Virtual analogue instruments: an approach to active preservation of the Studio di Fonologia Musicale

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Electroacoustic music is a young form of art. Nevertheless, it is still necessary to take care of its preservation, due to the limited life of the recording supports, of the reading systems of the data, and of the instruments. Moreover, preservation and restoration of electroacoustic music works raise peculiar technical and philological issues. With particular regard to electrophone instruments, many technological generations have passed since the appearance of the first instruments, and many electronic components used in their construction do not exist anymore or are only available with difficulty.

Electrophones are considered to be the only musical instruments which produce sound primarily by electrical means. Electrophones are one of the five main categories in the Hornbostel-Sachs scheme of musical instrument classification.[156] Although this category is not included in the original scheme published in 1914, it was added by Sachs in 1940,[157] to describe instruments involving electricity.

Preservation of supports, reading devices, and instruments of electroacoustic music requires specific knowledge, adequate funding within institutional frameworks, and interdisciplinary collaboration among several experts in the field, because damage produced by unsuitable preservation or inadequate restoration is irreversible. Production by composers is considerable: already in 1967 Hugh Davies had catalogued world-wide around 5000 electroacoustic music works,[158] and this number is today much larger.

Alarm bells are already ringing, and recent years have seen increasing attention to these issues, and a growing awareness of how precarious the passive preservation of this cultural heritage of the recent past can be. The EU is particularly sensitive to these issues: an example of this awareness is the EU-funded DREAM

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156. See Moritz von Hornbostel – Sachs, "Classification of musical instruments," *Galpin Society Journal*, XIV, no. 3 (1961): p. 29. Translated from the original German by Anthony Baines and Klaus P. Wachsmann.

157. See Sachs, *The history of musical instruments*, New York: W. W. Norton & Co. Inc., 1940 (first edition). In particular, Sachs broke down his 5th category into 3 subcategories:
–   5.1 = electrically actuated acoustic instruments;
–   5.2 = electrically amplified acoustic instruments;
–   5.3 = instruments in which make sound primarily by way of electrically driven oscillators, such as theremins or synthesizers, which he called radioelectric instruments.

158. See Davies, *International Electronic Music Catalog*, Cambridge, MA: MIT Press, 1967.

project,[159] whose results are discussed in this essay. This project defines an approach to an active preservation of the electrophone instruments of the SdF, and is one of the first attempts to address this issue from a multidisciplinary perspective involving engineering, interaction design, and musicological competences. The final goal is to develop an installation consisting of a software-hardware system that re-creates the electronic lutherie of the SdF, allowing users (both musicians and amateurs) to interact with such lutherie. Achieving this goal implies:

I.   analysing the devices through project schemes and direct inspection;
II. validating the analysis through simulations with *ad hoc* tools;
III. developing physical models of the analogue devices, which allow efficient and accurate numerical simulations of their functioning;
IV. designing appropriate interfaces to interact with the virtual devices.

In order to illustrate this process, some specific electrophone instruments of the SdF, the early sinusoidal oscillators and the so-called amplitude selector, will be considered in this essay as relevant case studies, both from a technical and from a historical and musicological viewpoints.

The different sides of the electroacoustic music heritage

With the advent of the electroacoustic and telecommunication technologies, electrophone instruments and new musical forms were born and developed throughout the second half of the last century.

Electronic music, *musique concrète*, electroacoustic music, tape music, experimental music, acousmatic music, live electronics, computer music: all these terms denote musical works that make use of technological means and, together with their instruments and performance praxis, constitute what is usually called the 'electronic music heritage'. Preservation of these materials raises issues that are very different from those of classical musical works, mainly because they are stored not only on paper but also on other (e.g. magnetic) supports, which are more volatile and are based on a great variety of data coding systems.

Although it may seem paradoxical, in an era where almost any information is recorded and saved (sounds, gestures, images, sequences, etc.), the preservation of this enormous quantity of data constitutes a daunting problem and can only be realized through institutional commitment, with funds and specialized personnel. In a sense this makes our society vulnerable, as a catastrophic event or a period of long recession that interrupts preservation activities could obliterate many years of music history. This is the other side of the coin, the price that we need to pay in order to preserve the information of our age.

Contemporary society witnesses continuous technological evolution and constant renovation of daily objects, and the concept of time has changed radically. Correspondingly, the parameter 'duration' has been introduced in cultural heritage preservation. Common materials like paper and ink, which have transmitted

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159.   See the official project website: http://dream.dei.unipd.it

human thought through the centuries, do not have the duration that they used to have. Similar considerations apply to magnetic or digital storage means. These means are not thought of as 'eternal', because the market does not require it. Since artists and composers often realize their work without thinking about the problem of their preservation, many music works (including recent ones) have already disappeared or are seriously deteriorated. The analogue electronic era, with its massive use of magnetic and/or optical storage, amplifies these issues greatly because, beyond the maintenance of supports, it also requires maintenance of the devices that can read the stored data.

Musical works that use electronics can be grouped in different categories, with regard to their preservation.

RECORDED MUSIC includes works performed and recorded by the author (or by other performers under the direction of the author). An example is *Ricorda cosa ti hanno fatto in Auschwitz* (1966), by Italian composer Luigi Nono. Typically these are works for tape only, or for instruments and tape, in which the recorded musical materials are fixed and are ready for the performance independently from their nature, since neither a score nor indications from the author exist. For musicological research, preserving the sound materials used for the tape processing is as essential as preserving the graphic schemes or the software used for the processing or the synthesis of the sounds.

LIVE ELECTRONICS includes works in which acoustic sounds (voices or traditional instruments) are processed in real time during the performance, without the use of pre-recorded materials. An example is *Mikrophonie I* (1964), by German composer Karlheinz Stockhausen. Preserving these works means preserving, in addition to the paper score, detailed documentation of the electronic processes used (patches) and the live electronic score. Patches must be documented in an abstract form (i.e. to describe functional abstract principles), independently of the actual devices used (since these have a brief life), and independently of specific units of measurement, in order to be easily transferrable from one system to another. To this end, it is often necessary to preserve the technical documentation of the devices as well (or the devices themselves, if they have no technical documentation or are unique prototypes). Other considerations exist that impose the preservation of the devices. Especially in analogue devices, intrinsic imperfections of the underlying technology are source of acoustic transformations that become part of the 'timbre' of the device. In other cases, unique prototypes are realized by the composer or under his guidance: technical choices are often driven by aesthetic factors, so that the machine becomes part of the musical work itself. Belgian composer Henri Pousseur[160] was one of the first to give prominence to the study of electroacoustic equipment in the analysis of electronic music compositions, and to highlight the limits of the so called analysis-to-synthesis method: electroacoustic equipment is characterized by specific inertias and indetermination. These are able to interact with the compositional model. Consequently, the knowledge of the equipment,

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160.   See Pousseur, *Fragments théoriques I sur la Musique expérimentale,* Brussels: Editions de l'Institut de Sociologie, Université Libre de Bruxelles, 1970.

of its circuit scheme, of the signals transmitted from/to its components, and of the usage guidelines by the composer, is an essential piece of information if we wish to reconstruct the historical identity of the musical work.

