Acoustical analysis of woodwind musical instruments for virtual instrument implementation by physical modeling

Panagiotis Tzevelekos and Georgios Kouroupetroglou
National and Kapodistian University of Athens
Department of Informatics and Telecommunications
{koupe, taktzev}@di.uoa.gr

ΠΕΡΙΛΗΨΗ

Στην εργασία αυτή παρουσιάζουμε την ανάπτυξη ενός πλαισίου μεθοδολογιών, οι οποίες επιτρέπουν αφενός τη δημιουργία ακουστικών αναλύσεων από corpora ηχογραφήσεων ξύλινων πνευστών μουσικών οργάνων και, αφετέρου, την υλοποίηση αντίστοιχων εικονικών μουσικών οργάνων με τη μέθοδο της φυσικής μοντελοποίησης. Έμφαση δίδεται στα παραδοσιακά μουσικά όργανα, ξεκινώντας από τον ζουρνά. Η ανάλυση υπολογίζει τις κατάλληλες ακουστικές παραμέτρους του οργάνου (χρόνοι ανάκρουσης-ελευθέρωσης, κατανομή φασματικών αρμονικών, καμπύλες τονικού ύψους και έντασης κ.ά.). Επίσης, σε συνδυασμό με μετρήσεις από λαρυγγογράφο, προσδιορίζονται χωριστά στοιχεία τεχνοτροπίας του εκτελεστή. Οι παράμετροι που εξάγονται από τις ακουστικές μετρήσεις είναι απαραίτητες για την ανάπτυξη αντίστοιχων εικονικών οργάνων με τη μέθοδο της φυσικής μοντελοποίησης. Πιο συγκεκριμένα, γίνεται χρήση της προσέγγισης των ψηφιακών κυματοδηγών, με την οποία προσομοιώνεται η διάδοση του ηχητικού κύματος στο όργανο.

ABSTRACT

In the present paper, we present the development of a framework of methodologies, which allow the creation of acoustic analysis, by woodwind musical instrument recordings corpora, as well as the implementation of virtual instruments, by physical modeling. We emphasize on traditional instruments, starting with the zournas. By analysis, acoustical aspects of the instrument are derived (attack-release time, spectral harmonic distribution, pitch and intensity contours et.c.). Moreover, in conjunction with measurements by a laryngograph, features of the player's performance style are recovered. The parameters extracted are necessary for developing virtual instruments by physical modeling. To be more precise, digital waveguide models will be used to simulate the sound wave propagation in the instrument.

1. INTRODUCTION

Woodwind instruments have a long tradition in many countries. A wide range of scientists, from physicists to musicologists, conducted research on their acoustics [1,2,3]. However, most studies refer to classical western instruments. Research on traditional non-western instruments begun not many years ago [4] and the results are considered valuable for musicological scopes, as well as for the sound synthesis industry.

The *shawm* was the most widespread woodwind double reed instrument of the Middle Ages and is still found throughout Europe, North Africa, Middle East, India and China. It is considered to be the ancestor of the oboe. The Greek shawm-like instrument is called *zournas* and is considered to derive from the Ancient Greek *aulos*. There are several types of zournas, which differ in size, number of holes and other characteristics.

In this paper, we present acoustical properties of a certain type of zournas, which derived from recordings of performance by an expert player. They are presented and commented in section 2. In section 3, we discuss about characteristics of the player's performance and how they are related to measurements taken. Last, we suggest the steps necessary for virtual instrument implementation.

2. ACOUSTICAL ASPECTS OF THE ZOURNAS

2.1 Technical Issues

Zournas, as most woodwind instruments, consists of three major parts as shown in Fig. 1. The mouthpiece is shown in Fig. 2. The cane double reed acts as a pressure controlled valve. Through the connector, which is covered with fiber, the embouchure connects to the instrument bore. The cylindrical part, some times conical, at the end of the mouthpiece, as shown in Fig. 2, is usually made of cork, and is entered inside the instrument bore.

The bore is conical, like the one of the oboe. The number of toneholes depends on the type of zournas. The one that we used for the recordings had 7 toneholes and a register tonehole on its back side. It was tuned in Si*b* Uşşac mode.

