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Summary

The paper describes an Audio Terminal, TAU2, capable of producing complex sounds in real time under instructions elaborated by a general purpose digital computer.

The terminal, which can be widely used in experiments on electronic sound synthesis, is a useful tool in Computer Music; it has good musical features, allows interaction between user and computer, and requests low CPU time to generate musical pieces. This last feature makes it completely different from other systems used in Computer Music; moreover, TAU2 can be connected with the computer in time-sharing, as a general peripheral unit.

Some conclusions based on an experimental use of the terminal are given.

1. Introduction

A musical piece, in a broad sense, can be expressed by parametric formulas: in fact a piece is composed by series of sounds, a sound is essentially a collection of notes, and a note is a basic signal characterized by pitch, intensity, tonality and duration[1].

For many years musical pieces have been composed or elaborated with the aid of digital computers; early experiments were made twenty years ago. Even if it is rather simple to write programs which control the computer in musical code production, it is harder to transform such codes into sounds. Moreover, computer-processed texts must be played either by human executants with traditional instruments, or by suitable devices in an automatic way: if this procedure is adopted, not only the music player is released from ardous conventional technics, very boring in Computer Music but also an exact and undistorted performance is obtained[2].

When automatic performances are desired, it is necessary to convert digital data processed by the computer into signals suitable for driving electro-acoustical transducers. There are two general methods for the synthesis of electro-acoustical signals. In the first, data processing and signals synthesis are both performed by digital computers, which calculates the sampling values of the signal to be synthesized and transfers them to an ADC[3]; in the second one the computer can be used for data processing only: the sound parameters, properly codified, are sent to a special device which performs the audio signal synthesis.

The first method is flexible but expensive, owing to the long CPU time requested, the second one is obviously stiffer but also cheaper, because it allows to save up processing time and allows users to listen to the results of processing in real time.

Some researchers of I.E.I. have been working, jointly with researchers of CNUCE (Centro Nazionale Universitario di Calcolo Elettronico), on the electric signal synthesis for automatic music composition[4,5]. The second method previously described has been followed, and a first goal was reached in 1972 with the experimental prototype TAU1: this is an Audio Terminal which yields analog signals by harmonic synthesis, under the instructions received off-line from a digital computer[6].

TAU1 was built to evaluate the optimal quantization levels of the sound defining parameters, so as to attain a good compromise between the quality of the emitted sounds and the quantity of data processed by the computer; on the basis of this experiment a new Audio Terminal has been designed: TAU2[7].

This device, which is endowed with enhanced musical and structural characteristics, is capable of continuously producing complex sounds in real-time; a TAU2 terminal has been operating at I.E.I. since the second half of 1975.

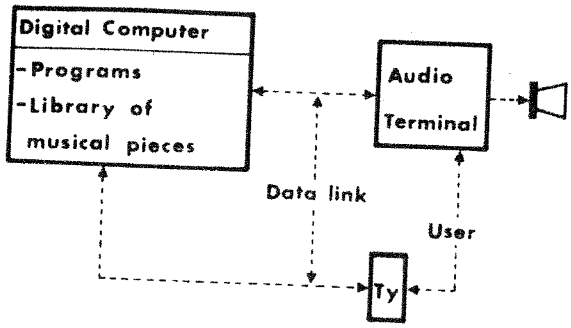
2. Structure of a Computer Music System

The organization of a system using the TAU2 terminal is shown in fig. 1. We can see:

A digital computer, which stores data processing programs and the musical pieces library.

A teletypewriter, by which the user communicates with the computer.

The Audio Terminal, which receives the parameters of the sounds to be emitted from the computer and controls the transmission



(fig.1) - System organization

and reception of the data.

At first the user prepares the piece to be processed, either recalling it from the library, or loading it via an input terminal; then the user defines the programs to be executed and starts the job. When data are transferred to the terminal the execution of the piece begins.

3. The TAU2

Operating Principles.

We have already said that analog signals in TAU2 are obtained by harmonic synthesis; we shall now examine this process. The mathematical description that follows is not exact, results are still adequate enough for musical piece synthesis.

Any stationary signal s(t) can be expanded in series of trigonometrical functions:

$$s(t) \simeq \sum_n a_n \cos(2\pi f_n t + \varphi_n) \qquad (1)$$

where:

- f_n = n-th harmonic component frequency
- a_n = " " " amplitude
- φ_n = " " " phase angle

The values of parameters a_n, f_n, φ_n are obtained from Fourier's analysis of s(t); for each time variable functions, the amplitude spectrum $s(\omega)$ and the phase spectrum $\Phi(\omega)$, are defined.

