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TOPOLOGY, GEOMETRY, MATTER OF VIBRATING STRUCTURES SIMULATED WITH CORDIS-ANIMA. SOUND SYNTHESIS METHODS

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ABSTRACT: Physical modelling of musical instrument offers wide and rich possibilities for the simulations of physical phenomena. The CORDIS-ANIMA system uses this formalism for sound synthesis. The aim is to simulate of all the components of an instrument and in particular the central element of this chain, the vibrating structure. Many experiments have been driven in this way and gave interesting results regarding the topological and geometrical characteristics and beside the physical parameters of inertia, stiffness and viscosity of the network that describe the structure.

1. INTRODUCTION.

Sound Synthesis by physical model developed at the ACROE with the CORDIS-ANIMA system (Cadoz, 78), (Cadoz, 93) is based on the simulation of vibrating structures from their elementary mechanical components (matter points, visco-elastic links). These components are represented in the digital world by some specific algorithms that describe the fundamental laws of Newton's mechanics. Thanks to this system we performed several experiments centered on the study of the basic components of an instrument: the vibrating structure (VS), the excitator (EX), link element between the gesture and the VS, and below, a device (table, resonance chamber...) describing the general environnement (GE). Each of these elements plays a specific role that the auditory system can distinguish and identify to a large extent. The individual and combined study of these elements enables to determine and control the elementary musical attributes. In this paper we present an investigation regarding in particular the central element of this causal chain: the vibrating structure (Incerti 95a). It represents the minimal material for vibrating phenomena production, provided there is an excitator system to perform the energy transfer. Amongst the infinite range of VS that can be simulated, we pointed up several categories selected for their relevance from a perceptual point of view.

2. CORDIS-ANIMA

2.1. Physical Model

The CORDIS-ANIMA system enables the computer-based modelisation and simulation of physical objects that can be seen, heard and handled (by means of a specially designed Force Feedback Keyboard (Cadoz, 90)). An object is a modular assembly of *elementary mechanical components* picked up amongst a limited number of types with very simple associated *elementary simulation algorithms*. Their assembly constitutes the global simulation algorithm of the modelled object. A simulation is a computation of every displacements and forces transfers inside the object. Under definite parametric conditions these evolutions may correspond to acoustic vibrating phenomena. The transmission of the extensive position variables, via a DAC to a loudspeaker, provides an audible signal considered as the sound emitted by the object. This general formalism enables a great flexibility for the construction of virtual objects wich have, or may have not, a referent in the real world. In the same way, it enables highly relevant simulations of physical phenomena that would be very difficult to describe in an analytical way.

2.2 Basic Elements and Connection Laws

2.2.1 Communication Points

In classical continuous mechanics, physical interactions between two objects are unoriented, instantaneous, and involve two dual variables. One is intensive (force) and the other is extensive (position, displacement). In digital processes the communication is essentially unidirectional. To represent a mechanical link between two objects, pairs of input/output are needed. Such I/O pairs, oriented and in opposite directions, are called *communication points*. There are two kinds of such points (*fig.1a*):

- the first one, named $\langle M \rangle$ Point, receives an intensive variable (force) at the input, and returns an extensive variable (position) at the output.
- the other one, named $\langle L \rangle$ Point, receives a position and returns a force.

Furthermore, the communication delay from input to output cannot be reduced to zero.

2.2.2 Atoms and Connections

The construction of a C.A. object, is the assembly of some components by the connection of their communication points. These points are connected, according to the connection laws:

- The output of the first becomes the input of the second and vice versa. So, the only possibility is $\langle M \rangle$ Point to $\langle L \rangle$ Point.

- Several $\langle L \rangle$ Points may be connected to the same $\langle M \rangle$ Point. The resulting force received by the $\langle M \rangle$ Point is the sum of the forces issued from the $\langle L \rangle$ Points.

- It is impossible to connect more than one $\langle M \rangle$ Point to each $\langle L \rangle$ Point.

An *atom* is then a minimal object which may be simulated and combined with others in order to build more complex structures. These minimal C.A. components are of two dual types (*fig.1b*):

- The $\langle MAT \rangle$ atoms, named *Material Point*, that have a spatial location and represent the matter granulation; their algorithms return a position from the different forces applied by their environment.

