NEW POSSIBILITIES IN SOUND ANALYSIS AND SYNTHESIS

Xavier Rodet, Philippe Depalle, Guillermo Garcia

IRCAM, 1 place Stravinsky, 75004 Paris, France
Tel: (33.1) 44.78.48.45, Fax: (33.1) 42.77.29.47, e-mail: rod @ircam.fr

ABSTRACT

In this presentation we exemplify the emergence of new possibilities in sound analysis and synthesis with three novel developments that have been done in the Analysis/Synthesis team at IRCAM. These examples address three main activities in our domain, and have reached a large public making or simply listening to music.

The first example concerns *synthesis* using physical models. We have determined the behavior of a class of models, in terms of stability, oscillation, periodicity, and finally chaos, leading to a better control of these models in truly innovative musical applications.

The second example concerns additive synthesis essentially based on the *analysis* of natural sounds. We have developed a new additive method based on spectral envelopes and inverse Fast Fourier Transform, which we name FFT^{-1} and which provides a solution to the different difficulties of the classical method. Commercial applications are announced for this year, for professional users and soon for a larger public.

The last example is an original work on the recreation of a castrato voice by the means of sound analysis, *processing* and synthesis. It has been done for the soundtrack for a film and a CD about Farinelli, the famous castrato of the eighteenth century. The CD and the film have reached millions of people all around the world.

1. INTRODUCTION

Since the birth of computer music technology in the 1950's, new possibilities in analysis and synthesis of sound have emerged from research institutions and have come gradually in public use. In this presentation we will exemplify this emergence by focusing on three novel developments that have been done by the Analysis/Synthesis team at IRCAM. These examples are typical since they address three main activities in our domain, synthesis, analysis and processing. They are typical also because they are issued from laboratories and have reached not only professionals but also a large public making or simply listening to music.

The first example concerns *synthesis* using the class of models known as physical models [1], [2]. Compared to signal models, such as additive synthesis, physical models have only recently received as much attention, because, partly due to their nonlinear nature, they are very complex to construct and handle. But for musical applications, one should not merely *build* models and deliver them to musicians. It is indispensable to go into the understanding of the models, to conceive abstractions of them and to propose explanations useful to the users. In particular, this comprehension is indispensable for elaborating control of synthesis models, which are at the same time efficient and musically pertinent [3]. Consequently, we have studied a family of differential and integral delay equations which retain the essence of the behavior of certain classes of instruments with sustained sounds, such as wind, brass and string instruments [4]. We have determined the behavior of our models, in terms of stability, oscillation, periodicity, and finally chaos, leading to a better control of these models in truly innovative musical applications.

The second example concerns one of the oldest methods of computer music called additive synthesis, that is the summation of time-varying sinusoidal components, essentially based on the *analysis* of natural sounds [5], [6]. But despite rapid gains in computational accuracy and performance, the state of the art in affordable single chip real-time solutions to the problem of additive synthesis offers only 32 oscillators. Since hundreds of sinusoids are required for a single low pitched note of the piano, for example, current single chip solutions fall short by a factor of at least 20. And the development and use of additive synthesis have also been discouraged by other drawbacks. Firstly, amplitude and frequency variations of the sinusoidal components are commonly described in terms of breakpoint functions. When the number of partials is large, control by the user of each individual breakpoint function becomes impractical. Other arguments against such breakpoint functions is that for voice and certain musical instruments, a spectral envelope [7], [8] captures most of the important behavior of the partials. Finally, the usual oscillator method for additive synthesis does not provide an efficient way for adding colored noise to sinusoidal partials, which is needed to successfully synthesize speech and the Japanese Shakuhachi flute, for example. This is why we have developed a new additive synthesis method based on spectral envelopes and inverse Fast Fourier Transform, which we name FFT^{-1} and which provides a solution to the different difficulties that we have mentioned [9], [10]. Commercial applications should appear this year for professional users and soon for a larger public [11].

The last example is an original work on the recreation of a castrato voice by the means of sound analysis, *processing* and synthesis [12]. It has been done to produce the soundtrack for a film and a CD about Farinelli, the famous castrato of the eighteenth century. The film, realized by Gérard Corbiau, and the CD produced by AUVIDIS, brings back to life a repertoire which could not be sung anymore. The musical consultant of the film Marc David has recovered unedited scores from the French National Library. This example is particularly interesting for several reasons. First it is extremely difficulty to synthesize high quality (concert or CD) singing voice [13], secondly 40 minutes of a new castrato-like singing voice have been produced in a limited schedule, thirdly it is the first application of a technique which is analogous to *morphing* and finally the CD and the film have reached millions of people all around the world.

2. ANALYSIS, PROCESSING AND SYNTHESIS

The work described here has been done at the Institut de Recherche et de Coordination Acoustique/Musique (IRCAM), Paris, by the Analysis/Synthesis team. Since IRCAM is devoted to musical research and production, our main goal, on a short term and a long term basis, is artistic as well as scientific in nature. Computer generated music occupies a central role in artistic production at IRCAM, in the form of aid and tools for musicians and composers in the process of research and of the production of musical compositions. Among activities of computer music that our team is devoted to, we can mention sound analysis and processing, natural sound simulation and creation of new types of sounds [14]. In order that these different musical objects be useful for musical composition, it should be possible to modify them at will to introduce such effects as expressivity or different playing techniques. Therefore, sounds should be defined by *models* which will be considered as *instruments*. In the synthesis of musical sound as in many other fields of simulation, the concept of model is essential for a better comprehension and use of the properties of sound analysis and synthesis methods. In particular, it is necessary to understand the structure of the space of *instrumental* sounds.