The bore ends up at a bell. The flare of the bell also depends on the type of zournas. However, in most types the flare is bigger compared with the bell of an oboe. Round the bell, one can usually find small holes. These are not toneholes, but are made for better air flow inside the bore, which leads to a better overall tuning of the instrument.

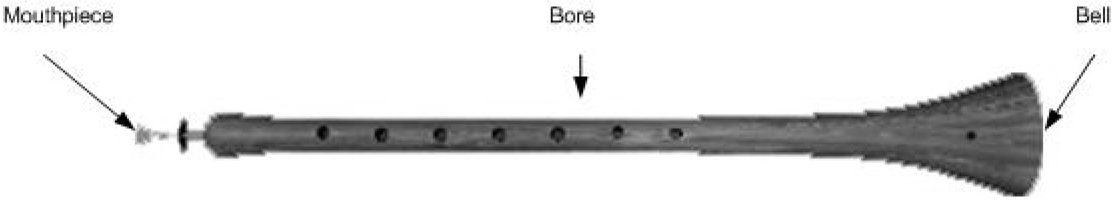

Fig. 1. The zournas consists of tree parts: the mouthpiece/reed assembly, the instrument bore and the bell.

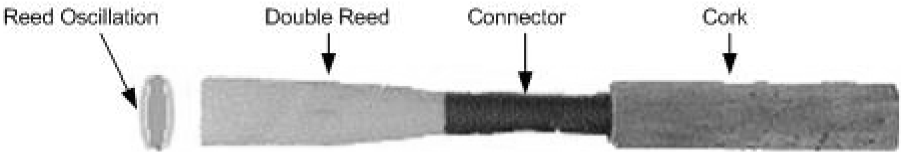

Fig. 2. The zournas mouthpiece and reed assembly.

Some facts for the zournas we used are presented in Table 1 and Table 2.

Table 1: Geometrical and technical features for the zournas used.

Mouthpiece		Bore		Bell	
Reed length	1,5 cm	Bore diameter	2 cm	Bell diameter	8 cm
Connector length	1,9 cm	Tonehole diameter	0,6 cm		
Cork length	1,9 cm	Total instrument length		34,5 cm	
Diameter at the end	0,6 cm				
Reed opening at rest	0,1 cm				

Table 2: Tonehole distance from bore start.

Tonehole Number	Distance (cm)
1	6,2
2	8,7
3	11,2
4	13,7
5	16,4
6	18,6
7	21,4
Register tonehole	7,5
Bell holes	27

2.2 Recording the zournas

For the recordings of the zournas, an LCM 85 LP microphone, by SD Systems, was used. This microphone attaches to the bell of the zournas and is considered to be a good choice for recording woodwind instruments. Sound recorded into a Yamaha AW16G Audio Workstation with a sampling frequency $f_s = 44{,}1\ \mathrm{KHz}$.

During the performance, a Field Electro-Laryngograph by Laryngograph LTD was used, in order to register the vocal folds' motion. A pair of electrodes is positioned on the player's neck, in front of the wings of the thyroid cartilage and connects to laryngograph's main body. Laryngograph outputs a signal, which is recorded in synchronisation with the signal from the zournas. By analysis of the laryngograph's waveform, one can find out whether the player's vocal folds were used during the performance and with what way.

The player who performed was a professional zournas player. He used his own zournas, described in paragraph 2.1. He started by playing a melodic up and a melodic down Si*b* Uşşac mode, the tune mode of the zournas. Then, we asked him to play separately every note, covering the instrument's whole range. Due to the double reed excitation mechanism, pitch of the note played is greatly determined by the blowing pressure. Hence, for every fingering, two recordings took place. At the first, the player tried to produce the correct pitch which corresponds to the certain fingering. At the second, the player kept the same fingering, while altering the blowing pressure from a minimum to a maximum and, thus, altering the pitch. The second set of notes is only used for pitch and harmonic deviation measurements. 15 notes were played and recorded with both ways. Last, the player performed a traditional music piece named *Makrynitsa*.

