

# Physical Modelling of Environmental Sounds

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## Abstract

*This paper presents work in progress on automatic generation of "environmental sounds" based on physical modelling. The increase in complexity of the Graphical User Interfaces, the expansion of Virtual Reality and multimedia applications has led to the necessity of using sound to ease the human computer interaction. This category of sounds can be used as non-speech audio presentation of objects and as interaction mechanisms to non-visual interfaces. They occur in everyone's experience and exclude the necessity of previous special training. They are also very suggestive, permitting the meaningful mapping of events from the real world to computer-related activities and are not annoying for the user.*

## 1 Introduction

Every sound could be described as result of interaction between objects in specific environments. Each interaction has attributes that influence the generated sound. One can distinguish between object-specific and context-specific attributes. The first category includes material parameters, shape, size and allows us to find for each object a physical model (i.e. the equation of motion with boundary conditions and their solutions), assuming that the natural modes of vibration are at the origin of the sound. The second one includes parameters such as: position of the interaction point related to the body of objects, the speed and force at the moment of interaction, etc. These attributes control the manner in which the individual natural modes of vibration are excited (initial spectrum of the sound), the behaviour of their amplitudes in time (modal damping), and the overall decay of the sound wave (system damping or reverberation time). The last one needs a thorough description of the whole system, including the acoustical room where the interaction takes place and is very difficult to be modelled through mathematical descriptions. In this case a qualitative analysis is preferred that provides values for different usual interaction patterns.

## 2 Physical Description of Sound Generating Interactions

### 2.1 General Considerations:

In order to describe sounds that we hear in nature, we need models for simple interactions as for example collision between a homogeneous and isotropic sphere and a homogeneous and isotropic plate/beam. Then, for complex structures, the finite elements method helps us to simulate although other impacts between more complicated objects. On the other hand, another

category of complex impact sounds (like bouncing, scraping, rolling, breaking, etc.) can be simulated reproducing repeatedly simple impact sounds, applying adequate algorithms (see 2.3).

## 2.2 Simple Interactions: Sound Following the Collision between Spheres and Standard Structures as Plates or Beams

### 2.2.1 Approach

The physical description of the behaviour of the plate's or beam's oscillations following the impact with the sphere provides variations of air pressure that we are able to hear. The sphere hits the plate or beam and stimulates vibrations of the natural modes. The natural frequencies of the impacting object (small solid body) are usually not in the audible range, therefore we don't care for the time being about their contribution in the sound generating process.

A qualitative analysis of impact sounds shows that they decrease in intensity exponentially. Theoretical considerations and real sound analysis lead us to a system of damped natural modes of vibration ( $\omega_n$ ) with various initial amplitudes ( $A_n^0$ ). However, this approach only applies to certain materials, those which are homogeneous, isotropic and non dispersive. A formal description for the approach is:

$$w(t) = \sum_n A_n^0 \cdot e^{i\omega_n \cdot t} \cdot e^{-\delta \cdot t}$$

$w(t)$	displacement
$A_n^0$	initial amplitude
$\delta$	damping
$\omega_n$	eigen-frequency

### 2.2.2 Initial Amplitude / Excitation

Research by Koller [8], based on previous work by Zener [11] investigates the influence of impact force upon the initial spectrum of sound. Analyses of that force shows that the impact time in the case of elastic objects is very short ( $\cong 40\mu s$ , fig. 1). The uncertainty formula leads to the conclusion that the impact can be approximated with a Dirac impulse in the audible range:

$$\Delta\omega \cdot \Delta t \cong 1, \text{ with } \Delta t \cong 40\mu s, \text{ thus } \Delta\omega \cong 25kHz$$

The spectral range which can be perceived by humans, resides between 20 Hz and 20 kHz; human sensitivity decreasing with higher age. Therefore, we can consider for our purposes that all the natural modes of vibration are equally excited or with other words the influence of the impact force on the initial spectrum can be ignored.