Analysis of musical sounds is aimed at getting some precise information concerning the signal itself, the way it has been produced or the way it is perceived [15], [8]. Such an information can be very specific, this is the case of the fundamental frequency, or it can be fairly general such as all the information which is needed to rebuild a quasi identical sound with some synthesis technique [8]. Synthesis of musical sounds can be viewed as a two stage process. In the second stage, the synthesizer itself computes a sound signal according to the value of parameters. In the first stage, the determination of adequate values of these parameters is essential for getting the desired sound output. For example, parameters may be obtained by some analysis technique [6] or generated by rules [16], [17], [18], [19], [20], [21].

Processing of musical sounds can be divided in two classes. On one hand, a processing system may be independent of the signal: this is the case of modulation, filtering or reverberation. On the other hand, a processing system may consist of an analysis stage producing time dependent parameters, a modification of these parameters and a synthesis stage from the modified parameters. A well known example of such processing uses the so called *phase vocoder* [22], [23].

An analysis or a synthesis method is always referring to some model of sound representation and of sound production. This model can be the so called *physical model* [24], [1] which is explicitly based on the physical laws which govern the evolution of the physical system producing the sound. Or it can be a model of the sound signal which consists in one or several parametered structures which are adapted to represent and reproduce time domain and/or frequency domain characteristics of studied sounds [25]. As these

signal models include few constraints, they are simple, general and low cost. This is the case of an oscillator reproducing a periodic waveform extracted from a natural sound.
In between signal models and physical models, one can find models that share properties with both classes : this is the case of a lattice filter as model of the vocal tract or of some simplified physical models as proposed by J. Smith. But a more general way to encompass both classes of models in the same formalism, is the so called State Space representation studied in our team [26], [27]. One can always gradually transform a signal model into a physical one (or inversely), by including (or removing) some constraints on the structure of the model [28]. According to the previous requirements, our models rely on description of perceptually relevant features of the sound or of its Short Time Fourier Transform (STFT) or of the system that has produced the sound. This description goes from the more general features - e.g. spectral envelope - to the more subtle details, e.g. those of the STFT such as harmonicity, partials, and noise [7]. Parameters of a model are usually to be updated at a rather low rate called frame rate or parameter rate (typically lower than 200 Hz). Considering that the purpose is to allow musicians to process existing sounds or to create new sounds, the control parameters have to be intuitive, direct, and easy for musicians to use.

3. UNDERSTANDING AND CONTROL OF PHYSICAL MODELS

3.1 Introduction

This section describes an approach to the functioning of musical instruments from the point of view of the theory of nonlinear dynamical systems. Our work provides theoretical results on instruments, their models and on a class of equations with delay, as well as on sound synthesis itself. Experimental and practical results open new sonic possibilities in terms of sound material and in terms of the control of sound synthesis which is particularly important for performers and composers of contemporary music.

The complexity of physical models comes partly from their nonlinear nature. We try to define resemblance and differences between several classes of instruments. This attitude is necessary for artistic production which cannot be confined to traditional instruments and for which we have to understand the structure of the space of *instrumental* sounds. To fulfil these requirements, we have highlighted a characteristic common to instruments with sustained sounds, i.e. the existence of delay terms in the equations of models [29]. As a consequence, we have studied a family of differential and integral delay equations which are particularly difficult and are not well understood [30]. We have determined the behavior of our models, in terms of stability, oscillation, periodicity, and finally chaos. Moreover we have found analytically some conditions for these behaviors. We have realised digital simulations of our models on a workstation. We have shown that observing in real time the solutions of an equation and their properties, such as the Fourier spectrum, while changing parameter values, is a powerful tool for mathematical exploration.

An interesting finding is the control of chaotic behavior of our models [31]. It seemed previously that chaotic sounds could not be of any musical interest. On the contrary, we have found that these signals exhibit very interesting properties, such as a clearly perceived pitch or an intermittent type behavior [32]. We have also shown that a signal which is mathematically chaotic can be heard in a very different way. What could be named the "*proportion* of chaos" can be faint or predominant, from sounds perceived as harmonic without noise, up to essentially noisy sounds. Finally, we want to control the "*proportion* of chaos" in synthetic signals, opening a new field of fascinating research and application [33].

3.2 Mathematical Model

The trumpet is an example of an instrument uncommonly difficult to model because of the complicated features of nonlinear elements, lips and air flow between lips, which are not easy to measure. We have studied such a model of the behavior of the trumpet and we have tested its operation rather extensively [34]. Without further simplifications, this system of five non-linear differential equations would be nearly impossible to understand and control. To only compute a numerical solution would be very unsatisfactory for our musical and artistic purpose. This is why we have started the study of the *basic behavior* of classes of instruments. In the case of the trumpet or of the clarinet, seen from the mouthpiece, the bore appears roughly as a delay line with a sign inversion reflection and some low pass filtering [29]. The basis of the oscillatory behavior is to be found in the coupling of the passive linear part with the nonlinear reed, and similarly for string instruments, where the delay comes from transverse waves along the string.

In this way, many sustained musical instruments can be described by an autonomous system of integral and differential delay equations. These equations are extremely difficult and have not received as much attention as usual differential equations [35]. However, a feedback loop formulation provides some light on their properties [36]. One of the simplest system is written, for $x \in R$, with a instantaneous nonlinearity γ:

$$x(t) = h * \gamma(x(t-\tau)) \qquad (1)$$

where $\gamma: R \rightarrow R$, $\tau \in R$ is some time delay, $h: R \rightarrow R$ is an impulse response and $*$ is the convolution operator. Even in the case of this simplified equation (1), the solutions and their stability are known only partially and in restricted cases [37].