During the performing, temperature and humidity conditions did not change appreciably.

2.3 Measurements and results

Each recording was saved as a .wav sound file and analyzed. The time domain waveform was used to obtain data about the attack and release time, the intensity envelope and the pitch deviation of each note. For these calculations the Sony Sound Forge 7.0 and the Praat 4.2.06 software was used. Although the Praat software is usually used for speech synthesis and phonetics analysis, we found that is also suitable for musical acoustic analysis.

In Table 3, the attack and release time for every note, as well as their mean values and standard deviations. For naming the notes we use the latin system (la^3 = 440 Hz). The symbol ↓ shows a note lowered by an interval of ¼ tone (Uşşac mode). The notes correspond to the fingering and not the actual pitch. From the statistic results, the sol^3↓ data were excluded, according to Chauvenet's criterion.

By the results, it is obvious that the zournas has relatively quick attack and release, which is common for woodwind instruments. Comments on specific notes will be made later on, as they arrive from performance issues.

Table 3: Attack and release time for every note.

Note	Attack (sec)	Release (sec)
sol^3↓	0,057	0,027
$sol\#^3$	0,034	0,026
$si\flat^3$	0,031	0,025
si^3	0,035	0,028
do^4↓	0,023	0,022
do^4	0,023	0,022
$do\#^4$	0,017	0,023
re^4	0,017	0,020
$re\#^4$	0,020	0,020
mi^4	0,014	0,015
fa^4	0,016	0,014
$fa\#^4$	0,027	0,023
sol^4↓	0,025	0,023
$sol\#^4$	0,018	0,020
$si\flat^4$	0,038	0,022
Average $\bar{x}$	0,024	0,022
Average Deviation $\sigma_{\bar{x}}$	0,006	0,003

Table 4: Pitch variations for variable blowing pressure levels, during certain fingerings.

Note Fingering	Reference Pitch (Hz)	Min Pitch (Hz)	Max Pitch (Hz)	Max-Min Difference (Hz)
sol^3↓	380,84	372,8	412,0	39,20
$sol\#^3$	415,31	406,8	446,8	40,00
$si\flat^3$	466,16	387,4	489,3	101,9
si^3	493,88	458,0	545,6	87,60
do^4↓	508,35	437,0	556,0	119,0
do^4	523,25	465,2	661,8	196,6
$do\#^4$	554,36	487,5	625,7	138,2
re^4	587,34	560,1	743,0	182,9
$re\#^4$	622,26	550,5	749,7	199,2
mi^4	659,26	626,9	783,7	156,8
fa^4	698,46	644,7	842,7	198,0
sol^4↓	761,68	679,7	863,2	183,5
$sol\#^4$	830,62	759,8	953,2	193,4
$si\flat^4$	932,32	780,6	1127,4	346,8

Perhaps the most characteristic feature of the zournas is the ability that gives the player to significantly change the pitch of the note played by changing the air pressure blown. This is also true for all reed woodwinds [5], but for the zournas the effect is so drastic that prohibits the player from playing the same note in different volume levels. The second set of recordings, described in paragraph 2.2, was held to examine this effect.

On Table 4, a list of pitch variation data is given for various fingerings. The reference pitch corresponds to the certain fingering, using the equally tempered tuning. The minimum and maximum frequency values derived from a pitch contour that Praat software provides. It is seen, that is more difficult to change pitch with blowing pressure for lower notes, lower frequencies, while higher notes tend to be more flexible in pitch variation. For the highest note $si\flat^4$ a pitch shift of 348,8 Hz was measured. The spectrogram and the pitch contour of this note are shown in Fig. 3. The deviation is obvious in both graphs. The high leap in the pitch contour at the end of the recording is due to the fact that strong overblowing caused sound to “crack”. This happened in many recordings of this set.

