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A GOALS-BASED REVIEW OF PHYSICAL MODELLING

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ABSTRACT

Physical modelling (PM) encounters a growing success. Though, in the context of Computer Music, it covers numerous goals, needs and challenges. The article aims at contributing to their understanding. It provides a bibliographic overview of the various goals that researchers and musicians may pursue. It introduces a set of features that an ideal PM technique should offer.

1. INTRODUCTION

Physical modelling (PM) approaches to sound synthesis (also called model-based approach) appeared at the end of the sixties and have considerably been developed since the late eighties. As a result, the words "physical modelling" cover today different significances. The diversity of the approaches and works makes it useful to chart the field. To that aim, this article focuses on two questions:

1) *What are the goals pursued against PM in the contexts of music?*

The 1st section distinguishes amongst the acoustician's approach to PM and the more music-oriented works. With the end-user's point of view rather than in a technical manner, the 2nd section reviews the various interests for using PM in the context of music – which correspond with as many challenges for research.

2) *How can we compare the various PM techniques along each other?*

PM techniques are not equivalent regarding the goals pursued. The 3rd section introduces a set of features for an hypothetical "ideal PM technique". It can be viewed as a summary of the goals discussed in section 2 and as a practical mean for comparing existing techniques.

2. ACOUSTICS DOES NOT MATCH FULLY MUSICAL NEEDS!

A few but fundamental distinctions regarding goals and methodologies can be made amongst research on PM in acoustics and in Computer Music or Applied Signal Processing, that are more oriented to music creation.

Traditional Musical Acoustics is rooted on the search of a better understanding of the real instruments mechanisms, by designing precise and complex models. In this context, traditional physics (with continuous time and space) is a key tool. A computable model is eventually obtained by implementing a numerical analysis process. Simulation is then mainly used in order to study the validity of a model of a specific sound structure, by comparing the model's outputs with measurements on the real structure, through both hearing and signal analysis.

As for them, despite their various motivations, researchers working on PM in Computer Music or Applied Signal processing commonly aim at finding the appropriate physical rules, reusable modular algorithms or integrated tools that could empower musicians with PM. This empowerment concerns both quality in the sounds and usability (i.e.: the possibility for a musician to practice PM by himself). Models are evaluated mainly through subjective judgments, and they have no interest apart their possible musical uses. Modelling does not necessarily call for a study or an analysis of a real instrument, but more for a synthesis process: the "model" can emerge from a construction of "physically-relevant" building blocks, and may have no real counterpart. Based on these characteristics, one may say that the activity in the field is concerned with Physically-Based Modelling or Synthesis – as opposed to traditional PM – though, to simplify, this distinction in terms will not be made in the following.

As a matter of fact, the frontier that separates the two domains is not that clear. Mutual empowerment is possible, and obviously needed. But researchers in Acoustics/PM and Computer Music/PBM, point goals, needs, and results that are different.

3. REASONS FOR USING PHYCIAL MODELLING IN MUSIC – A SURVEY

This section proposes a bibliographic overview of the interests one may find in practicing or searching on PM, in the context of music creation. It also offers a comparison with the domain of signal-based synthesis.

3.1. Imitations, metaphors, and beyond

Many musicians, especially in popular music, consider the re-synthesis of the sound of real instruments as a very important feature. Indeed, Imitation is often considered as the major interest of PM. Compared to signal-based models, physical models excel to that aim. They have sometimes been compared to kinds of 'structured samples', with physical parameters sampled instead of air pressure [13]. Though, a digital artefact will probably never be as expressive as its real counterpart, whatever the model complexity could be. Moreover, though it may offer practical interests to musicians, it will never dramatically enhance creativity. The search for imitation does not correspond with a real empowerment of our creation tools.

Trying to find equilibrium between reality and 'virtuality', through what we may call a process of ‘metaphorisation’ of real instruments, may be a more relevant attitude when dealing with PM. But a more original step is possible. By assembling basic but appropriate physically-based building blocks, one may obtain a model able to synthesize sounds that have absolutely no real counterpart – so that a physically-based model can be considered as a “musical reality generator” [1]. However, the possibility of such a process is not sufficient to ensure its interest: we need to evaluate the quality of the sounds thus produced.

3.2. “Physical Plausibility” of Sounds

Among other roles, we know that hearing is innately tied to inquiry into the physical origin of a sound. Consequently, synthesized sounds are more easily accepted by listeners and have a better profile when they lead the subject to think they were produced by an hypothetical real object [9].

We then may say that a certain “realism” or verisimilitude is needed for synthesized sounds. However, the term realism is far too close to the real world, which we want not to reproduce but to extend. Other qualifications of the sounds produced with physically-based models have been proposed: “rich and homogeneous” [1], “organic and complex” [8], etc.

We here introduce the notion of “physical plausibility” of a sound. The important feature for a musical sound is not to correspond with the sound of a real cause, but to present a set of subtle dynamic variations among perceptual parameters that lead the listener to feel that some physical process was involved in its generation. A sound may be far from evocating any real acoustic source while still being “plausible”. Since they are based on the modelling of some physical process, physical models tend naturally to generate plausible sounds, even when they are not designed with reference to any real object. This extends to performance situations. Inputs in a physical model tend to modify in a coherent manner various perceptual parameters. With physically-based models, we hope that the dynamic evolutions in sounds are ‘physically plausible’ and strongly reinforce the illusion of a permanent cause.

More generally, the search for algorithms that may ensure plausibility but without damaging creativity in modelling is a key-point in the field of PM.

3.3. Signal vs. Physically-Based Parameters

The modification of a physical parameter within a physically-based model tend to produce a consistent effect on perception [7, 12]. With a physical model, you will hardly modify independently the perceptual parameters (loudness, timbre…), which is possible with signal-based models. However, you may obtain relevant and robust series of models by modifying a parameter.

3.4. Off time and real time playability

By promoting a representation of the dual concepts of force and position, physical models enable an intuitive representation of the action we perform with musical instruments, such as plucking, striking, damping, etc. They allow the user to deal with metaphors of the instrumental gesture in case of off-time simulations.

In the context of real-time performance, the search for expressive digital instruments is a major concern in the PM field. Indeed, physically-based models offer better prospects than signal-oriented methods. They tend to displace the origin of the sound vitality from the control flow to the model itself. They do not need an artificial “mapping” of the inputs on the parameters of the models. They are, in addition, particularly promising when using haptic interfaces, which interest for real-time playing has been proved: their connection does not require a complex dedicated layer in the model and they are able to generate relevant gesture feedbacks.

3.5. A Mean for Multisensoriality

While it developed in Acoustics and Computer Music for sound synthesis, PM proved to be useful for the synthesis of other categories of phenomena in other research fields. PM today appears to be a relevant paradigm for virtual reality systems, based on multisensory and interactive simulation, including gesture interaction and sound and visual outputs. Indeed, the use of a single model for generating the various categories of phenomena allows enhancing energetic coherency amongst the phenomena.

Incidentally, as well as the signal-based approaches have developed in parallel with researches in psychophysics during the 20th century, PM may become a mean for approaching perception as a global system, developing new branches in cognitive sciences [9]. It may help, for example, to identify the processes involved in the construction of the mental representations of objects, or conversely the necessary but sufficient conditions to trigger the sense of presence of virtual objects [10].

This paragraph does not deal directly with Computer Music, but we should keep in mind that approaching PM only through sound synthesis may be restrictive compared to its potential for creating virtual, convincing and expressive sensorial artefacts.

3.6. Practicing PM: a New “Musical” Activity

Researchers often consider that musicians should not be in charge of the modelling itself, since it is usually assumed to be difficult and to require a scientific knowledge they rarely possess. Thus, within most of the environments dedicated to musicians the modelling process tends to be hidden to the user. From our point of view, a different approach should be encouraged.