We have found a similarity between this model and the so called *Time-Delayed Chua's Circuit*, a modification of the famous Chua's circuit governed by the same equation (1) which we have simulated in real-time [38]. While the original Chua's circuit [39] happens to be relatively difficult to control and does not offer as rich a palette of *timbres* as wished for musical applications, the Time-Delayed Chua's Circuit is much richer and flexible. A large variety of sounds can be produced by the system. This is due to the combination of the rich dynamics of the nonlinear map together with the numerous states represented by the delay line τ as opposed to the minimum number of states of the original circuit. Information is contained in these states and very complex signal patterns come out of the interaction of the states through the nonlinear function. The feedback loop can also viewed as a *stabilisation* loop added on the original Chua's circuit to render its control much easier [40]. Therefore, the delay in natural instruments can be viewed the same way.

In the case of the clarinet the reed can be considered as massless, i.e. the nonlinearity is *instantaneous*, and the system is described by (1). In the case of the flute [41], [42], it seems that there is essentially one nonlinearity but two feedback loops with different delays. This still complies with equation (1) but the open loop transfer function becomes a complicated combination of the influences of the two loops. In the case of the trumpet or of the voice, the reed can no more be considered as massless, i.e. the nonlinearity is not instantaneous [43]. Therefore, the model now consists of the nonlinear coupling of a feedback loop and a mass oscillating with one or several degrees or freedom [44]. It seems that some important characteristic of the timbre of each of the previous classes of instruments, particularly in the transients, is related to the corresponding basic structure as just described above.

3.3 Some results about the nonlinearity and the linear element

Let us consider a map γ such that the origin O is a fixed point, with a slope s_1 about O and a slope s_2 at some distance from O. Two important characteristics of the sound, transient onset velocity and richness, are controlled by the slopes s_1 and s_2 [38]. A.N. Sharkovsky [45] has shown analytically that the time-delayed Chua's circuit exhibits a remarkable period-adding phenomenon. In some regions of the (s_1, s_2) plan, the system has a stable limit cycle with period respectively 2, 3, 4, etc. In between every two consecutive periodic regions the system exhibits a *chaotic* behavior. We have shown that in the k-periodic regions, the harmonics k, 2k, 3k etc. are absent [32]. This is an interesting result from a *musical* point of view as well. The map γ can be simulated by a polynomial nonlinearity, or better, a rational function nonlinearity [33].

Let us consider our system (1). The open-loop transfer function is:

$$G(j\omega) = e^{-j\omega\tau} H(j\omega)$$

where H is the transfer function of h. The system does not oscillate if the limit value $1/s_1$ lies to the left of all intersections of the Nyquist plot of $G(j\omega)$ with the real axis. In the absence of the filter h or with a zero phase filter, the delay leads to an oscillation frequency $f_0 = 1/2\tau$. On the other hand the supplementary delay added by the filter h can move the oscillation frequency away from $1/2\tau$.

The intersections of $G(j\omega)$ with the negative real axis define the frequencies of the modes of the instrument. The system generally oscillates at the frequency of the strongest mode. If the argument of $G(j\omega)$ is different from zero, the modes can be moved away from harmonic positions. We have shown that, when simultaneously γ is not odd symmetric and there is a filter h, then even partials can appear. When γ is not very far from odd symmetry, if the argument of $G(j\omega)$ is zero then the even harmonic partials are of small amplitude (clarinet). If the argument of $G(j\omega)$ is different from zero, then the even harmonic partials can be of large amplitude (saxophone). The case where the argument of $G(j\omega)$ is different from zero can lead to surprising results which look like quasi-periodicity or inharmonicity.

Physical models often have more than one oscillating solution for a given setting of their parameters. If the solution reached by the system is unpredictable, the usage of a physical model will be rather difficult in a real-time musical performance. Therefore, another of our goals is to study and limit the numerous stable solutions of physical models. We have found that a path toward such a goal could eventually be based upon the low pass character of the linear element [33].

3.4 Hopf bifurcation and periodic solutions

The Graphical Stability Test given above is valid as long as we can partition our system into a instantaneous nonlinearity and a linear feedback loop. Since we are interested in periodic oscillation, we mention a more general method which allows us to prove of the existence of a periodic solution when it occurs, and provides estimates for the frequency and amplitude of the oscillation. It also applies to an even more general class of systems encountered with sophisticated physical models of instruments. The Graphical Hopf Theorem [36] and its algebraic version apply to a nonlinear multiple feedback loop system where γ is C^4. Then under certain conditions on the nonlinearity γ and the open-loop transfer function G, this theorem provides the existence, uniqueness and test for the unique stable periodic solution required in our application.

3.5 Chaotic signals and musical applications

We have simulated our systems on a workstation [46] and we have written a graphical-user interface allowing for easy experimentation with the parameter values and display of the output signal, of its Fourier Spectrum, etc. Harmonic sounds and, in chaotic regions, *noisy* sounds are obtained. Noisy sounds exhibit the simultaneous presence of harmonic components and noise in the signal [32]. This is very interesting since this occurs for the majority of natural instruments and since this is relatively difficult to model in a way which is useful for musical purposes. The noisy and sinusoidal components coming from our system are correlated and *fuse* together. The control on the "*proportion* of chaos" in the signal provides musicians with the possibility to control precisely the *amount* of *chaotic* or *noisy* components which they introduce in the signal [33]. Chaotic sounds, even when they can be extremely noisy, keep some of the harmonic structure derived from the fundamental frequency that corresponds to the delay τ. The persistence of the harmonic structure in the chaotic signal is heard as a *pitch* of the noisy sound! Moreover, the value of the pitch and the amount of tonal sound perceived as compared to noise can easily be controlled. Finally, the gradual passage from one periodic region to the next gives very innovative sounds, changing progressively from harmonicity to chaos but keeping at will more or less of the harmonic structure induced by the delay line.