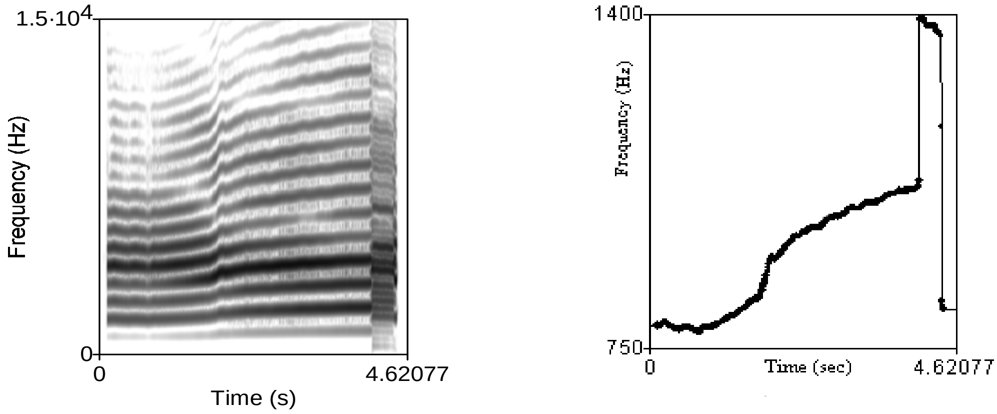

Fig. 3. Spectrogram and pitch contour graph for note si*b*^{4} *while changing the blown air pressure. The pitch shift is obvious.*

In Fig. 4(a), the waveform of note si*b*^{3} and the corresponding spectrum are presented, as given by Praat software, and in Fig. 4(b) the same graphs for note sol#^{4}.The spectrums were produced by Praat’s FFT (Fast Fourier Transform) algorithm.

By examining the spectrum in these examples, as well as the spectrum of every note, it is clear that the sound output of the zournas exhibits a very rich harmonic distribution. First of all, the spectrum contains both odd and even harmonics, as expected for an instrument with conical bore. We come across strong harmonics up to the region of 8-10 KHz, depending on the note. In both examples is obvious, that the prominent harmonic is not the fundamental one. This is common for woodwinds with conical bores e.g. the oboe. It is due to the fact that such bores show peaks rising in height with increasing frequency, in their impedance graphs. Therefore, the radiated spectrum initially rises with increasing frequency until, above cutoff, it typically falls [6].

The double reed effects are seen both in the waveforms and the spectrums. The reed channel in the double reed is long and narrow (though not as narrow as in oboe’s) and, as well as introducing inhibiting flow separation and inducing a Bernoulli effect, this long channel introduces appreciable flow resistance and cause the reed to be always in beating mode [6]. All harmonics of the flow are reinforced by resonances. This means, that the waveforms can be quite asymmetrical, which was obvious in most of them. Reed harmonics strongly shape the rich spectrum of zournas.

The flared bell of the zournas is also of great importance. As in horns, the flared bell acts like a highpass filter, meaning that the reflection point for waves of low frequency is further inside the mouth of the bell than for those of high frequency [3,6].

All the features mentioned above give the zournas a bright, strong and reedy timbre. The relatively short-lengthened bore, the flared bell and the wider reed make its sound not as warm as oboe’s but acute and strident.

