The Clarinet Timbre as an Attribute of Expressiveness

Philippe Guillemain, Robin T. Helland, Richard Kronland-Martinet, and Sølvi Ystad

CNRS-Laboratoire de Mécanique et d'Acoustique
31, chemin Joseph Aiguier. 13402, Marseille cedex 20, France
guillem@lma.cnrs-mrs.fr

Abstract. In this paper we analyze clarinet sounds produced by a synthesis model that simulates the physical behavior of a real clarinet, in order to find a relationship between the clarinet timbre and the interpretation. Sounds have been obtained by varying two important control parameters of the synthesis model, namely the blowing pressure and the aperture of the reed channel. These parameters are also used to control real reed instruments. Four different timbre descriptors have further been applied to the sounds in order to investigate the timbre evolution as a function of these control parameters. The validity of the synthesis model has been verified thanks to an experimental setup with an artificial mouth, making it possible to generate and record sounds from a real clarinet while controlling the pressure and aperture of the reed channel. A relationship between the timbre and the physical behavior of the instrument has been found thanks to the physical synthesis model.

1 Introduction

The aim of this study is to use a physical synthesis model of the clarinet to get a better understanding of how a clarinet player controls the timbre during the play. For this purpose we use an existing synthesis model developed in our research group which closely simulates the physical behavior of a real instrument and which generates synthesized sounds that are extremely close to natural clarinet sounds. Initially the synthesis model was developed as a new tool for musicians and was adapted to a specific Yamaha WX5 controller that measures the aperture of the reed channel, the blowing pressure and the finger position. These parameters constitute the most important set of controls that a player uses on a real instrument. We have chosen to study the evolution of the timbre as a function of the aperture of the reed channel and the blowing pressure, in order to find out how the player controls the timbre of the instrument during the play. The advantage of using a synthesis model rather than a traditional instrument to study the timbre is that it gives access to calibrated and reproducible values of the control parameters and to a physical interpretation of the timbre behavior. Obviously the synthesis model has to be validated to make sure that it behaves like a traditional instrument with respect to the values of the physical

control parameters. This was done by generating sounds from a real clarinet with an artificial mouth making it possible to calibrate the reed aperture and the blowing pressure like in the synthesis case. The sounds recorded from the real instrument globally depended on the control parameters in a similar manner as those from the synthesis model. This study also represents a starting point for future studies on interpretation, since the control device makes it possible to detect the values of the control parameters that a musician uses when playing this new instrument. This means that the instrument can be used as a tool to understand how the musician uses the timbre as a part of the interpretation.

The paper starts with a brief introduction of the physical model and its control parameters. In section 3, the timbre descriptors that were applied to the sounds are presented. Section 4 presents the results and links them with the physics.

2 Simplified Physical Model of a Clarinet

In this section, we briefly present the physical model used for the sound synthesis. It is made of three coupled parts. The first part is linear, and models the bore of the instrument using the impedance relation between the acoustic pressure and flow at the entrance of the resonator. The second part is nonlinear, based on the classical Bernoulli equation, and models the interaction between the acoustic velocity and the pressure differences between the mouth of the player and the entrance of the resonator. The acoustic flow is the product of the acoustic velocity with the aperture of the reed channel, which is linked with the reed displacement. The reed displacement is modeled as a pressure-driven single mode oscillator. In what follows, we use dimensionless variables for the pressure, flow, and reed displacement, according to [Kergomard, 1995].

2.1 Bore Model

The first linear part of the physical model corresponds to the resonator of the instrument. We here consider a highly simplified geometry made of a cylindrical bore. In particular, we neglect the role of the embouchure, the toneholes, the radiation losses and the register hole. Whatever the complexity of the bore geometry, its role on the sound generation process is fully determined by its input impedance. In the Fourier domain, the impedance links the acoustic pressure P_e and flow U_e in the mouthpiece. For the cylindrical geometry, assuming that the radiation impedance vanishes, the input impedance is classically written as:

$$Z_e(\omega) = \frac{P_e(\omega)}{U_e(\omega)} = i \tan(k(\omega)L) \tag{1}$$

Here, U_e is normalized with respect to the characteristic impedance of the resonator: $Z_c = \frac{\rho c}{S_r}$, $S_r = \pi R^2$. R is the radius of the bore: $R = 7.10^{-3}$ in the clarinet case. This radius is large with respect to the boundary layers thicknesses and the wavenumber $k(\omega)$ is then expressed by: $k(\omega) = \frac{\omega}{c} - \frac{i^{3/2}}{2}\alpha c \omega^{1/2}$,

where $\alpha = \frac{2}{Rc^{3/2}} \left(\sqrt{l_v} + \left(\frac{c_p}{c_v} - 1 \right) \sqrt{l_t} \right)$. Typical values of the physical constants, in mKs units, are: $c = 340$, $l_v = 4.10^{-8}$, $l_t = 5.6.10^{-8}$, $\frac{C_p}{C_v} = 1.4$, $\rho = 1.3$.