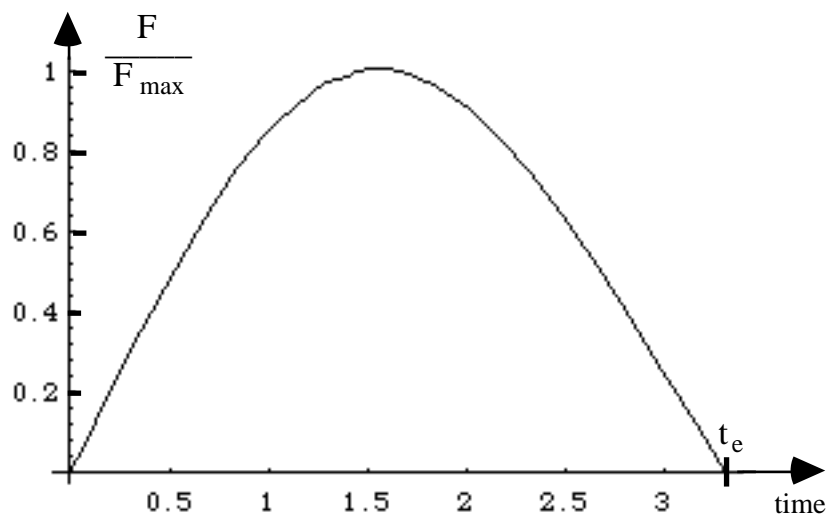


Figure 1: Impact force

Nevertheless, the exact location where the impact force strikes has a great influence on initial amplitudes. Obviously, an impact force applied on a node of a natural frequency does not excite the respective modes of vibration (fig. 2). On the contrary, when the sphere strikes right in the peak of an eigen frequency wave, this mode will be fully excited.

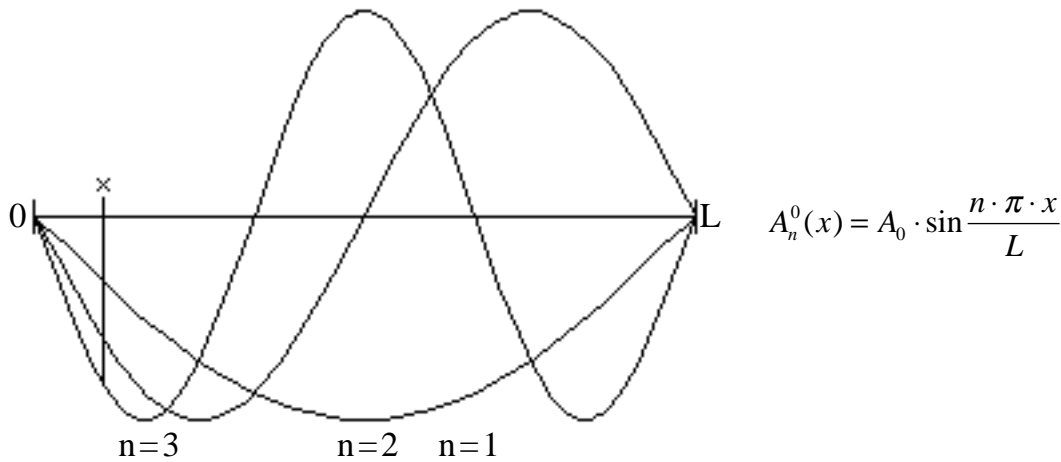


Figure 2: Excitation localisation

The above explanations consider only relative amplitudes of different frequencies among each other. Even though it is possible to calculate the absolute amplitudes as well. What we really hear is dependent on the distance from sound source. Therefore, we consider only the relative initial amplitudes and their evolution related to the impact point.

### 2.2.2 Natural Modes of Vibration

The eigen-frequencies (natural frequencies) of each object depend on its material properties ( $E$ ,  $I$ ), its geometric shape and boundary conditions ( $\lambda$ ). Solving the wave equation in each particular case allows description of simple geometric forms like plates, beams, rings, shells, etc.[1]. Complex geometric forms however require decomposition in simple elements and intensive numeric calculations. As an example we present the natural frequencies for the case of beam:

$$f_n = \frac{\lambda_n^2}{2\pi L^2} \sqrt{\frac{E \cdot I}{\delta'}}$$

- $f_n$  n-th eigen-frequency
- $E$  elasticity
- $\delta'$  mass per unit length
- $L$  length
- $\lambda_n$  dimensionless parameter, function of the boundary conditions applied to the beam
- $I$  moment of inertia of the beam cross section

and plate:

$$f_{m,n} = \frac{\lambda_{m,n}^2}{2\pi a^2} \sqrt{\frac{E \cdot h^3}{12\gamma(1-\sigma^2)}}$$