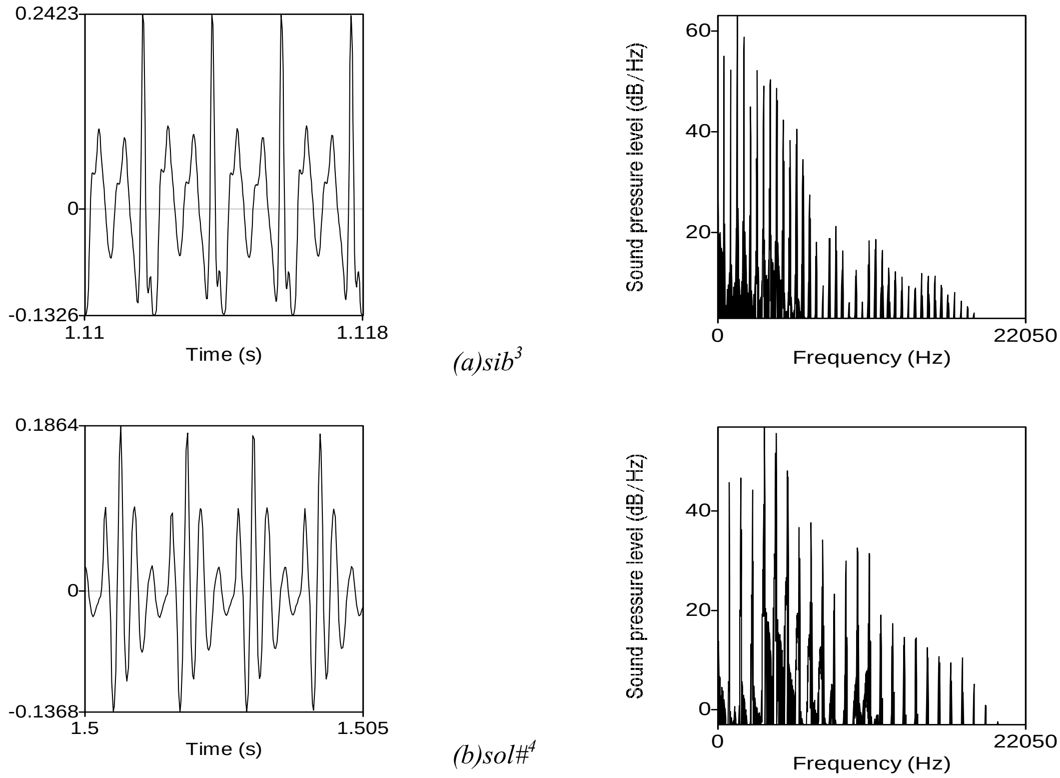

Fig. 4. (a) Waveform and spectrum for note si*b*^{3} *and (b) similar for note* sol#^{4}.

3. THE PLAYER'S MUSIC PERFORMANCE

Unfortunately, recovering physical playing parameters from the sound analysis to characterize a performance or a performer is still an open problem [7]. In this paper, we use the results discussed in the later section in conjunction with the signal from the laryngograph to obtain information about the player's performance tendencies and style.

Attack and release time issues were discussed in paragraph 2.3. Data on Table 3 showed that attack and release time for the zournas are quite short. However, by taking a closer look in these data, one can spot some differences from note to note which are not accidental, but have to do with the performer. Longer attack times are noticed in notes difficult to play, such as very high or very low notes (e.g. sol^3↓, sol#^{3}, si*b*^{4}) and notes not belonging in the natural tuning of the instrument (e.g. fa#^{4}). For these notes, it is harder for the player to attain the right pitch. He needs more time to adjust the blowing pressure, or the position of his fingers over the toneholes, in order to tune. Thus, in the time necessary to build up the correct sound, that is the attack time, few milliseconds are added. This argument was confirmed by the player. Release times are not affected in that way, and thus show smaller deviation.

The fact that the pitch of a note is easily bended by the blowing pressure, forces the player to use the same level of dynamic throughout a note. He can't change from a *pp* to an *f* without changing the pitch of the note played. To get the right pitch he played rather loud. He usually accented his attacks, at both the note by note recordings and the music piece recordings. This was either because of the pitch problem mentioned, or because he set the reed beating quite abruptly. It was also observed that he stored a great amount of air in his mouth, in order to maintain a convenient air flow in the reed and easily adjust the pitch.

The results taken from the laryngograph's signal were of great importance. It was found that throughout most of the player's performances, there was no movement of its arytenoids, aryepiglottic fold or vocal folds in an oscillating manner, as during speech or singing. The signal of the laryngograph is in this case aperiodic. This was observed at the first and second recorded set of the 15 separate notes. However, the signal recorded during the performance of the piece *Makrynitsa* had some very interesting aspects. Even though, in the biggest part of the piece, the signal showed that the player breathed and blew without using his vocal folds, there were very short instances where the laryngograph's signal came periodic, revealing an oscillating motion of the player's vocal folds.

In Fig. 5 such a point is presented. The figure contains three graphs. The upper is the sound waveform. The middle shows the pitch (bold) and the intensity (normal) contours. The lower is the signal obtained by the laryngograph. All graphs are drawn for the same time window of 551 ms. In the laryngograph's signal, at approximately 11,85 s and 12,02 s, periodic forms arise which, as mentioned above, implie a periodic movement of the player's vocal folds. It is interesting that at the exact time points, similar oscillations are observed in the pitch and intensity contours, while the amplitude in the sound waveform falls.

