FILTERING WITHIN THE FRAMEWORK OF MASS-INTERACTION PHYSICAL MODELING AND OF HAPTIC GESTURAL INTERACTION

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ABSTRACT

A variety of filters have been designed, synthesized and used in the history of electronic and computer music. All the approaches aimed to provide filters fulfilling several specifications such as frequency response, phase response, transient state characteristics like rise time and overshoot, realizably conditions concerning the technology used for the implementation and even economical considerations. One of the most important aspects concerning the filters dedicated to musical applications is the control structure they provide to the musician, who is in charge for the integration of the filtering operation in the compositional process and performance. Designing filters using the mass interaction scheme embedded in the CORDIS-ANIMA formalism (used for sound synthesis and composition by physical modelling) offers a different methodology in the control which is coherent with the philosophy of musical composition by 'physical thinking'. This article introduces a technique to design filters using the CORDIS-ANIMA simulation language.

1. INTRODUCTION

Filters play a crucial role in the history of sound transformation. They have been in use since the very early days of electronic music. The first systematic design approaches date back to first decades of the previous century. Many electronic instruments of the 1930s including the Trautonium, used analogue filters [1]. Filters were standard components in electronic music facilities such as the West German Radio (WDR) studio in which K. Stockhausen, G. M. Koening and other composers worked in the 1950s and 1960s.

In the field of computer music, digital filters first appeared in sound synthesis languages such as Music IV after 1963. Nowadays, among several common used filters are the digital resonator which are special two-pole bandpass filters [2], the state variable filter [3], the simulations of the Moog four pole filter like the one proposed by Huovilainen [4] and the parametric filter structures like the Regalia or the Zolzer filters[5].

A filter structure is expected to give direct or indirect aspects to the perceptual parameters like the center/cutoff frequency, the bandwidth and the gain. This is accomplished by controlling the transfer functions coefficients describing the designed filter. In this scenario the filter is conceived as a mathematical operation that transforms the audio signal. This functional point of view disallows the "Physical Instrumental Interaction" with the system which performs the filtering operation and guides to the general question of mapping between the control signals and the available input parameters of the system – in this case the transfer function coefficients.

What we call " Physical Instrumental Interaction " [6] is here crucial:
It is indeed the type of physical interaction which we establish with a real instrument. In this interaction, the "ergotic function" [7], [8], [9] which is what allows in a direct way to act on the physical instrument and to feel it by the haptic perception, plays an essential role. This lets to perform the gesture in an expressive way and then to produce and even transform expressively sounds. In digital sound synthesis or transformation, the ergotic function can be supported by specific force-feedback gestural transducers [10],[11]."Physical thinking" and "Physical Instrumental Interaction" are very closely associated.

So we can envisage that the filtering process is performed by a simulated physical mechanical system and not by an abstract signal processing algorithm. In this case we are able to establish by involving a suitable ergotic interface, a physical interaction between the musician and the filter which has now a virtual material substance. In this type of control there is no mapping between gesture and sound since no representation is involved in this situation, but only physical processes. The CORDIS-ANIMA simulation system [12], which in fact is a formalism intended for simulating the instrumental relationship, permits to synthesize and control filters using this physical modeling approach.

Therefore the purpose of this study is to synthesize audio filters using CORDIS-ANIMA networks. For the design part of the filter other well known methods were adopted like the pole/zero placements and approximation techniques for all pole filters like the Butterworth approximation [13]. In this essay we designed the filter by putting in parallel a certain number of second order sections: the well known simple two-pole filters. Evidently the actual intention of this research is not to propose a new implementation of filters but to give to filters the character, the nature and "charm" of a physical tangible object that can be manipulated and controlled by physical gestures. These CORDIS-ANIMA filter models are transferred to the GENESIS environment mainly dedicated to musical composition by physical modeling [14] and eventually will be used in combination with force-feedback gestural interfaces for real time musical applications.

