Sound Synthesis and Musical Composition by Physical Modelling of Self-Sustained Oscillating Structures

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Abstract — **In this paper we present the first results of a study that is carried out with the sound synthesis and musical creation environment GENESIS on self-sustained oscillating structures models. Based on the mass-interaction CORDIS-ANIMA physical modelling formalism, GENESIS has got the noteworthy property that it allows to work both on sound itself and on musical composition in a single coherent environment. By taking as a starting point the analysis of real self-sustained instruments like bowed strings or woodwinds, our aim is to develop generic tools that enable to investigate a wide family of physical models: the self-sustained oscillating structures. But, if this family is able to create rich timbres, it can also play a new and fundamental role at the level of the temporal macrostructure of the music (the gesture and the instrumental performance level, as well as the composition one). So we propose also in this paper to use the relatively complex motion of a bowed macrostructure as a musical events generator, in order to work with the musical composition possibilities of this type of models.**

Keywords: Sound Synthesis, Physical Modelling, Self-Sustained Oscillating Structures.

I. INTRODUCTION

Sound synthesis by physical modelling was born from the search of a naturalness of digitally synthesized sounds. Logically researches began not on the sound itself, but on what produces this sound, that is the physical object, which is able to vibrate at acoustical frequencies. Indeed, human’s ear was built by evolution for a precise purpose: to give us information about our environment. So, it is very sensitive to sounds (musical or not) produced by a well-determined physical cause. Consequently, physical modelling will be an easier way to produce realistic sounds than signal processing.

But if we talk about music, what is physical is not only the sound produced by real instruments but also the instrumentalist’s performance. Hence the use of physical modelling only to produce sounds with realistic timbre is a little restrictive. Using the physical modelling we can try to model also the instrumentalist itself, or at least some of its physical behaviour. This gives an approach of the sound construction at the scale of the musical macrostructure and, then offers a way to work at the composition level.

GENESIS [1], a software based on mass-interaction modelling, takes this idea into account by proposing an environment where we can build objects that move at acoustical frequencies as well as at gesture frequencies (more generally at macrotemporal frequencies). As a result, within this environment, the arbitrary boundary between the timbre, the composition and the performance tends to be erased.

Among the infinite variety of physical models the environment allows to build, the category of self-sustained oscillating structures is particularly interesting and represents a vast domain of investigation. Indeed the modularity of the CORDIS-ANIMA formalism enables us to build a multitude of various physical networks. The aim of this study is to develop generic tools allowing producing and analysing self-sustained oscillations of these ones. Among all the models that we can obtain, simple structures like homogeneous lines are special cases but their study can be a good start since they can easily refer to real instruments that were much studied. Furthermore, a good understanding of these ones is necessary to investigate more complex self-sustained oscillating structures.

The aim of this study is not only to produce rich timbre sounds but also, to use our self-sustained oscillating structures at low (gestural) frequencies in order to obtain complex movements that can support rich expressivity. So this article presents the first results obtained on simple models referring to violin, clarinet or oboe, developed in the GENESIS environment and aims at finding the relevant parameters of these models that can be used for rich timbre sound synthesis or for complex musical structures production.

Throughout this paper, we will successively speak about various topics that can be related to one of the three fundamental areas of computer music stated in the conference main topic and reflected symbolically by the three primordial muses of Ancient Greek mythology: Melete (research), Mneme (memory, archiving) and Aoidos (music making).

II. PHYSICAL MODELLING WITH GENESIS

A. *The theoretical basis of GENESIS: CORDIS-ANIMA*

GENESIS is a coherent environment used for sound synthesis and more generally music creation. It is based on an axiomatic mass-interaction formalism called CORDIS-ANIMA [2]. Every object built with this formalism is constituted of different modules communicating with each other. We can distinguish two types of modules: <MAT> modules represent material points that for example may be provided with inertia. <LIA> modules link two <MAT> modules and represent the interactions between them (stiffness, viscous friction…). So, with the CORDIS-ANIMA language, we can build an infinite variety of mass-interaction networks that correspond in a certain way to a space and time discrete view of Newton's laws. The main advantage with this coherent modular language is that everything is modelled with the same tools (the elementary modules), ensuring the consistency of every model. Furthermore, it is very simple to build interactions between two models developed with CORDIS-ANIMA, since they are done like interactions between two elementary <MAT> modules. Hence, it is possible to build models that are composed of many elements (for example the model of a string or of a pipe…) and simply make them interact by means of one or several <LIA> modules.

GENESIS, based on the CORDIS-ANIMA formalism, is used for sound synthesis and music creation. It enables to build graphically any mass-interaction network with the <MAT> and <LIA> elementary modules. Here are basic modules used in the GENESIS environment:

- <MAT> modules: the SOL (fixed point), the MAS (ideal inertia), the CEL (one degree of freedom damped oscillator)
- <LIA> modules: the RES (stiffness), the FRO (viscous friction), the REF (viscoelastic link) and non-linear modules BUT and LNL (they will be developed below).
- <MAT> and <LIA> degenerate modules link the environment with external elements (loudspeaker, data-files…): the ENF and the ENX (respectively force and position input), the SOF and the SOX (respectively force and position output). SOF and SOX modules are used to "hear" a structure vibrating.