Thus a signal s(t) can be built by suitable signals in accordance with the results obtained from the analysis of s(t); the signal s(t), specified by the set of parameter

$$s(t) = \{A_i, F_i, \varphi_i\} \qquad (2)$$

where

A_i = amplitude of the i-th component

F_i = frequency " " " "

φ_i = phase of the i-th component

can be obtained by harmonic synthesis if trigonometrical functions are used as building signals.

Actually, audio signals are not constant, thus for each of the notes to be emitted we can detect an attack, a quasi-stationary state and a decay, which have time-varying spectra $s(\omega,t)$ and $\varphi(\omega,t)$[8]. Consequently, the parameters which define the notes are time dependent; we can thus specify a note with the expression:

$$q(t) = \{F(t), A_1(t), \varphi_1(t), I(t)\} \qquad (3)$$

where:

F = pitch of the note

A_1 = amplitude of the i-th component

φ_1 = phase " " " "

I = loudness of the note

Only the frequency of the fundamental component is defined, because the frequences of the harmonics are simply integer multiples of it. The phases of the signals generated by TAU2 are not controlled, for the purposes requested; the parameters φ_i are then omitted, the remaining parameters are quantized and defined at discrete time intervals, and espression 3) becomes:

$$q_n \simeq \{F_n, A_{i,n}, I_n\} \qquad (4)$$

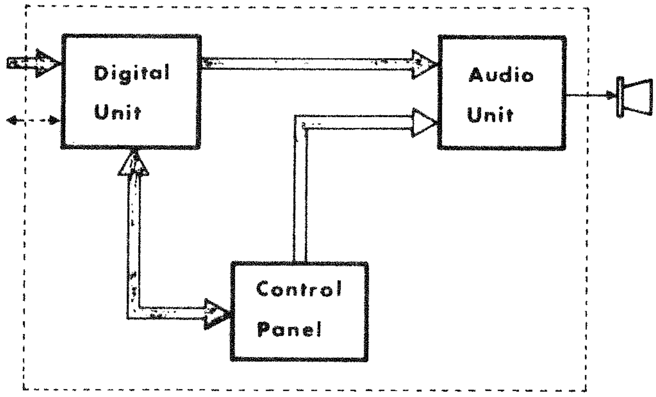
The number of possible values which can be assumed by each parameter and the length of time intervals have been chosen by taking into consideration the characteristics of the hearing perception[9] and some requirements of simplicity in the realization. In order to simplify data processing and data exchange between the computer and the terminal, a single clock has been adopted so that all the notes to be emitted are changed at the same time. The minimum time interval to perform standard pieces is 10 ms.

Figure 2 shows the structure of TAU2. Two main parts are distinguishable: the Digital Unit, which processes data coming from the computer, and the Audio Unit which produces analog signals specified by the digital parameters processed by the Digital Unit.

Project Criteria.

Three classes of requirements have been taken into consideration to define TAU2 features:

a) Acoustic and musical requirements: a quantity of simultaneous notes has to be emitted so that a rather complex piece can be performed. Each parameter has to be singly specified, and the performance of a piece of music has to be independent of data trans-



(fig.2) - TAU 2 structure

mission rate.

b) Computer programming requirements: the set of the operations needed for driving TAU2 has to be as simple as possible.

c) Hardware requirements: the circuits must be highly reliable, moreover the architecture of the system must allow future improvements and an easy maintenance.

Musical Requirements.

In order to be able to simulate different sources of sound over a plane TAU2 can generate sounds on three channels, simultaneously; each channel is capable of generating a set of up to four notes at the same time. All the notes of the set are characterized by the same loudness and the same harmonic composition (up to 7 harmonics). The pitch of each note can be selected between 255 possible values, which extend over more than seven octaves; the frequency resolution is 1/3 of semitone.