SYNTHETIC SOUNDS are used in several electronic music compositions, i.e. the sounds are composed and annotated in terms of sound synthesis algorithms (defining the rules of sound production), and of time-varying control parameters of the algorithms (analogous to the traditional score). An example is *Kontakte* (1959-60) by Karlheinz Stockhausen. Preservation of this information is needed in order to allow resynthesis, both for re-recording or live performance purposes. Preservation of this typology of works poses similar problems to the case of Live Electronics, although in many works of synthesis with musical recorded parts the preservation of algorithms and parameters is not required for performance purposes. This kind of information is particularly relevant from a musicological standpoint, as it helps reconstruct the musical genesis of the piece and the underlying compositional thought.

COMPUTER AIDED COMPOSITION refers to works that do not necessarily use electronic sounds, but involve the aid of some form of computational process in the composition (even in cases where traditional instruments are used). Examples are *ST/4*, *ST/10*, and *ST/48* (1962), by Greek composer Iannis Xenakis, who is recognized as one of the pioneers in computer assisted composition. In this case also, preserving the algorithms/software used for the composition is especially useful for musicological research, since the rules used are formalizations of the composer's thought. Therefore, preservation of the archive of the software realized by a composer is extremely important for the analysis of his work.

Preservation and restoration

We define 'active preservation' of electroacoustic music as the set of all the actions aimed at keeping alive the musical compositions, by transferring the recordings and the instruments to the digital domain, allowing performance and functionality both for musicological research and for philological analysis. Although in many cases the musical compositions are indissolubly linked to the production systems, it is preferable to separate, where possible, the problem of preservation of musical compositions from that of the instruments and the performance praxis. In particular, we relate:

I.   the 'preservation' process to the actions aimed at maintaining cultural heritage (recordings, software, instruments) in its original form;
II. the 'restoration' process to the actions aimed at making cultural heritage available, following subjective aesthetic principles.

Therefore, restoration is part of the interpretation process made by the performer and it is subject to the aesthetic choices of the operator, and to the aesthetic influences of the historical period in which he works.

The above discussion has shown that in most cases electroacoustic works, as produced by the author, are composed of several elements. This leads to the necessity of preserving graphic and textual materials (score, schemes, suggestions), audio documents (musical parts or the whole piece), software (for sound synthesis, live electronics, etc.), and electrophone instruments. The first materials are usually on paper and are thus related to the more general problem of paper material preservation.

Audio document preservation is categorized into 'passive'[161] preservation, meant to protect the original documents from external agents without altering the electronic components, and 'active' preservation, which involves the data transfer from the analogue to the digital domain. In the 1970s and 1980s, expert associations (Audio Engineering Society: AES; National Archives and Records Administration: NARA; Association for Recorded Sound Collections: ARSC) were still concerned about the use of digital recording technology and digital storage media for long-term preservation. They recommended re-recording of endangered materials on analogue magnetic tapes, because of:

I.   rapid change and improvement of the technology, and thus rapid obsolescence of hardware, digital formats, and storage media;
II. lack of consensus regarding sample rate, bit depth, and recording formats for sound archiving;
III. questionable stability and durability of the storage media.

Digitization was primarily regarded as a means to provide access to rare, endangered, or distant materials, rather than a long-term solution for preservation. Nevertheless, in 1999, Smith suggested that digitization should be considered as a means for access and not for preservation – 'at least not yet'.[162]

Nowadays, it is well known that preserving the supports and maintaining the dedicated equipment for their reproduction is hopeless. The audio information stored in obsolete formats and supports is at risk of disappearing. To this end, the audio preservation community introduced the concept 'preserve the content, not the carrier.' Consequently, analogue documents must be digitized. At the end of the 20th century, the traditional 'preserve the original' paradigm shifted to the 'distribution is preservation'[163] idea of digitizing the audio content and making it available using digital libraries technology. Now the importance of transferring into the digital domain (active preservation) is clear, namely, for carriers at risk of disappearing, respecting the indications of the international archive community.[164]

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161. Passive preservation is divided into 'indirect', which does not physically involve the carrier, and 'direct', in which the carrier is treated without altering its structure and composition.

162. See Smith, *Why digitize?* Washington, DC: Council on Library and Information Resources, 1999.

163. See Cohen, *Preservation of audio in folk heritage collections in crisis*, Washington, DC: Council on Library and Information Resources, 2001.

164. See Orio – Snidaro – Canazza – Foresti, *Methodologies and tools for audio digital*

On the other hand, the preservation of electrophone instruments is a new, interesting field, where many questions remain as yet unanswered.

Electroacoustic music instruments differ from traditional ones in many respects: the use of electric energy as the main sound producing mechanism, rapid obsolescence, the dependence on scientific research and available technology.[165] Before discussing the preservation and restoration of these instruments, it is necessary to describe their characteristics. Unlike Sachs,[166] we prefer (from the standpoint of preservation) to cluster electrophone instruments in three categories: electroacoustic, electromechanical, and electronic (analogue or digital).[167]

In an ELECTROACOUSTIC INSTRUMENT, transducers transform acoustic vibrations of a body (e.g. a string, a reed) into a voltage variation representing the acoustic pressure signal. Sound is produced through an amplification system, while the original acoustic sound is hardly perceivable. Transduction may be of an electromagnetic, electrostatic, photoelectric, or piezoelectric nature. Examples are the microphone, the electromagnetic pick-up of the electric guitar, the piezoelectric pick-up of the turntable.

In ELECTROMECHANICAL INSTRUMENTS, voltage variations are caused by sound storage on a rotating disk or a tape in motion (an optical film or a magnetic tape) according to electromechanical, electrostatic, or photoelectric principles. The main electromechanical generator is the audio-wheel used for the first time by Thaddeus Cahill at the beginning of the 20th century, for his Telharmonium. The audio-wheel is generally composed of several disks on a pivot started up by a synchronous motor. Successful electromechanical instruments include the Hammond organ (audio-wheel) and the Mellotron (magnetic tape). Unlike the electroacoustic case, in electromechanical instruments sound can be heard only through amplification.

In ELECTRONIC INSTRUMENTS, sound is synthesized by one or more electronic generators without any acoustic or mechanical vibrations. Electronic components used for synthesis in the 20th century range from valves and semiconductors, from early integrated circuits to LSI and to VLSI circuits, with analogue technologies being quickly replaced by digital ones. Sound is synthesized through combination and interconnection of 'primitive' components like oscillators, noise generators, filters, , envelope generators, mixers, etc.). Examples of electronic instruments are electronic organs and synthesizers. Electronic instruments lose the traditional characteristics of a musical instrument, and become programmable and interactive 'systems' that can provide complex sonic results even when played (in real time or off-line) by only one performer (sometimes the composer himself). In this respect,

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archives, International Journal of Digital Libraries, X, no. 4 (2009): pp. 201-220.