2. CORDIS-ANIMA AND GENESIS

CORDIS-ANIMA is a real-time mass-interaction physical modeling and simulation system. This highly modular language was used during this study to simulate physical models that play the role of digital audio filters. CORDIS-ANIMA allows designing and simulating virtual objects that are composed of two types of elements, called modules:

- <MAT> modules represent punctual material elements. The most used is the MAS module, which simulates an ideal inertia. The <MAT> modules are elementary subsystems and can be characterized in terms of their input/output relationships.
- <LIA> modules represent physical interactions between pairs of <MAT> modules. Available interactions are based on linear or nonlinear elasticity and friction. The <LIA> modules are elementary subsystems and can be characterized in terms of their input/output relationships.

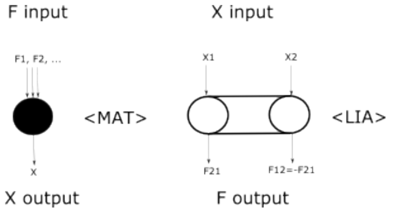

Figure 1 : *<MAT> and <LIA> modules with their inputs and outputs*

Thus, CORDIS-ANIMA models are networks of interconnected <MAT> and <LIA> modules.

Position and force are the two fundamental variables upon which CORDIS-ANIMA modules operate. At each sample a <LIA> computes two opposite forces according to the relative distance and/or velocity of the two <MAT> it links while a <MAT> computes its position according to the forces it receives from the <LIA> modules it is linked with. It should be noticed that some <MAT> modules are fixed points, so received forces have no effect on them. The algorithms can be found on [15]. In figure 1 the <MAT> and <LIA> elements are depicted with their inputs and outputs.

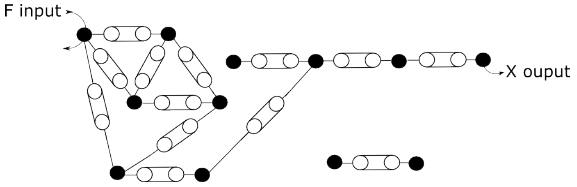

Figure 2 : *A CORDIS-ANIMA network*

GENESIS [16] is a graphical environment for musical creation based on CORDIS-ANIMA. The user builds CORDIS-ANIMA networks at an elementary level, since models are created by direct graphical manipulation and connection of individual modules on a virtual workbench. A number of higher-level tools are available for editing multiple parameters at the same time, generating large structures, visualizing models during simulation, etc. GENESIS implements ten types of modules. While CORDIS-ANIMA does not specify the dimensionality of the modules, GENESIS' simulation space is one-dimensional. <MAT> modules can only move in the direction that is perpendicular to the workbench, and distances and velocities are computed along this axis. For convenience, graphical manipulations take place in the 2D-space of the workbench, but the position of the modules on this plane have absolutely no consequence on the simulation: the workbench representation is only topological.

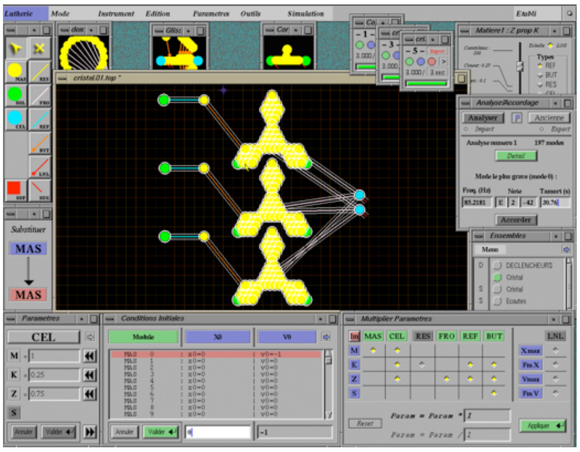

Figure 3 : *A screenshot from the GENESIS software*

The normal set of GENESIS' building blocks is composed of:

- Linear modules: ideal mass (MAS), fixed point (SOL), second-order damped oscillator (CEL), elasticity (RES), friction (FRO), elasticity and friction combined (REF);
- Nonlinear interactions: the BUT and the LNL;
- Output modules: the SOX and the SOF, which respectively record a position and a force signal.

The BUT module simulates a conditional viscoelastic interaction. Installed from one MAS (M1) to a second one (M2), when the difference between the positions of M_1 and M_2 is smaller than a given threshold S, the BUT simulates the effect of a null-length damped spring between M_1 and M_2; otherwise, the two modules are not linked.

