Physical-inspired synthesis

a tutorial

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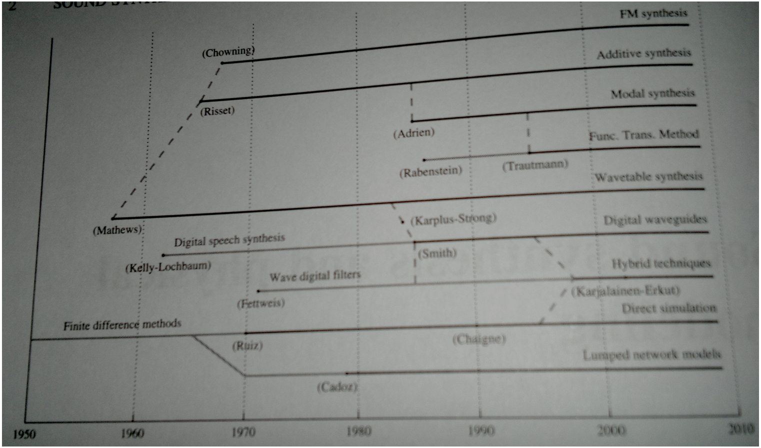
Historical perspective



source: S. Bilbao, Numerical sound synthesis, Wiley, 2010

Physical-modeling (1/3)

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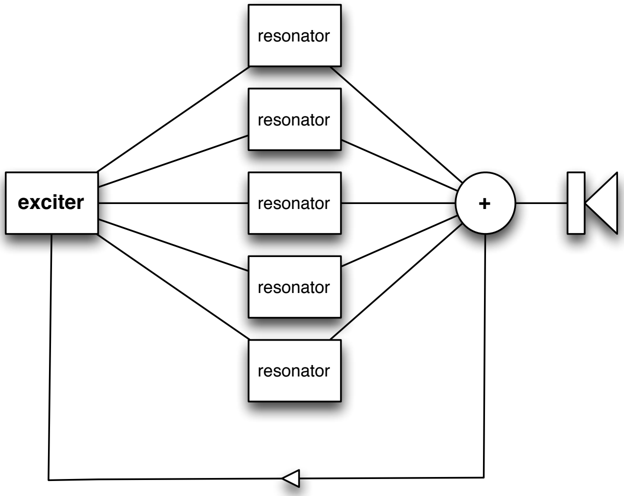
- It is based of the solutions of physical equations on waves
- It realizes the natural dissipation of energy present in all real interactions
- It is usually represented by the system *exciter-resonator*

Physical-modeling (2/3)



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- Karplus-Strong (1983): delay-line + lowpass filter
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- Waveguides (1990/2000, Smith): two delay lines with taps and various filters
- Modal-synthesis: twopoles-filters and weights

Mechanical vibrations

A vibrating object can be represented by the *spring-mass* system:

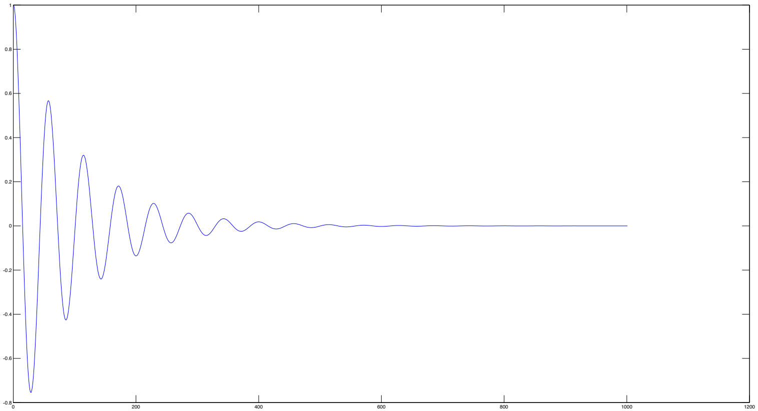
$$x = e^{-\alpha t} A cos(\omega_d t + \phi) \tag{1}$$

where:

- α is the *decay constant* of the system and depends on the mass and on the stiffness of the spring;
- ω_d is the natural angular frequency;
- A and ϕ are the respectively the amplitude and the phase of the vibration and are determined by the initial displacement and velocity.