Fast periodic pitch variations are common in singing and instrument performances and produce the *vibrato* effect. Practically, vibrato is usually followed by *tremolo*, a periodic amplitude variation. Both vibrato and tremolo are present in our example. Oscillation of the vocal folds during vibrato means that the player used throat vibrato. Vibrato is generally believed to be produced on woodwind instruments by using one of three sets of muscles: those of the abdomen and diaphragm, of the throat, and of the lip of jaw. It appears that the air column was modulated by movement of the vocal folds [8]. This caused changes in the speed and amount of air reaching the reed of the zournas, and resulted in changes in the intensity of the sound. Assuming constant pressure from the abdominal muscles, the volume and intensity of the air would decrease as the vocal folds are approximated. As they are opened, the volume and intensity would increase. Research on woodwind vibrato is found for western instruments [8].

The player stated that he didn't use vibrato willingly nor did he realize doing it. He believed that he might have used it spontaneously, due to the nature of the notes played at the time. Similar vibrato evidence was found in rather long valued non legato notes throughout his performance. Therefore, short vibrato in similar points can be considered as a characteristic feature of his performance.

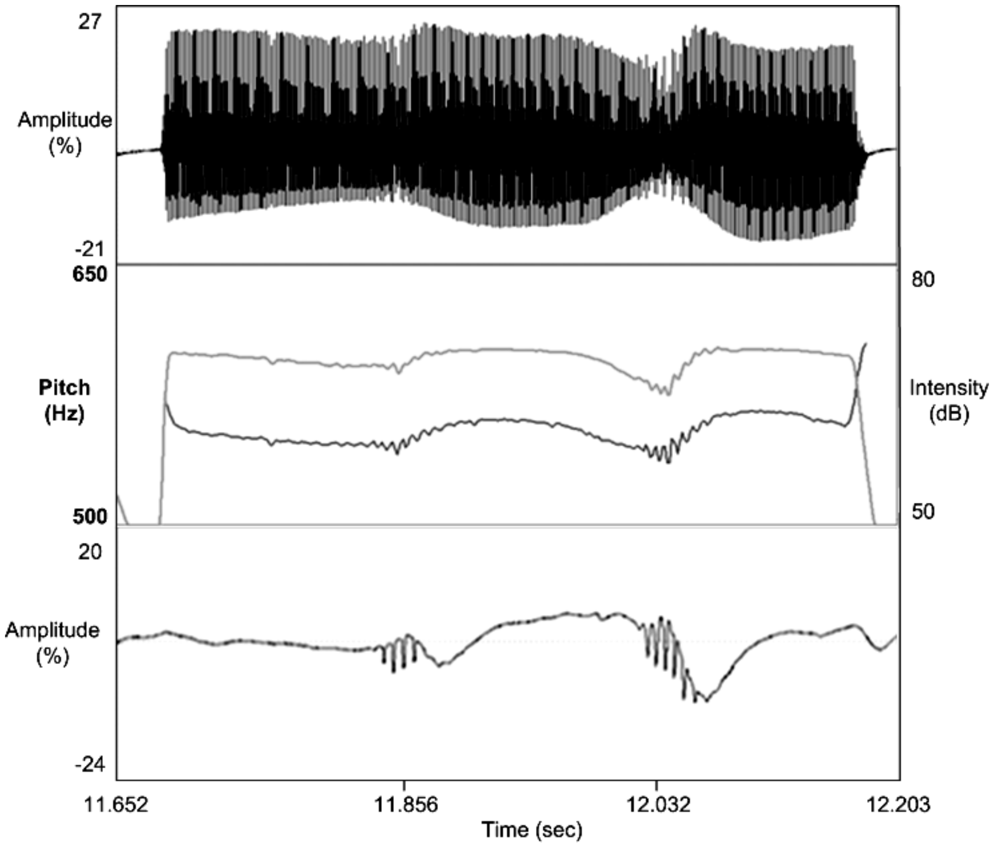

Fig. 5. From top to bottom, the waveform, the pitch (bold) and intensity contours and the laryngograph's signal for a time window of 511 ms of the music piece Makrynitsa are shown. Vocal fold oscillation and vibrato effect are evident.