- $f_{m,n}$  eigen-frequency of mode (m,n)
- $E$  elasticity
- $\gamma$  mass per unit area of the plate
- $a$  a characteristic dimension of the plate
- $\lambda_{m,n}$  dimensionless parameter, function of the boundary conditions applied to the beam
- $\sigma$  Poisson's ratio
- $h$  thickness

### 2.2.3 Damping

In 2.2.1 we have included all the damping aspects in the term  $e^{-\delta \cdot t}$ . In fact, this is a sum of two kinds of damping for real sounds: intrinsic (modal,  $\delta_n$ ) and system damping ( $\delta_r$ ). The intrinsic damping results from the material's internal friction. It is possible to calculate intrinsic damping by the complex elasticity modulus for various materials [10]:

$$\delta_n = \omega_n \cdot \tan \phi \quad M = M(1 + i \cdot \tan \phi)$$

$\delta_n$	modal damping
$\omega_n$	eigen-frequency
$\phi$	phase between strain and stress
$M$	complex elasticity modulus
$M$	real part of elasticity modulus

Typical events where intrinsic damping is much more important than system damping are: vibrating strings, tuning-forks and bells. System damping is very important when additional (boundary) conditions exist and the whole system undergoes damping. Window panes, doors and tables are typical examples from daily life. A precise mathematical calculation of system damping is impossible, so experimental values and empirical formulas are called for. For a system it is possible to determine this damping coefficient measuring the reverberation time (the time needed for the mean of the plate's density of energy to decrease at  $10^{-6}$  from the initial value at the end of excitation). The empirical relation between this parameters is given in [3]:

$$\delta_r = \frac{6.9}{T}$$

$T$	reverberation time
$\delta_r$	system damping

## 2.3 From Simple Impact Sounds to Complex Sounds

To create complex environmental sounds it is possible to imbed the algorithm for additive synthesis of impact sounds in an other that calls it at certain intervals, changing each time the synthesis parameters according to the sound producing event [2]. With this method we can simulate sounds as bouncing, breaking, spilling, etc. There are also complex sounds where the spectrum does not remain constant in time. A typical example is scraping. For this category of sounds an extractive method is preferred (white noise passed through filter banks whose transfer function can be time-varied).

As an example we discuss in the following how to model the bouncing of a sphere dropping onto a plate. The restitution coefficient is very difficult to compute in real time after every collision. It depends on how viscoelastic the materials are. Solving numerically the equations of motion for the sphere and plate in few particular, significant cases provides the values in fig. 3. After polynomial fitting we have obtained the desired dependence of restitution coefficient ( $R_i$ ) on inelasticity parameter ( $\lambda_i$ ):

$$R_i = -0.5 \cdot e^{-3\lambda_i} + 1.5 \cdot e^{-2\lambda_i}$$

The parameter  $\lambda_i$  is given [11] by the following formula and includes material properties and interaction parameters:

$$\lambda_i = \frac{\pi^{\frac{3}{5}}}{\sqrt{3}} \left( \frac{r}{d} \right)^2 \left( \frac{2gh_i \rho_P}{E_P} \right)^{\frac{1}{10}} \left( \frac{\rho_K}{\rho_P} \right)^{\frac{3}{5}} \left( \frac{E_K}{E_K + E_P} \right)^{\frac{2}{5}}, \quad \text{where: } E'_K = \frac{E_K}{1 - \sigma_K^2}, \quad E'_P = \frac{E_P}{1 - \sigma_P^2},$$

$E_K, E_P$ elasticity coefficient sphere/plate	$\rho_K, \rho_P$ density sphere/plate
$\sigma_K, \sigma_P$ Poisson constant sphere/plate	$h_i$ height after the i-th bouncing
$r$ radius sphere;	$\lambda_i$ inelasticity parameter for bouncing i
$d$ thickness plate/beam	$R_i$ coefficient of restitution after the i-th bouncing
$g$ gravitation constant	

