Physically-based modeling and music vs. physical modeling and acoustics

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Abstract

Until the late 70's, in musical Acoustics, the practice of physical modeling (PM) was mainly the prerogative of acousticians. Since then, other research and uses more oriented to music have developed. A new scientific community has been emerging, which may be pointed out as dealing with "Physically-Based Modeling" (PBM) - as opposed to traditional PM. However, there is still some misunderstanding of these recent works. This article proposes a bibliographic overview of their specificities, goals, and needs. A few ideas are discussed that may help to distinguish amongst the topics on which acousticians and musically oriented researchers interested in PBM work respectively on. The various interests of the research on PBM in the context of music creation are synthesized. As a summary, 10 challenges for an optimal a PBM scheme are introduced.

1. Acoustics *vs.* Music-Oriented Research. Physical *vs.* Physically-Based Modeling.

For the last 30 years, models of musical instruments and physical modeling schemes have developed in parallel in Acoustics and Computer Music or applied Signal Processing. As a result, the words "physical modeling" cover today different significances, which often results in some misunderstandings. Indeed, a few but fundamental distinctions can be discussed.

Historically, 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 it, the research oriented to musical creation was originally introduced as an extension of traditional signal-based sound synthesis. Various motivations rooted the interest in PM. However, researchers in the field share some common goals. They aim at finding the appropriate physical rules, reusable modular algorithms, physically-based languages or integrated tools that could empower musicians with PM. This empowerment concerns ideally both quality in the sounds and usability (that is: the possibility for a musician to practice physical modeling by himself, as a musical tool that can profoundly modify Computer Music creation processes). The research then necessarily deals at the same time with technical aspects (PM schemes, devices for interacting with the models, appropriate user interfaces, etc.) and psychological or at least psychophysical concerns (perception, acceptability of end-users toward the practice of PM, etc.). In this context, anyhow, models are evaluated mainly through subjective judgments, and have no interest apart their possible musical uses. The study of reality is nether a aim but, when needed, a tool for further research, and precision in modeling is not the major aim. Moreover, modeling does not necessarily call for a study or an analysis of any real instrument, but more for a *synthesis* process: ideally the model emerges from a construction of "physically-relevant" building blocks. Based on these characteristics, one may say that the activity in the field is concerned with Physically-Based Modeling (PBM) or Synthesis – as opposed to traditional PM.

As a matter of fact, the frontier that separates the two domains is not that clear. Mutual empowerment is possible, and needed. For example, "acoustical" physical models often led to convincing musical sounds and uses, and research on PBM can result in tools to be employed by acousticians. But researchers in Acoustics/PM and Computer Music/PBM, respectively operating from acoustical and end-user-oriented perspectives, point goals, needs, and results that remain different. The following aim at better situate the research on PBM, compared to Acoustics.

2. Interests of Physically-Based Modeling

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

2.1. 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. Compared to signal-based models, physical models excel to that aim. Imitation, indeed, is often considered as the major interest of PBM [1]. Though, a physically-based digital artifact 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. Thus, 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 PBM. 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" [2]. 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.

2.2. "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 [3].

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" [2], "organic and complex" [4], etc. We here introduce the notion of "physical plausibility" of a sound. The important feature for a musical sound is not to cause the listener to infer its physical cause, but to present a set of subtle dynamic variations among perceptual parameters that lead the listener to think it was produced in some physical manner. A sound may be far from evocating any real acoustic source while still being "plausible". Since they are based on the modeling of some physical process, physical models tend to synthesize naturally plausible sounds, even if 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 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 modeling is a key-point in the field of PBM.

2.3. Signal *vs.* Physically-Based Parameters

The modification of a physical parameter within a physically-based model tend to produce a consistent effect on perception [1, 2]. 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 series of models by modifying a parameter.

2.4. 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, dumping, etc. They allow the user to deal with metaphors of the instrumental gesture in case of off-time simulations, and are particularly relevant for real-time performance.

The search of real-time models and expressivity for digital instruments is a major concern in the PBM field – which is not necessary the case in Acoustics. To that aim, 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 and thus do not need an artificial mapping of the inputs on the parameters of the models [1]. They are, in addition, particularly promising when using haptic interfaces, which have proven their great interest in the context of real-time playing: their connection does not need a complex dedicated layer in the model and they are able to generate relevant gesture feedbacks.

2.5. A Mean for a Global Approach to Perception

More generally, PBM appears to be a relevant paradigm for virtual reality systems, based on multisensorial and interactive simulation, including gesture interaction and sound and visual outputs. Thus, it is a mean for approaching perception as a global system. Just as the signal-based approaches have developed in parallel with psychoacoustics, PBM may nowadays be relevant for developing new branches in cognitive sciences. 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 – which are today major research topics [5].

2.6. Practicing PBM: a New Musical Activity

Researchers often consider that musicians should not be in charge of the modeling 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 modeling 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 are intuitively prehensile through our body and our everyday life. Our experience, especially with the numerous users of the GENESIS environment [6], proves that modeling may be accessible to every one, based on what we call an intuitive 'physical thought'. Moreover, practicing physical modeling 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 PBM.

2.7. From Synthesis to Musical Composition...

Recently, Cadoz proposed an approach to composition entirely based on the mass-interaction modular scheme [7]. As Cadoz explains, one can obtain a succession of sound events rather an isolated sound by assembling in

a complex structure both high frequency models 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 major advantages. 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 physical modeling 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.

To conclude, PBM concerns, theoretically as well as practically, the entire musical creation process: from instrumental playing to compositional activity, through instrument design. By displacing the focus from sounds to virtual objects, by promoting a specific vocabulary, by changing composer's mental approach to music, it may lead to relevant musical practices, provided the necessary research is conducted.

