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SIMULATION -USING COMPUTER-PILOTED POINT EXCITATIONS- OF VIBRATIONS INDUCED ON A STRUCTURE BY AN ACOUSTIC ENVIRONMENT

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Abstract

It is now possible to compute the overall levels and spectral densities of the responses measured on a launcher skin (at fairing for instance) and merged into a random acoustic environment during take-off.

But the analysis of the transmission of these vibrations to the payload needs the simulation of these responses by mean of a shaker-control system using a small number of distributed shakers.

This closed-loop computer-based digital system allows the realisation of auto and cross spectral densities equal to those of the responses previously computed. Its possibilities are large (for instance road and runways profiles).
The problems to be solved are : multiple input-output system identification, multiple true random signal generation and real-time programming; the system now in progress should allow the control of four shakers.

Nomenclature

* Auto-power spectral density :

power of the output of an ideal filter, the transfer of which is centered around a frequency f and has a bandwidth of Δ f, when the input is the signal to analyze.

* $\phi_{R_i R_i}(f)$:

auto-power spectral density of the output of a sensor situated at point R_i on a structure.

* j :

complex element : $j^2 = -1$.

* f : frequency.

* F(t) : force, evoluating with time, imposed to a structure.

* $\gamma(t)$: acceleration measured on a structure.

* $V_e(t)$: voltage, input of a power amplifier

* $I_e(t)$: current, driving an electro-dynamic shaker.

* $V_e(t)$: current, driving an electro-dynamic shaker.

* db : decibel.

* DAC : Digital to Analog Converter.

* ADC : Analog to Digital Converter.

* Drive spectrum :

auto-power spectral density of $V_e(t)$ or F(t).

* $\phi_{CC}(f)$:

desired auto-power spectral density at frequency f.

* $H_c(f)$:

transfer funciton of the digital compensator.

* H(f) :

transfer function of the physical system.

* ϕ_{FF} (f) :

auto-power spectral density of F(t).

* $\phi_{\gamma\gamma}$ (f) : idem for $\gamma(t)$

* PSD : Power Spectral Density.

* $\underline{S}(f)$:

complex vector : each term is the Fourier transform of a time series of an output $S_i(t)$ of the physical system.

* $\underline{E}(f)$: idem for an input of the physical system.

* $\underline{C}(f)$.: idem for the input of the digital system.

* K(f) :

inverse of the square transfer matrix of the physical system.

I. Introduction

While crossing through the atmosphere, the structure of a spacecraft is submitted to unsteady loads generating forced vibrations sometimes dangerous for the strength of the launcher and of its payload or for the working of the embarked apparatus. Beyond excitations due to the combustion of the propelling stages, transmitted to the sensitive points by the mechanical path, the most important sources of vibration are due to the engine noise during the launching phase and to the intense aerodynamic instability which characterises the transonic phase of the flight (buffeting). The skin of the launcher, and particularly the fairing level which shelters the payload and the equipment bay are then submitted to a random fluctuating pressure field in a frequency range extending to several thousands of Hz and able to lead to important vibrations of the skin, and, by means of mechanical and acoustical transmission, to vibrations of the internal structures. The detailed study of these phenomena and of their mechanism being difficult by a purely theoritical approach, the execution of preliminary laboratory tests becomes indispensable to be sure of the qualification of the sub-assemblies to the ambience which they will have to bear during the actual launch. The classical means of these tests are big powerful shakers on the first hand and acoustic reverberant rooms on the other hand. The specimen is so tested according to a procedure and specifications which are defined by conventional standards warranting, as a principle, testing conditions at least as severe as the actual conditions during the flight. This idea of "equivalent severity" is in fact only a language convenience, the real content of which is very vague. In fact, most of the time, one ignores if the laboratory test uselessly penaltizes the specimen in comparison to its environment during the flight, or conversely, if it does not underestimate the danger against which it will be actually exposed, which may have serious consequences.

The necessity to carry out laboratory tests which really represent a realistic simulation of the flight conditions is again emphasized by the development of large launchers, able to carry very voluminous payloads. The dimensions and the cost of corresponding ground facilities become huge, which gives a stimulus to the necessity of serious guarantees concerning the conclusions of the tests (which are executed within).

There are difficulties found in giving a correct theoretical base to this question which have lead ONERA to propose a new approach, the first application of which has been executed on the fairing of the ARIANE launcher in 1979. This simulation method uses random punctual excitations applied to the skin of the specimen at a small number of points and piloted by a computer. The aim of the simulation consists consequently to reproduce, by means of punctual excitations, the vibratory field at the skin level as it appeared during flight under the action of the actual environment. In other words, the question is to simulate the vibratory response of the structure and not the external pressure field (as one tries to do in a reverberant acoustic room for instance).