The LNL module is a user-defined nonlinear viscoelastic interaction. The user chooses the points defining two curves and may interpolate them using linear interpolation, splines, hyperbolic interpolation. The first curve (LNLK) gives the force to be applied to the modules according to the difference of their positions (nonlinear elasticity). The second curve (LNLZ) gives the force according to the difference of their velocities (nonlinear friction).

All <MAT> modules have an initial position (X0). Mobile <MAT> modules also have an inertia parameter (M) and an initial velocity (V0). <LIA> modules have elasticity (K=k/Fs^2 – k measured in S.I, Fs the sampling rate) and/or friction (Z=z/Fs, z measured in S.I) parameters.

During this study, we used a particular version of GENESIS that includes two extra modules, ENX and ENF. These are input modules that read an input file and translate its data into a time-changing position (ENX) or force (ENF). The input file represents a 1D temporal signal, sampled at 44100 Hz. It may derive from the measurement of a real gesture, the recorded movement of a <MAT> module in a previous simulation, or from an audio file. Consequently, input modules can be used to input any audio signal into GENESIS' models.

ENX is a massless <MAT> module whose position corresponds at each moment to the last sample read in the input file. ENF is a <LIA> module that connects to a single <MAT>, to which it sends a force proportional to the input file data.

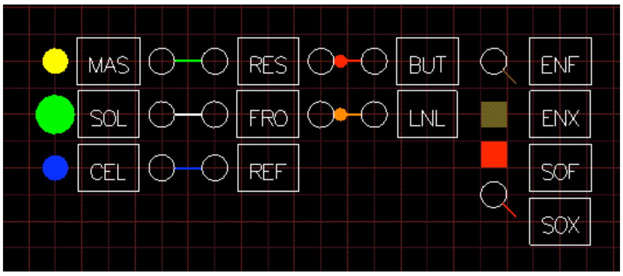

Figure 4 : *GENESIS basic modules*

3. GENERAL ASPECTS OF DESIGNING AND IMPLEMENTING DIGITAL FILTERS WITH CORDIS-ANIMA

The basic idea behind any digital audio effect and in our case the filters using physical modeling techniques are the forced oscillations. Sometime, it happens that a system is put into vibration because it is linked with another oscillating system which is called the driving system. The important feature on forced oscillations is that the driven system does not feed back any appreciable amount of energy to the driving system so the perturbation effects are negligible. The input sound for the digital audio effects takes the role of the driving system.

In the simulated world of CORDIS-ANIMA there are two ways to connect two mechanical systems. It is possible to consider as the output of the first system and as the input of the second system either the force or the position, according to the fact that the first is of <LIA> category or of <MAT> category, even though the variables in the Newtonian mechanics are duals and are not separable. On the other hand the computer simulation and the real time control force the separation of these variables. In general all physical communications (which are intrinsically non-oriented) are presented by two-way communication carried out by divisible input/output pairs (this is a constraint inherited by the information theory and the capabilities of the technology) [12]. A special case is envisaged for the force oscillations where the driving force or driving position is not presented by divisible input/output pairs but with a single input communication channel. Therefore we are able to apply directly a force to a <MAT> module or a position to a <LIA> module by an input file acting as the input sound (ENF and ENX modules in GENESIS – used only as external input). In a similar situation, whereas the physical model acts as the driving system, we can deliver a position using a <LIA> where it returns a zero force to the model or we can deliver a force using a <MAT> where it returns a zero position to the model (SOX and SOF modules in GENESIS – used only as external output). In this case the position or the force are considered as the output signal and it is recorded in sound files.

In reality we always have feedback links between interacting mechanical systems. However it is possible to reach situations of forced vibrations when we link mechanical systems where we approximately ignore the feedback of energy either because the linkage is very weak or else because the driving one has so much reserve energy that the amount of feedback is comparatively negligible [17] . So in CORDIS-ANIMA models, we can control the feedback interconnection following this principle and approximately pass from feedback interconnections to feedforward ones. We are able to do this either by changing the impedance of the systems (the one with the considerably higher impedance drives the other) or by using a weak link.