165. See CHADABE, "Le principe du voltage-control et ses implications pour le compositeur," *Musique en Jeu*, no. 8 (Paris: Le Seuil, 1972): pp. 36-40.

166. See SACHS, *The history of musical instruments* op. cit.

167. A further distinction – beyond the limit of this work – could be traced between monophonic, partially polyphonic, and polyphonic instruments.

each electronic instrument – or system – reflects, through its components and operating characteristics, a particular musical thought.

Preservation of these instruments poses several problems. First of all, making an inventory is a very difficult task since, borrowing the words of Hugh Davies,

> the total quantity of electronic instruments built in the 70 years since the first models were manufactured already numbers many millions […] the day is not far off when [electronic instruments] will outnumber all other instruments made throughout human history.[168]

Secondly, these instruments should be preserved not only for museal purposes, but also to preserve their functionality. Any violin virtuoso dreams of playing a Stradivari or a Guarneri del Gesù. Nevertheless, in order to adapt these instruments to modern tunings and to avoid aging, its structure needs to be modified, often in irreversible ways. Therefore, it is important to trace a line between the functionalities that are critical for instrument preservation (passive preservation) from those finalized to musical performance (active preservation).

In our opinion, it is necessary to keep music alive, independently from its original instruments, whose careful preservation defends a cultural heritage that is precious to historical and musicological research. The same is true for electrophone instruments, although their restoration and the recovery of their functionalities is often of electronic rather than mechanical nature, and constrained by the availability of working components to substitute for deteriorated ones. In this case, using new components that have different characteristics from the original ones requires a re-design of the circuitry.

It is also necessary to make a distinction between commercial instruments, produced on a large scale, and experimental prototypes realized in musical research labs. Given their commercial nature, the former are typically closed and compact instruments whose operational aspects are well documented and often protected by patents. Large-scale production makes their preservation less problematic, in terms of availability of replacement components. On the contrary, experimental prototypes realized in research laboratories are harder to preserve, because of scarce technical documentation, and because of 'cannibalism', i.e. the practice of reusing some components for the assemblage of new devices. This phenomenon also makes it hard to date prototypes, and to know their characteristics at the time when the musical work was realized. In this case active preservation is very difficult, since, even when the instrument's history is known, it is necessary to choose whether to maintain the modifications, or to bring it back to the original project. In fact, alterations are often irreversible. These issues become more and more relevant as the rate of technological evolution increases, and technicians specialized in obsolete technologies – as well as substitute components – tend to disappear.

In light of the above discussion, we propose to transpose the categories of passive preservation and active preservation – usually applied to document preserva-

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168.   See Davies, "Electronic Instruments." In *The New Grove Dictionary of Music Online.* Edited by L. Macy (2003). Available from http://www.grovemusic.com.

tion – to the field of electrophone instruments. In this context, passive[169] preservation is meant to preserve the original instruments from external agents without altering the electronic components, and active preservation, which involves a new design of the instruments using new electronic components or a virtual simulation of the instrument. Similarly to what happened during the 1980s and 1990s for the preservation of audio documents, the vast majority of the scientific community nowadays considers active preservation of electrophone instruments a useless exercise, mostly because of:

I.   rapid change and improvement of the technology, and thus rapid obsolescence of SW used in the simulation;
II.   lack of consensus regarding the virtual model of the electronic components and the environments used for archiving;
III. information loss with respect to the original instruments, i.e. loss of all the particular inertias and specific indeterminations that characterized the analogue devices[170] and were creatively exploited by the composers.

As a consequence, active preservation is considered to be primarily a way of providing public demonstrations to rare, endangered, or distant materials – not a permanent solution to the preservation problem.

In contrast with this view, we are convinced that – similarly to the audio documents field – active preservation of electrophone instruments is needed in order to prevent this equipment from disappearing, and it is desirable because it is the only way to introduce in this field the 'preserve the content' and 'distribution is preservation' concepts, discussed above. Specifically, active preservation of instruments allows access to them on a wide scale (i.e. it may allow access to the instruments in virtual spaces that can be reached even remotely by large communities of users).

This also requires preservation of the laboratories where all the steps of the musical work production process were performed. In fact, electroacoustic music production is often linked to a system composed of several instruments rather than to a particular instrument, so that the preservation of a single device does not supply the complete testimony of the practices and methodologies of a composer in a particular historical period. The WDR Studio für Elektronische Musik in Cologne has been reconstructed in the same configuration used in the 1950s: this is where Karlheinz Stockhausen spent almost the whole of his artistic career. The studio is completely operational, including most of the original equipment. The exhibition at the Cité de la Musique in Paris includes a section dedicated to electrophone instruments related to the experience of real-time computer music in the 1980s. At the Biennale in Venice, in 1986, a temporary exhibition titled *New Atlantide* was prepared, in which the most important instruments and electronic music systems of the last century were exposed for several months.

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169.   Keeping the analogy with audio documents, passive preservation approaches can be further categorized into indirect preservation, which does not involve physical treatment of the instrument, and direct preservation, in which the instrument is treated without altering its structure and composition.

170.   See Pousseur, *Fragments théoriques I sur la Musique expérimentale* op. cit.

Active preservation of electrophone instruments through virtualization

Active preservation of electrophone instruments, as discussed above, represents a major technological and scientific challenge. It requires the analysis, understanding, and simulation of the behaviour of complex devices, assembled from several components, some of which are non-linear, some of which have partially unknown characteristics. Our approach to active preservation of such instruments amounts to developing 'virtual' counterparts in the digital domain, which retain as much as possible the characteristics of the original, analogue devices.

The main problem to be tackled is the 'information loss' issue discussed in the previous section. Consider the example of Lietti's sinusoidal oscillators. Despite being designed to be 'low-distortion' devices, i.e. devices able to synthesize an almost pure sinusoid, their components and construction have intrinsic limitations which cause the produced sounds to be non-sinusoidal, especially at high dynamic ranges. Moreover, due to the electronics inside the circuits, the sounds exhibit transient behaviours, particularly amplitude modulations. All these imperfections, which are due to the physical construction of the instruments, contribute to defining their timbre and their identity. It should be clear at this point that replacing Lietti's sinusoidal oscillators with standard digital oscillators (which synthesize perfect sinusoids with no spurious transient behaviours) would be a highly unsatisfactory solution to the preservation problem, as it would cause the loss of a major amount of information about the original electrophone instruments.