4. SPECTRAL ENVELOPES AND INVERSE FFT SYNTHESIS

4.1. Introduction

Many musical sound signals may be described as a combination of a pseudo-periodic waveform and of colored noise [14]. The pseudo-periodic part of the signal can be viewed as a sum of sinusoidal components, named *partials*, with time-varying frequency and amplitude. Some of the first attempts at sound synthesis were based on the method called *additive synthesis,* that is the summation of time-varying sinusoidal components [5]. This *signal modelling* approach inherits a rich history of signal processing techniques. As an example, we have developed methods to automatically analyze sounds in terms of partials and noise that can then be applied directly to additive synthesis [47]. In the sinusoidal model, harmonic or inharmonic partials are easy to synthesize and partial parameters (frequency and amplitude) can easily be mapped into the human perceptual space, are meaningful and easily understood by musicians. Thus, additive synthesis is accepted as perhaps the most powerful and flexible method. However, its development and use have been discouraged by severe drawbacks. This is why we have developed a new additive synthesis method based on spectral envelopes and inverse Fast Fourier Transform, named FFT^{-1} [9], [10].

The first drawback of the classical *oscillator method* of additive synthesis is the computation cost: a low pitch piano note that can sometimes have more than a hundred partials. The FFT-1 method provides a gain of 10 to 30 versus the classical method. The second drawback of the oscillator method is the difficulty of introducing precisely controlled noisy components which are very important for realistic sounds and musical timbres. Our method makes noisy components easy to describe and cheap to compute. Last but not least, controlling hundreds of sinusoids is a great challenge for the computer musician. A scheme based on spectral envelopes renders this control more simple, direct and user friendly.

4.2. The oscillator method

Additive synthesis is usually done with a bank of sinusoidal oscillators. Let us call J the number of partials of the signal to be computed at a certain time, that is at a certain sample n. Let the frequency, the amplitude and the phase of the j^{th} partial, $1 \le j \le J$, be named respectively f_j, a_j, and ψ_j. More precisely, since they are functions of time, i.e. of n, we write them $f_j[n]$, $a_j[n]$, and $\phi_j[n]$. Usually, $f_j[n]$ and $a_j[n]$ are obtained at each sample by linear interpolation of the breakpoint functions which describe the evolution of f_j and a_j. The phase is redundant with the frequency and for simplicity we ignore it here. For a sampling rate Sr, the j^{th} partial is therefore defined by:

$$c_j[n] = a_j[n].\cos(\Phi_j[n]) \ , \quad \text{with}$$

$$\Phi_j[n] = \Phi_j[n-1] + 2\pi \frac{f_j[n]}{Sr}$$

and the signal to be computed is: $s[n] = \sum_{j=1}^{J} c_j[n].$

In the oscillator method, the instantaneous frequency and amplitude are calculated first, by interpolation. Then the phase $\Phi_j[n]$ is computed. A table lookup is used to obtain the sinusoidal value of this phase and the sinusoidal value is multiplied by $a_j[n]$. Finally $c_j[n]$ is added to the values of the j-1 previous partials already computed. The computation cost of the oscillator method is of the form α.J per sample, where α is the cost of at least 5 additions, 1 table lookup, 1 modulo 2^p, and 1 multiplication. Even though it is possible to modify the sinusoidal oscillator in order to produce large or narrow band-limited random signals by combined amplitude and phase modulation, this has rarely be done.

4.3. Inverse Fast Fourier Transform additive synthesis

In our method [9], the computation of the partials is not done by a bank of oscillators but by an Inverse Fast Fourier Transform (FFT^{-1}) of short term spectra (STS) $S_l[k]$ into the corresponding time-domain signals $sw_l[n]$. To better explain the method, let us consider first the analysis by FFT such as used in the Phase Vocoder [22] which is familiar to many people: The signal s[n] is first cut into successive frames $s_l[m]$ which overlap. Each frame is multiplied by a so called *window* signal w[m] such as the Hanning window. With an appropriate choice of w and of the overlapping factor d, s[n] can be exactly reconstructed from the windowed frames $sw_l[m]$ by the so called *overlap-add* method [23]. Then the complex STS of each frame is computed by FFT, leading to a succession of complex valued spectra $S_l[k]$. Now the FFT^{-1} method is easily understood as just the inverse process: Start from the spectra $S_l[k]$, compute their Inverse FFT to get the $sw_l[m]$ and overlap-add them in order to obtain the time-domain signal s[n].

For reasons of efficiency a partial is represented in a spectra by a few points of non-negligible magnitude, typically K=7. To build the contribution of a given partial in the STS $S_l[k]$, we only have to compute these K spectral values and add them to $S_l[k]$. If N is the size of a frame (typically N=256), we find here a gain in computation roughly proportional to N.d/K = 36. Other implementation optimisations are given in [9], [10] and [48]. Simply note that the number K of significant values in the spectrum W of the window can be adjusted at best by use of an auditory model. As a simple example, partials with low amplitude require a smaller K.

In our FFT^{-1} synthesis method, we can introduce noise components precisely in any frequency band narrow or wide and with any amplitude. We simply add in the STS under construction, at proper places, bands of STS's of w windowed white noise signal. This is easy and inexpensive if the STFT has been computed and stored in a table before the beginning of the synthesis stage. There exist analysis methods, [49], [25], [47], [6], to separate the noise components from the sinusoidal ones, allowing the preparation of data for noise component STS's.

The FFT^{-1} algorithm has been implemented on the MIPS RISC processor of the SGI Indigo [46], [48]. In terms of cost, one of the critical elements is the construction of a STS S_l. By careful coding, many of the performance enhancing features of modern processors [50], [51] may be used to efficiently implement the critical inner loop. The SGI Indigo implementation takes advantage of the ability of the R4000 to overlap the execution of integer address operations, floating point additions and multiplications, delayed writes and multiple operand fetches into cache lines. It is interesting that the table for the oversampled window transform is small enough to fit into on-chip data caches of modern processors. This is not the case for the larger sinusoid table required in standard oscillator based additive synthesis. A detailed comparison of different implementations is given in [48].