Though musicians are not commonly confronted in an intellectual manner with the notions of inertia, damping, physical interaction, etc. all these notions can be intuitively apprehended through our body and our every-day life. Our experience, especially with the numerous users of the GENESIS environment [4], proves that modelling may be accessible to every one, based on what we call an intuitive 'physical thought'. Moreover, practicing PM can be particularly interesting for a musician: among other lexical fields, the musical vocabulary employs physical concepts, such as energy, waves, motion, force, etc. – concepts that are particularly well addressed by PM.

3.7. From Synthesis to Musical Composition…

The potential impact of PM on musical composition processes is a question today. In the case studies of compositions that use physical models [6], composers most often emphasize that they benefit from the robustness of the parameters and the richness of the timbres (which we pointed as 'plausibility'), rather than from the PM process itself. Most often, their methodology in composing seems not to be deeply transformed by using PM. Though, other ways are possible.

As example, an approach to composition entirely based on the mass-interaction modular scheme was proposed [3]. As this article explains, one can obtain a succession of sound events rather than isolated sound by assembling in a complex structure both high and low frequency models. Cadoz demonstrated that this approach can be extended dramatically. His experimental piece "pico..TERA" is made of a single model with thousands of masses and tens of different "objects" of different scales interacting. 5 minutes of music is then obtained by executing this model without any external interaction nor post-treatment.

This "compose (with) physically-based models" process presents various interests. First, low frequency models are slightly perturbed in a natural manner by retroaction from sound models. The sound events generated thus do present convincing short-term evolutions, expressiveness and musicality, such as changes in a rhythm or in the timbre of successive musical events – somehow as a musician would do. Second, the process proves that PM makes it possible to meld within a single paradigm both sound synthesis and computer-aided composition. Third, it proved to be relevant for dealing with musical ideas: the "think physical" dictum discussed above may be extended to the compositional scale.

4. FEATURES FOR AN OPTIMAL PHYSICAL MODELLING TECHNIQUE

The diversity of the attempts impacts the requirements for PM techniques. As a mean for summarizing the goals for developing and using PM, this section introduces a set of features that an ideal, though hypothetical, PM technique or approach should present. The section covers computer efficiency (4.1), phenomenological requirements (4.2 to 4.4), and usability (4.5 to 4.9).

4.1. Efficiency of the Algorithm

Computational efficiency influences the maximum complexity of a real-time simulation, and the possible number of iterations in improving a "deferred time" model. For a given richness of sound, computational efficiency of two PM techniques may be very different. Though computer power increases, efficiency is still critical and a major topic for PM researchers.

4.2. Faithfulness of the Synthesized Sounds

Given the importance of imitation (§3.1), an ideal technique should allow both precision in modelling and faithfulness in sound results. This is crucial when the aim is to propose digital instruments that could stand for their real counterpart. However, it is of a lesser importance when the user is mainly seeking a convincing sound plausibility and an empowerment of his musical means by the practice of modelling.

4.3. Diversity of the Categories of Instruments

An ideal technique should be usable in an elegant and efficient manner for modelling any real sound structure (winds, strings, non linear musical instruments, etc.). By maximizing diversity, such a technique could be particularly interesting as a basis for a general-purpose environment for musical creation. However, it may at the same time minimize the previous faithfulness feature. Anyhow, while some existing techniques allow modelling a large range of sound generation mechanisms, others are more restrictive.

4.4. Diversity of the Categories of Phenomenon

Given the growing importance of multisensoriality, an optimal technique should allow the modelling of non-sounding objects and enable various sensorial outputs or interaction, including haptic and visual ones. In the specific (and restrictive) context of Music, the diversity of the phenomena that can be generated covers two challenges. First, a visual representation of a simulation may help to understand the model's dynamic properties [4]. Second, Cadoz' "composing (with) physical modelling" process (§3.7) calls for PM techniques that are not dedicated to sound structures but, more generally, to the modelling of many sorts of objects and to the simulation of the instrumental gesture.

4.5. Robustness of Physical Plausibility

While modelling, a musician will hardly put into practice the physical knowledge of a scientist. His process may be nothing but empirical and intuitive. The 4 next paragraphs (4.5 to 4.9) deal with usability of PM techniques. They discuss the needs for allowing a musician to practice PM by himself.