The BUT is a viscoelastic conditional link, that is to say, a viscoelastic link which is effective if the difference between the positions of the two <MAT> elements that it links is under a given threshold. This module is often used for collision simulation. The LNL module let us draw the interaction between two <MAT> by means of a function F(ΔX) or F(ΔV), with F the output force, ΔX and ΔV respectively the difference between positions or velocities of the two linked <MAT>. The user can draw every one-variable function he wants.

B. *The Instrumentarium*

In parallel to the GENESIS models development, a library of these models, called the *Instrumentarium*, has been built in order to compare and classify them according to an accurate conceptual organization. Analysing various models, fundamental functions and features have been identified, isolated and used as a classification basis. The aim of this library is to define generic models or modelling techniques which could be easily used by GENESIS users, whether he or she is a composer or for example a pedagogue who wants to use GENESIS as a support for his or her teaching in Newton's mechanics. Consequently it is very important to take this into account during the development of our models in order to prefer generic models to ones that use ad-hoc functions.

The *Instrumentarium* is a permanently under construction project and deals with the "Mneme's domain", that is storage. Indeed, in order to be able to use efficiently all the models developed with GENESIS, it is necessary to analyse them and to regroup them according to fundamental functions that they express. This is the only way that can ensure the storage and transmission of the musical characteristics of our different model.

C. *The study of self-sustained oscillating structures*

Many studies were carried out about physical modelling of self-sustained oscillations of musical instruments with the aim of digital synthesis of real sounds. For example the digital waveguide physical modelling technique was used by Smith, Cook and Scavone to synthesise woodwind [3] [4], bowed string [5] and singing voice sounds [6], or by Karjalainen and Välimäki to model wind instrument bores [7] and vocal tract [8]. The modal synthesis [9] is also a good way to produce this kind of sound.

In the domain of musical acoustics, many researches were undertaken on self-sustained oscillations of musical instruments, which are a good basis for physical modelling in computer music. One can quote inter alia the names of Benade [10] [11] for woodwind instruments or Cremer [12] for bowed strings.

The study presented in this paper, which aims at filling the lack of self-sustained oscillations instrument models in the GENESIS *Instrumentarium*, uses many results obtained by musical acousticians. That is why simple models of bowed strings or woodwinds are presented below, but it is important to notice that our goal is not to model a specific real instrument in the most accurate way but to develop tools that are generic for self-sustained oscillating structures modeling in order to deal with sound synthesis as well as musical composition.

III. RESEARCH ON BOWED STRUCTURES

This section corresponds to the part of our work that is reflected by the muse Melete. It deals with our researches carried out on the development of self-sustained vibrating structures models and their behaviours analysis.

A. *A bowed simple vibrating structure*

One of the most studied families of instruments is the bowed strings. Thus we will first study the bowing of a vibrating structure in the GENESIS environment. As for all self-sustained oscillations instruments, there is a non-linear element in the instrumental chain of the bowed strings that ensures the production of a high frequency oscillation (vibration of the string) from very low frequency behaviour (movement of the bow). This is the non-linear interaction that takes place between the rosin on hair of the bow and the string. We can see its shape on the graph below:

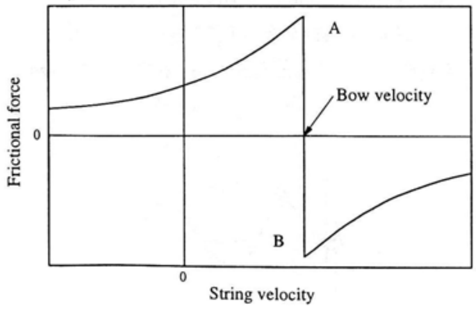


Fig. 1. Frictional force as a function of the string velocity for a bowed string. After Fletcher and Rossing, 1998 [13].

The LNL module of GENESIS environment let us use this type of interaction since it is possible to draw a F(ΔV) function. Below, you can see the curve that has been chosen:

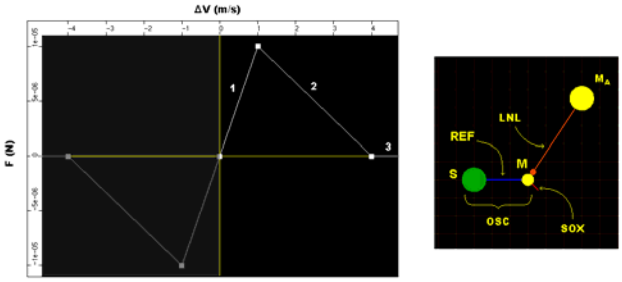


Fig. 2. Left, frictional force as modelled in the LNL window. Right, model of a bowed basic structure.