4.4. Control by spectral envelopes

In usual implementations of additive synthesis, $f_j[n]$ and $a_j[n]$ are obtained at each sample by linear interpolation of breakpoint *functions of time* which describe the evolution of f_j and a_j versus time. When the number of partials is large, control by the user of each individual breakpoint function becomes impossible in practice. But in the case of the voice and of certain instruments, a source filter model [7], [8] is a better representation of some of the behavior of the partials. Then the amplitude of a component is a function of its frequency, i.e. the transfer function of the filter [7], [15]. That is, the amplitude a_j depends of some spectral function, named *spectral envelope*, at the frequency f_j. The amplitude variation induced by frequency variation such as vibrato can eventually be very large [13]. To take into account these amplitude variation, a breakpoint function of time may have many breakpoints. Moreover, the amplitude of a partial is then not an intrinsic property of the *timbre* independent of other characteristic such as fundamental frequency. Amplitudes stored in breakpoint functions of time, also disallow modifications of fundamental frequency or vibrato.

On the contrary, a spectral envelope can be described as an analytical function of a few parameters, whatever number of partials it is used for. It can vary with some of its parameters for effects such as spectral tilt or spectral centroid changes known to be related to loudness and brilliance. Spectral envelopes can be obtained automatically by different methods e.g. Linear Prediction analysis [8]. If the amplitudes and frequencies of the partials are already known from sinusoidal analysis, the Generalized Discrete Cepstral analysis [52], [53], provides reliable envelopes, the smoothness of which can be adjusted according to the order. We can use spectral envelopes defined at specific instants, for example the beginning and the end of the attack, sustain and decay of a note, etc. Then at any instant, the spectral envelope to be used is obtained by interpolation between two successive recorded envelopes [21]. Frequencies, phases and noise components also can be described by similar envelopes that we call *generalized spectral envelopes*. [19]

4.5. Applications

Our new method of additive synthesis by FFT^{-1} [54] brings a solution to the three main difficulties of classical additive synthesis. The processing time (calculation cost) can be divided by a large factor. It is easy and not costly to introduce noise precisely in any frequency band narrow or wide, and with any amplitude. Control is made easier by use of *spectral envelopes* instead of the time-functions classically used for additive synthesis. Under the name F*A*R [11], the company OberheimDigital has developed a real time multi-timbral instrument based on FFT^{-1}. This instrument has all the possibilities of present day synthesizers, plus many others such as the precise modifications of sampled sounds, speech and singing voice synthesis.

5. THE RECREATION OF THE VOICE OF A CASTRATO: FARINELLI

5.1. Introduction

The recreation of a castrato voice by the means of sound analysis, processing and synthesis has been done for a musical film about Farinelli, the famous castrato of the eighteenth century [12]. The film, realized by Gérard Corbiau, and the CD of the soundtrack produced by AUVIDIS bring back to life a repertoire which could not be sung anymore. The musical consultant of the film, Marc David, has recovered unedited scores from the French National Library. Forty minutes of processed singing voice have been produced with a high level audio quality as needed for a CD.

Castrati were generally well known for the special *timbre* of their voices. Their voices had not changed with puberty and, with maturity, castrati lung capacity, chest's size, physical endurance and strength were generally greater than those of normal males. Farinelli could sustain a note longer than one minute and he could sing long phrases of more than two hundred notes without seeming to take a breath. Their small and supple larynx along with their short vocal cords, allowed them to vocalise in three octaves and a half and to sing with a great vocal flexibility, to sing rapidly large intervals, cascading scales and trills. All the more that castrati were selected among the best child singers and trained very intensively.

Castrati's specific repertoire takes their high level singing technique into account, therefore it is extremely difficult to sing. There is practically no recorded references. The last castrato has recorded less than one hour of singing voice on wax cylinders. This historical recording has little technical utility due to its poor quality. Nevertheless, we have taken into account the physical characteristics of the vocal production system of the castrati, the global aesthetic of the historical recording and descriptions found in the literature. The voice has also been designed according to the wishes of the film and music producers.

5.2. Recording and editing of the voice

Two voices have been chosen, a counter-tenor, Derek Lee Ragin and a coloratura-soprano, Eva Godlevska, with similar and good baroque singing techniques. The recording has been made in the concert hall "L'Arsenal" in Metz, France by the *Les Talens Lyriques* Orchestra conducted by Christophe Rousset. Due to artistical constraints, sound engineer J.C. Gaberel was obliged to record voice and orchestra simultaneously, despite the evident interest of a multitrack recording. One consequence is the presence of orchestra components at 20 to 30 dB under the mean average level of the singing voices. This constraint obliged us to built very robust processing methods. The recording was made on a Nagra IV-D machine with a precision of 20 bits. The remarkable editing, sometimes note by note, has been made by J.C. Gaberel on a Sonic Solution machine.

5.3. Processing

First, as one of the artistic specifications was to make the finally processed voice sound close to the counter-tenor one, we modify the soprano-coloratura parts to match the counter-tenor timbre. This *voice morphing*, constitutes the main and critical step of the scheme. Secondly, we give the voice a more juvenile aspect by using global modifications. For instance, we attenuate some high frequency bands to reduce the kind of breathiness found in Derek Lee Ragin's voice. We also make the voice sound brighter by modifying the spectrum envelope. Vowel *timbres* not only depend upon phonemes, but also upon pitch and intensity. Thus, a reference data base composed of all the combinations phoneme-pitch-intensity of the two voices had to be set up.