Motivated by this discussion, our approach to instrument virtualization is based on an innovative digital sound synthesis paradigm, known in the scientific literature as 'physical (or 'physically-based') modelling'.[171] Physically-based sound synthesis became possible in recent years, thanks to advent of ever faster computers and processors. Already in the early 1970s, computer simulations were used in music acoustics research, as a complementary tool to physical measurements on real instruments. Such simulations are computationally intensive as they entail the numerical resolution of all the equations governing the physics of a given sound-producing system, be it a mechanical, acoustic, or electronic system. Researchers quickly realized that such numerical simulations could be used not only as a means to gain further insight into the physics of a musical instrument, but also to synthesize digital signals representing the sounds produced by that instrument. It was indeed 1971 when Hiller and Ruiz, in a well known paper about the numerical simulation of the wave equation, envisioned the possibility of using their approach for sound synthesis applications.[172]

> This is a completely new approach to electronic sound synthesis insofar as the starting point is the physical description of the vibrating object [...]

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171. See DE POLI – ROCCHESSO, "Physically-based sound modelling," *Organised Sound*, vol. 3, no. 1 (1998): pp. 61-76.

172. See HILLER – RUIZ, "Synthesizing Musical Sounds by Solving the Wave Equation for Vibrating Objects: Part II," *Journal of the Audio Engineering Society*, XIX, no. 7 (July 1971): pp. 542–551.

A decade later McIntyre, Schumacher, and Woodhouse published their classic study on the use of non-linear maps for modelling the generation of self-sustained oscillations in musical instruments:[173]

> [...] a fast minicomputer could produce results at a cycle rate in the audible range. The result would perhaps have some novelty: an electronic musical in-strument based on a mathematical model of an acoustic instrument [...]

Nowadays, the algorithms described by these authors can be easily realized in real-time on general-purpose hardware. It has become common practice to use the term physical modelling to refer to sound modelling techniques in which the syn-thesis algorithms are based on a description of the physical phenomena involved in sound generation.

Figure 56 provides a schematic representation of the difference between physi-cal modelling and earlier sound synthesis techniques, such as additive, subtrac-tive, or frequency modulation (FM) synthesis. These techniques are based on a description of the sound signal (i.e. in terms of its waveform or its spectrum) and make no assumptions on the sound generation mechanisms, whereas physically-based modelling starts precisely from the sound generation mechanisms and, in a way, obtain sound synthesis as a by-product of a more general simulation of such mechanisms.
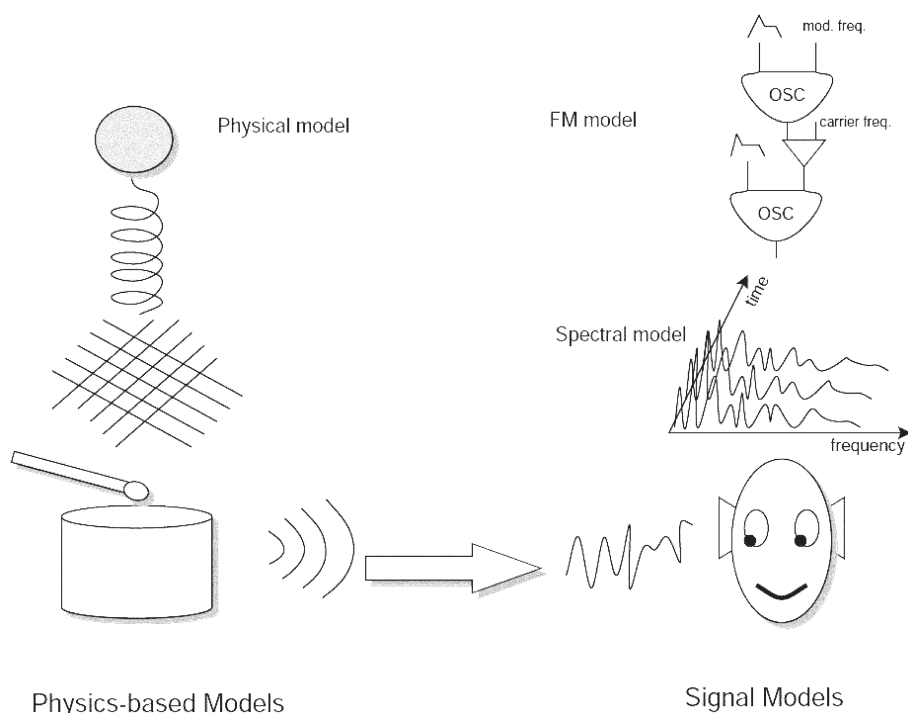

Figure 56 – Physical models as opposed to signal models for sound synthesis.
Reproduced from DE POLI – ROCCHESSO, "Physically-based sound modelling" op. cit.

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173.   See MCINTYRE – SCHUMACHER – WOODHOUSE, "On the Oscillations of Musical Instru-ments," *Journal of the Acoustical Society of America*, 74, no. 5 (November 1983): pp. 1325–1345.

In cases where the sound-producing (or sound-processing) device to be simulated is an analogue electronic system, rather than a mechanical or acoustic system, the term 'virtual analogue synthesis' is commonly used to refer to physically-based sound synthesis of these devices.[174] This term started to become popular in the late 1990s, when a new generation of products entered the market of sound synthesis software: these included digital simulators of analogue subtractive synthesizers of the 1960s and 1970s, and of the traditional analogue electronics of vacuum-tube amplifiers, such as those used by electric guitar, bass and electric organ players.

Possibly the most interesting quality of physically-based sound synthesis lies in the mapping between the model parameters and the features of the resulting sound. Unlike in earlier synthesis techniques, this mapping is 'objective', i.e. it is defined by the laws of physics. In non-physics-based synthesis techniques, the sound designer has to choose the representation of the model parameters. As an example, if the sound of a string is simulated using additive synthesis, defining a 'string dissipation' parameter requires subjectively tuning the decay times of all the sinusoidal components of the additive synthesizer. On the other hand, in a physical model such a string dissipation parameter is already 'hard-wired' in the sound synthesis scheme, as it is part of the equations that originated the synthesis algorithm.

An important consequence for our discussion is that idiosyncratic behaviours and possible imperfections of the original instrument will also be preserved and reproduced in the virtual one, if the simulation is accurate enough. In this respect, the 'information loss' issue involved in the active preservation of electrophone instruments, and discussed in the previous section, is duly considered in the virtual analogue synthesis approach. The case studies reported next provide some relevant examples of idiosyncratic behaviours that are retained in the virtual instruments.

Case Studies

As already mentioned earlier in this book, most of the devices originally realized to equip the SdF were unique pieces designed and constructed by Lietti by assembling the electronic components that he could find in the Rai warehouses.

The original project schemes are generally well documented in terms of characteristics of the basic components and of circuitry. In some cases where the documentation is not detailed enough, it is necessary to inspect directly the original instruments through *ad hoc* measurements on some components.