This simplified curve that models the interaction between the bow and the string is sufficient to work with, and we will see that it leads to phenomena that are characteristic of real bowed strings behaviours. But the aim is also to use this interaction with other structures than a modelled string; the simplest vibrating structure that we can use is the elementary module CEL. So, we will first work with it in order to illustrate the bowing of oscillating objects. On fig. 2 (right) we can see the representation of the model as it appears on the graphical interface of GENESIS. The MAS module called M_A represents the bow inertia and the structure called OSC which contains a SOL (S), a MAS (M) and a REF link, has got the same behaviour as a CEL module except that it is not optimized. But for a best readability we will use it. So OSC is a damped harmonic oscillator that M_A will bow via the LNL link.

NB: It is important to keep in mind that the representation plan is not a metric space but a topologic one. That is to say, only the links between <MAT> elements will influence the behaviour of our model, not how the <MAT> elements are placed on this plan. Furthermore, the <MAT> modules can move along the axis perpendicular to this plan and only along this axis. That is why GENESIS is called a one-dimension simulation environment. But it is generally not a problem for sound synthesis, since oscillations develop themselves mainly on a single axis and it is possible to take into account two or three dimensions effects via LNL links or judicious use of modularity.

We can separate half of the symmetrical friction curve into three parts (noted 1-3 on fig. 2). The first one is called the “sticking zone” and the second one the “sliding zone”. For a real bow, the slope of the sticking zone is almost infinite (cf. fig. 1) but if we use such a characteristic, the value of the equivalent viscosity Z (i.e. the value of the slope) is almost infinite too. That is why we must use a finite slope unless the algorithm diverges when the difference of velocity is such as the operating point is in the sticking zone of the curve, leading to a sound with more or less white noise (that can get a certain interest). Furthermore, as McIntyre, Schumacher and Woodhouse say in [14] the finite slope of the sticking zone can partially take into account the effects of torsional waves along the string.

Moreover, we must take into account the particularity of our model of interaction. For example, if we start from an oscillator that is at rest and a bow that has got a constant velocity, this velocity must be included between the two boundaries of the sliding zone to obtain a self-sustained oscillation. Indeed, if the velocity is in the third part, no force is applied on the oscillator, and if it is in the first part, no sliding friction can occur and the movement of the oscillator is quickly stabilised in an elongation position that depends of its stiffness (cf. fig. 3).

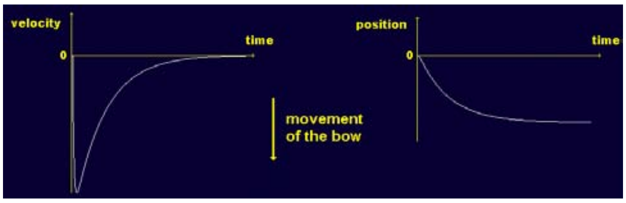


Fig. 3. Velocity and position signals for the bowed oscillator described on fig. 2, with a bow velocity in the sticking zone of the LNL characteristic. No oscillation occurs. The behaviour is the one of a damped harmonic oscillator in aperiodic regime (exponential decrease).

For the bow velocity in the sliding zone of the LNL characteristic, a self-sustained oscillation is obtained as we can see on fig. 4. This fact is due to the negative slope of the curve in the sliding zone. We can see on the velocity signal, for each period, when the operating point passes from the sticking zone to the sliding one (inflexion point, see fig. 4). One can note that before this inflexion point, we can see the same behaviour as when the velocity of the bow is in the sticking zone (exponential decrease). After this point, the velocity increases drastically because of the sliding friction; this leads to oscillations.

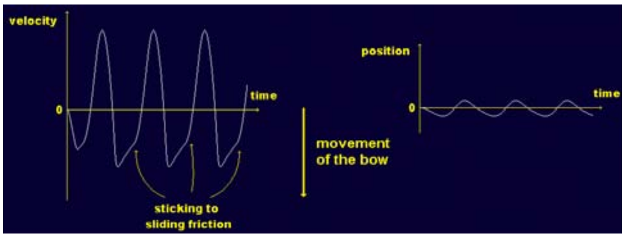


Fig. 4. Velocity and position signals for the bowed oscillator described on fig. 2, with a bow velocity in the sliding zone of the LNL characteristic. We can see on the velocity signal the change of behaviour when the system goes from sticking to sliding friction.

Another parameter that we must precisely adjust is the sliding zone slope, that is the negative damping coefficient value (we note it Z_{neg}). Indeed, if the absolute value of this parameter is lower than the positive damping (Z_{pos}) of the vibrating structure, the self-sustained oscillations regime cannot develop. This can be understood by adding the straight characteristic of the oscillator damping to the one of the LNL link. Indeed, the undamped oscillator will come under the sum of these two characteristics. If the positive damping is higher than the absolute value of the negative one, the sum of the two characteristics will be separated in three parts too, but all with a positive slope. So this situation can be compared to the one where the bow velocity is in the sticking zone and the vibrations of the oscillator quickly decrease. One can compare this behaviour to the minimum bowing force that must be applied on a real string in order to obtain self-sustained oscillations. For low forces, the sliding friction zone has got a very low slope and cannot compensate the damping of the string. A minimum bowing force is thus needed to start self-sustained oscillations.