Then the musical phrases to be processed must be segmented and labelled in terms of singer, phoneme, pitch, power, begin and end times. Precise fundamental frequency estimation is made by the algorithm described in [55]. A first segmentation pass is performed automatically on the fundamental frequency evolution by a method recently developed in our team [56], then begin and end times and labels of the vowels are adjusted by hand in a second pass. Our voice morphing first consists in modifying the spectral envelope of the soprano voice to match that of the counter-tenor voice. This is achieved by frequency domain filtering (the phase vocoder S.V.P., [22]). As scores are written for castrati, most of the songs are high-pitched, and it's a common fact that in this case the frequency response of the vocal tract is poorly estimated. Then, voice morphing would not reach the target timbre and the transformation could emphasize some partials of the orchestra. One could imagine computing a Discrete Cepstrum envelope [57]. But the soprano-coloratura often changes continuously the shape of her vocal tract when singing a cascade of notes on the same vowel. In addition, the tremolo correlated to the vibrato effects makes spectral envelope estimation even more difficult. Under such conditions, instantaneous spectrum envelopes becomes useless. In the middle range frequencies (2.5 to 5 kHz), the spectrum envelope shape remains constant in time for a given vowel note, it's global amplitude is modulated and this effect is emphasized by the loudness. It follows that average spectrum envelopes are a good mean to cope with these fluctuations. In the upper range frequencies (greater than 5 kHz), the average level is perceptually more important than the precise shape of the spectrum. Therefore, we use the shape of the envelope weighted by a coefficient in order to control the breathiness of the voice.

We build the filter frequency response in low frequencies by using additive synthesis parameters [47]. These parameters, amplitudes and frequencies of the partials, are used to impose on the processed sound the same relative amplitudes between harmonics than those of the corresponding phoneme stored in the data base. Moreover, frequency parameters are used to draw a frequency response which only acts on the vicinity of each voice partial, in order to let the partials of the orchestra unchanged. The width of each frequency response active band is computed according to the frequency deviation due to the vibrato in the temporal window used by the phase vocoder. The phase vocoder represents the sound without any loss of information and allows the application of any precise frequency response.

6. CONCLUSION

The developments detailed in this presentation exemplify new possibilities in sound analysis and synthesis. On one hand, theoretical results have been obtained, e.g. in the domain of physical models. These results allow the construction of better computer instruments for musicians, by improving the versatility and the control of these instruments, and by offering new sonic possibilities such as chaotic sounds.

On the other hand, applications which where impractical a few years ago, are now, not only possible in research centers but also made available for a large public. This is the case for the additive synthesis revivified by the FFT^{-1} method. Experience with implementations on affordable desktop workstations has led to a real-time multi-timbral instrument based on FFT^{-1}. It has all the possibilities of present day synthesizers, such as the sound quality of sampling, plus many others such as precise and unlimited modifications of recorded sounds, speech and singing voice synthesis. The recreation of a new singing voice, which would have been considered out of reach until recently, has been made possible by improved processing techniques, precise sinusoidal partial analysis and frequency domain filtering for instance. This result not only permits to bring back to life the castrato repertoire which could not be sung anymore, but also reaches a public even larger than amateur musicians. There is no doubt that other techniques will have similar developments and success in the near future. Music will see a widespread use of such computer generated sounds and computer assisted composition.

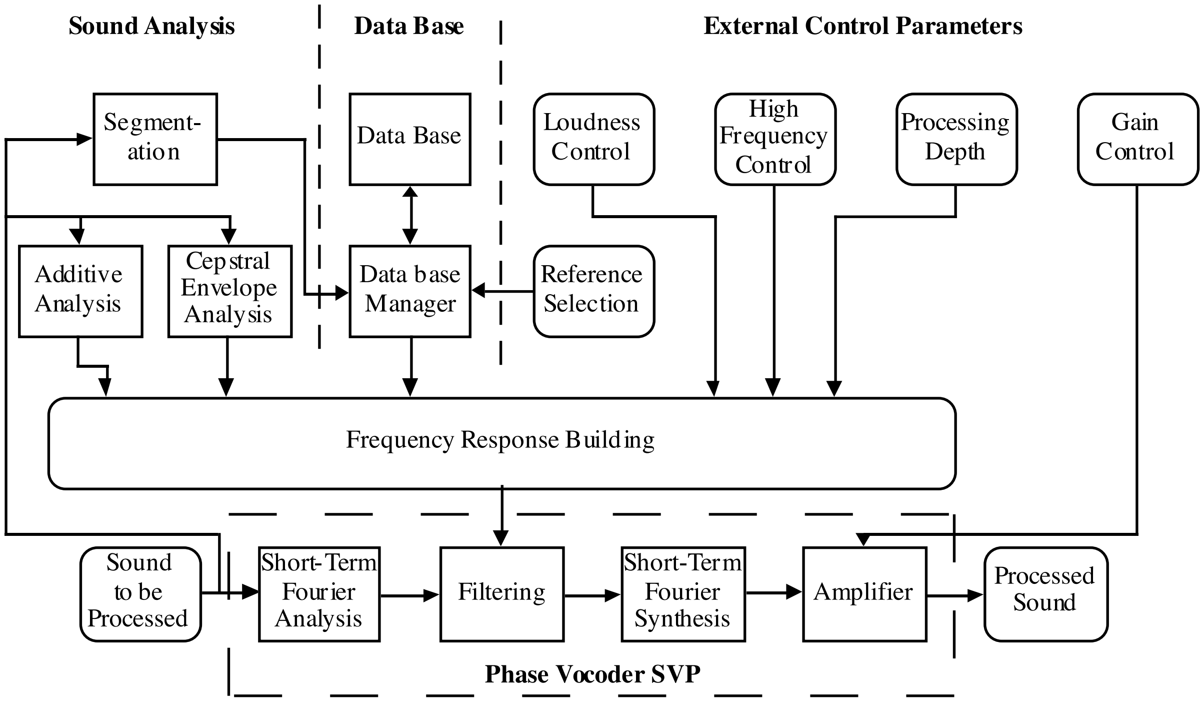

Figure 1 : General Synopsis of the voice processing.