In the remainder of this section, we examine a few relevant case studies, with the purpose of exemplifying the potential of our approach. Examples of both sound production devices (the 1955 sinusoidal oscillators) and of sound processing devices (the amplitude modulator) will be shown. The oscillators are particularly interesting because they no longer exist, and only the original project schemes are still available. On the other hand, the amplitude modulator is of particular interest both for its design (it is a highly non-linear filter based on an original project by Lietti), and for its historical role in the musical production of the SdF.

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174. See Vesa Välimäki – Stefan Bilbao – Julius O. Smith – Jonathan S. Abel – Jyri Pakarinen – David Berners, "Virtual analog effects," in Zölzer (ed.), *DAFX – Digital Audio Effects*, Chichester, UK: John Wiley & Sons, 2011 (2nd edition).
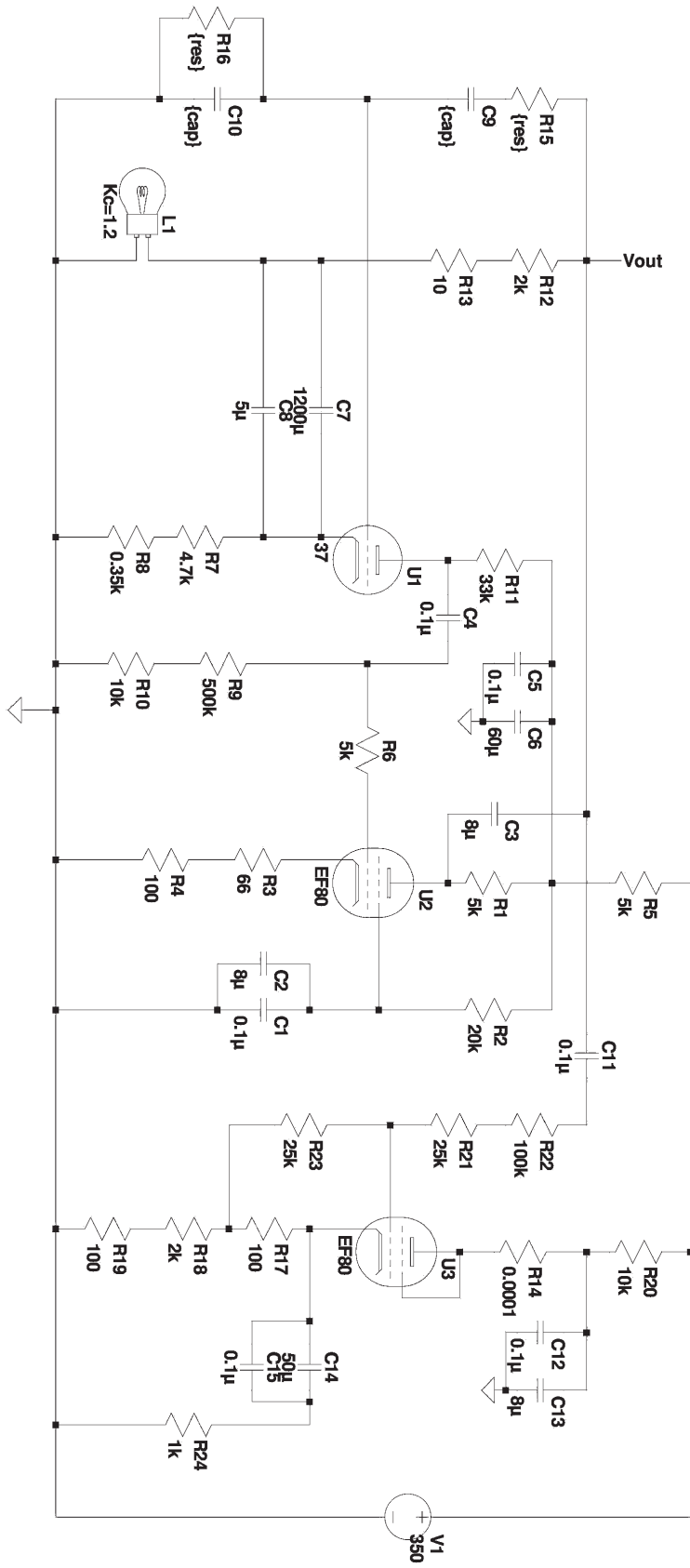
Figure 57 – Circuit scheme of the oscillator used in the numerical simulations.

OSCILLATORS

By analysing the original schemes drawn by Lietti, one can see that the oscillators' project is based on a well known bridge circuit: the 'Wien bridge oscillator', originally developed by German physicist Max Wien in 1891,[175] and commonly used for audio sinusoidal oscillators.

The modern circuit is derived from the formulation proposed by William Hewlett in his master's degree thesis at Stanford University (1939): building on this work, the first product released in 1940 by new-born company Hewlett-Packard (co-founded by Hewlett and David Packard) was a precision Wien bridge oscillator. One of the first clients of Hewlett-Packard was Walt Disney, who used eight of these oscillators in the production of *Fantasia*.[176] Therefore, Lietti developed the project of the oscillators starting from a well known model, available in the technical literature, and implemented it with the components that he had at hand.

The original project scheme for the oscillators is shown in the essay by Antonio Rodà (see *supra* p. 44). In Figure 57 we show the equivalent scheme developed with the software SPICE[177] for numerical simulation. Very briefly, the circuit is composed of a simple linear RC (resistance-capacity) arm, which determines the frequency of oscillation. As explained in the essay by Rodà (see *supra* pp. 44-46), the control interface included two knobs: the first one allowed switching between six different frequency bands, while the second one was used for fine tuning of the sinusoid frequency within a given band. In the original circuit scheme, these controls are reflected in the presence of six different resistances with fixed values (one per band), and of one resistance with variable value (for the fine tuning).

However the circuit schemes also contain some additional resistive elements, one of which is a temperature-dependent resistor, i.e. a thermistor whose resistance increases as its temperature increases. The purpose of these additional elements is to ensure stability of the circuit. In particular the thermistor has the role of limiting the gain and consequently minimizing the distortion of the circuit.[178] Interestingly, the formulation proposed by Hewlett made use of a light bulb as a thermistor. When the bulb is operated well below the point at which the filament actually illuminates, increasing current flowing in the filament also increases its resistance, which in turns reduces the feedback signal, thus preventing signal clipping that would cause distortion. From the original schemes, it can be seen that also Lietti used a light bulb in his project. It may be guessed that the motivations behind this choice included, among other considerations, also affordability and ease of retrieval of such a component.

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175. See WIEN, "Messung der Inductionsconstanten mit dem 'optischen Telephon' " [Measurement of Inductive Constants with the 'Optical Telephone'], *Annalen der Physik und Chemie*, vol. 280, no. 12 (1891): pp. 689–712. Text in German.

176. See LAING, *Digital retro*, London: The Ilex Press Ltd, 2004.

177. The acronym SPICE stands for 'Simulation Program with Integrated Circuit Emphasis'. SPICE is a software especially designed to analyse and simulate analogue electronic circuits. See NAGEL – ROHRER, "Computer analysis of nonlinear circuits, excluding radiation," *IEEE Journal of Solid State Circuits*, vol. SC, no. 6 (1971): pp. 166–182.

178. We refer to distortion as an alteration of the theoretical waveform (a sinusoid in the case examined here), by which the resulting signal possesses a different, usually richer, spectrum than the theoretical one.

The circuit scheme was numerically simulated using SPICE. Values for all the circuits components are available from the original documentation. Here we show a few simulation examples, which provide concrete examples of our earlier discussion about the physical modelling and virtual analogue approaches. The following examples show in more detail that the numerically simulated oscillator exhibit non-ideal behaviours that qualitatively resemble those of the original analogue circuits.[179]

Figure 58 shows two non-ideal transient behaviours. Figure 58.a shows the sinusoid envelope in time immediately following 'ignition' of the oscillator. It can be noticed that the sinusoid build-up is far from ideal. Instead, the amplitude rises at a relatively slow rate, exhibits an overshoot, and then stabilizes at a constant value. Moreover, it can be seen that this transient behaviour spans several tenths of second, thus being clearly perceivable.

Figure 58.b shows the sinusoid envelope immediately after the circuit has been disconnected and re-connected again, as would happen when turning the frequency-band knob to switch from one frequency band to another. Again, it can be seen that the envelope exhibits a transient behaviour that is to be attributed to the 'inertia' of the circuit: after the circuit has been re-connected again, the amplitude continues diminishing, and starts rising only after 2 tenths of seconds, approximately. Then, similarly to the previous example, the envelope exhibits an overshoot and stabilizes at a constant value.

Figure 58 – Examples of transient behaviours exhibited
by the sinusoidal oscillators (waveform envelopes are shown).

a) Initial attack transient.

b) Transient following a change of frequency band.


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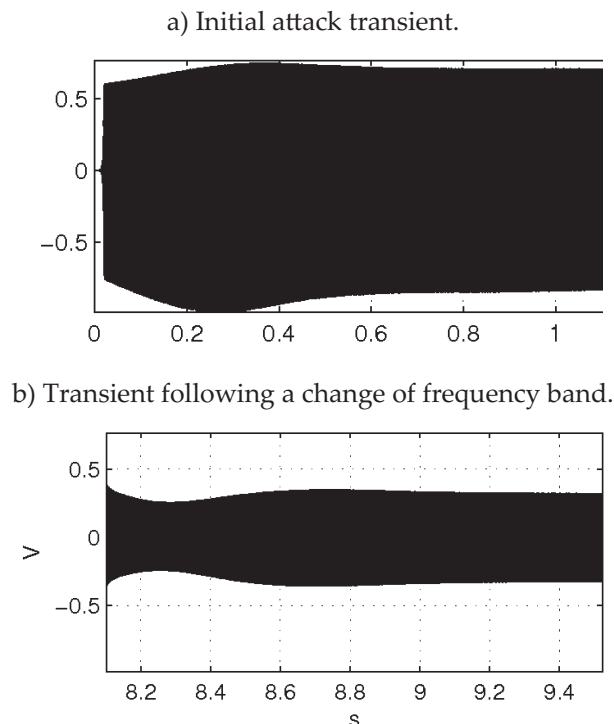
179.   Clearly, since the original devices do not exist anymore, a thorough quantitative comparison is not possible.

Figure 59 provides an example of the effects of distortion on the waveform and on the corresponding spectrum. Figure 59.a shows a portion of the waveform produced by the virtual circuit, at a high dynamic level. It can be noticed that the waveform is not exactly sinusoidal, and is instead distorted especially in its positive portion, where some form of clipping is detectable. The scientific literature refers to this kind of phenomenon as asymmetric distortion, because the positive and negative portions of the waveform are clipped by different amounts.[180]

The effects of distortion can also be appreciated by looking at the signal spectrum (Figure 59.b). If the signal were an ideal sinusoid, its spectrum would exhibit a single 'line' located at the sinusoid frequency (around 1600 Hz in this example). Instead, the actual spectrum provides evidence that the signal is composed of several harmonic components in addition to the fundamental.

Figure 59 – Example of distorted sinusoid at high dynamics.

a) Waveform detail.

b) Spectrum.

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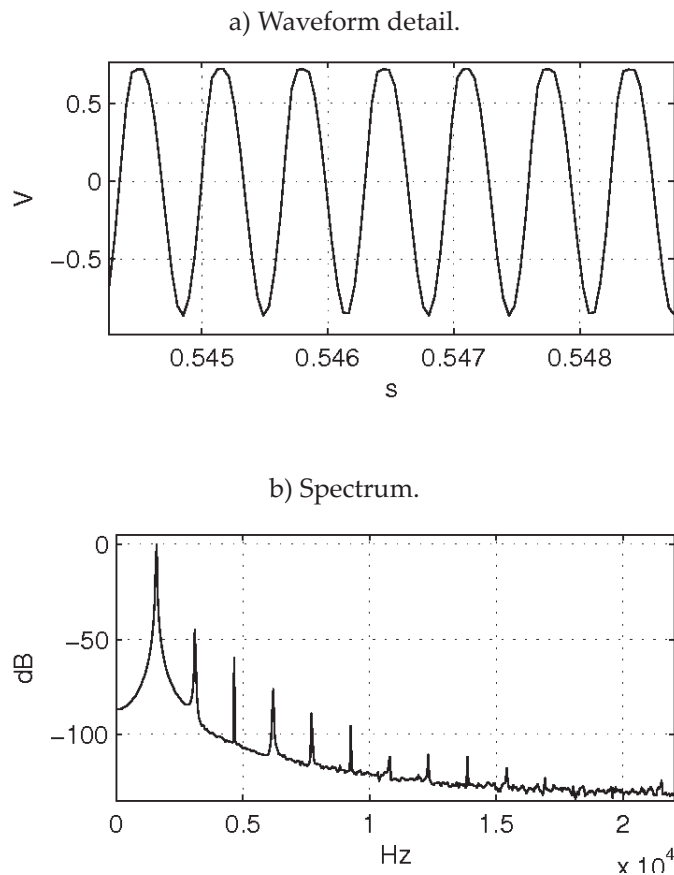
180. See P. Dutillieux – K. Dempwolf – M. Holters – U. Zölzer, "Nonlinear processing," in ZöLZER (ed.), *DAFX – Digital Audio Effects*, Chichester, UK: John Wiley & Sons, 2011 (2nd edition).

The effects of distortion can be quantified using a mathematical parameter called total harmonic distortion (THD), which measures the amount of energy of higher harmonic components with respect to the total energy. For an ideal sinusoid, the THD is exactly zero, because all the energy of the signal is allocated to the first harmonic component and no higher harmonics are present. Instead, the signal shown in Table 3 exhibits a THD of about 11%.

