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Physical modeling for sound synthesis with particle-interaction Networks: Study of the percussion phenomena and conception of a generic module for percussion

Patrick Fourcade and Claude Cadoz

ACROE, UJF and INPG University
email: Patrick.Fourcade@imag.fr

Abstract

We developed a first elementary model of percussion using the general formalism of particle-interaction physical modeling. We highlighted four perceptive/productive categories. We also showed that this model allows an incursion in the field of granular synthesis, and allows an original approach of vocal onomatopoeias. Lastly, we developed a very general model of strike by adding to this first model two new properties (non-linear elasticity in power of X, and viscosity in series). With few control parameters, our model takes into account dissipation and hysteresis and enables to reproduce the majority of the percussion phenomena. These results extend the impact of sound particle-interaction physical models.

1 Introduction

We developed an environment for physical modeling sound synthesis with particle-interaction networks. It consists of a simulation system and a graphical user interface for the design and the use of the models. The simulation system is based on a general language that has been developed and used for years in basic experimentations and in several musical pieces.

Using this environment, we systematically study and model all the basic phenomenon categories that appear in sound physical structures, in response to a gesture. Therefore, among these categories, we studied the percussion phenomena. Our goals were the following: (1) having a better understanding of percussion from this knowledge, (2) extracting a model based on our formalism to produce all the percussion phenomena with an optimal set of parameters.

First of all, we present in this paper the general framework and the physical formalism we developed. Then, we introduce a first elementary model of percussion without dissipation, built within this formalism. A systematic study of this model leads us to highlight perceptive / productive categories of the percussion. We present, then, several applications of this model, showing its generic power despite the absence of dissipation. Based on recent work on felted hammers, we define a more elaborate but optimized model, that integrates the relaxation and hysteretic phenomena inside the felt. Finally, we propose a general model of percussion and show its applications for the percussion of strings, membranes, gongs and any vibrating structure built with our formalism.

2 Physical formalism of modeling per network of particles and interactions

Among these various physicals modeling approaches for sound synthesis, one can first distinguish the methods that mainly aim at understanding the real musical instrument phenomena. They digitize with different techniques the physical equations that govern the instruments. Furthermore, the digital simulation of these equations can be compared with measurements and observations made on real instruments.

The second variety of approaches does not aim always in reproducing reality but proposes generic systems and algorithms. It is also inspired from the physical reality of the instruments. However, the sounds it synthesizes can be realistic or not. Among other approaches, there are two that are important in this category:

Method of the wave-guides: The starting point was the delay-line model introduced by Karplus and Strong (1983). Smith later generalized it with the theory of numerical filters that led to the concept of guide of waves; **Method of networks of particles and interactions:** This method models any physical object as a whole of punctual masses and viscoelastic interactions (linear and non-linear). The work we present here deals with this second method.

The system we developed in the laboratory is based on a general and coherent formalism (Cadoz, Luciani, and Florens 1993). It is conceived to simulate any physical object in such a way that an operator can handle the object in real-time by gesture. He can simultaneously perceive its behavior through the acoustic, visual, and tactile senses. The system is entirely modular. At all levels, interactions (such as module to module interaction and whole model to operator interaction) are always physical. Thus, the basic elements of modeling in this system are, themselves, elementary physical objects. They are of two kinds:

(1) Material elements, with inertia, likely to move in a physical space (either 1D, 2D or 3D).

(2) Connecting elements, which represent the physical interactions (mainly viscoelastic) between the material elements.

These basic elements are associated with basic algorithms (numerically optimized) which perform the physical functions that they are supposed to model. The specificity of the system lies in the characteristics of the optimizations: Algorithms use the minimum possible number of numerical operators that create inertia-like and interaction-like behaviors.

To these main physical basic elements we add, within the same formalism, in/out modules that interface the transducers (module that represent the force feedback gesture transducer; out loudspeakers module; module that display on screen the masses positions…).

In order to construct any object, we connect physical and in/out modules (thus, we assemble their modular algorithms). The behavior of the whole object is physically consistent, whatever the network of material elements and interaction is.

3 Elementary model of percussion

The first model that we worked on, is built with the minimum number of elements required and sufficient to obtain a percussion process. It consists of two elements: the striker itself and an elementary vibrating structure (Fourcade, and Cadoz 1996).

The latter consists of a mass moving along an axis (1D space) and connected to a fixed point with a linear viscoelastic interaction. It is actually a mechanical oscillator of the second order. Its parameters are the inertia Mc of the mass, the stiffness Kc of the spring and the viscosity Zc of the damper. At rest, the specific mass is with X-coordinate 0.

The striker consists of another mass (inertia Mp) and of a non-linear connection element, called 'buffer spring' in the formalism. This buffer spring consists of a spring (Kl) and a damper (Zl) which are active only when the X-coordinate of the striker is lower or equal the X-coordinate of the struck mass (here the elementary vibrating structure) and are inactive otherwise. Giving an initial speed to the mass Mp, we achieve a percussion process. While the striker and the vibrating structure are coupled, the system is linear (figure 1). As a consequence, the initial speed value of Mp does not change the nature of the signal, but only its amplitude. Therefore, we decide to normalize the amplitude of the movements during the experiments.

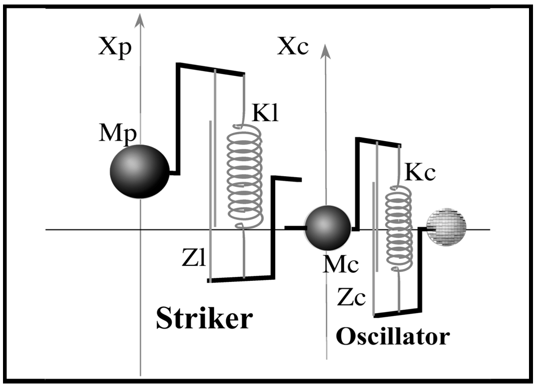

Figure 1. The elementary model of percussion

Using this model, we carry out an investigation by considering three spaces of representation, while the parameters of the oscillator are fixed to nominal values:

(1) the signals space (movement of the striker, movement of the oscillator, forces between striker and struck); (2) the parameters space (Mp, Kl, Zl); (3) the perceptive space (perception of the percussion phenomena).

In this elementary model, the viscosity Zl has nearly no effect on movement. Actually, the listening tests proved that four main perceptive categories are relevant. Besides, each one clearly corresponds to a specific area in the 2D plan of Mp and Kl parameters:

(1) $Mp < Mc$ and $Kl/Mp > Kc/Mc$: percussion without any audible 'attack identity' (sounds 1).

(2) $Mp < Mc$ and $Kl/Mp = Kc/Mc$ or $Mp = Mc$ and $Kl/Mp > Kc/Mc$: ' dry ' percussion very audible (in the first area, the Eigen frequencies of the striker and of the oscillator are equal) (sounds 2).

(3) $Mp > Mc$ and $Kl/Mp < Kc/Mc$: ' massive' percussion (feeling of heaviness of struck objects) (sounds 3).

(4) $Mp > Mc$ and $Kl/Mp > Kc/Mc$: occurrence of a particular 'coloring' phenomenon during the attack (this particular effect is due to the multiple rebounds of the striker under the oscillator during the attack phase) (sounds 4).

We discovered that for $Mp < Mc$ and $Kl/Mp = Kc/Mc$ we obtain the same percussion timbre. This result is also available on more complexes vibrating structures like strings.

This experiment with a very simple model shows off a direct relationship between physical parameters and perception. It confirms that physical modeling is relevant in controlling the perceptive attributes of synthesized sounds.

4 Anecdotal applications of the elementary percussion model

We expose now two anecdotal uses of this elementary model, which give an idea of the range of its applications in spite of its simplicity.

4.1 Multiple percussions, ‘granular synthesis by physical modeling’

Actually, it is possible to generate a stationary signal by carrying out multiple percussions on a vibrating structure at regular and controlled intervals of times. This can be realized ‘projecting‘ equidistant and identical strikers on this vibrating structure. By controlling their distance, we regulate the sound fundamental frequency. By controlling the striker parameters, we modulate the sound timbre.

This marginal use of our elementary model and its control parameters opens an original way to interpret in physical terms granular synthesis.

4.2 Evocation of plosive consonants

We based this investigation on one of the early works in speech synthesis, from Cooper (1952). He associates the evocation of the consonants /p/, /t/ and /k/ with the presence of a ‘burst’ in sound (short sequence at a given frequency) right before the vowel signal.

To obtain / p / the burst must be at a high frequency. To obtain / t / the ‘burst’ is at the frequency of the second formant of the vowel. To obtain / k / the ‘ burst ‘ is at the frequency of the first formant.

We synthesized consonant-like sounds by adjusting the parameters of the elementary percussion in order to obtain these frequencies during the transient of the percussion. The synthesis of /pa//ta//ka/, /pœ//tœ//kœ/, /pi//ti//ki/, /po//to//ko/ can be heard first of all without the resonant vibrating structure (sounds 5) then with it (sounds 6). The results, although largely supplanted by more recent works in speech synthesis, suggest an interesting way to categorize certain percussion phenomena using vocal onomatopoeias (Fourcade, and Cadoz 1999).

5 Improvement of the model: introduction of dissipation - felted hammer model

Although it is relevant because of its sound potentialities, this elementary model has a fundamental limit that we have already mentioned: The linearity of the striker-struck system, during coupling, implies that the phenomenon is not correlated to the speed of the striker (except for the amplitude of the movements). Moreover, the striker speed is a significant playing parameter for percussion players. In addition, many usual strikers use matter as felt, which presents a specific dynamic behavior with hysteresis.

This behavior implies a process of dissipation of energy, which does not appear in usual viscous medium. Studying Boutillon's works (1988) and Stulov's works (1995) on the piano felted hammers, we introduced into our model an additional element that models the contribution of the felt.

Stulov proposed an analytic model of the felt that takes into account the hysteretic phenomenon during its compression by describing the compression law (according to the force applied) in the following form:

$$F(t) = \frac{-F_0}{d^p}\left(U^p(t) - \frac{\varepsilon}{\tau_0}\int_{t'=0}^{t} e^{-\frac{(t-t')}{\tau_0}} U^p(t')dt' \right)$$

where F is the compressing force, U the compression, τ_0 the relaxation constant, ε the hysteresis constant, F_0 a constant of force, d the diameter of the excited string, p the exponent constant.

This expression, comparing to the linear case, presents two new terms: an exponent p on the variable U and an integral. These two terms can be introduced into our percussion model, while respecting the formalism, adding an element to the modeling base. To achieve this, we defined non-linear elastic modules that produce a force as

$$F = K_2.X^p$$

and we replaced the linear module of viscosity in the first basic model with a module made up of a viscosity and a non-linear elasticity in series (figure 2).

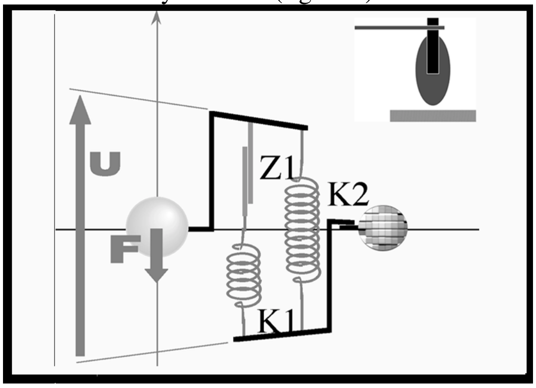

Figure 2. Model of felted hammer. Adding a viscosity and a non-linear elasticity in series.

To be more precise, the computer elements obey to the following equation:

$$F + \frac{Z_1}{K_1}\dot{F} = -\frac{Z_1}{K_1}\frac{(K_1+K_2)}{d^{p-1}} pU^{p-1}\dot{U} - \frac{K_2}{d^{p-1}}U^p$$

, with k_1, K_2 stiffness, Z_1 viscosity, p and d some constants.

We checked that such a model fits precisely, with the right parameters, the desired hysteretic behaviors (figure 3).

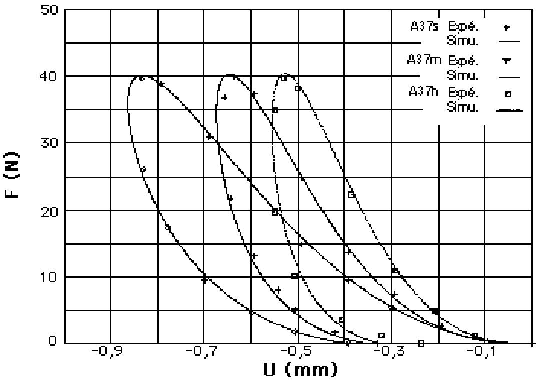

Figure 3. Fitting of hammer characteristics F(U): points are Yanagisawa experiments (in Stulov 1995); lines are simulations of our models. A36s: soft, A36m: middle, A36h: hard.

We used this model of felted hammer to carry out simulations of percussion on strings. These last were modeled by homogeneous chains of masses, connected to each others with linear viscoelastic interactions.

The experiments showed a widening of the signal spectrum when the striker speed increases. We hear "crescendo" series firstly on a soft hammer (sounds 7), secondly on a hard hammer (sounds 8). In (sounds 9), we hear successively seven percussions: hard, middle and soft hammer percussion then hard and soft percussion, repeated twice. Although the model of string implemented is quite simple, the sounds obtained approach the sound of piano strings in an encouraging way. With nearly the same model, exploring striker parameters, we obtain singular percussions (sounds 10).

We then applied this model to various other vibrating structures, without seeking particularly the simulation of a precise instrument. These experiments reveal very interesting properties in the percussion model. In particular, they show the contribution of these two forms of non-linearity during the transient. These phenomena are complementary to those one can obtain by introducing non-linearity (with similar process of simplification and formalism) into the vibrating structure itself.

6 Conclusion

We developed a first elementary model of percussion using the general formalism of particle-interaction physical modeling. We highlighted four perceptive/productive categories. This first model is easy to implement. Applied to all the vibrating structures built within the formalism, it is possible to model and synthesize a large variety of percussion sounds.

We also showed that this model allow an incursion in the field of granular synthesis, and an original approach of vocal onomatopoeias - even though these sound phenomena are not strictly part of percussion sound.

Lastly, we developed a very general model of strike by adding to this first model two new properties (non-linear elasticity in exponent of X, and viscosity in series). With few control parameters, our model takes into account dissipation and hysteresis and enables us to reproduce the majority of the percussion phenomena.

These results extend the impact of sound particle-interaction physical models. They supplement other results that are dual of percussion (bow friction, reeds of wind instrument….) and were obtained within the same formalism to model the continuous excitation phenomena.

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