Furthermore, if the absolute value of Z_{neg} is higher than Z_{pos} but if these two values are comparable, the transient is very long with a percussive attack at its start. So to quickly obtain a self-sustained oscillations regime, the absolute value of Z_{neg} must be much higher than Z_{pos}.

B. Generalisation to other structures

The effects noted for this simple oscillator can be generalised for more complex vibrating structures. For example, we model a string by a chain of MAS linked by REF modules. This chain is fixed at both extremities to SOL elements.

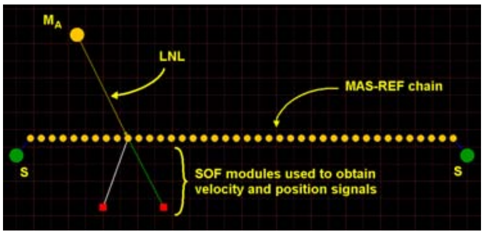


Fig. 5. Model of a bowed string. The two SOF modules are linked to a MAS via RES and FRO modules in order to obtain the velocity and position signals at the point of bowing.

If we give the correct values to the parameters that we spoke about in the simple oscillator study, the bowing of this structure leads to the well-known Helmholtz motion of the string as we can see on fig. 6.

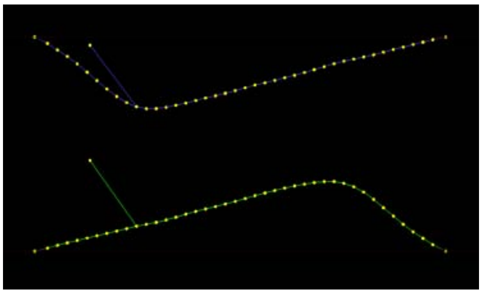


Fig. 6. The Helmholtz motion of the string at two moments which have got a difference in phase of a half period. The bow is moving up at a constant velocity.

Furthermore, position and velocity signals at different points of our chain are comparable to experimental measures on real bowed strings (cf. fig. 7 and 8).

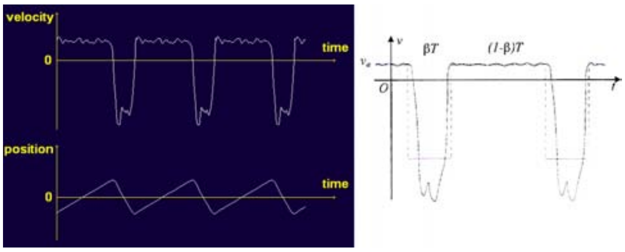


Fig. 7. Left: velocity and position signals taken at the bowing point for our bowed string model. The bowing point is at a quarter of the string. Right: velocity of the real string at the bowing point. β is the ratio of the distance between the bowing point and the bridge, upon the length of the string. v_a is the velocity of the bow. After Boutillon, 2000 [15].

So, the simplified friction characteristic used in our model is sufficient to obtain realistic behaviours and moreover to get plausible bowed string sounds. Note that the real friction force does not tend to zero when the difference between the bow velocity and the string one is high, whereas it does in our model. The aim is to be able to produce particular gestures like a bow that ends without the bow on the string (in order to be able to produce the sound of the free motion of a string after bowing). Indeed, if we want to cut the link between the vibrating structure and the MAS M_A, we just need to accelerate it until the operating point is always in the third part of the friction characteristic.

So the LNL link described in this part can be used to bow many different structures such as strings, bars, membranes…and more generally every mass-interaction network, even with non-linear elements. And as we will see below, this LNL link may be relevant for woodwind instruments modelling too. This leads to a generic approach of self-sustained instruments of different physical natures such as bowed strings and woodwinds.

C. A particular bowed structure

Now, if we take our previously developed string model and link only one of its extremities to a SOL module, the produced sound when we bow the free extremity (using the same LNL as above) sounds like a clarinet. In order to explain this, we can analyse the non-linear characteristic of a woodwind reed (cf. fig. 9). It represents the volume flow through the reed as a function of the difference of pressure between the player’s mouth and the reed. A remarkable fact is that the friction characteristic of the LNL module developed previously can easily approximate the shape of the curve shown on fig. 9, with the help of an analogy that we explain below.

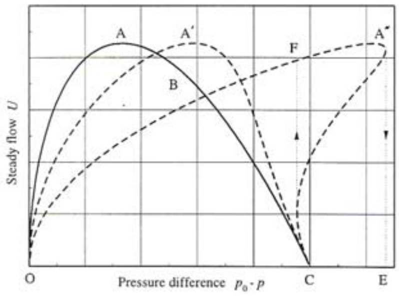


Fig. 8. Characteristic of volume flow as a function of pressure difference for a woodwind single reed (OABC curve) and a woodwind double reed (one of the three curves, according to the reed channel resistance). After Wijnands and Hirschberg, 1995 [16].

The analogies between mechanical systems and aeroacoustical ones are well known and have been developed in many acoustics books [17]. First of all, the comparison between our LNL characteristic and the curve above suggests that the force applied on and the velocity of the MAS module are respectively the analogue of the volume flow and the pressure inside the reed. But in order to be more precise, let us consider two fluid tanks at different pressures P1 and P2, connected by a channel where a volume flow U of fluid circulates. According to the Euler’s equation, we have got in this case:

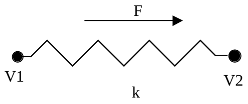
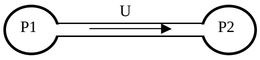
$$\rho \frac{dv}{dt} = -\frac{dp}{dx} \Rightarrow \Delta P = P1 - P2 = \frac{L\rho}{S}\frac{dU}{dt}, \tag{1}$$

with L and S respectively the length and the section of the channel, v the speed of the fluid particles and ρ its density. One often calls the factor Lρ/S the acoustic mass. The expression connecting the difference in pressure between the two tanks and the volume flow is similar to the one connecting the difference in speed between two masses connected by a spring:

$$\Delta v = \frac{1}{k}\frac{dF}{dt}, \tag{2}$$

with Δv the difference in speed between the two masses, K the stiffness coefficient of the spring and F the modulus of the force applied on the two masses. One can then carry out the analogies gathered in the following table:

TABLE I.
ANALOGIES BETWEEN MECHANICAL AND AEROACOUSTICAL SYSTEMS

Mechanical system	Aeroacoustical system
	
$\Delta v = \frac{1}{k}\frac{dF}{dt}$	$\Delta P = \frac{L\rho}{S}\frac{dw}{dt}$
F	U
v	P
1/k	$L\rho/S = M_a$

These analogies let us develop easily woodwind instruments models with mass-spring networks. Indeed, just as our strings are modelled by a succession of masses connected by springs, the body of the wind instruments can be seen as a succession of tanks connected by cylindrical channels.

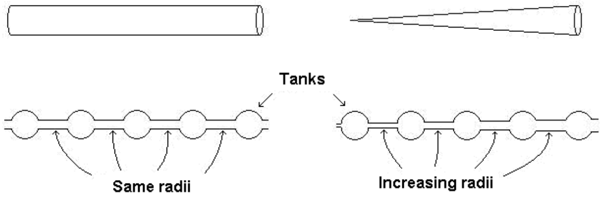


Fig. 9. Simple models of cylindrical and conical bores for wind instruments. In the second case, on the right, the channels have increasing radii in order to model the widening of the bore.

So, one can translate now this schematized aeroacoustical model into a mass-spring system by means of the developed analogies. On the figure below, we can see the GENESIS model that can be used for woodwind sound synthesis.

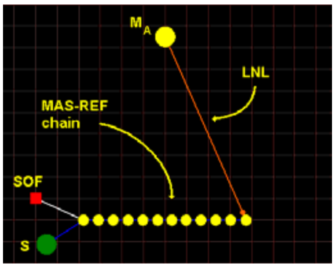


Fig. 10. Woodwind as modelled in GENESIS. The non-linear characteristic used is the same than for the bowed string. The left part of the mass-spring chain is fixed to a SOL module and represents the bell. The other one represents the embouchure.

So the mass-spring chain is bowed at its free extremity, that is to say, where the v/F ratio is the highest. This is coherent with the behaviour of woodwind instruments for which the P/U ratio is the highest at the reed. On the contrary, a fixed point will represent a hole in the bore. So the SOL at the left extremity represents the hole of the bell. It is possible to model the tone holes too, by adding SOL modules linked to masses along the chain.

As we said above, it sounds like a clarinet for a homogeneous mass-spring chain. This is understandable since the clarinet has got a cylindrical bore. Thus, it might be interesting to try to model other bores, for example a conical one, to obtain oboe-like sounds. The section of the bore of the oboe increases like the square of the distance to the mouth (since its diameter is proportional to the latter). The analogue of the section S is the constant of elasticity K (with a constant factor Lρ). Thus, by giving values, according to a parabolic law, to the K parameters of the consecutive REF modules, it is possible to obtain oboe-like sounds.

On the figure below, it is possible to compare the differences of behaviour between the homogeneous string model (called CLARINET) and the non-homogeneous one (called OBWA).

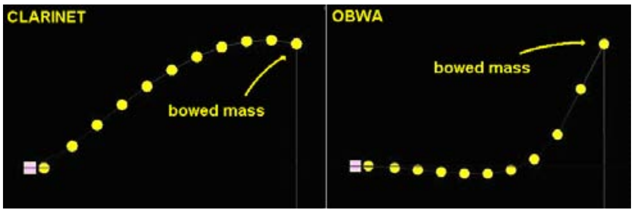


Fig. 11. Aspect of the mass-spring chain at the same phase for the cylindrical bore model (left) and the conical one (right).

The figure above shows that the behaviours of the two models are not the same. In the first case, the string moves as a whole, the masses of the model being at every moment all on the same side of the rest plan of the string. This shows the prevalence of the fundamental mode on the other ones. On the contrary, for the second model, the mass on which is the excitation is often in opposition of phase with part of the string. This fact is confirmed by spectra of the sounds obtained. These are presented on fig.12 and a comparison is done with experimental data taken in [13]. It is also possible to compare these with the results given in the chapter 21 of [10].

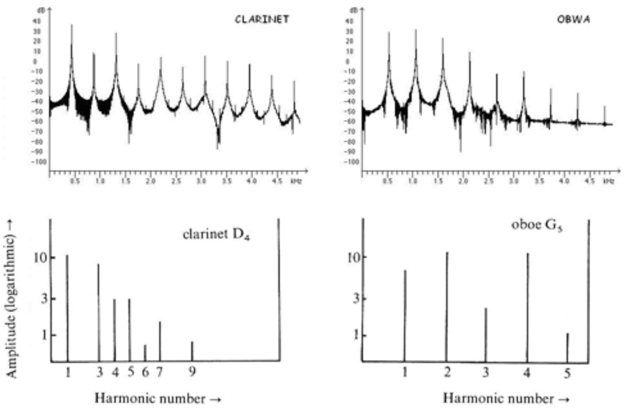


Fig. 12. Spectra of the sounds that we obtained with the CLARINET and OBWA models and comparison with experimental data on real woodwinds. After Fletcher and Rossing 1998 [13].

So, as for the real instruments, the fundamental prevails for the CLARINET whereas the second harmonic does for the OBWA. Furthermore, as for a real clarinet, the sound obtained with our CLARINET model has got prevalent odd-numbered harmonics. Even-numbered harmonics are not absent of the spectrum, which has been explained in different references [10] [18]. Nevertheless, these have too high amplitude for our model compared with the experimental data. This can be explained by the space discretisation of the model (for longer MAS-REF chains it is less noticeable) and to the coupling of the modes by the “bow”.

The analogies developed in this part are very useful since an air column will be simply modelled by the same modules than a string. So it will be very easy to couple structures like strings or membranes with a tube: we only need a <LIA> module. Thus, one can hear for example an oscillating structure vibrating through a duct that has got vocal formants in order to produce vocalizing sounds. This example illustrates the coherence of CORDIS-ANIMA as a general formalism; there is no need to deal with the compatibility of the different models that we develop since the language itself ensures the compatibility.

The LNL characteristic shown in fig. 2 appears to be generic since it enables to model vibrating phenomena of different physical origins. So it has been used to produce self-sustained oscillations on more complex structures. For example soft coupling between different bowed strings can enrich the timbre of sounds obtained. It can also lead to a more accurate modelling of real bowed strings since one MAS-REF chain can be used for transverse modes modelling and another for torsional ones. Other networks are now investigated like membranes or “fibrous” structures, with strings colliding each other.

IV. THE BOWING OF MACROSTRUCTURES

This last section deals with the “Aoidos’ domain” since we will use the bowed structures behaviour in order to work at the composition level. Indeed, by using bowed macrostructures we can develop features and tools in the GENESIS environment that enable to create events at macrotemporal (compositional and instrumentalist performance) scale. The “macrostructure” term is used to talk about structures that have much inertia and can vibrate at very low frequencies, in the domain of instrumentalist’s gestures. The underlying idea is that everything that has got inertia is modelled by a MAS module in GENESIS. Consequently, the MAS module, used to model the bow in our models above, can itself be a part of a vibrating macrostructure, which can lead to a complex movement of our bow. It is important to say here that our aim is not to model in the most accurate way a real human performer but to use “inanimate performers” which behaviours depend on physical laws. The aim is to obtain particular characteristics that can be related to real performance due to the fact that a human instrumentalist is also subjected to the laws of physics.

A. Orpheus’ lyre

If we consider a bowed string, as in the second part, but with a ratio M/K much higher in order to obtain low frequency modes (~1Hz), and if different MAS modules of this string are used to interact with vibroacoustical structures, it is possible to create a complex play with this macrostructure. On the figure below, we can see such a model, with a bowed “macrostring” that contains plectra, as it has been built in GENESIS.

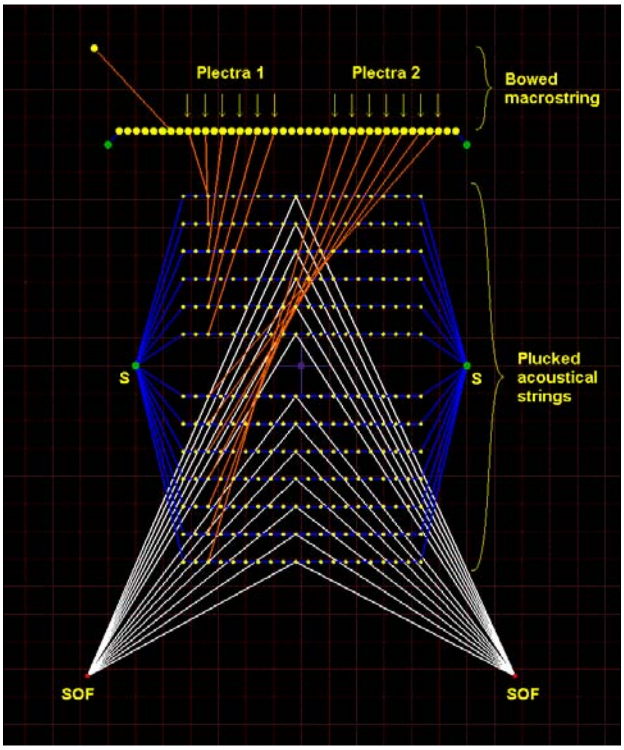


Fig. 13. Model implying a “macrostring” which contains thirteen plectra playing on different acoustical strings.

The model, as it appears on fig. 13 has been conceived in order to produce a particular play going from low to high acoustical frequencies. Indeed, from top to bottom, the thirteen acoustical strings’ fundamental frequency increases. So we have separated these into two groups, each one plucked by a type of plectra (1: low frequency strings, 2: high frequency strings). The first type of plectra corresponds to a LNL module which is calibrated to obtain plucking when the MAS modules of the “macrostring” are at a precise negative altitude “x=-a” (the acoustical strings are in the “x=0” plan), which is an altitude reached by the “macrostring” during its very long transient (cf. fig. 14). The second type of plectra is calibrated to pluck when the MAS modules reach the “x=0” plan. On fig. 14 and 15 we can see the advantage of working with two plectra groups. Indeed, the string behaviour is typical of a bowed string transient. But for this system, it is very long because of the very low frequency of the string oscillation. So what we can see on fig. 14 and 15 is a movement between two plans. That is why it is interesting to use some plectra for the moment when the string is in one plan and other plectra when it is on the other plan.

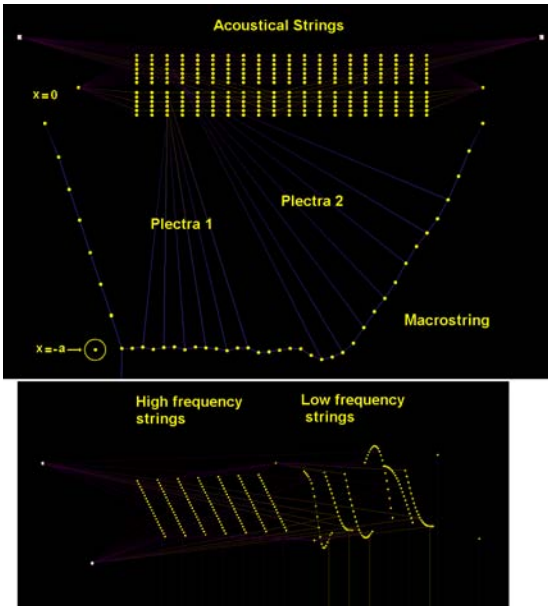


Fig. 14. Two different viewpoints of the simulation of the model shown on fig. 13 at 1,25 second. First phase of the period of the “macrostring” movement. This one goes down until it reaches an altitude located by the MAS circled (top picture). The six plectra on left are calibrated to pluck the low frequency strings at this altitude. So we can see on the bottom picture that these six strings oscillate. On this picture, the vertical scale is much lower than for the top picture.

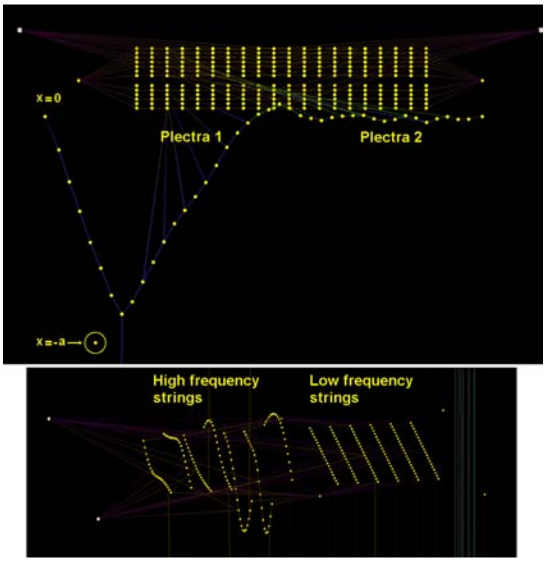


Fig. 15. Two different viewpoints of the simulation of the model shown on fig. 13 at 2,5 seconds. Second phase of the period of the “macrostring” movement. This one goes up until it reaches the “x=0” plan. So now the seven plectra of the second group pluck the high frequency strings as we can verify it on the bottom picture.

So the “instrumental play” has got a repeated cycle that is divided into two phases: the first when the “macrostring” is at its negative altitude (fig. 14) and the low frequency strings are plucked, the second when it is at the zero altitude and the other strings are plucked.

This produces a periodic alternation between complex series of low and high-pitched notes. Furthermore, these musical events evolve in time since the behaviour of the “macrostring” described above is the transient one. Progressively, higher amplitude oscillations take place, and it results in less plucks (but more disorganised). This gives the impression to pass from a vigorous part with lots of musical events to calm and quietness.

Finally, we can say that the bowed “macrostring” produces an “instrumental play” that is not precisely predictable but, so far, not unpredictable either. Its periodic oscillation leads to a pulsation. Moreover the precise analysis of the model’s behaviour can give information on how to use it, to privilege a precise note for example. Furthermore it has got very rich possibilities. For instance, it is possible to change the period of the instrumental play by changing the K/M ratio of the “macrostring” or to increase or decrease its transient by influencing the bow’s friction characteristic. It is possible to change the acoustical strings damping in order to get more or less resonant sounds, or to bow these ones instead of plucking them…

B. The role of excitation and vibroacoustical structure

As we can see above, a macrostructure with a complex behaviour is not sufficient to obtain a rich “instrumentalist like” model. One must work also on the type of excitation and on the vibroacoustical structure. Indeed, the bowed macrostring used in the previous part can lead to a particular complex instrumental play with the plectra described but a completely different one with bows for example. This is due to the position dependence of the plectrum interaction and the velocity dependence of the bow one. Thus, the type of excitation will reveal differently our macrostructure behaviour. That is why we name the latter a “potential events generator” since it must be connected to vibroacoustical structures with appropriate links in order to obtain particular musical events. Moreover, different appropriate links will reveal different sides of the potential events generator behaviour. For instance, it is possible to change hardness or length of the plectra used above in order to obtain different types of plucks. For example, hard plectra grip the string but do not release it, which leads to soft percussive sounds with “sliding fundamentals”. Consequently, the resulting play will be very expressive.

Furthermore, different vibroacoustical structures will reveal more or less the complexity of the potential events generator behaviour. For example, the plectra dynamic has little influence on the behaviour of the acoustical strings used in the previous part. If we make possible a contact between the strings during their movement, we can obtain a totally different vibroacoustical structure which behaviour depends strongly on plectra dynamic. By connecting our different acoustical strings with BUT modules (see II-A) with appropriate thresholds, they will be free for low amplitude movements but not for large amplitude ones. So according to the hardness of the plucks (related to the plectra velocity), they will collide or not. At the beginning, the plucks will lead to lots of collision but progressively as the amplitude of the macrostring increases, the collisions will more and more seldom occur and finally there only will remain plucked strings that oscillate freely. So, this vibroacoustical structure will clearly reveal the macrostring behaviour evolution via the musical events timbre.

C. Conclusion of this part

We saw in this part that the composition with GENESIS corresponds to a different approach than the "classical" one. Indeed, in this environment, everything is modelled with physical mass-interaction networks and the arbitrary boundary between the timbre, the composition and the performance tends to be erased: for example one changed parameter of the vibroacoustical structure can have an influence on these three levels of music creation. Furthermore, concerning the "Mneme's domain", the objective memory of timbre, composition and performance is ensured with our approach since everything is calculated from our model; and the latter can be then archived in the *Instrumentarium* (N.B: the term "objective" means here that it has a material support and the term "performance" refers to our "inanimate performers"). In a "classical" approach of music creation the two levels of timbre and composition can be considered as partially objectively memorized by means of instruments and score, but it is not the case for the physical performance since it is linked to the instrumentalist's play, which is subjective. On the contrary, the problem of the physical performance memory can be considered as solved in our environment since it is determined by the simulation of our model. Nevertheless, the question that remains is: according to which criteria is this "physical performance" relevant? Is its physical origin sufficient? Is it necessary that it sounds like a real performer play? There is no doubt that the research on this point with GENESIS is at its infant. But it will be certainly fruitful to carry out researches in this way.

V. CONCLUSION

The self-sustained oscillating structures category is a very useful family of models that is relevant for studies upon both timbre and composition in GENESIS and thus that must be developed and inserted into its *Instrumentarium*. We saw that, by means of analogies, real musical instruments of different natures can be simply modelled by almost the same bowed structure. Moreover, since the same elementary modules are used for the building of the structures, the compatibility of all the models is thus ensured. So it is very easy to couple all our different vibroacoustical structures in order to produce more complex and interesting timbres. The studies are now carried out on other structures too. For example, structures with lots of vibration modes can produce interesting evolving sounds when bowed repeteadly.

As for the composition in GENESIS, bowed macrostructures offer many possibilities but need to be deeply analysed in order to be used in precise ways. For this, a time analysis of position or velocity signals appears to be more appropriate than a frequency one. In any case, a good comprehension of their behaviours is necessary in order to be able to insert this kind of tools in a musical piece with GENESIS.

Finally, the fact that the researcher can, with the GENESIS environment, deal with the three fundamental domains of computer music reflected by Melete, Mneme and Aoidos, proves the relevance of this environment.

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