AMPLITUDE SELECTOR

As already discussed in the essay by Rodà (see *supra* p. 33), the amplitude selector is a non-linear sound processing device which alters its input sound depending on the amplitude.

Among the musical works that make use of the amplitude selector, one of the most famous ones is *Scambi*, by Henri Pousseur. The audio material used in *Scambi* was obtained by passing white noise through the amplitude selector with varying parameter values, thus obtaining a set of noise-like sequences with different timbral characteristics. The compositional process and the technical solutions involved in the realization of *Scambi* are further discussed in the essay by Dack (see *infra* p. 123).
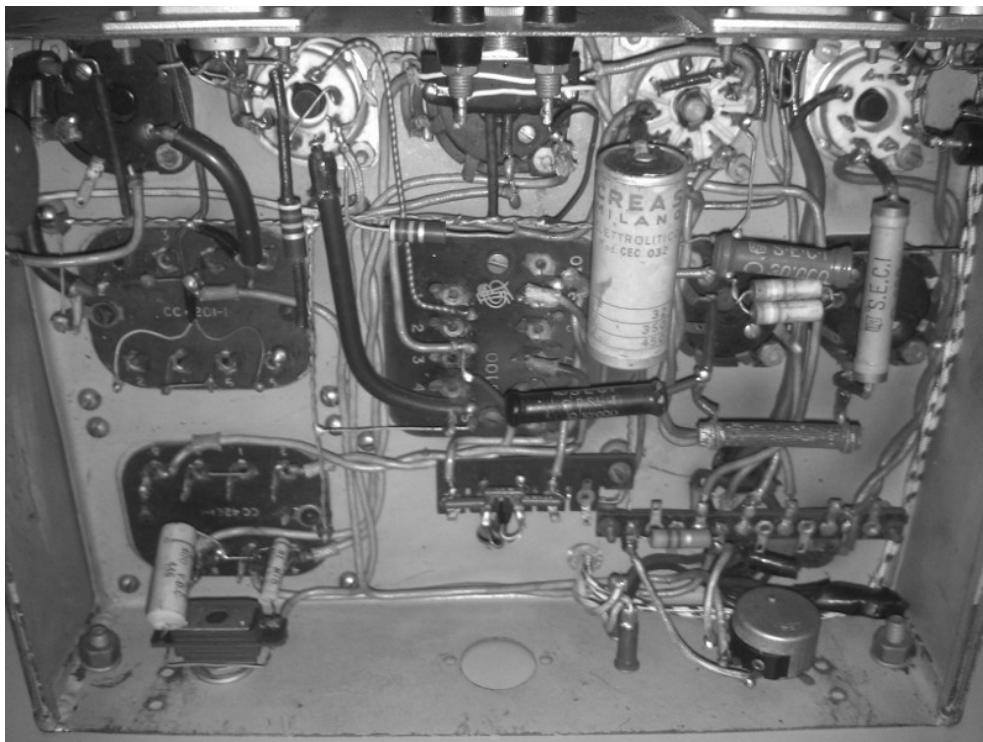

Figure 60 – Internal circuitry of the amplitude selector – Photo: Avanzini–Marchetto.

Unlike the oscillators, the amplitude selector still exists, although the control panel is not the one originally developed by Lietti in 1955, and is instead the one which was incorporated in the post-1968 SdF equipment. Therefore, we were able to directly inspect the device. Such direct inspection showed that the original project schemes provide an accurate documentation of the actual circuitry.

The inspection also allowed us to resolve an inconsistency between the original scheme and an alternative description of the device given by Lietti in a technical paper:[181] the two schemes report different values for a resistance in the circuit. We were able to verify that the value reported in the original scheme is the one actually used in the final realization. Finally, we found that one of the valves currently installed in the instrument does not correspond to the one indicated in the original scheme. This inconsistency is probably to be attributed to a later replacement due to failure of the original component.

Some details of the circuit cannot be inferred from the scheme, in particular the characteristics of the transformers. These cannot be assessed simply through visual inspection, and can be measured only by using *ad hoc* invasive techniques, at the risk of damaging the device. Therefore it was decided not to take the risk, and instead we used an indirect approach in order to obtain an approximate estimate of the transformers' characteristics.

Figure 60 shows the internal circuitry of the amplitude selector. The picture was taken during our physical inspection of the device. Among other things, it is worth noting the hole visible in the metal case at the bottom of the figure. The presence of this hole shows that the second (post-1968) control panel was simply superimposed on the original one. In fact, the position of the hole corresponds to that of the connector that was part of the original panel, which disappeared in the second panel.

Again, the circuit scheme was numerically simulated using the SPICE software (Figure 61, on the following page, shows the equivalent scheme). Both theoretical analysis and numerical simulations showed that the circuit has two operating modes, which depend on the activation status of the main non-linear element of the circuit (the pentode).

Without delving into technical details,[182] the first operating mode occurs when the pentode is switched off, In this case the rest of the circuit behaves in such a way that the input signal passes unchanged through the device except for a scaling factor. On the other hand, when the pentode is switched on, the output signal will be zero or not, depending on the value of a potentiometer, and depending on the amplitude of the input signal with respect to a reference voltage value. Both these values can be controlled from the front panel, using the knob at the bottom left.

The activation status of the pentode depends on a complex feedback mechanism in the circuit and is regulated by the input signal. The speed at which the pentode is switched on and off depends on the speed at which the RC (resistance-capacity) feedback circuit responds to changes in its feedback signal. The switch at the bottom right of the front panel lets the operator select between two time constants (0:001 s and 0:01 s).

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181.   See Lietti, "Soppressore di disturbi a selezione d'ampiezza" op. cit. pp. 1–3.