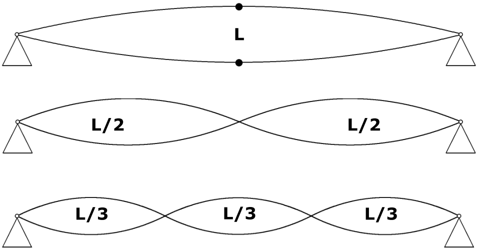
Modes

A natural mode of vibration, as described by eq. 1:



Modeling of complex systems

The complex dynamic behaviour of a vibrating object may be decomposed into contributions from a set of modes each of which oscillates at a single complex frequency (modal synthesis):

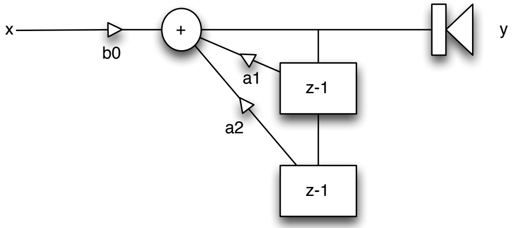


Digital resonators (1/2)

In digital domain, equation 1 can reproduced by means of the following second-order differential equation:

$$y = x \cdot b_0 - y \cdot z^{-1} \cdot a_1 - y \cdot z^{-2} \cdot a_2 \tag{2}$$

where z^{-n} is the delay of n digital samples, b_0, a_1 and a_2 are called coefficients and x is an input signal



Digital resonators (2/2)

A two-poles filter can be designed to produce a peak at a specified frequency:

- $a_1 = -2 \cdot r \cdot cos(2 \cdot \pi \cdot f \cdot T_s)$
- $a_2 = r^2$

where r is the pole radius and T_s is the sampling period; the coefficient b_0 is consequentially computed to have a magnitude at the peak equal to 1.

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- Frequencies and the decay rates are based on physical properties (such as *inharmonicity*), **amplitudes are usually determined by the feedback interaction between the resonators and the exciter**
- Injecting a digital impulse into the resonators, will equally excite all resontaros and consequently all the amplitudes will be the same.

Exciter/resonator interaction (2/2)

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- Each filter will react independently to the stimulus and will assume a different amplitude, thus generating a particular *timbre*
- This interaction is normally regulated by a set of weights (called *modal weights*) that are multiplied to the individual output of each resonator and that derive either from wave equations or from experimental measurements

Physical-inspired synthesis (1/2)

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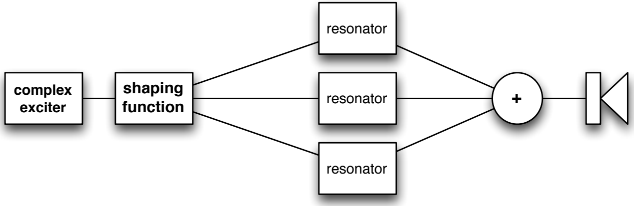
- The simulation of a real vibrating object by means of modal synthesis (for example a musical instrument) can be a difficult task because of the complex analysis required for the estimation of the parameters
- The simulation of a *likely*-physical instrument can be an interesting creative activity
- This kind of physical-inspired sound synthesis generates sounds that have special physical characteristics while not being generated by real vibrating objects

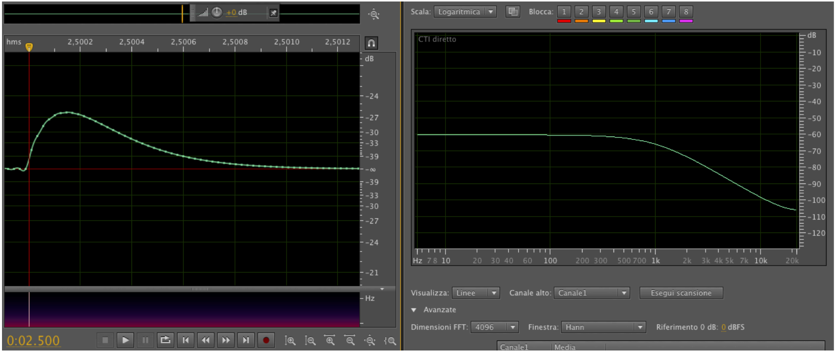
Physical-inspired synthesis (2/2)

A physical model differs from a physical-inspired model because of the missing interaction between the exciter and the resonators in favour of a shaping function is applied to exciter:



Fundamental principle of exciter transformation

A filtered impulse exhibits a temporal smearing and a frequency equalization:



Models of spectral shaping (1/2)

companded harmonic this model uses the companded series proposed by McAdams to create two related vectors for frequencies and amplitudes of each modes:

$$f_n = n^\alpha \cdot f_0 \tag{3}$$

where f_0 is the fundamental frequency of the sound, α is the *compantion* coefficient and n is the mode

geometric series this model propose a simple law for frequencies and amplitudes based on the geometric accumulation of values:

$$f_n = \beta \cdot f_{n-1} \tag{4}$$

where β is the geometric ratio

Models of shaping (2/2)

model based amplitudes and frequencies are inferred from the spectral analysis of a target sample; the spectrum if first searched for peaks and then a spectral envelope is computed: