional transmission line model may not be satisfactory for the study of the horn, and that a more complex model is needed for this instrument.

Such models can be developed using finite-difference techniques, and we propose to parallelise the simulation algorithm using a high-level parallel library. Indeed, the model is complex and resolution is computationally highly intensive and would be cumbersome if performed in a sequential manner.

Initial tests to perform calls to MATLAB functions in parallel through the use of a parallel library have shown promising results in the case of the 1D-TL models, with the help of the MATLAB Engine. This work is ongoing, and further work remains to be done before we can fully assess the performance of the parallel algorithm based on the simulation using the finite-difference techniques.

To conclude, we have shown that a new model is needed to assist in the development of orchestral horns, and we have outlined the design of such a model. Having tested the integration of MATLAB models with the parallel library, we believe that our methodology is robust and will result in a useful and reliable design tool.

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