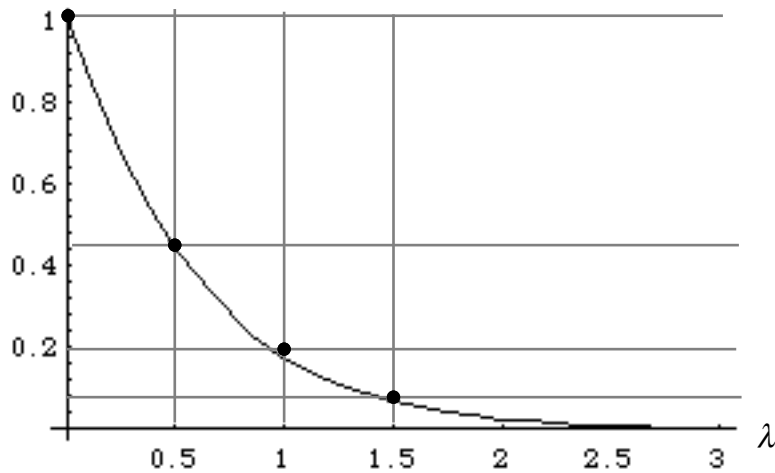


fig.3 Variation of restitution coefficient with inelasticity parameter

We need also a temporal pattern to call the impact sound synthesis algorithm repeatedly, according with the successive impacts. Therefore, we have to compute the time between two successive bouncings:

$$t_{i,i+1} = 2 \cdot \sqrt{\frac{2 \cdot h_{i+1}}{g}}$$

$t_{i,i+1}$	time between bouncings
$R_i$	coefficient of restitution after the i-th bouncing
$h_{i+1}$	the height reached after the i-th bouncing

The successive heights depend on the restitution coefficient of the collision relation:

$$h_{i+1} = h_i \cdot R_i^2$$

### 3 Synthesis

Real time behaviour plays a major role in sound synthesis. For user interface applications synthesised sounds need to be made in real time. The two techniques of sound synthesis, which are described below, can be although efficiently implemented in silicon to exploit the parallelism of the algorithms.

#### 3.1 Additive Synthesis

The technique of additive synthesis reflects our approach for which the formula was already given above. It is possible to implement an efficient and fast algorithm by using the Euler formula [2]. Real time behaviour is only limited by the amount of generated frequencies. The simplicity of this technique has many advantages as well as disadvantages. The advantage lies in the controllability of the results, which always fulfil expectations, but its power is quite restricted. However, this technique is well suited for testing and generating synthetic sounds.

#### 3.2 Filter Bank

In contrast to the additive synthesis this technique is an extractive one. With some white noise as input, only some frequency bandwidth is able to pass through the filter. Some parallel filters, so-called filter banks are used. The transfer characteristic of this filters is derived from material properties and the geometry of sound producing objects. The advantages of this technique are that the transfer characteristic can be controlled in time and there are a large number of parameter choices. It allows the generation of more complex impact sounds, like scraping, rolling, rubbing or breaking.

## 4 Potential Applications

- **Human Computer Interfaces.** Sound can provide information and can ease the communication between computer and user. Many transitions, events, operations, file/resource management tasks are suited to be signalled with adequate, not annoying sounds. Our every day experience provides meaningful analogies so that we can easily find "audio" correspondents for the above-mentioned activities.
- **Virtual Reality.** Most of the sounds that are used in the current virtual reality applications are stored on disk and need large memory space. These applications are always interactive and allow the user to self-configure his virtual spatial room. The sound library is often limited and can not contain correspondents for all the possible sound producing events in the virtual room. Model generated sounds offer the possibility to configure the virtual space also from the acoustical point of view, in a sense that all the objects, through their parameters and physical model, can produce sounds according to their possible interactions. This is a much more powerful technique than a simple sound rendering of the virtual space with arbitrarily chosen sound sources and increase the degree of "reality" of these applications. The drawback of the method, its expensive computational cost in case of complex interacting objects, becomes less and less significant, as the computing power of the new machines increases.
- **Visually Impaired Computer Users.** Blind or visually impaired people make use of everyday sounds for orientation in their life. The integration of everyday sounds in user interfaces brings forward new ways for this group of computer users. The use of software systems and applications (for instance learning tools for training) supplemented with everyday sounds become easier and more intuitive because these sounds are close to their mental model.

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