4. CAUER REALIZATIONS FOR LC ELECTRICAL CIRCUITS

The Cauer synthesis procedure of passive electrical networks concerns the implementation of a specified immittance function by a particular form of ladder electrical networks. It is one among several other methods used for the synthesis of driving point immittances [18]. Immittance is a general term used to include both impedance and admittance. In many cases the required immittance is realized using only LC circuit elements: inductors L with $Z_L(s) = Ls,\ Y_L(s) = \frac{1}{Ls}$ and capacitors C with $Z_C(s) = \frac{1}{Cs},\ Y_C(s) = Cs\cdot$

The necessary conditions that must by satisfied by a rational function that is realizable as the LC driving-point immittance may be synopsized [19]:

- The poles are simple and on the $j\omega$ axis
- The zeros are simple on the $j\omega$ axis
- The poles and zeros alternate
- There is a pole or a zero at the origin
- There is a pole or a zero at infinity
- The residues of the poles are real and positive
- The functions are reactance functions whose value along the $j\omega$ axis is purely imaginary, i.e. $Z_{LC}(j\omega) = jX(\omega),\ Y_{LC}(j\omega) = jB(\omega)$
- $dX(\omega)/d\omega$ and $dY(\omega)/d\omega = jB(\omega)$ are always positive
- The functions are odd rational functions which mean that if the numerator is an even polynomial then the denominator is an odd polynomial and vice-versa.

The general form of a realizable LC driving-point immittance *I* is

$$I_{LC}(s) = \frac{k_0}{s} + k_\infty s + \sum_i \left[\frac{c_i}{s - j\omega} + \frac{c_i^*}{s + j\omega}\right] \quad \overset{c_i = c_i^*}{\Rightarrow}$$

$$I_{LC}(s) = \frac{k_0}{s} + k_\infty s + \sum_i \frac{2c_i s}{s^2 + \omega^2}$$

where k_0, k_∞, c_i are the residues of the poles at the origin, at the infinity and on the $j\omega$ axis, respectively.

The ladder network has a specific topology with alternating series and shunt branches as shown in figure 5. This singularity allows the driving-point immittance to be expressed in the following form [20]:

$$Z = Z_1 + \cfrac{1}{Y_1 + \cfrac{1}{Z_2 + \cfrac{1}{Y_2 + \dots}}}, \quad Y = Y_1 + \cfrac{1}{Z_1 + \cfrac{1}{Y_2 + \cfrac{1}{Z_2 + \dots}}}$$

The heart of this method follows from considering an LC driving-point immittance which consequently has poles at infinity, the origin and complex-conjugate poles on the $j\omega$ axis. Removing any poles of this function results in a function which is as well LC realizable.

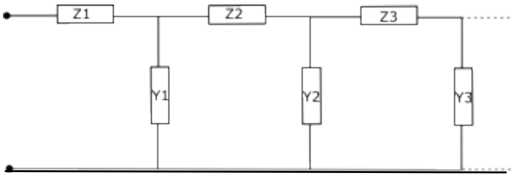

Figure 5 : *Ladder network*

Each division can be carried out starting either with the highest or with the lowest power of s. When each division starts with the highest powers, the procedure is known as *Cauer I* method. On the other case the procedure is known as the *Cauer II* method. If the order of the numerator is greater than the order of the denominator the *Cauer I* method is used which always leads to a ladder with series inductors and shunt capacitors. In a similar way if the order of the numerator is smaller than the order of the denominator the *Cauer II* method is used which always leads to a ladder with series capacitors and shunt inductors

For example the admittance function $Y(s) = \frac{s^4+4s^2+3}{s^3+2s}$ can be expanded in the form $Y(s) = s + \cfrac{1}{s/2 + \cfrac{1}{4s + \cfrac{1}{s/6}}}$

This corresponds to a realizable circuit with Y_{C1}=1s, Z_{L1}=1/2s, Y_{C2}=4s, Z_{L2}=1/6s.