2.2 Reed Model

We use a classical single mode reed model. It describes the displacement $x(t)$ of the reed with respect to its equilibrum point when it is submitted to an acoustic pressure $p_e(t)$:

$$\frac{1}{\omega_r^2} \frac{d^2x(t)}{dt^2} + \frac{q_r}{\omega_r} \frac{dx(t)}{dt} + x(t) = p_e(t) \tag{2}$$

where $\omega_r = 2\pi f_r$ and q_r are respectively the circular frequency and the quality factor of the reed. Typical values for these parameters are: $f_r = 2500Hz$ and $q_r = 0.2$.

In the Fourier domain, this last expression becomes:

$$X(\omega) = P_e(\omega) \frac{\omega_r^2}{\omega_r^2 - \omega^2 + i\omega q_r \omega_r}$$

which shows that the reed displacement is a low-pass and band-pass filtered version of the acoustic pressure.

2.3 Nonlinear Characteristics

The nonlinear characteristics is the most important part of the model, since it is the engine of the self-oscillations production. The simple model used here is based on the stationary Bernouilli equation that links in a nonlinear way the acoustic velocity with the pressure difference between the bore and the mouth of the player. The acoustic flow entering the bore is then the product between the reed channel opening and the acoustic velocity. By using dimensionless variables, the acoustic pressure $p_e(t)$, the acoustic flow $u_e(t)$ and the reed displacement $x(t)$ are linked in a nonlinear way at the input of the resonator as follows:

$$u_e(t) = \frac{\zeta}{2}(1 + sign(1 - \gamma + x(t)))sign(\gamma - p_e(t))(1 - \gamma + x(t))\sqrt{|\gamma - p_e(t)|} \tag{3}$$

The parameter ζ characterizes the whole embouchure and takes into account the lip position and the section ratio between the mouthpiece opening and the resonator: $\zeta = \sqrt{H}\sqrt{\frac{2\rho}{\mu_r}} \frac{cw}{S_r \omega_r}$, where μ_r and w respectively denote the mass per unit length and the width of the reed. ζ is proportional to the square root of the reed position at equilibrium H and represents an important control parameter on which the player can act. Common values of ζ for the clarinet are between 0.2 and 0.6.

The parameter γ is the ratio between the pressure inside the mouth of the player and the pressure for which the reed closes the embouchure in the static case: $\gamma = \frac{p_m}{p_M}$, where $p_M = H\omega_r^2 \mu_r$ is the static beating reed pressure. In a

lossless bore model, γ evolves from $\frac{1}{3}$ which is the oscillation step, to $\frac{1}{2}$ which corresponds to the position at which the reed starts beating.

The parameters ζ and γ are the most important continuous performance parameters since they respectively represent the way the player holds the reed and the blowing pressure inside the instrument.

Figure 1 represents the non linear characteristics of the reed for the limit case $\omega_r = \infty$ ($\zeta = 0.3, \gamma = 0.45$). In this case, the displacement $x(t)$ of the reed reduces to the acoustic pressure $p_e(t)$ itself: the reed activity can be considered as a single spring. As we shall see in the next sections, such a situation occurs when the frequency support of the acoustic pressure remains smaller than the reed resonance frequency. This plot shows one discontinuity at its left side, corresponding to a cancellation of the acoustic flow for $p_e = x = \gamma - 1$ when the reed closes completely the input of the bore, and one infinite derivative at its right side for $p_e = \gamma$ corresponding to the limit between a positive and negative acoustic flow.

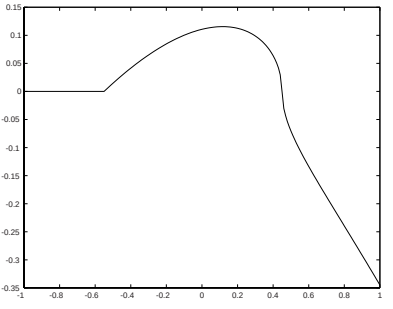


Fig 1: *Nonlinear characteristics of the reed (u_e as function of p_e)*

2.4 Coupling of the Reed and the Resonator

Combining the impedance relation, the reed displacement and the nonlinear characteristics, the acoustic pressure, acoustic flow and reed displacement in the mouthpiece can finally be found by solving the following set of equations:

$$\frac{1}{\omega_r^2}\frac{d^2x(t)}{dt^2} + \frac{q_r}{\omega_r}\frac{dx(t)}{dt} + x(t) = p_e(t) \tag{4}$$

$$P_e(\omega) = Z_e(\omega)U_e(\omega) = i\tan\left(\frac{\omega L}{c} - \frac{i^{3/2}}{2}\alpha c\omega^{1/2}L\right)U_e(\omega) \tag{5}$$

$$u_e(t) = \mathcal{F}(p_e(t), x(t)) \tag{6}$$

The flow diagram corresponding to this system of three coupled equations, in which the reed and the non-linearity are introduced as a nonlinear loop linking the output p_e to the input u_e of the resonator, is shown in figure 2.

From the pressure and the flow inside the resonator at the moutpiece level, the external pressure is calculated by the relation: $p_{ext}(t) = \frac{d}{dt}(p_e(t) + u_e(t))$. This expression corresponds to the simplest approximation of a monopolar radiation.

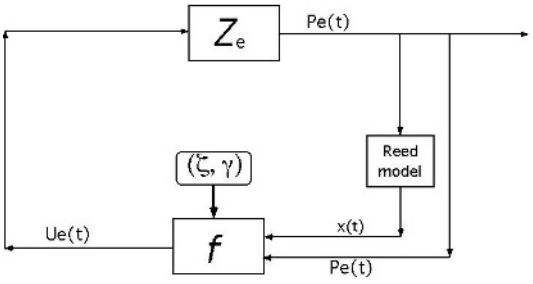


Fig 2: *Nonlinear Synthesis Model*

The digital transcription of equations (4,5,6) and the computation scheme that explicitely solve this coupled system is achieved according to the method described in [Guillemain, 2002].

3 Caracterisation of Timbre by Classical Descriptors

Timbre is a component in auditory perception which has been studied and described by several authors [McAdams, 1995][Menon, 2002][Grey, 1977][Jensen, 1999]. It is probably the most important feature of auditory events, and yet we do not have a precise definition or a complete understanding of timbre. It is often described by an "anti-definition" commonly referred to as those aspects of sound quality other than pitch, loudness, perceived duration, spatial location, and reverberant environment [McAdams, 1993]. For this reason, we don't take into consideration the loudness in this study, though this attribute is obviously an important part of the interpretation. More concretely, timbre can be considered as the principal feature that allows us to distinguish different instruments playing the same note. It is generally assumed to be multidimensional and is often described by a 3 dimensional space. [Grey, 1977] defines the 3 dimensions as spectral centroid, attack time and the irregularity of the spectrum, while [McAdams, 1995] in some studies uses the mean value of the variation of the spectral components as a function of time (spectral flux) as a descriptor for the third dimension. Authors seem to agree that the spectral centroid and the attack time are important timbre descriptors, while the last dimension is more ambiguous. As mentioned in the introduction, the aim of this study is to find a relationship between the timbre and the physical behavior of the instrument in order to get a better understanding of the relationship between timbre and interpretation. The sounds that are used in this experiment are generated by the synthesis model based on a physical model simulating sounds close to natural clarinet sounds and suimmarized in section 2. This model has been constructed to propose a new tool for musicians and can be piloted by a wind-like instrument controller. Since we restrict ourselves to the use of two parameters to control the sound (reed aperture, blowing pressure), we have chosen to study the timbre evolution for different values of these control parameters for a sustained sound

with a fixed length of resonator. Actually, these two control parameters are explicitely related to the parameters ζ and γ described in section 2. The values of the control parameters were chosen within a "reasonable" range, meaning that we only considered sounds that corresponded to a common play.

In the clarinet case where the amplitudes of the spectral components vary a lot, especially the ratio between odd and even harmonics, the spectral irregularity which represents a measure of the amplitude differences between successive components seems to be important [Jensen, 1999]. Since we restrain this study to sustained sounds, the spectral flux will not be important since the spectral centroid remains constant during the stable part of the sound. Thus, as a first approach we have studied the evolution of the attack time, the spectral centroid and the spectral irregularity of the synthesized clarinet sounds with respect to the physical parameters. The spectral centroid, which is related to the brightness of a sound, can be calculated from the formulae [Beauchamps, 1982]:

$$SC = \frac{\sum kA_k}{\sum A_k}$$

where k is the index of a spectral component and A_k is the amplitude value of the k^{th} component.