First, as a particularly important feature, an optimal technique should be robust as for sound "physical plausibility": it should naturally generate 'plausible' sounds, no matter how it is employed. As a matter of fact, existing techniques are not equivalent regarding robustness.

4.6. Modularity

Modularity has been regarded as an important feature since the very beginning of Sound Synthesis. As said Mathews, it is necessary to obtain at the same time generality, power and simplicity [11]. In the context of PM, modularity may be approached through various points of view: existence of basic modules and composing rules, size and meaningfulness of the modules, possibility of an incremental modular process rather than a one-shot modelling, etc. They altogether should be maximized by an optimal scheme.

4.7. Effectiveness of the Mental Model

From a cognitive point of view, the “user’s mental model” (or conceptual model) is the set of representations the user builds in his mind regarding a system. The use of a system is not based on its real properties, but on the user’s mental model. A good mental model should let the user anticipate the results of his action and facilitate explorations. The mental model associated with a PM technique may hardly depend on the user’s knowledge of Physics. Many sorts of mental models may be relevant for a musician. However, we consider that the mental model will be more interesting if it lets the user build and handle his models as if they were real objects, and not as a set of equations or theoretical constructions. An optimal technique should display intuitive notions and promote an “impression of reality” when implemented.

4.8. Deepness of the Modelling Process

According to [2], three categories can be distinguished among the models we can build: phenomenological, functional and structural. The recording of a sound is a phenomenological model. A signal-based model for the re-synthesis of the sound is a functional model. When one does not consider the observed phenomenon but the object that generated it, decomposing recursively this object in smaller interacting objects, and proposes a model for each of the latter, a structural modelling process is performed. A physical model, then, is nothing but the result of some structural modelling process. The deepness of a model is the point at which the structural decomposition is stopped and replaced by a functional (or phenomenological) approach.

It is not a priori necessary to perform a deep modelling in order to maximize the phenomenological precision (§3.2), particularly in the case of isolated sound events. However, a technique that enables a deep modelling process tends to be easier to use. First, it is modular and second, since the basic modules are smaller, they may be more comprehensible for the user.

4.9. Efficiency of Algorithms for Generating Models

An optimal technique should allow designing efficient parameter estimation or model generation algorithms, for the re-synthesis of a set of perceptual parameters (frequency, timbre, etc.). By establishing a connection between the signal (or phenomenological) space and the physical model space, such tools can help in designing a model. However, they should be used carefully: one of the major interest of PM is to be found in the shift in the mental approach to music creation it calls for, which may be reduced by generalizing generation tools.

5. CONCLUSION

The set of ‘optimal features’ for an ideal PM technique focused on processing cost, phenomenological interests, and usability. It aims at offering a better understanding of the challenges PM covers, and will cover in the coming years. Incidentally, it also allows comparing briefly the techniques that have been introduced for 30 years, as it is briefly summarized in the table, next column – see [5] for details and explanations.

To conclude, PM concerns the entire musical creation process: from instrumental playing to compositional activity, through instrument design. Practicing PM is not (only) practicing sound synthesis. In the context of Music, PM does not aim only at offering new (and possibly better) sounds, but rather at proposing new systems for sound and music creation, and at encouraging new creative processes by using these systems.

	acoustician’s methodology	mass-interaction scheme	wave-guides scheme	modal scheme	non-linear black-box approach
Computer efficiency		+	++	+	
Faithfulness of the sounds	++	+	+	+	+
Musical Instrument diversity	++				
Phenom. divers.- multisensoriality	-	++	-	-	-
Robustness	-	+			
Modularity	-	++		-	-
Mental model effectiveness	-	+		+	-
Deepness of modelling process	+	+			
Means for generating models		-		++	

PM thus calls for a paradigm shift in our creation tools. Though it could take a long time, it has the power to impact dramatically musical creativity. This is, indeed, a responsibility for both musicians and researchers in the field.

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