5. SYNTHESIS BASED ON CAUER TECHNIQUE

Every CORDIS-ANIMA model has an analogue Kirchhoff network in the continuous time domain. This analogy, permits in a certain number of cases to apply the Cauer method in the CORDIS-ANIMA simulation system. A detailed analysis concerning the Kirchhoff/CORDIS-ANIMA analogy is out of the scope of this article. In figure 6, the analogue of a LC ladder network is presented by the CORDIS-ANIMA network topological diagram. For this case, the analogy displayed in the table 1 was used. Z, K, M are the variables used in GENESIS.

force F $\Leftrightarrow$ *potential U*	$m = L \Rightarrow M = L$
velocity V $\Leftrightarrow$ *current I*	$k = \frac{1}{C} \Rightarrow K = \frac{1}{CF_s^2}$
position X $\Leftrightarrow$ *charge Q*	$z = R \Rightarrow Z = \frac{R}{F_s}$

Table 1 : *CORDIS-ANIMA/Kirchhoff analogy*

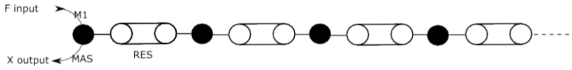

Figure 6 : *LC Ladder network in CORDIS-ANIMA*

The double discretization scheme adopted by CORDIS-ANIMA unfortunately does not permit the use of a direct transformation method from the s-domain to the z-domain. Nevertheless we may use an indirect method using the modal decomposition. The desired filter function is designed directly in the discrete time simulation space of CORDIS-ANIMA using a bank of second order parallel resonators. Each resonator is tuned to a certain resonating frequency F_i and Q-factor Q_i. We remark that in this research the peak of the resonators is approximated by their natural frequencies. From these filter perceptual characteristics we compute the physical characteristics i.e. the mass M, the elasticity K and the friction Z. Approximately M affects the amplitude of the filter, M/K the resonant frequency and Z the Bandwidth or the Q parameter. The adopted Cauer synthesis procedure is for LC networks and so non-dumped structures were treated and synthesized. In this case $Z = 0 \Rightarrow Q = \infty$. Using the M and K physical parameters or the m and k in the S.I system we form the second order parallel resonators on the continuous time. Having computed the impedance function we are ready to apply the Cauer technique. A detailed description of the algorithm is depicted below.

Algorithm

1. $$Y_{CA_i}^{sos}(z) = \frac{X_i(z)}{F_i(z)} = \frac{1/(M_i F_s^2)z^{-1}}{1+(K_i/M_i - 2)z^{-1} + z^{-2}} \rightarrow$$
   $$K_i/M_i = 2 - 2\cos(\frac{F_{CAi}2\pi}{F_s})$$
   where F_s = *sampling rate,* F_{CAi} *desired frequency in Hz*

2. $$Y_i^{sos}(s) = \frac{Q_i(s)}{V_i(s)} = \frac{1}{L_i s^2 + 1/C_i} \rightarrow Y_{all}(s) = \sum_i Y_i^{sos}$$
   where $L_i = M_i,\ C_i = 1/(K_i F_s^2)$

3. $$Z_{Cauer}(s) = \frac{V(s)}{I(s)} = \frac{V(s)}{Q(s)s} = \frac{1}{Y_{all}(s)s} \Rightarrow$$
   $$Z_{Cauer} = Z_1 + \cfrac{1}{Y_1 + \cfrac{1}{Z_2 + \cfrac{1}{Y_2 + \ldots}}}$$

4. $$\left.\begin{aligned} Z_i(s) &= L_i s \\ Y_i(s) &= C_i s \end{aligned}\right\} \begin{aligned} M_i &= Z_i(s)/s \\ K_i &= s/(Y_i(s)F_s^2) \end{aligned}$$

It is possible to reach a more approximative solution if we start the algorithm from the step 2: We can tune directly the second order sections in the continuous time domain:

$$F_i = \frac{1}{2\pi}\sqrt{k_i/m_i} \rightarrow k_i/m_i = (F_i 2\pi)^2$$

where $L_i = m_i,\ C_i = 1/k_i$

More details concerning the second order sections for the continuous time and the discrete time case can be found in [3], [13], [21].

In the following graph (figure 7) the deviation in the resonating frequency is depicted between the 2-pole filter in the continuous time domain and after the discretization scheme used in CORDIS-ANIMA. We observe that for frequencies smaller than 1000 Hz the difference is negligible-less than 1 Hz. So when we design filters in the region 0-1000Hz we can design them directly in the continuous time domain.