It is so necessary to first know, by means of a provisional calculation, the statistical characteristics of the vibrations of the skin (power spectral density, mean square level) in the presence of the real environment.

This calculation is excuted by the aid of the methods which have been used successfully by ONERA for several years, in the framework of the "statistical dynamic approach".

The simulation is then realized by introducing such a force distribution that the vibrations which it induces have the same power spectral density and the same overall level.

II. Putting of the problem

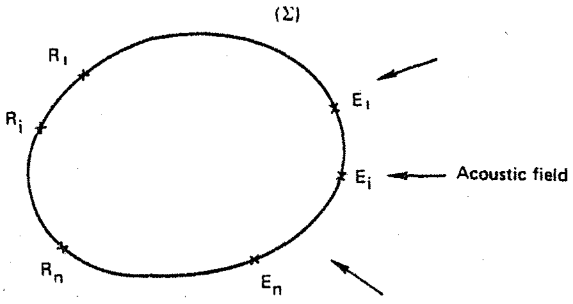
II.1. Provisional calculations

The provisional calculations allow one to know the auto and cross power spectral densities of the velocity or acceleration of the skin of the structure at some points of interest. These responses are worked out from the knowledge of :

- the dynamical characteristics : they are normalized cross-spectral densities of the responses measured at the wall, due to a random concentrated mechanical force applied at the very point where we want to know the response in the actual environment (see figure 1). Such a quantity has been called "generalized Green's functions". In order to obtain these characteristics we need to perform tests in the laboratory. The frequency range of interest extends from 0 to 2000 Hz.

- an extrapolation of the model of the acoustic field in which the structure is immersed. The modelling is either analytical (for instance in the case of a perfect diffuse field) or built up from previous investigations. The major quantity to be determined here is the cross-spectral density of the fluctuating pressure acting on the body.

Figure 1



(Σ) : structure under test
E_i : point where the mechanical force is applied in order to obtain the dynamical characteristics
R_i : point where the predicted response is computed.

II.2. Principles of the simulation

The aim of the simulation is to physically reproduce by means of a few number of shakers distributed on the structure, the previously computed responses due to the acoustic environment. So, the vibration of the external envelope is thought to be very close to the vibration due to the actual acoustic field. Consequently, the acoustic transmission inside the structure and the vibration level also transmitted to internal substructures by mechanical path can be measured directly. Typical examples are those of a single equipment attached to the main structure on the payload inside the fairing of a launcher. The principle is to apply at the excitations points E_i (see figure 1) non coherent random mechanical forces, the auto-power spectra of which being controlled such that at R_i points one obtains the predicted power spectra. The prediction at n points R_i is defined either by a power spectral vector :

$$\begin{bmatrix} \phi_{R_1R_1}(f) \\ \vdots \\ \phi_{R_iR_i}(f) \\ \vdots \\ \phi_{R_nR_n}(f) \end{bmatrix}$$

if the outputs R_i have undefined cross-power spectra, or a diagonal matrix :

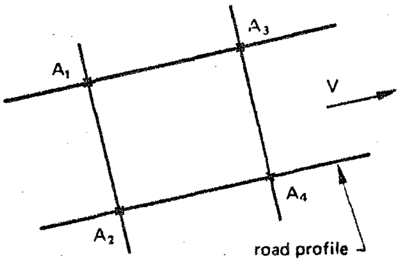
$$\begin{bmatrix} \phi_{R_1R_1}(f) & & o \\ & \phi_{R_iR_i}(f) & \\ o & & \phi_{R_nR_n}(f) \end{bmatrix}$$

if the outputs need to be non coherent. This matrix is called the desired matrix.

II.3. Simulation of coherent process

When the responses which are to be simulated are uncoherent, the power spectral matrix is diagonal (see above). For other general applications, this matrix may be of any kind; as an example of such a general problem, let us consider the case of straight displacement of a four-wheel vehicle on a rough road : the inputs are now the displacements imposed to the wheels by the roughness of the road and the outputs can be chosen as the actual forces sensed by the wheels (see figure 2).

Figure 2



V : velocity of the vehicle
A_i : contact point of the wheel with the road

During the motion, the displacement of A_1 (resp. A_2) is the same as that of A_3 (resp. A_4) but with a delay depending on the speed V of the vehicle. In the power spectral density expression of the inputs, the non diagonal terms are then proportional to the coupled terms $e^{j\varphi(f)}$, φ being an angle. Generally speaking, the desired matrix is hermitic with any diagonal terms.

II.4. Application to the acoustic transparency

Let us consider the fairing of a launcher which shelters a payload (satellite for example) in the acoustic ambience at taking off. The aim of the simulation applied to transparency, consists in the prediction of the acoustic levels within the fairing. To reach that, one reproduces the power spectral densities of the predicted calculations by the method described in the chapter II. which are the effects on the fairing due to the external field; one admits that, the effects of the actual field on one hand and the effects of the shakers during the simulation on the other hand being the same, the internal acoustic field is the same. Such a procedure allows a simulation in the laboratory or at the factory. Figure 3 shows the implementation of the sensors and shakers during the test which has been performed on the fairing of launcher ARIANE LO1.

II.5. Results obtained on launcher ARIANE LO1

During launching of ARIANE LO1, which occurred on December 1979, at Kourou, noise measurements performed within the fairing have given an idea of the acoustic level transmitted to the cavity and able to generate payload vibrations.

Figure 3

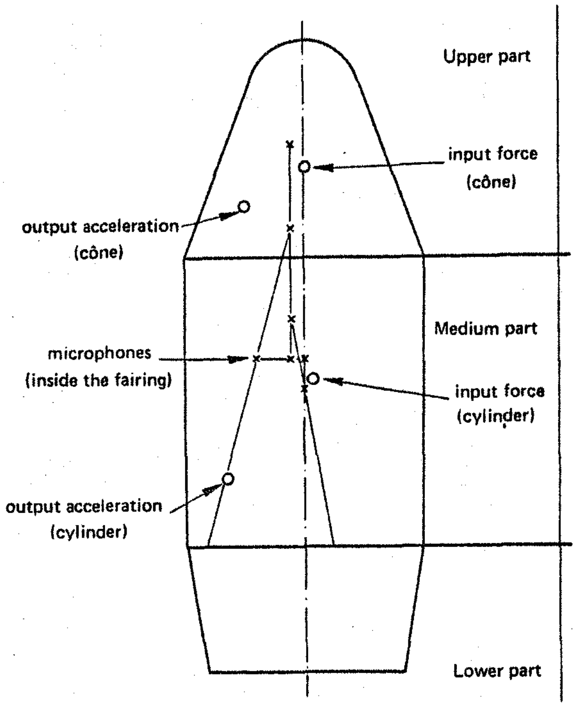
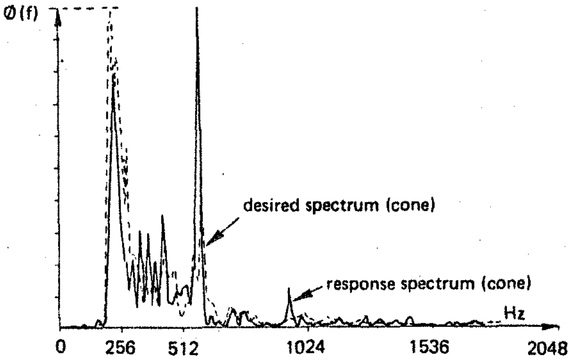
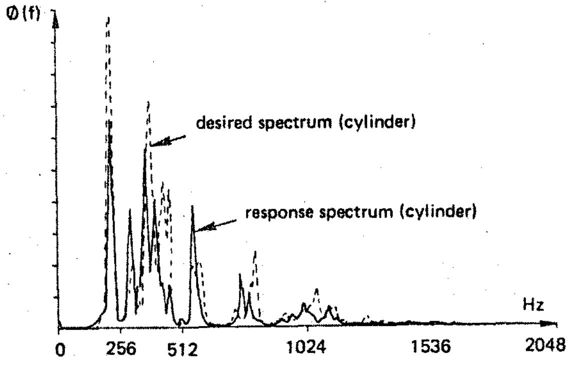


Figure 3bis



Upper part



Medium part

The skin vibrations of the fairing has been reproduced in laboratory by means of shakers piloted by a computer; two shakers were piloted off line from two time series generated on the computer. These tests permitted to know the internal acoustic field due to skin vibrations of the fairing and to compare the overall levels to those measured during launching.

The overall internal levels computed during the test were :

upper part : 135.8 to 137.8 db

medium part : 134.7 to 136.7 db

lower part : 134.6 to 136.6 db

The first analysis of the internal measurement during actual launching in the medium part gives an overall level of 138 db. Figure 3bis gives the desired spectra for the upper and medium parts and the corresponding response spectra (spectra to be simulated).

III. Recall on the principles of single shaker random vibration control

The recall on single channel theory will allow comparisons with the multiple channel case. In the single channel case, one reproduces one auto-power spectral density.