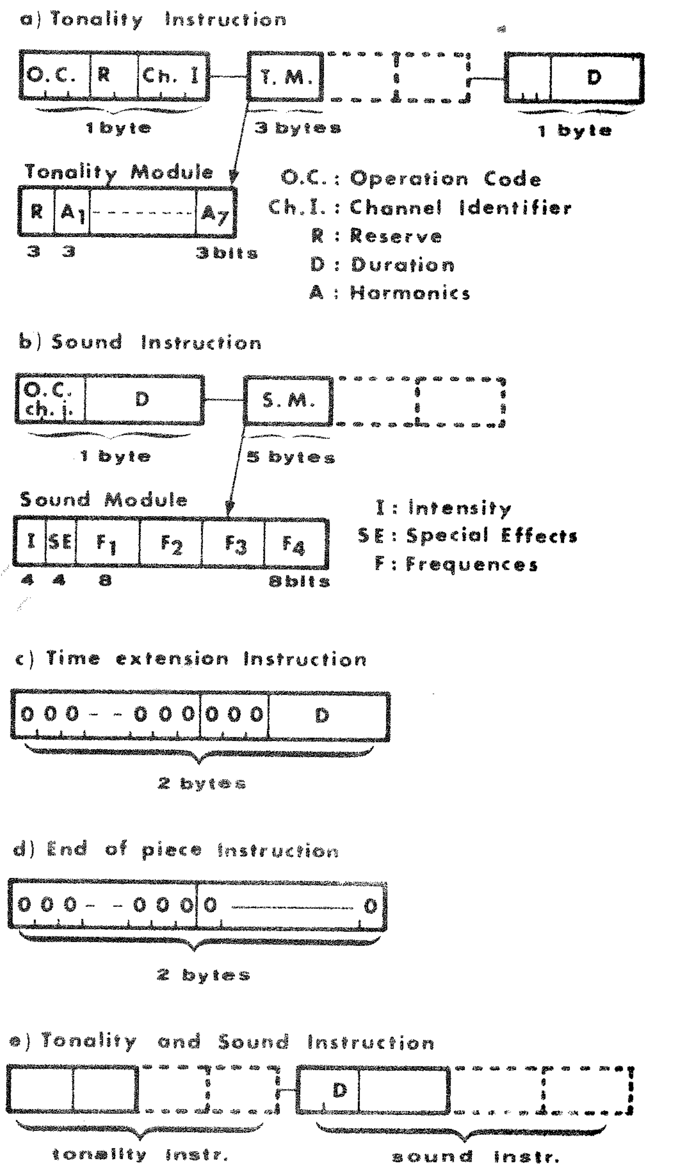
The intensity of each harmonic component, specified by proper instructions, can assume one of 8 values; the loudness level of each channel can be controlled over a range of 16 values.

The lenght of constant parameter sounds, given in internal time units, goes from 1 to 31; the absolute value of the time unit can be set to any value from 1 ms to 999 ms in steps of 1ms.

Data Organization.

To reduce data flow, changing parameters should be individually sent to TAU2, and input data should be assembled in many different ways. A great flexibility is thus obtained, but several bits are to be sent for channel and parameter identification, and the Digital Unit structure gets more and more complicated.

Looking then for simpler organization, input parameters have been assembled according to homogeneity and modularity criteria. Two types of variable-length instructions have been defined: one, named Tonality Instruction, which contains tonality parameters only and another named Sound Instruction, in which all remaining parameters are specified. The minimum data format used in the processing system, 1 byte of 8 bits, is an obvious condition for determining the instruction formats; considering that when the tonality of a note changes usually also several harmonic amplitudes change, it was decided to group all harmonic amplitudes togeter in a Tonality Instruction. The amplitudes of the harmonics of the notes emitted by one channel are specified in a 3-bytes module; two or three modules can be added to simultaneously modify the tonalities of two or three channels.



(fig.3) - TAU 2 instruction formats

The other input parameters, according to a similar criterion, have been assembled in Sound Instructions; in one module of this instruction the parameters of frequency and intensity valid for one channel are defined. The sound module is 5 bytes long. A sketch of the format of the two instructions is given in fig. 3.

TAU2 data input are then strings of "musical instructions"; a set of identification bit label channel selection and instruction formats, and modules of information compose the operands of the instructions.

The information flow is sligthly redundant, because whenever a change of few parameters occurs a module of instruction is transmitted, which contains also unchanged parameters; nevertheless having adopted the modular subdivision described, a reasonable compromise between the amount of transmitted data and the complexity of the Digital Unit is obtained.

The two types of instructions contain the parameter D, which specifies, in terms of relative units, the time interval which has to elapse before the next instruction is executed; the real time is given by:

$$t = D.T \qquad 1 \leqslant D \leqslant 31$$

where T is the time base set on the control panel of TAU2. Tonality and sound parameters can be modified together with the instruction shown in fig. 3e, while the instruction shown in fig. 3c can be used to hold constant parameters during time intervals longer then 31xT. With the instruction of fig. 3d, End of piece, no sounds are emitted from the Audio Unit, while the Digital Unit is still ready to start the execution of the next piece without any operation on the Control Panel.

If necessary, further information different from that described can be transmitted by means of Tonality Instructions using label bits 4 and 5 for code extension.

Description of TAU2.

In the previous paragraph the logical structure of the input instructions has been described: during the operation the instructions must be sequentially tested and interpreted, and must be executed according to the modality stated in the instruction itself.

In paragraph 3 it was stated that the input parameters should be modified at least every 10 ms: TAU2 must then receive sets of instructions at a rate of 100 Hz. This is a peak rate, whose occurrence depends on the complexity of the pieces to be executed; usually the mean data rate is much lower, however a peripheral unit cannot usually accede to the computer with those rates. TAU2 has been then supplied with a buffer memory in order to match the discontinuous data flow from the computer with the data flow required by the execution.

The buffer memory is a FIFO circular queue, byte addressed and divisible into blocks of equal length. To avoid spurious gaps in piece reproduction the following equation must be satisfied:

$$\frac{N}{2} \geq (T + T_w)\, R_r \qquad (5)$$

with $T_w = \frac{N}{2r_t}$ or $\frac{N}{2R_m}$ whichever is greater

In the above expressions the symbols have the following meaning:

- N = Buffer capacity
- T = Access time
- T_w = Half-storage writing time
- R_r = Mean reading rate
- R_t = Data transmission rate
- R_m = Maximum writing rate

The following values have been assigned to the parameters: R_t = 4800 bit/s. This is a safety data transmission rate in communication links with available modems. T = 5s. An IBM 370/168 time-shared system usually allows shorter access time R_r= 1600 bit/s. This value results from empirical analysis conducted on a set of polyphonic pieces: the mean rate at which instructions are changed into 10s time intervals was found to be 20 instructions/s. Assuming that two out of three channels are simultaneously modified, we obtain R_r 1600 bit/s.

Substituting these values in eq. 5) and neglecting T_w we obtain $N \simeq 24.000$ bits.

A 32-K memory has been adopted. The block diagram of TAU2 is shown in fig. 4; the component parts are:

A) Digital Unit, which is subdivided into

1) Input interface: it provides two 8-bits input ports and several control or timing lines.

2) Buffer memory: the 32-K RAM is supplemented with two 12-bits address pointers.

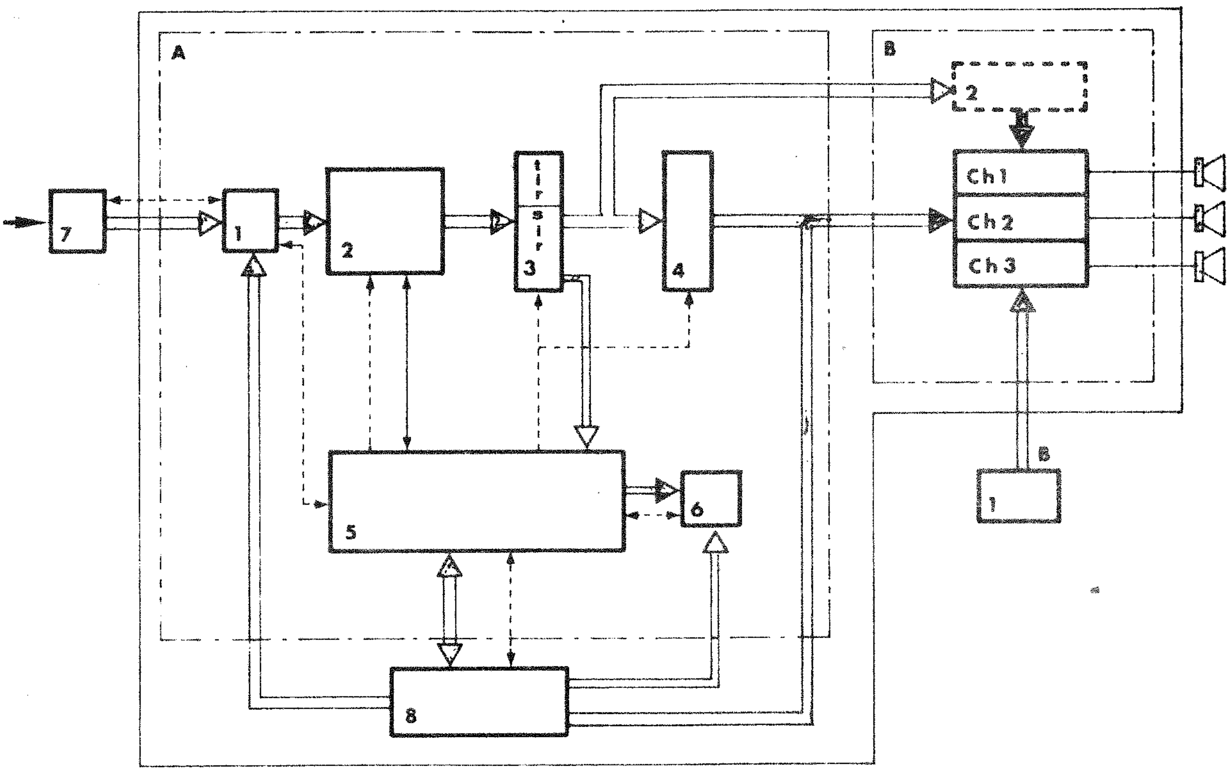
3) Instruction register: the Tonality instructions are stored in the part TIR, and the Sound Instructions are stored in the section SIR.

4) Output register: six programmable ports receive the information modules from IR.

5) Control Unit: transfer check, decoding and execution of the instructions are controlled by a microprogrammed unit.

6) Time base; is a clock for timing the execution of instructions.

7) External interface: the link interface has an internal control so that transfer mode can be varied without modifications of TAU2 structure.



(fig.4) - TAU 2 block diagram: see text.

8) Console: The user communicates with the Digital Unit via a Control Console.

B) Audio Unit: the system which converts digital parameters into electro-acoustic signals is organized into three identical Channels, C_1 C_2 and C_3.

1) Musical keyboard: it allows the user to manually play the notes emitted on channel 1; channels 2 and 3 are always controlled by the computer.

2) Special effects: sounds generated by the three channels can be modified by progra mable devices (to be developed).

TAU2 operates according to the following procedures. Input data blocks of equal size are transferred and loaded into the TAU2 memory; at present each block contains 2048 bytes.

Either computer or terminal can initiate the data transfer. When transmission runs TAU2 Control unit surveys the access to the memory: whenever the buffer can store a new data block, Control unit sends a request to the Computer; moreover if the data block to be read has been already read or if it has not been completely and correctly loaded, reading process is interrupted until a valid data block is loaded.

The instructions stored in the buffer are sequentially executed: instruction I_{n+1} is read when time D, specified by instruction I_n, has elapsed. While Audio Unit emits the sounds defined by I_n, Control prepares I_{n+1} into I R register, so that gaps in the piece performed are avoided.

TAU2 was settled to allow synchronous or asynchronous data transfer at a speed up to 50 K bytes/s: data writing and reading proce dures must thus be interleaved. A properly organised Control Unit supervises the conflict ing accesses to the buffer.

Digital Unit. The Digital Unit of TAU2 has been microprogrammed: this organization has been adopted because it allows a simpler design of the Control unit and an easier maintenance of the whole system[10].

As in a general microprogrammed digital system, also in the TAU2, two interconnected sequential machines can be recognized: the Control unit and the Operating unit[11].

The Control unit syncronizes the following main procedures:

A) Data load and transmission
B) Instruction fetch
C) Instruction timing and execution

Procedures B and C are sequentially executed by means of a same microprogram; an asyncronous circuit counts the execution time and raises a flag when counting has ended. Another microprogram, which is called like a general subroutine, executes procedure A.

Procedures B and C usually engage the control; when the Input interface requests to write an incoming byte, the microprogram is interrupted at the end of the running microinstruction and the control is assigned to procedure A. At the end of procedure A the control is assigned again to procedures B and C till next request.

The "Written byte" signal has been conveniently delayed, so that several micro-instructions of procedures B and C are executed between two following As procedures. This way the instructions are correctly extracted from the buffer and prepared in the IR register: at a data input rate of 50-K bytes/s, a maximum format instruction is prepared in 1ms.

A single up-down counter syncronizes the operations which occur at the beginning or at the end of the data blocks; the design of the mechanism is based on the criteria described in[12].

The Operating unit is obviously a Moore's machine; also the Control unit of TAU2 is based on a Moore's model[13]; the micro-program pattern and the microinstruction structure are similar to those described in [14]. According to the performed algorithms a 64x33 bits read-only memory has been used; the ROM is implemented with discrete logic, so that microprograms can be handily modified[15].

More details on the design and the implementation of the Digital Unit are given in[16].