References

1. "*Modèles Physiques, Création Musicale et Ordinateurs*", Proceedings of the Colloquium on Physical Modeling, ACROE, Genoble,France, Oct. 1990, Editions de la Maison de Sciences de l'Homme, Paris, France, 1992.
2. Keefe, D., "Physical Modeling of Wind Instruments", Computer Music Journal, MIT Press, Vol 16 No. 4, pp. 57-73, Winter 1992.
3. Cook, P., "A meta-wind-instrument physical model", Proc. International Computer Music Conference, San Jose, pp. 273-276, Oct. 1992.
4. Fletcher, N.H., Rossing, T. D., *The Physics of Musical Instruments*, Springer Verlag, 1991.
5. Risset, J.C., Mathews, M.V., "Analysis of musical-instrument tones", Physics Today, 22(2):23-30, Feb. 1969.
6. Depalle, Ph., Garcia, G., Rodet, X. "Tracking of partials for additive sound synthesis using hidden Markov models", IEEE *ICASSP-93*□ Minneapolis, Minnesota, Apr. 1992.
7. Rodet, X., Depalle Ph., Poirot, G., "Speech Analysis and Synthesis Methods Based on Spectral Envelopes and Voiced/Unvoiced Functions", European Conf. on Speech Technol., Edinburgh, U.K., Sept. 87.
8. Depalle Ph., "Analyse, Modélisation et Synthèse des sons fondées sur le Modèle Source-Filtre", Thèse de Doctorat de l'Université du Maine, Le Mans, Déc. 1991, 175p.
9. Rodet, X., “Spectral Envelopes and Inverse FFT Synthesis", Proc. AES, San Francisco, 1992.
10. Depalle, Ph., Rodet, X. "A new additive synthesis method using inverse Fourier transform and spectral envelopes", Proc. of ICMC, San Jose, California, Oct. 1992.
11. "F*A*R Fourier Analysis Resynthesis, Tecnology Dossier", OberheimDigital, 1994
12. Depalle Ph., G. Garcia, Rodet, X., "A virtual castrato (?!)", Proc. of ICMC, Copenhagen Oct. 1994.
13. Bennett, G., Rodet, X., "Synthesis of the Singing Voice", in *Current Directins in Computer Music Research*, ed. M.V. Mathews & J.R. Pierce, MIT Press, 1989.
14. Rodet, X., "Analysis and Synthesis Models for Musical Applications", IEEE Workshop on application of digital signal processing to audio and acoustics, Oct. 1989, New Paltz, New-York, USA.
15. Rodet, X., Depalle Ph., "Use of LPC Spectral Estimation for Analysis, Processing and Synthesis", 1986 Workshop on Appl. of Digital Sig. Process. to Audio and Acoust., New-Paltz, New York, Sep. 1986
16. Cointe P., Rodet X., "FORMES: an Object & Time Oriented System for Music Composition and Synthesis", Conf. Rec. 1984 ACM Symp. on Lisp and Functional Programing, Austin, Texas, Aug. 1984.
17. Rodet, X., Barrière, J.B., Potard, Y., "The Chant Project : from the synthesis of the sung voice to synthesis in general",Computer Music Journal MIT Press, fall 84.
18. Rodet, X., Depalle Ph., "Synthesis by Rule: LPC Diphones and Calculation of Formant Trajectories", IEEE-ICASSP, Tampa, Fl., March 85.
19. Rodet, X., Depalle Ph., Poirot, G., "Diphone Sound Synthesis", Int. Computer Music Conference, Koeln, RFA, Sept. 88.
20. Depalle Ph., Rodet X., Poirot,G., "Energy and Articulation Rules for Improving Diphone Speech Synthesis", Proc. ESCA Int. Conf. on Speech Synthesis, Autrans,France, Sept. 90.
21. Depalle Ph., Rodet, X., T. Galas, G. Eckel "Generalized Diphone Control", Proc. of ICMC, Tokyo Sept. 1993, pp. 184-187.
22. Depalle Ph. and Poirot, G., "A modular system for analysis, processing and synthesis of sound signals", Proc. of the Int. Comp. Music Conf., Montreal, Canada, 1991.
23. Moulines, E., Laroche, J., "Non-parametric methods for pitch-scale and time-scale modification of speech", Speech Communication 16 (1995) 175-205.
24. Smith, J.O., "Efficient simulation of the reed-bore and bow-string mechanism", Proc 1986 Int. Computer Music Conf., P. Berg, eds., Computer Music Assoc., San Francisco, pp. 275-280, 1986.
25. Serra, X. "A system for sound analysis/transformation/synthesis based on a deterministic plus stochastic decomposition", Philosophy Dissertation, Stanford University, Oct. 1989.
26. Depalle Ph., Rodet, X., D. Matignon, "State-Space Models for Sound Syntesis", IEEE ASSP Workshop on Appl. of Digital Sig. Process. to Audio and Acoust., Mohonk, New Platz, New York, Nov. 1991
27. Matignon, D., Depalle, Ph., Rodet, X., "State space models for wind-instrument synthesis", Proc. International Computer Music Conference, San Jose, pp. 273-276, Oct. 1992.
28. Rodet, X., Depalle Ph., "Modèles de Signaux et Modèles Physiques d'Instruments", Proc. of the Colloqu. on Physical Modeling, Genoble, France, October 1990 Editions de la Maison de Sciences de l'Homme, Paris, France, 1992.
29. McIntyre, M.E. et al., “On the Oscillations of Musical Instruments”, JASA 74 (5), Nov. 83
30. Hale, J.K., "Dynamics and Delays", in Delay Differential Equations and Dynamical Systems, Proc., 1990, S. Busenberg & M. Martelli (Eds.), Lecture Notes in Mathematics 1475, Springer Verlag, 1991.
31. Madan, R.N., "Learning chaotic phenomena from Chua's circuit", Proc. 35th Midwest Symp. on Circuits and Systems, Whasington, D.C., August 9-12, 1992.
32. Rodet, X., "Flexible yet Controllable Physical Models: a Nonlinear Dynamics Approach", Rodet, X., Proc. Int. Computer Music Conference, Tokyo, 10-15 Sept. 1993.
33. Rodet, X., "Stability/Instability of Periodic Solutions and Chaos in Phyical Models of Musical Instruments", Proc Int. Computer Music Conference, Copenhaguen, Sept. 1994.
34. Rodet, X., Depalle Ph., "A physical model of lips and trumpet", Proc. International Computer Music Conference, San Jose, pp. 132-135, Oct. 1992.
35. Ivanov, A.F., Sharkovsky, A.N., "Oscillations in Singularly Perturbed Delay Equations", in *Dynamics*

Reported, C. Jones, U. Kirchgraber & H.O. Walther edit., Springer Verlag, pp. 164-224, 1992.
36. A. I. Mees, "*Dynamics of feedback systems*", Wiley, 1981.
37. Chow, S. N., Green, D. Jr., "Stability, Multiplicity and Global Continuation of Symmetric Periodic Solutions of a Nonlinear Volterra Integral Equation", Japan Journal of Applied Mathematics, Vol. 2, No. 2, pp. 433-469, Dec. 85.
38. Rodet, X., "Models of Musical Instruments from Chua's Circuit with Time Delay", IEEE Trans. on Circ. and Syst., Special Issue on Chaos in nonlinear electronic circuits, Sept. 1993.
39. Chua, L. O., Lin, G.-N., "Canonical Realization of Chua's Circuit Family", IEEE trans. Circuits & Syst., Vol. CAS-37 (July. 1990) No. 7, pp 885-902.
40. Rodet, X., "Applications of Chua's Circuit to Sound, Music and Musical Instruments", Proc. 1993 Proc. 1994 Int. Symp. on Nonlinear Theory and its Applications, Hawai, Dec. 1994.
41. Verge, M.P., "Jet Oscillations and jet drive in recorder-like instruments", Acta Acustica 2 (1994), pp 403-419.
42. Rodet, X., "Basic structure and real-time implementation of J.M. Verge's flute model", internal report, IRCAM, Mai 1995.
43. Rodet, X., Steinecke, I., "One and two mass models oscillations for voice and instruments", unpublished internal report, IRCAM, March 1994.
44. Rodet, X., "One and two mass models oscillations for voice and instruments", *to appear in* Proc Int. Computer Music Conference, Banth, Canada, Sept. 1995.
45. Sharkovsky, A.N., Mastrenko, Yu., Deregel, Ph., Chua, L.O., "Dry Turbulence from a time-delayed Chua's Circuit", in J. of Crts., Syst. and Comp., Special Issue on Chua's Circuit: a Paradigm for Chaos, Vol. 3, No. 2, June 1993.
46. Freed, A., "Tools for Rapid Prototyping of Music Sound Synthesis Algorithms and Control Strategies", Proc. Int. Comp. Music. Conf., San José, CA, USA, Oct. 1992
47. García, G., "Analyse des signaux sonores en termes de partiels et de bruit. Extraction automatique des trajets fréquentiels par des modèles de Markov cachés", Mémoire de DEA en automatique et traitement de signal, Orsay, July 1992.
48. Freed, A., Rodet, X., Depalle Ph., "Synthesis and Control of Hundreds of Sinusoidal Partials on a Desktop Computer without Custom Hardware", Proc. ICMC, Tokyo, 1993.
49. McAulay, R.J., and Quartieri, Th. F., "Speech analysis/synthesis based on a sinusoidal representation", IEEE Trans. on Acoust., Speech and Signal Proc., vol ASSP-34, pp. 744-754, Aug 1986.
50. Hennessey, J. L., Patterson D. A., 1990, "Computer Architecture: A Quantitative Approach", Morgan Kaufmann, Palo Alto, CA.
51. Lee, E. A., "Programmable DSP Architectures", IEEE ASSP Magazine, October 1988
52. Galas, T., Rodet, X., "A parametric Model of Speech Signals:Application to High Quality Speech Synthesis by Spectral and Prosodic Modifications", Proc. ICSLP, Kobe, Japan, 1990, p.801-804.
53. Galas, T., Rodet, X., "Generalized Functional Approximation for Source-Filter System Modeling", Proc. Eurospeech, Genova, 1991, p.1085-1088.
54. Freed, A., Goldstein, M., Goodwin, M., Lee, M., McMillen, K., Rodet, X., Wessel, D., Wright, M., "Real-Time Additive Synthesis Controlled by a Mixture of Neural-Networks and Direct Manipulation of Physical and Perceptual Attributes", Proc Int. Computer Music Conference, Copenhaguen, Sept. 1994.
55. Rodet, X., Doval, B., "Estimation of Fundamental Frequency of Musical Sound Signals", IEEE ICASSP, May 1991, Toronto.
56. Cerveau, L., "Segmentation de phrases musicales à partir de la fréquence fondamentale", Rapport de DEA ATIAM, IRCAM, Juin 1994.
57. Galas T., Rodet X., "A new power spectrum estimation method: applications to acoustic signals", IEEE Workshop on Appl. of Digit. Sig. Process. to Audio & Acoust., Oct. 1989, New Paltz, New-York, USA.

KEYWORDS

Physical-model, dynamical system, Additive, Singing.