4. VIRTUAL MUSIC INSTRUMENTS

4.1 Physical Models

Physical models describe the mechanism that the instrument uses to produce and propagate sound. They are based on mathematical models than can describe the physical acoustics of the instrument. That is, if it is likely to collect all the equations corresponding to sound generation and render them by computing means, then the sound output would have great resemblance with the one of the real instrument.

Hence, modeling involves the decomposition of the instrument in several components and the generation of a mathematical description of each component. The combination of these descriptions yields a complete model that can be used in virtual instrument implementation and real-time performance. Fig. 6 (after [9]) shows a typical model of single-reed woodwind instrument. The advantage of this approach is that libraries of components can be built and attached in a favorable way [10].

An important class of physical models is the digital waveguide models. These are essentially discrete-time models resulting from the generic solution of the wave equation that describes the system, often combined with models of lumped elements. The frequency-domain analysis of musical instrument acoustic behavior provides much information regarding the linear components of these systems. Nonlinear behavior, however, is best examined and determined in the time-domain. Digital waveguide techniques provide efficient time-domain simulation (wave propagation), while permitting frequency-domain features to be incorporated into the model in a straight-forward manner [10].

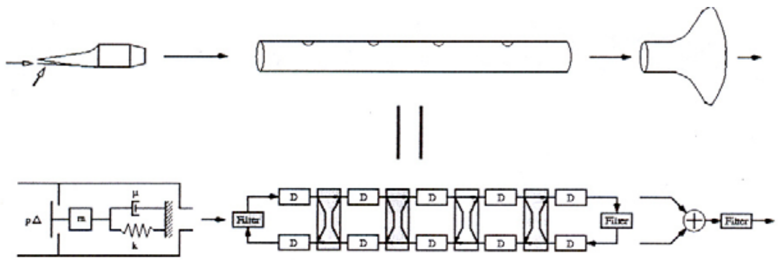

Fig. 6. Typical physical model for woodwind instrument. From left to right one sees the nonlinear excitation mechanism (reed), the instrument bore and the bell. The filters and the delay lines form the digital waveguide.

4.2 Physical Model of the Zournas

To build the physical model of the zournas, one must follow the steps described above, that is to design digital components for the major parts of the zournas: the embouchure, the bore and the bell. To begin with, one must derive the equations that describe the sound generation and propagation in each of the parts, as well as those that describe their connection.

The first part to describe would be the embouchure. Despite the research in single reeds, little is known about double reeds and the aero-acoustic effects that take place during a blow. As in all reed instruments, the reed itself behaves as an oscillator driven by the pressure difference between its inner and outer sides. The two reeds oscillate synchronously, so one could argue that the double reed model could be described by the single-reed model, with few changes. However, the timbre difference between single and double reeds is so great, that is rather logical not to use a single-reed model.

In contrast with single reeds, in a double reed a difference exists between the pressure at the beginning of the reed and the acoustic pressure at the beginning of the bore. This difference is due to the geometry of the canal downstream of the reed, which cause flow perturbations. The flow is restricted to a smaller section of the reed, due to the *Vena Contracta* effect. Such aspects make the modeling of the reed perhaps the most significant part of the entire zournas's model. Models of double reeds were recently proposed, but all scientists agree that more research is to be to done for a realistic double reed model [11].

After describing the embouchure, one must continue with the bore. The bore behaves as a linear resonator, which takes input by the excitation mechanism (the embouchure). Delay lines connect to form the digital waveguide in witch samples travel, simulating the acoustic wave propagation. Wave phenomena, like reflection, transmission, and viscous-elastic losses that take place in the real instrument, are modeled using filters. In order to calculate reflection coefficients, the acoustic impedance of the mouthpiece and the bore needs to be found.