3. Criteria for Physically-Based Schemes

The search for modeling schemes adequate to musicians needs is a major aim in the field of PBM. Various have been proposed for the past 30 years [2]: mass-interaction, wave guides, modal approach, etc. This part focuses on their problematic. It introduces 10 criteria that should be maximized by a hypothetical optimal scheme dedicated to music. Though these criteria allow comparing existing schemes, this will not be down in the article (see [8]). They are given here as a straightforward way for summarizing the goals of the PBM field and as a tool for a better comprehension of its specificities (as compared to Acoustics). They cover computer efficiency, phenomenological requirements, usability, and environments for practicing modeling.

3.1. 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 PBM schemes may be very different. Although computer power increases, it still remains critical and a major topic for PBM researchers.

3.2. Faithfulness of the Synthesized Sounds

Given the importance of imitation (§1.1), a scheme should ideally allow precision in both modeling and faithfulness in sound results. This is a crucial need 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 modeling.

3.3. Diversity of the Categories of Instruments

This criteria evaluates the diversity of the real sound structures (such as winds, strings, non linear musical instruments, etc.) and, more generally, of the real-world sound generation mechanisms that can be modeled in an elegant and efficient manner by implementing a given scheme. A scheme that maximizes this criterion may be particularly interesting for being the base of an environment for musical creation with a general purpose. However, it may at the same time minimize the previous criterion.

3.4. Diversity of the Categories of Phenomenon

In the specific context of musical creation, the diversity of the phenomena that can be generated by using a scheme covers two challenges. First, a visual representation of a simulation may help to understand the model's dynamic properties [1, 4]. However, while some schemes naturally lead to a relevant visual representation, others don't. Second, Cadoz' "composing (with) physical modeling" process (§2.7) calls for schemes that are not dedicated to sound structures but, more generally, to the modeling of every sort of objects and to the simulation of the instrumental gesture. Thus, an optimal scheme should allow the modeling of non-sounding objects and enable various sensorial interactions, including haptic and visual ones.

3.5. Robustness of Physical Plausibility

While modeling, a musician will hardly put into practice the physical knowledge of a scientist. His process may be nothing but empirical and intuitive. The three next criteria (§3.5 to 3.8) aim at evaluating whether or not a scheme is a good candidate for being implemented by a musician himself.

First, certain schemes do not naturally lead to 'plausible' sounds, and may thus be hard to practice by musicians. The robustness of sound "physical plausibility" is a particularly important criterion.

3.6. 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 [9]. In the context of PBM, modularity may be approached through various points of view: existence and meaningfulness of basic modules and composing rules, possibility of an incremental modular process rather than a one-shot modeling, etc. They altogether represent this criterion.

3.7. Effectiveness of the Mental Model

From a cognitive point of view, the "user's mental model" (or conceptual model) is the 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 PBM scheme may hardly depend on the user's knowledge of Physics. Nevertheless, a scheme can be easier or more difficult to elaborate and implement, depending for example on the intuitiveness of the notions it displays. Many sorts of mental models may be relevant for a musician. However, we consider that the mental model will be more interesting if it let the user build and handle his models as if they were real objects, and not as a set of equations or theoretical constructions. As a consequence, an optimal scheme should promote an "impression of reality" when used.

3.8. Deepness of the Modeling Process

As proposed by Cadoz [10], three categories can be distinguished among the models we can build: phenomenological, functional and structural. The recording of a sound is, for example, 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 proposing a model for each of the latter, a structural modeling process is performed. As a matter of fact, says Cadoz, a physically-based model is nothing but the result of some structural modeling process. The deepness of a model is the point at which the structural decomposition is stopped and replaced by a functional (or even phenomenological) approach. This criterion then consists in evaluating the deepness of the modeling process associated with the scheme.

It is not a priori necessary to perform a deep modeling in order to maximize the phenomenological precision criterion (§3.2), particularly in the case of isolated sound events. However, a scheme that enables a deep modeling 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.

3.9. Efficiency of Algorithms for Generating Models

The 9th criterion studies whether or not there exist algorithms for parameter estimation or model generation for the re-synthesis of a set of perceptual parameter (frequency, timbre, etc.), and evaluates their effectiveness. Such tools would establish a connection between the signal (or phenomenological) space and the physical model space, and thus they can help in designing a model. However, they should be used carefully: one of the major interest of physically-based modeling is to be found in the shift in the mental approach to music creation it calls for, which may be reduced by generalizing these tools.

3.10. Possibility of Environments for Musicians

As commonly argued in Human-Computer Interaction, the 'end-user oriented' part of an environment should not be seen as an opportunity to circumvent shortcomings in usability of the 'functional core', but should be designed in order to provide a clear-as-possible interface to the 'functional core'. Translated into our context, this idea shows that a given scheme may or may not be well-adapted for implementation in a musician-oriented environment, depending on its 'innate usability' – which is pointed out by our 10th criterion.

4. Conclusions

Though they were originally designed for evaluating PBM schemes [8], the 10 criteria allow distinguishing amongst Acoustics and research on PBM for creating music. Acoustics mainly try to maximize precision (§3.2), and can concern every category of sound objects (§3.3). Conversely, it deals less closely with the other criteria, which are more specific to the research on PBM. Works in this field should not be regarded as a simplification of those in Acoustics. They do not aim at developing knowledge on musical instruments, nor, eventually, at allowing new sounds, but rather at proposing new systems for sound and music creation, that could empower musicians with PM. This is far from traditional Acoustics concerns. PBM calls for a paradigm change in our creation tools, and, though it could take a long, it has the power to impact dramatically musical creativity. This is, indeed, the responsibility of both musicians and researchers in the field.

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