The spectral centroid has been calculated by convolution of the time varying signal with a hanning window of size 1024 samples, with 50% overlap between frames. For each frame the centroid is calculated up to the frequency $22050Hz$. For each clarinet sound, a centroid value has been obtained by calculating the mean value of the time-evolving centroid over a duration corresponding to the second half of the sound (from 0.5 s to 1s), so that the steady state is reached for all sounds.

The global attack time AT was found by calculating the time elapsed for the amplitude of the clarinet sound to increase from 10% to 90% of its maximum absolute value. The individual attack times of the five first harmonics were also calculated, but these were not found to be significant compared to the global attack time.

The spectral irregularity (IRR), which is a measure for the amplitude difference between successive components and which is highly important for clarinet sounds since it represents the differences between odd and even components, was obtained from the expression [Jensen, 1999]:

$$IRR = \frac{\sum (A_k - A_{k+1})^2}{\sum A_k^2}$$

As already mentioned, traditional timbre descriptors are often insufficient to describe the subtle timbre variations of the same instrument, and are often more similar for sounds from different instruments with the same pitch than for sounds from the same instrument with a different pitch [Jensen, 1999]. As we shall see in section 4 where the results from the analysis are described, this observation is confirmed by our approach. It was therefore necessary to look for additional criteria that would make it possible to distinguish sounds with similar attack

times, spectral centroids and spectral irregularities, but different timbre qualities. For this purpose we have proposed a descriptor related to the spectral bandwidth (SBW). This descriptor is linked to the spreading of the spectral components and corresponds to the standard deviation of the curve defined by the energy envelope of the symmetric spectrum for negative and positive frequency values. This avoids the SBW to be correlated with the spectral centroid.

4 Results

In this section we describe the results of the analysis of the clarinet sounds generated by the physical synthesis model described in section 2. As already mentioned we have chosen to vary two control parameters (ζ and γ) linked to the blowing pressure and the reed aperture. Hence, 100 clarinet sounds generated with the same bore length (L=0.5) (fundamental frequency $\simeq$ 171Hz) have been obtained by varying γ from 0.4 to 0.5 (10 different values) and ζ from 0.2 to 0.5 (10 different values). We first give a description of the timbre variations related to the different sounds. Then we give a physical interpretation of the observed results.

4.1 Timbre Variations as a Function of the Control Parameters

In this section we show how different timbre descriptors vary with the reed aperture and the blowing pressure. We have calculated the four timbre descriptors for the hundred clarinet sounds; namely the attack time, the spectral centroid, the spectral irregularity and the spectral bandwidth. Figures 3 to 6 show the descriptors as a function of ζ and γ. The two control parameters seem to have similar effects on the timbre descriptors. Figure 3 shows that increasing ζ and γ increases the values of the spectral centroid. We also see that in several cases the centroid is the same for different sounds (i.e. different combinations of parameters). For low values of ζ and γ, these sounds are perceptually similar, while they are different for higher values. This might indicate that the spectral centroid is a sufficient descriptor for small parameter values while other descriptors have to be added for higher parameter values. The spectral centroid does not change significantly for low values of ζ and γ, but when the two parameters reach a given value, the centroid exhibits a steep increase. This is seen best in the contour plot, Fig 3, where the close lines indicate a sudden rise in the centroid value. Also, the pressure parameter is found to have a stronger effect on the centroid, giving a larger global increase than the aperture parameter. For low values of the control parameters the attack time changes very abrubtly, whereas the attack time is stable for higher values. The contour plot shows that almost half of the synthesis sounds have an attack time within a 50ms region, which makes the attack time a rather insufficiant descriptor when high parameter values are used. The spectral irregularity is the only descriptor that does not act monotonously with increasing ζ and γ. As seen from the 3D graph, an increase in blowing pressure causes an increase in spectral irregularity, provided that the reed aperture is

adequately low. Whereas for ζ values above 0.3, an increase of pressure causes a slight decrease in irregularity. The overall change in irregularity is more influenced by ζ than γ, which can be seen from the contour plot, where the contour lines are partly parallell with the pressure axes.