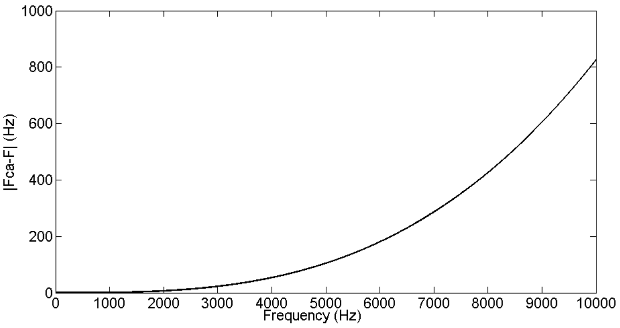

Figure 7 : *Deviation in the resonating frequency*

For a Cauer expansion to correspond to a realizable ladder network, all the coefficients of the expansion must be positive. The CORDIS-ANIMA simulation system on the other hand, permits to use negative coefficients.

6. RESULTS-A TANGIBLE FILTERING PARADIGM

Several filters were synthesized using the previous algorithm. All the scripts were written in matlab® and the results were transferred to GENESIS. We will present a simple example of a filter with resonating frequencies 200Hz, 240Hz, 450Hz and 530Hz and $Q = \infty$ which means that the filter will starts ringing in its resonating frequencies. The filter is designed with method described in the previews chapter. It has an admittance function given by the following formula:

$$Y_{CA}(z) = \frac{4 - 23.9646z^{-1} + 59.8586z^{-2} - 79.7880z^{-3} +}{1 - 7.9882z^{-1} + 27.9293z^{-2} - 55.8233z^{-3} +} \cdots$$

$$\cdots\frac{59.8586z^{-4} - 23.9646z^{-5} + 4z^{6}}{69.7645z^{-4} - 55.8233z^{5} - 27.9293z^{-6} - 7.9882z^{-7} + z^{-8}} \rightarrow$$

$$Y(s) = \frac{4s^{6} + 6.879e07s^{4} + 3.313e14s^{2} + 4.098e20}{s^{8} + 2.293e07s^{6} + 1.657e14s^{4} 4.098e20s^{2} + 3.18e26}$$

We verified that the algorithm is very accurate. The final physical model has the same admittance function as with that one we started from in the design phase of the filter. In figure 8 is illustrated this admittance function.

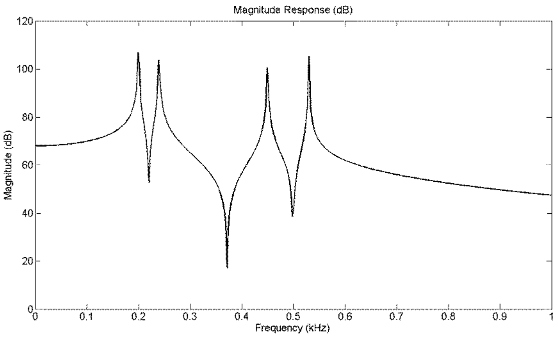

Figure 8: *Graph of the admittance function of the CORDIS-ANIMA realization of the filter*

The block diagram in figure 9 depicts a parallel form realization of the filter which is widely used in the digital signal processing domain. The control is based on the direct access to the parameters of the structure: the multipliers of the feedforward and the feedback paths. Every possible method can be used to translate the user actions into these parameters value.

The block diagram in figure 10 presents a CORDIS-ANIMA realization of the filter. This structure offers directly another type of control based on the “Physical Instrumental Interaction”. We don’t affect the parameters of the model -even though it is possible and previewed within the CORDIS-ANIMA system- but we apply forces to the <MAT> elements of the model using <LIA> elements. In this example we can interact physically with the masses M1, M2, M3 and M4.

It is straightforward that this type of control is totally physical and energetic coherent. Since physical models enable an intuitive representation of the action we perform with real objects we can imagine several physical gestures to play with our filter: dumping, pulling, pushing, e.t.c. This is still true for non real-time simulations and without the use of force feedback gestural interfaces but by designing models that simulate the physical gesture. The deferred-time simulation permits to design accurate and valid models of the control gesture with a precision that is not possible in the real-time situations. Figure 11, which is a snapshot taken for the GENESIS software, illustrate the physical model for the filtering operation described earlier and a physical model for the physical control of the filter. For the control we use a periodical gesture that dumps the movement of the string used as a filter when it reaches it.