- The $\langle LIA \rangle$ atoms or *Link Elements*, with two associated $\langle L \rangle$ Points. Their only spatial location is given by the two $\langle M \rangle$ Points on which they are connected. Their algorithms return two forces from the two positions they receive. The fundamental principle of Action-Reaction says that these two forces are co-axial, equal in intensity, and in opposite direction.

Among these atoms, three are very important and used for any vibrating structure:

- The free mass ($\langle MAT \rangle$ atom): made of a single matter point with a mass parameter m (kg). It represents the inertia of the system and its algorithm returns a position characterised by the second Newton's law.

$$(1) \quad F = m \frac{\partial^2 x}{\partial t^2}$$

- The visco-elastic link ($\langle LIA \rangle$ atom): link element with a stiffness parameter k (N/m), a damping parameter z (Ns/m) and, in some cases, a rest length parameter l^0 (m). Its algorithm returns:

$$(2) \quad F_1 = -F_2 = -k((x_1 - l_1^0) - (x_2 - l_2^0)) - z\left(\frac{\partial x_1}{\partial t} - \frac{\partial x_2}{\partial t}\right)$$

- The ground, or fixed point ($\langle MAT \rangle$ atom): absorbing matter point. It returns a constant position independently of what it receives. Its only parameter is its position. It actually represents a matter point with an infinite mass.

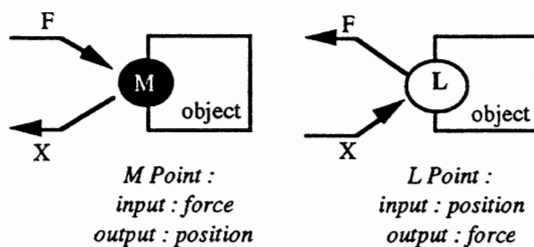


Fig. 1a : Communication Points

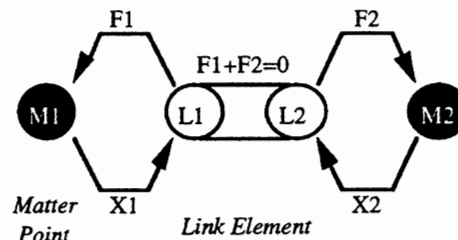


Fig. 1b : Atoms and connections

3. VIBRATING STRUCTURES FOR SOUND SYNTHESIS.

3.1. Excitators.

In this paper, we stress on the study of characteristics and properties of the vibrating structure. As mentioned in the introduction, the causal chain of simulation elements can be reduced to its simplest form: an excitator (EX) and a VS. The excitation mode plays a fundamental role in the simulation and would require very detailed explanations. Here we just present a short survey of the different kinds of excitators used in simulations. They can be classified in two main categories:

- instantaneous excitations: the VS is struck (with hammers, sticks or bouncing masses), or plucked with a plectrum. The sound is then the free vibration of the VS coming back to its equilibrium state.
- continuous excitations: VS may be bowed like a violin string or excited like the air column in a pipe. In this case, the mechanical interactions between EX and VS are non linear (Florens 90).

3.2. Topology, geometry and reductions.

Whichever synthesis technique is used, sound signal is a series of digital words representing a one-dimensional information. Thus, depending on which physical phenomenon is simulated, the simulation space can be reduced to one dimension. Any VS is then represented as a plane topological network in which nodes are <MAT> atoms and arcs are <LIA> atoms. Displacements and forces are stacked on a single axis, orthogonal to the network plane. The main consequence is that the geometrical distance between two matter points (nodes) is reduced to their relative distance on the vibration axis.

So every variation inside the VS is purely linear and computation sequences are very simple and cheap. The equations set governing the evolution of the system can be reduced to the matrix equation:

$$(1) \quad MX'' + ZX' + KX = F$$

where M (diagonal) and K, Z (symetric) respectively represent the inertia, viscosity and elasticity, F is an external force vector and X', X'' are the first and second derivatives of the position vector X.

There is a second fundamental consequence: if a specific "shape" (rectangular membrane, cylinder, pyramid...) is associated with the VS, it is just in reference to one possible graphic representation of the topological network. This shape will be selected according to the connection degree of the network and a real physical referent (string, ring, plate...)