182.   A thorough analysis of the circuit, as well as its numerical simulation, have been presented in Canazza – Rodà – Novati – Avanzini, "Active preservation of electrophone musical instruments. The case of the 'Liettizzatore' of 'Studio di Fonologia Musicale' (Rai, Milano)," in *Proc. Int. Conf. Sound and Music Computing* (SMC 2011), Padua: Padova University Press, July 2011: pp. 304-309.
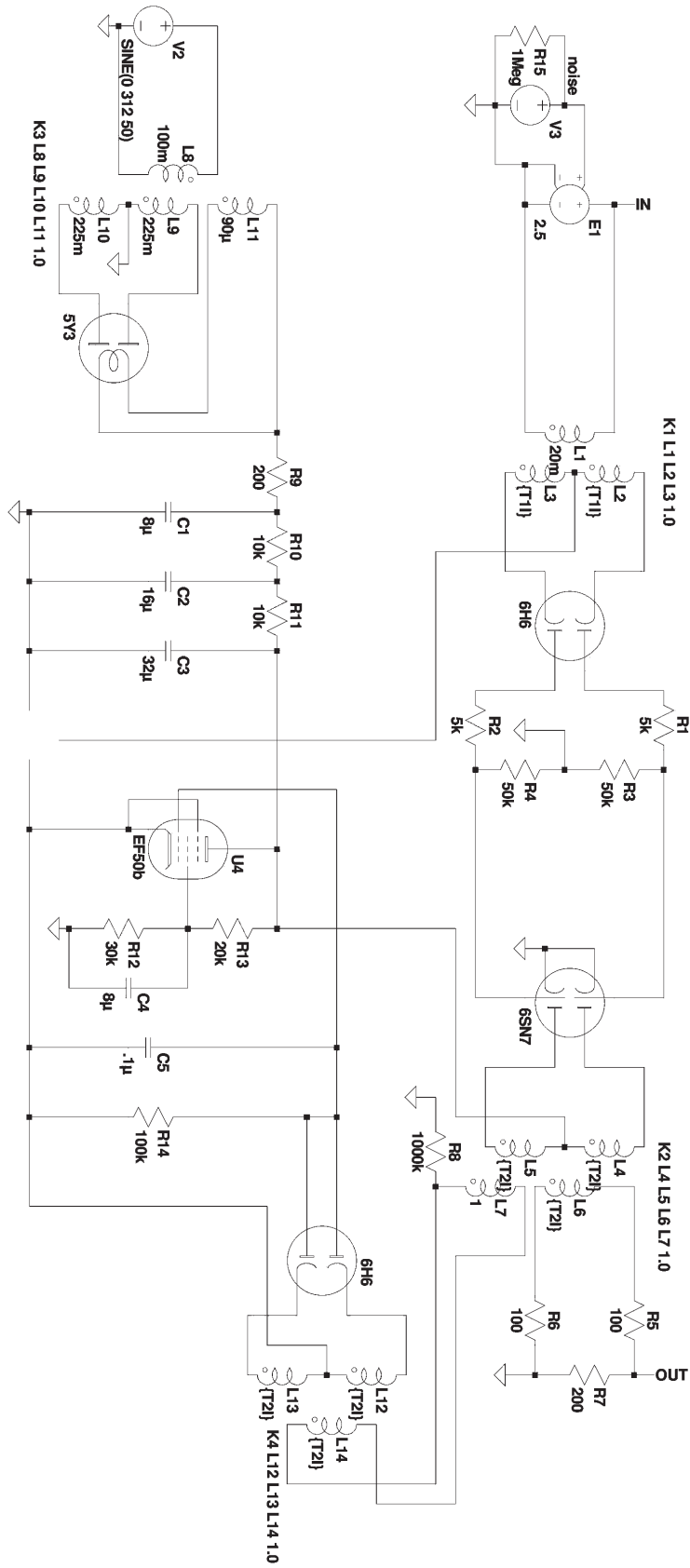
Figure 61 – Circuit scheme of the amplitude selector used in the numerical simulations.

Figure 62 (on the following page) shows a sample of the results obtained from our simulations. One can see a sinusoidal input signal with slowly increasing amplitude (upper panel) and the corresponding output from the device (lower panel). The output is silence, until the envelope of the input signal exceeds the reference voltage: at this point, the output exhibits a short transient and then becomes identical to the input sinusoid. In Figure 63 (on the following page), one can see a stochastic input signal (upper panel) and the corresponding output from the device (lower panel). Again, the output is silence until the input exceeds the reference signal. At this point, the pentode switches off and the output becomes identical to the input after a short transient. Finally, when the input signal decreases, the output goes gradually back to silence.

An important outcome of our simulations is that they demonstrate that, from a functional point of view, the amplitude selector behaves like a noise gate.[183] Interestingly, in his accounts about the realization of *Scambi* Pousseur describes it in a rather different way,[184] as a device able "to select from a group of signals (or from a longer, more complex sound phenomenon), only what exceeds a given dynamic level". Therefore, according to the composer's descriptions and accompanying figures, only the waveform portions that instantaneously exceed the threshold (i.e., the reference voltage) pass through the amplitude selector. Instead, our results show that the entire waveform passes through when the envelope exceeds the threshold. This demonstrates that our simulation approach provides evidence that would not be available from written accounts by composers.

183.   A noise gate is a device commonly used in the recording studio, that allows a signal to pass through only when its envelope exceeds a set threshold. If the signal envelope falls below the threshold, then no signal is allowed to pass. A noise gate is typically used to attenuate background noise: the threshold is set above the level of the noise, so that the gate opens only when there is signal (and both signal and noise pass through: a noise gate does not remove noise from the signal).

184.   See Pousseur, "Scambi. Description d'un travail," in *Écrits Théoriques 1954-1967*. Selected and edited by Pascal Decroupet, Sprimont: Mardaga, 2004: pp.147-159. See in English: http://www.scambi.mdx.ac.uk.

Figure 62 – Results from numerical simulations:
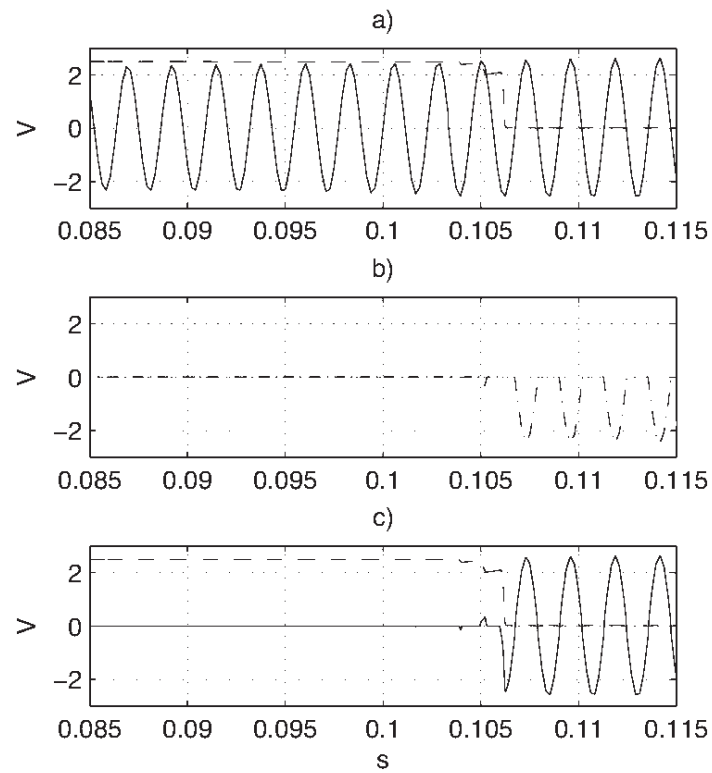response to a sinusoidal signal with slowly increasing amplitude.

Figure 63 – Results from numerical simulations:
response to a stochastic signal.