The results of these descriptors give us an indication of how the different control parameters influence the timbre. However, for high values of ζ and γ there is a need to apply an additional descriptor, since the attack time is almost constant and the spectral irregularity does not change significantly. Sounds with different control parameter values in the higher regions, which have the same mean spectral centroid, are found to be perceptually different. We have therefore proposed a fourth timbre descriptor that we have called the spectral bandwidth describing the spreading of the spectral energy. From 3D representations we see that the spectral bandwidth is useful as an additional descriptor to seperate sounds of equal mean spectral centroid, and give a perceptual description of the difference between these sounds. The spectral bandwidth rises steadily with increasing values of ζ and γ, meaning that the energy in high frequency components increases. Fig 3 also show that the reed aperture has a considerably larger influence on the bandwidth than the pressure, as opposed to the spectral centroid where the blowing pressure has the most influence.

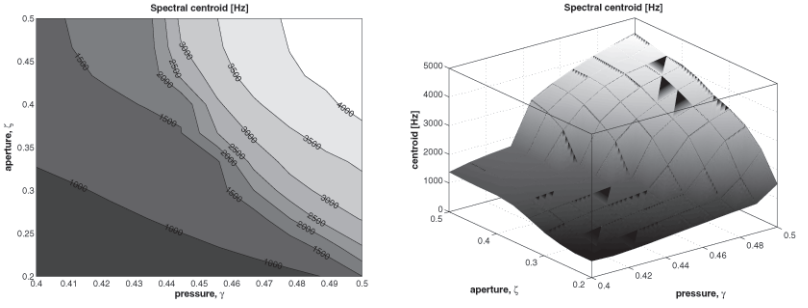


Fig 3: *Contour plot and 3D plot of the mean spectral centroid as it evolves for different values of blowing pressure and reed aperture. The values of γ and ζ evolve respectively from 0.4 to 0.5 and from 0.2 to 0.5.*

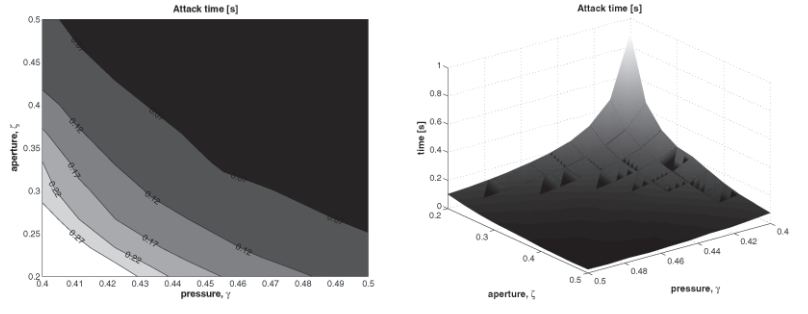


Fig 4: *Contour plot and 3D plot of the global attack times for the hundred clarinet sounds, for different values of pressure and aperture.*

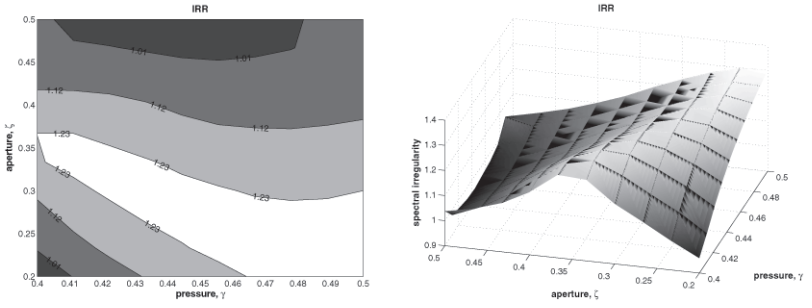


Fig 5: *Contour plot and 3D plot of the spectral irregularity, for different values of pressure and aperture.*

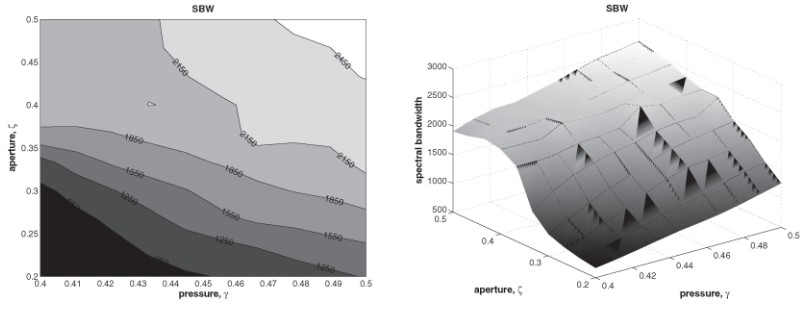


Fig 6: *Contour plot and 3D plot of the spectral bandwidth, for different values of pressure and aperture*

4.2 Physical Interpretation of the Timbre Variations

In this section, we consider four different situations, each corresponding to a particular combination of the control parameters ζ and γ. The first situation (γ small, ζ small) corresponds to figures (7,11,15). The second situation (γ small, ζ large) corresponds to figures (8,12,16). The third situation (γ large, ζ small) corresponds to figures (9,13,17). The forth situation (γ large, ζ large) corresponds to figures (10,14,18).

Several physical phenomena explain the evolution of the amplitude of the harmonics of the clarinet spectrum. For small values of the two control parameters ζ and γ, the non-linear mechanisms are responsible for the production of harmonics. Figure 7 (top, resp. bottom) shows the internal flow (resp. reed displacement) as a function of the internal pressure. This plot can be directly linked to figure 1 describing the non-linear characteristics of the reed. For low values of ζ and γ, the reed behaves like a simple spring and moves proportionally to the pressure (see figures 11,15). In this case the internal pressure and flow have a frequency support smaller than the resonance frequency of the reed.

For small values of the blowing pressure (parameter γ) and increasing values of the reed aperture (parameter ζ) (corresponding to figure 8, 12, 16), the

resonance frequency of the reed causes a "formant" to appear in the sound. In this case, the frequency spreading of the acoustic pressure is higher than the reed resonance frequency and the reed acts as a pressure amplifier around its resonance frequency. This can be seen on figure 8 by the hysteresis effect showing that the flow and reed displacement do not follow the same path when the reed opens and closes, and on the flow spectrum on figure 16.

For high values of γ and small values of ζ (figure 9,13,17) the important displacement of the reed provoked by the pressure causes the reed to beat against the table. This brutally cancels the flow (figure 13) and introduces a singularity in the sound creating a sudden increase in its brightness. For a given γ value the collision between the reed and the table happens for a particular ζ value, causing a sudden increase in the brightness of the sound.

For high values of both γ and ζ (figures 10, 14 18), the different mechanisms observed in the previous cases appear simultaneously. Moreover, the important variation of the flow compared to the small variation of the pressure when the reed is completely open causes the spectrum to gain even more components (the right part of the top curve of figure 10). Indeed, for $p_e(t) = \gamma$, the derivative of the non-linear characteristics is infinite and a very small variation of pressure causes an abrupt variation of flow.

Whatever the values of the pressure and reed aperture parameters, since the input impedance of the bore mainly contains odd harmonic peaks, the internal pressure $p_e(t)$ contains very few even harmonics and always looks like a square signal. This is visible on figures 15,16,17,18. The even harmonics come from the internal acoustic flow $u_e(t)$ and are produced by the nonlinearity, from the term: $\sqrt{\gamma - p_e(t)}$. This nonlinearity explains why the level of even harmonics in the flow increases when the difference in pressures between the blowing pressure and the bore pressure (and hence the blowing pressure) also increases. Since the external pressure is expressed as the time derivative of the sum of the internal acoustic flow and pressure, the rate of its even harmonics increases with respect to γ, and hence the spectral irregularity decreases.

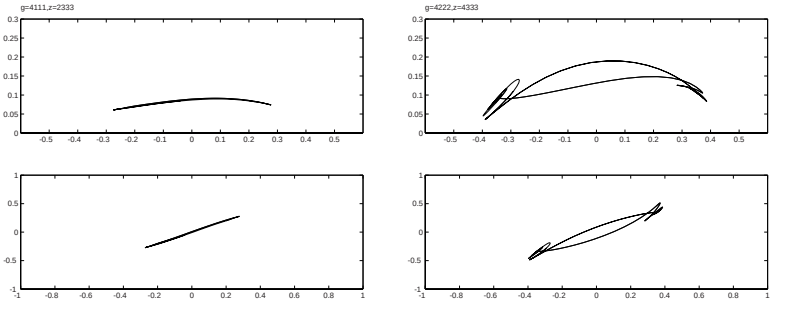


Fig 7(left),8(right): *internal acoustic flow (upper part of the figure) and reed displacement (lower part of the figure) as a function of the pressure for two different values of the control parameters γ and ζ. Figure 7 corresponds to γ=0.4111 and ζ=0.2333 while figure 8 corresponds to γ=0.4222 and ζ=0.4333.*

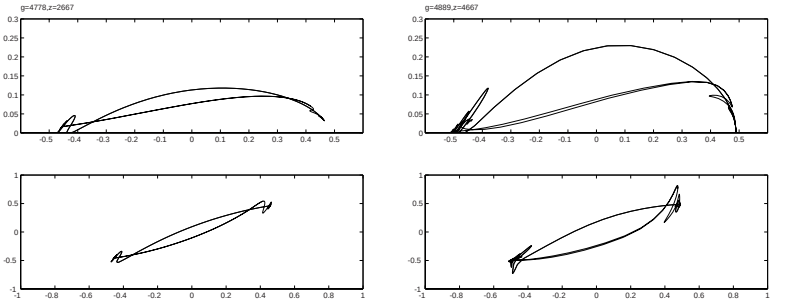


Fig 9(left),10(right): *internal acoustic flow (upper part of the figure) and reed displacement (lower part of the figure) as a function of the pressure for two different values of the control parameters γ and ζ. Figure 9 corresponds to γ=0.4778 and ζ=0.2667 while figure 10 corresponds to γ=0.4889 and ζ=0.4667.*

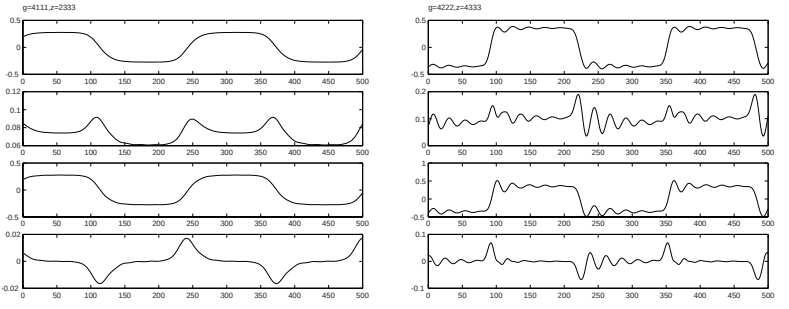


Fig 11(left),12(right): *from top to bottom :internal acoustic flow $p_e(t)$, acoustic flow $u_e(t)$, reed displacement $x(t)$ and external pressure $p_{ext}(t)$. Figure 11 corresponds to γ=0.4111 and ζ=0.2333 while figure 12 corresponds to γ=0.4222 and ζ=0.4333. Horizontal axis in samples.*

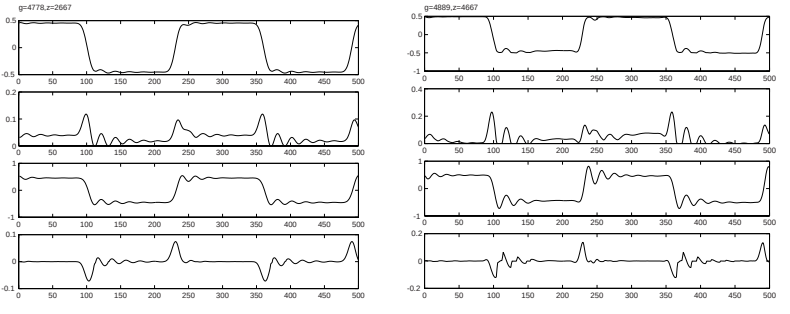


Fig 13(left),14(right): *from top to bottom :internal acoustic flow $p_e(t)$, acoustic flow $u_e(t)$, reed displacement $x(t)$ and external pressure $p_{ext}(t)$. Figure 13 corresponds to γ=0.4778 and ζ=0.2667 while figure 14 corresponds to γ=0.4889 and ζ=0.4667. Horizontal axis in samples.*