As far as the bell is concerned, in similar projects the bell filtering effect was included in the bore model. However, since the zournas has a flared bell, a highpass filter added before the output could represent its effect.

Results by recordings and measurements of the real instrument are very important for designing and testing the virtual instrument. On one hand, since waveguides form filters, processing the signal of the real instrument can give transfer functions, impedances and other signal related quantities of the instrument parts, essential for developing the filters. On the other hand, several acoustical aspects can be used after the implementation process, for testing and calibrating the model [10].

5. CONCLUSION

The results from the analysis presented in this paper can hardly cover all the acoustic aspects of the zournas, nor can they give all the information required for building a virtual zournas. However, this systematic acoustic analysis made for this instrument and both the methodology used and the data gained are very important for continuing the measurements and expanding them.

Further research will include recordings of different types of zournas, played by different players. New data, such as acoustic impedance, air pressure blown and reed signal will be measured. Hopefully, all results gathered, will allow as suggesting a complete model describing the main features of the double-reed, the bore and the bell behavior. Finally, with a complete model of the zournas and the current knowledge about the modeling of waveguides, we hope to achieve implementing a virtual zournas.

By applying the same methodology for other traditional instruments, we target to build a virtual orchestra of traditional Greek instruments, capable of reproducing the sound of real instruments and being controlled in a straight-forward manner by the performer.

6. ACKNOWLEDGEMENTS

We would like to thank the Institute of Research of Musical Acoustics (IEMA) and its Director Dr Kostas Moschos for offering technical support and valuable advices, as well as Alexandros Arkadopoulos for performing the zournas. This research was partially supported by the POLYMNIA project of the Operational Programme ANTAGONISTIKOTITA of the Hellenic Secretariat for Research and Technology under the 3rd European Community Support Framework for Greece.

7. REFERENCES

[1] N. Fletcher, T. Rossing, *The Physics of Musical Instruments*, chapter IV: Wind Instruments, New York, Springer-Verlag, 1998.

[2] C. Nederveen, *Acoustical Aspects of Woodwind Instruments*, Northern Illinois University Press, DeKalb, 1998.

[3] G. Scavone, *An Acoustic Analysis of Single-Reed Woodwind Instrumetns With an emphasis on design and performance issues and digital waveguide modelling techniques*, PhD thesis, CCRMA-Stanford University, 1997.

[4] A Czyzewski, B Kostek, *Waveguide modelling of the Panpipes*, in *Proceedings of SMAC 03 Stockholm Music Acoustics Conference August 6-9, 2003,* pp. 259-262.

[5] S. Carral, D. Campbell, T. Rossing, *Relationship Between Blowing Pressure, Pitch and Timbre of Scottish Bellows Blown Bordered Bagpipe*, in *Proceedings of SMAC 03 Stockholm Music Acoustics Conference August 6-9, 2003*, pp. 251-254.

[6] N. Fletcher, T. Rossing, *The Physics of Musical Instruments*, pp. 491-494, New York, Springer-Verlag, 1998.

[7] P. Guillemain and T. Voinier, *Characterization of Musical Performance Using Physical Sound Synthesis Models*, in *CMMR 2003, LNCS 2771,* pp. 64-73, 2004, Springer-Verlag, Berlin, 2004.

[8] A. Brown, *A Cinefluorographic Pilot Study of the Throat while Vibrato Tones are Played on Flute and Oboe*, article on the Internet, URL: http://www.zainea.com/vibrato.htm

[9] J. O. Smith III, *Physical Modeling Using Digital Waveguides*, in *Comp. Music J.*, vol. 16, no. 4, pp. 74-91, 1992.

[10] A. Nackaerts, B. de Moore, R. Lauwereins, *A Formant Filtered Physical Model for Wind Instruments*, in *IEEE Transactions on Speech and Audio Processing,* vol. 11, no. 1, January 2003.

[11] A. Almeida, C. Vergez, R. Causse, X. Rodet, *Experimental Research on Double Reed Physical Properties and its Application to Sound Synthesis*, in *Proceedings of SMAC 03 Stockholm Music Acoustics Conference August 6-9, 2003,* pp. 243-246.