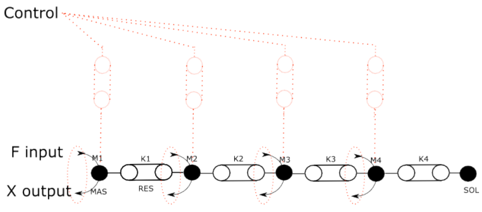

Figure 10: *A CORDIS-ANIMA filter realization*

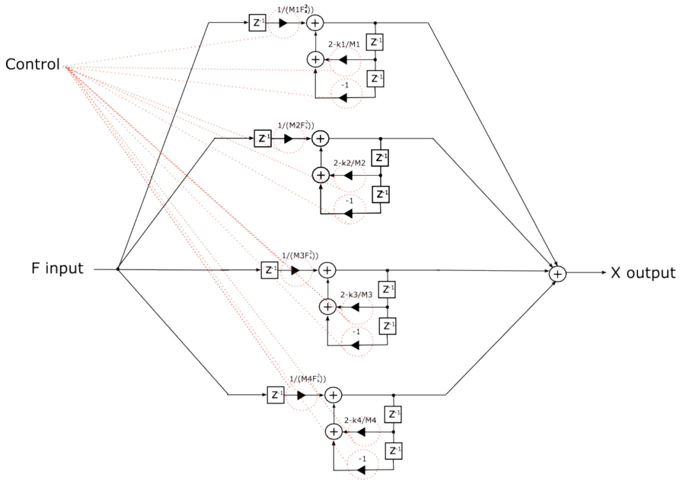

Figure 9: *A parallel form filter realization*

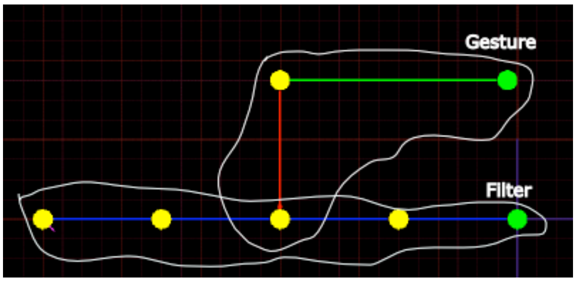

Figure 11: *GENESIS example of a virtually mechanical filter controlled by another physical structure*

7. CONCLUSION AND FUTURE WORKS

A method to synthesize filters using the mass interaction scheme was presented. Adopting the Cauer technique from the domain of the electrical networks, we designed physical models for filtering purposes. This permitted to benefit some of the advantages of the physical modeling in the audio signal filtering domain like the control based on physical interactions.

Even if the Cauer synthesis procedure goes further from the driving point immittance functions and may reach the implementation of a specified transfer function, in this study it was not crucial to reach this point. The main intention was more to tune up physical structures – strings in our case to a pre-given set of frequencies than to realize and implement a given transfer function. Several other methodologies were also examined. Amongst them, optimization algorithms were used i.e. the Newton method, which provides less precision but is much more general and can be applied for all kind of structures like pyramids, spirals, membranes [22]. These results could be the subject of another article. It is clear that the methodology using the optimization algorithms can be viewed as special case of the inverse problem: the values of some model parameters i.e. M, K and Z must be obtained by the observed/desired data.

The synthesis technique presented in this study may easily be transferred to other widely used physical modeling approaches like the digital waveguides [23]. In our case all the needed scripts were written in matlab® and the results were transferred in GENESIS environment for further physical manipulation, control and compositional research based on “physical thinking”.

The applications of physical modeling for sound synthesis are numerous. However the power of physical modeling for sound processing has not been explored yet. Filtering is the basic signal manipulation mechanism so it is straight forward why this research concerned audio filters and physical models.

This article is a part of a wider research focused on the design of physical models that would transform and process sounds using the CORDIS-ANIMA formalism. The objective is to offer to the transformation procedure an instrumental “character” with the purpose of hopefully getting more “warm” or “live” audio effects, and setting up a relation between the system and the musician of the type instrument/instrumentalist.

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