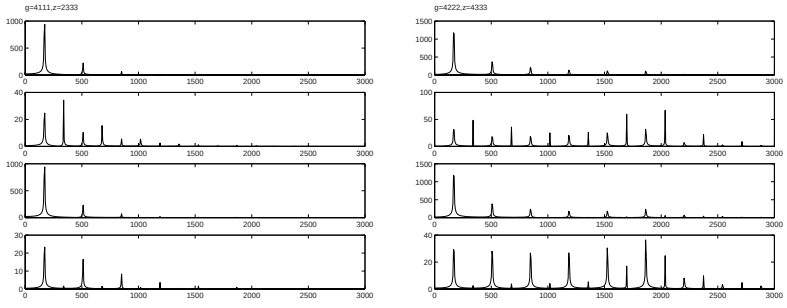


Fig 15(left),16(right): *from top to bottom :internal acoustic flow* $p_e((\omega)$*, acoustic flow* $u_e((\omega)$*, reed displacement* $x((\omega)$ *and external pressure* $p_{ext}(\omega)$*. Figure 15 corresponds to* γ*=0.4111 and* ζ*=0.2333 while figure 16 corresponds to* γ*=0.4222 and* ζ*=0.4333. Horizontal axis in Hertz.*

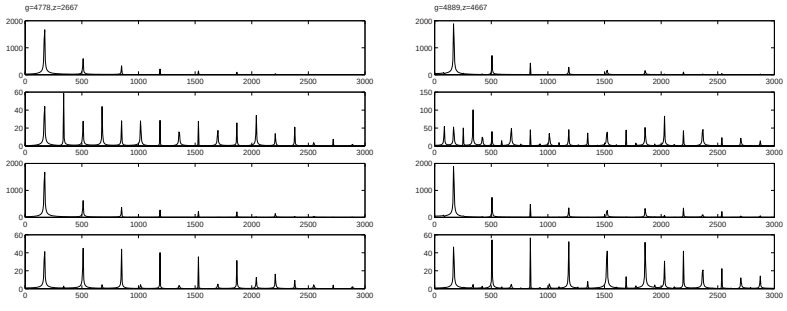


Fig 17(left),18(right): *from top to bottom :internal acoustic flow* $p_e((\omega)$*, acoustic flow* $u_e((\omega)$*, reed displacement* $x((\omega)$ *and external pressure* $p_{ext}(\omega)$*. Figure 17 corresponds to* γ*=0.4778 and* ζ*=0.2667 while figure 18 corresponds to* γ*=0.4889 and* ζ*=0.4667. Horizontal axis in Hertz.*

5 Conclusion

Musical interpretation is an extremely complicated process aiming at generating emotions to the listener. An interesting question we started to address is how the timbre variations of instruments are controlled in such a context. For that, we focused on the clarinet timbre for which accurate physical models running in real time can be designed. This allowed us to systematically study the way the timbre of this instrument varies with respect to two important control parameters: the blowing pressure and the reed aperture, both of them being controllable by the player. Four timbre descriptors have been studied for this purpose: the spectral centroid, the attack time, the spectral irregularity and the spectral bandwidth. All of these descriptors act quasi-monotonously with each control parameter. This is probably one of the reasons why this instrument allows an intuitive control of the sound. Another consequence is that given characteristics of the

timbre can be obtained in different ways by compensating the influence from one of the control parameters by the other one. This allows for example the brightness of the sound to be kept constant while changing its richness. Such possibilities probably are clues to a better understanding of the notion of playability and of the musical interest of an instrument. Actually, they are widely used by musicians during a musical performance. Thanks to the use of a realistic physical synthesis model, one then discussed the relationship between the physics of the instrument and the timbre. This is an important step towards a better understanding of what part of the instrument design is allowing subtle sound variations. Even though this is a preliminary study, we have shown the importance of the two regimes defined by the free motion and the beating of the reed on the table of the mouthpiece. These regimes are obtained for control parameters depending on the mean aperture and the stiffness of the reed, showing the importance of the design of the embouchure together with a good choice of the reed. Another important aspect of the timbre is linked to the first eigenfrequency of the reed. Actually, one has shown how the reed acts on the sound spectrum, increasing the brightness by accentuating the spectral peaks around the first reed eigenfrequency. The quality factor of the reed also seems to be of importance for the resulting sound since it acts on the spectral bandwidth altered by the reed. These conclusions show the close relationship between the clarinet, the playing and the timbre of the produced sounds. This leads to interesting possibilities of musical interpretation as soon as the physical design of the instrument is adequate in the sense that the control is easy enough and intuitive. Rather than answering the numerous questions linked to instruments and playing, this study has opened new fields of investigation. Indeed, an experimental setup using an artificial mouth connected to a real clarinet made it possible to perfectly control pressure and aperture of the real instrument just like we did with the synthesis model. This experiment made it possible to validate the synthesis model and confirmed its close behavior to a real instrument. This comforted us in our choice of using the physical synthesis model in our work towards a better understanding of the rules linking interpretation and timbre variations.

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