(Fig.2) shows two different graphical shapes for the same network. Actually, the only correct representation would be the one of (Fig.2a) but the selected shape will be the one of (Fig.2b) because it is much more explicit.

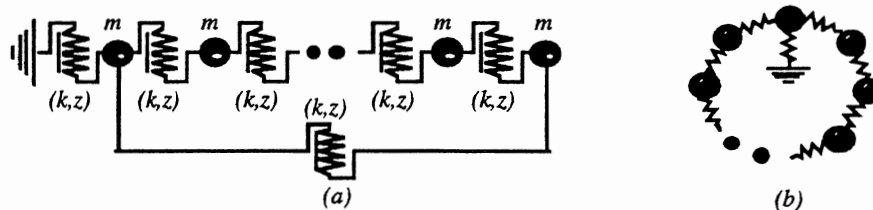


Fig.2: topological homogeneous structure (a) and one associated geometry : the ring (b)

According to this definition of topology versus geometry, several VS were studied. The topological conditions offer an infinite variety of possibilities. So, other restrictions are needed. The first self-imposed limitation was to consider only homogeneous VS: elementary parameters are the same for each mass (m) and link element (k,z). Thus, the system (1) can be reduced to:

$$(2) \quad mX'' + A(zX' + kX) = F$$

where A is the characteristic matrix of the underlying connection network.

Then, the second limitation was to strongly link (when possible) the (or one of the) associated shape to the connection degree of the network (Fig.2). It enables to associate a real referent to the VS. With this restriction, it was possible to stress on specific topological properties which may have an incidence on

physical properties: wave propagation criteria, spectra, symetries and multiple modes... The second important restriction led us to study only linear and homogeneous VS, that is defined only by their size (number of masses) and their elementary parameter (m, k, z).

3.3. The elementary cell.

It represents the simplest VS that enables a simulation for sound synthesis. It is made of a ponctual matter point of mass m linked to a fixed point by a spring of stiffness k and rest length $l_0=0$, and a micro-damper of viscosity z (Fig.3.a). From a perceptual point of view there is not much to say about it: what it produces is a simple sound with a definite pitch and its musical relevance is good only for very short damping time (high value of z). Anyway, some interesting and general theoretical results may be presented; they will be quite the same for any V.S.

A real physical oscillator is defined by a continuous time state equation (second Newton's law) and may evolves according to two different rates (non-periodic damped motion, pseudo-periodic damped oscillations with a frequency f_c depending only on m, k, z).

The simulated cell is defined by a second order numerical series in the discrete time space of computer:

$$(3) X_{n+1} = AX_n + BX_{n-1}$$

This cell may present three different rates (non-periodic, pseudo-periodic if $A^2+4B<0$ with a frequency f_d depending on m, k, z and the sample rate F_e , and numerical divergence of the algorithm)(Fig.3.b). Thus, with a given sample rate F_e , some simulated oscillator may have no physical equivalent, and some real physical oscillator may not be simulated at F_e .

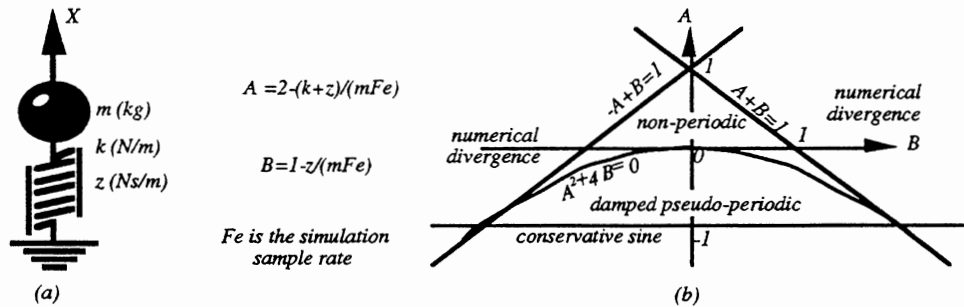


Fig.3: the CORDIS elementary cell (a), and its parametric sectors (b).

3.4. String structures.

They represent the simplest complex VS (ie. with the lowest connection degree). They allow the simulation of line-based structures. The simplest case is the closed string (Fig.4.a) which tends towards a mathematical vibrating line when its number of masses increases. The simulated string has as many modes as masses and this number is limited according to the set of parameters (like in Fig.3.b). The distribution of modes is subharmonic but tends towards harmonicity when the number of masses tends towards its limit (Fig.4.c). Beyond this limit the algorithm produces a numerical divergence. The distribution of modes is actually entirely defined by the spectrum (eigen values vector) of the network matrix A (see equ. (3)) and this is the same for any complex structure. This result is one of the basis of modal synthesis (Djoharian 93).

In the same way, the open line (that is fixed only by one of its ends) may represent a model of an air column in a pipe according to its mode shapes (Fig.4.b). Of course these properties do not appear when the structure is strocken or plucked, but only under a continuous excitation.

In the same class of string structures, the ring represents a natural evolution. Here again, this structure was choosen in reference to a particular kind of musical object: the bell. Such a VS presents in its spectrum some multiple (double) modes (Fig.4.c). Thus, with a little local perturbation, beats may appears in the sound. Modes distribution is still subharmonic and tends towards harmonicity.

These harmonicity properties appear in the sound, especially when the structure is bowed. Some general results may be presented about the excitation mode and output information. Whatever the excitation is, the closer to a fixed point it is applied, the greater number of modes will be excited (that hopefully corresponds to what happens with real instruments). In the same way, the sound information, received as a sequence of successive positions, is gathered at the output of a single matter point. So the closer this point is to a fixed point, the more complete this information will be. Of course it is just a local information and does not really represent the "sound produced" by the structure. But it is necessary to bear in mind that we are just concerned here with the study of the VS. For a complete simulation we should take into account the transmission of the vibration to a resonance table (which would replace the fixed points) and from the table to the air volume between the instrument and the auditory system. These questions are also investigated but are out of the scope of this paper.

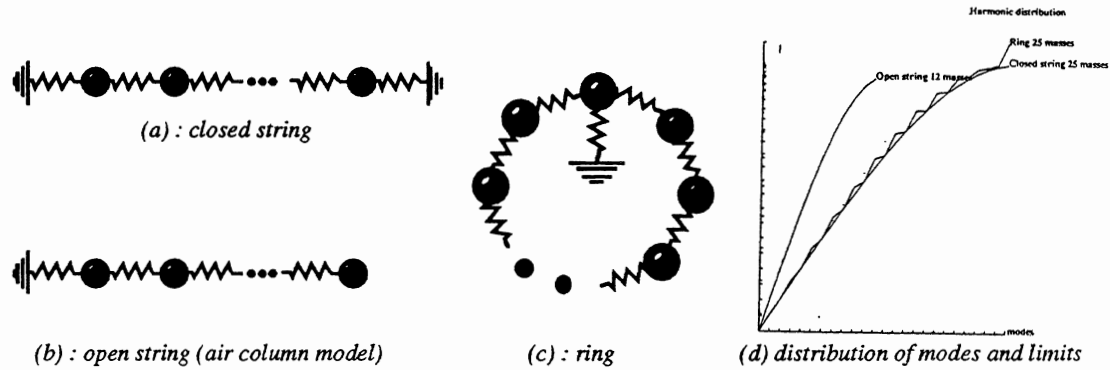


Fig.4 : string structures

3.5. Product structures.

These structures represent a special class of complex multi-dimensional network (that is with a connection degree greater than two). They are built by a simple product (direct product of matrix) of other simpler networks. For example, the rectangular membrane of (Fig.5.a) is the product of a N masses closed line with a P masses closed line; and the circular membrane (or cylinder, according to the associated shape) of (Fig.5.b) is the product of a 4 masses open line by a 8 masses ring. The main interest of these VS is that they are very easy to build and to analyse from their components.

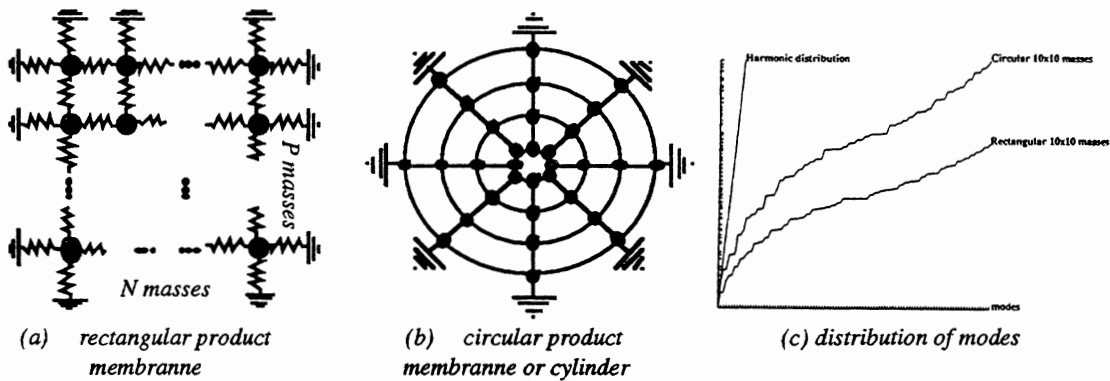


Fig.5 : product structures

Actually, all these VS have quite the same distribution of modes: highly subharmonic, with more or less multiples modes. The average slope of the distribution depends on the number of fixed points (Fig.5c). From a perceptual point view, the main property that appears is their great inharmonicity. Their musical

relevance appear only when the number of masses is great (at least several hundreds). They can also produce some interesting transients when they are bowed.

Anyway, it seems that their possibilities are limited: rectangular, circular or even torric or spherical products do not offer very significant differences (at least when not used in a compositionnal context). The interesting slight differences that can rise are mainly dependant on the choice of the physical parameters and the excitation mode. They appear in the matter associated with the object that the sound evokes.

It may be interesting to disturb their regularities, for example by introducing some global or local perturbation. But it is quite difficult to know which physical perturbation will have an effect (and what kind of effect) on the acoustic properties of the simulated object. Furthermore, this question is a matter more for the study of physical parameters than for topological and geometrical characteristics.

3.6. Spirals and 'double' structures.

Thus, this led us to study new topologies. The main idea was to consider VS in which a global inhomogeneity of the physical parameters was directly linked to a topological characteristic. The simplest case, that makes the connection with product structures, is the spiral (*Fig.6a*). It presents a privileged direction (the frame) whose physical parameters are homogeneous but different from them of the radial links (the interesting cases correspond to greater stiffness and lowest viscosity for the frame links). The underlying physical referents are fibered or cymbal-like structures (even if the cymbal is a very complex object with non-linearity properties).

The following step was to complexify the topology itself, but keep the same topological/geometrical references as above (membranes, spirals,...). Networks have higher connection degree, and the spatial distribution of matter points is not uniform (*Fig6b&c*). The paramaters of these structures are their size, the ratio number of turns vs number of spokes, as well as physical parameters. By modifying these various parameters (global inhomogeneity properties on radial links) and excitation points, a great vaiety of realistic sounds is obtained, from the bell to gongs and convincing approach of cymbals sounds ...

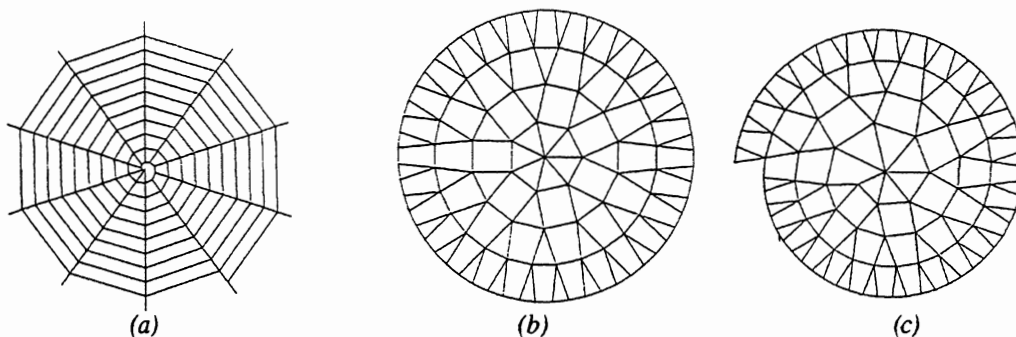


Fig.6 Simple spiral (a), double circular membrane (b) and double spiral (c)

3.7. Three-dimensional geometrical structures.

A more general three-dimensional version of the CORDIS-ANIMA formalism enables to start on the notion of spatial distance with its whole signification (the parameters of a link depend on its length).

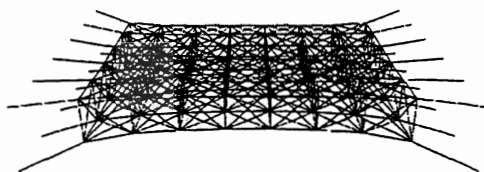


Fig.7: 3D thick plate

Thus, it becomes possible to build real geometrical VS which may be deformed, stretched or twisted. These structures own intrinsic non-linearity properties due to the calculation of spatial distances. But, if a previous mathematical analysis was possible for purely topological VS, it becomes much more difficult in the 3D situation. The main observations resulting from these experiments is connected to non linear phenomena caused by the real geometry of the network, whereas each separate component has linear characteristics.

3.8 First conclusions.

Of course it would be possible to go further and build very sophisticated networks with highly complex topologies designed to describe specific physical properties. But the numerous experiments that we made tend to prove that it would be a wrong way: complex networks mean complex algorithms and great computation tasks. Furthermore, some topological properties which are of great interest from a mathematical point of view, or even which may appear in nature (crystal symetries, growth process...) may have no meaning from an acoustic point of view. Here is the difficulty: we have to determine which physical properties are relevant in a simulation for sound synthesis.

Actually an important point arises from these general observations: the topological definition (ie. the mathematical construction) of vibrating structures is not sufficient for sound synthesis simulations. This definition is necessary to point out different classes and make a simple connection between geometry and topology, but it seems that a great variety of highly relevant simulations may be performed with a few simple topological structures and fitted parameters. The three or four classes presented here (strings, products, spirals and 'double' structures) are sufficient: they allow a wide range of possibilities simply by modifying their size and the way they are fixed. Then the following step, probably much more difficult, is the study of physical parameters.

4. PHYSICAL PARAMETERS.

Beside the size and topological or geometrical characteristics (including number and distribution of the fixed points), the major parameters of VS are the mass m associated with each matter point, the stiffness k associated with each spring and the rest length l_0 in the 3D case, the viscosity z associated with each damper. The physical and acoustic role of each parameter can be describe in board outline as follows. The global stiffness of the object (k/m in the homogeneous case) gives the pitch of the sound. The global viscosity (z/m) gives the damping time of the vibration, that will correspond to the duration of the sound. Actually, things are not that simple: all the physical and topological parameters are linked together by some strong relations. All these relations will play a role in the timbre of the sound. For example, a series of experiments have shown that regardless of the other parameters, the perception of permanence of duration may be associated with parameter $\beta=z/k$ and permanence of matter, with given excitation conditions, seems to be associated with k and β .

In the 3D situation, other important parameters lay in the initial conditions if the structure is prestressed (twisted or taut). However, the nature of the excitation, and especially the realism with respect to the simulated object may sometimes be preponderant for the evokation of a specific material (a membrane or a woodblock cannot be plucked).

5. CONCLUSION.

All these experiments on vibrating structures show that the physical modelling of musical objects with the CORDIS-ANIMA system offers a wide and rich field of investigation for sound synthesis. But another important point appears: this kind of simulation involves at least three levels of interpretation between physical, simulated and acoustic phenomena. Each level is described by specific sets of equations and parameters amongst which some are relevant for sound synthesis and others are not. For example, the

spectral distribution of a VS (that is, its modes) lays in the eigen values vector of its associated matrix. But other matrix (i.e. other VS) may have the same eigen values. Thus, both VS will have the same modes.

According to these issues, we are now looking for a more direct way between the simulated object and its acoustic properties, and then between the simulated object and the identification of physical phenomena that may produce the same effects.

In this way, we develop several tools, based on the same physical model formalism, for the analysis and identification of sounds and VS (Incerti 95b), (Szilas 93), and a more general interface, the GENESIS project, including each step of a musical creation process: design and construction of the virtual instrument, synthesis and analysis, and finally composition.

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