Microprocessing offers a useful procedure for musical and diagnostic purposes: a manually controlled switch allows the data transfer from the computer to be interrupted and the stored piece in the TAU2 buffer to be repeatedly played. Normal link and operations are restored when the switch is toggled again.

Some special test instructions are provided for the tuning and troubleshooting of the terminal.

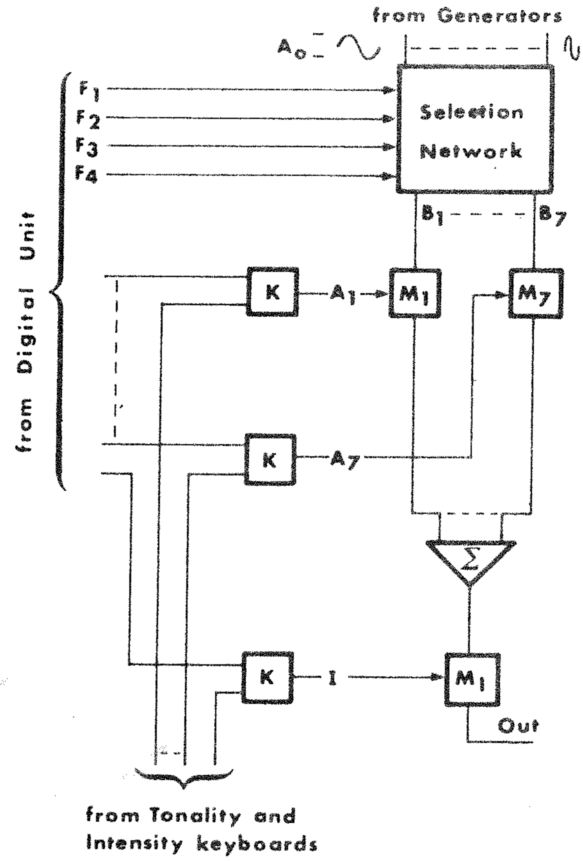
Audio Unit. Audio unit receives numeric parameters from Central Unit and converts them into analog signals according to the synthesis process mentioned in paragraph 3.

Voltage Controlled oscillators have not been used to implement component signals for two main reasons: the insufficient frequency stability of the devices avalaible when TAU2 was developed:
the large number of simultaneous signals emitted from Audio unit:

4 notes x7 harmonics x 3 channels = 84 signals.

Constant frequency signal generators have thus been used.

The frequences of the notes are regularly distributed over several octaves, each full octave containing 36 notes, so that the ratio between two contiguous notes is $\sqrt[36]{2}$. A set of 36 Xtal controlled oscillators has thus been used, which yields the highest octave notes: the other octave notes are obtained by repeated binary divisions. The square wave signals are converted into sinusoidal signals by L-C passive filters; a bank of low distortion , constant amplitude, constant frequency signals is thus obtained, from which the notes specified in the input instructions are selected by means of digitally controlled signal selectors.



(fig.5) - Audio channel structure: K = selector, M = amplitude modulators

The structure of an audio channel is shown in fig. 5; the following operations are performed. On bus B_1, or fundamental bus, the input signals are collected, whose frequences are defined by the values $F_1,\dots,F_4$ of the running instruction, while on B2,B7, the harmonics 2,...,7 are collected, owing to the selection network implementation.

Modulators $M_1,\dots,M_7$ set the amplitudes of the harmonics according to the values $A_1,\dots,A_2$; the components are then added and the resulting signal is amplitude controlled by modulator M_I, according to parameter I.

The channel output signal is thus given by:

$$U(t)=F(I)A_0 \sum_{n=1}^{7} f(A_n) \sum_{j=1}^{4} \sin\left(n\,\omega(F_j)t+\ \varphi(F_j)\right) \quad (6)$$

where:

A_o = peak amplitude of input signals

$\omega(F)$ = frequency " " "

$\varphi(F)$ = phase " " "

f = modulator transfer function

The expression is valid for the time D defined in the running instruction. More details are given in[17].

4. Conclusions.

An audio terminal has been built to try a computer controlled method for sound generation, which does not require long CPU time. The results given by TAU2 during several months of tests are very satisfactory both from a technical and a musical point of view. Software operating system is in an advanced stage of development at the Musical Division of CNUCE, and rather complex processes can be already obtained.

The easiness to operate the terminal has been made evident by the conducted experiments; by TAU2 also unexperienced users can use a digital computer to compose and process musical texts, wich is particularly helpful both to musicians who apply to musicology studies, and to students who follow didactic courses.

Acknowledgment

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