III.1. Principle and aim

Let us consider figures 4 and 5

Figure 4

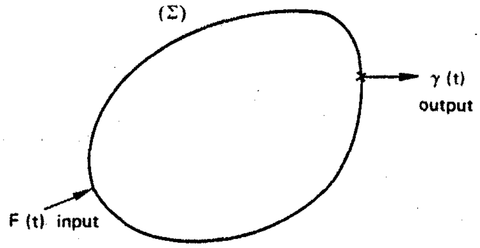
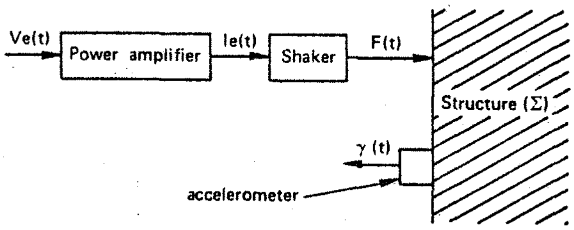
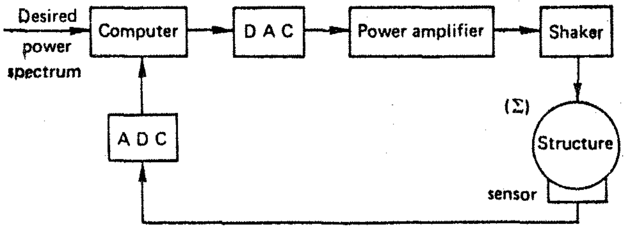


Figure 5



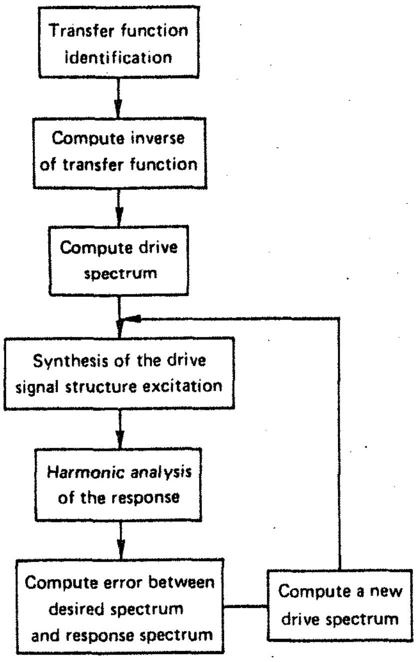
The aim consists in the realization of the numerical synthesis of the drive signal $V_e(t)$ which is the input of a power amplifier which drives an electrodynamic shaker, so that the power spectral density of the response signal (γ (t)) is equal for each discrete frequency (within an uncertainty tolerance of ± 3 db or ± 6db) to the desired power spectral density. The schematics of such a system is given below :

Schematic 1



The principle may be summed up in the following schematics :

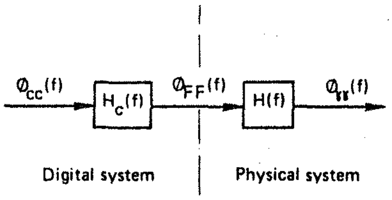
Schematic 2



III.2. Identification and compensation

From a functional point of view the system may be shortened to :

Schematic 3



The digital system includes the computer, ADC and the DAC : it can be considered in the frequency domain as a system the transfer function of which is Hc(f) with the desired spectrum $\phi_{cc}(f)$ as the input. The physical system includes the amplifier, shaker and sensor and has H(f) as a transfer function. One computes $H_i(f)$, computed transfer function of the physical system, by the ratio :

$$\left|H_i(f)\right|^2 = \frac{\phi_{SS}(f)}{\phi_{EE}(f)}$$

where $\phi_{EE}(f)$ is the auto-spectrum of an input which may be true-random, or better pseudo-random which needs less time excitation for the same accuracy. The compensation consists in the digital realization of a system, the transfer of which is:

$$\left|H_c(f)\right|^2 = \frac{1}{\left|H_i(f)\right|^2}$$

The frequency range of interest extends from 0 Hz to 2500 Hz. When there are frequencies where $H_i(f) \simeq 0$, an interpolation is necessary. Looking at the schematics n°3, we see consequently that the total transfer between the input of the digital system and the output of the physical system is unity : therefore if the power spectrum density of the input of the numerical system is $\phi_{cc}(f)$, the output will be theoretically the same if the following conditions are met :

-$H_i(f)$ equals the true transfer function and the dynamic range of the analog-digital converter is large enough to see peaks and valleys of the transfer functions.

- no loss of significance happens in the inversion of $H_i(f)$, particularly when computing the inverse of the values situated in the valleys.

- the randomization does not modify the power spectral density of the drive signal at the input of the physical system.

The P.S.D. of the drive signal becomes therefore :

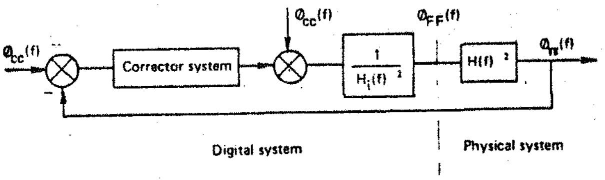
$$\frac{\phi_{cc}(f)}{\left|H_i(f)\right|^2}$$

III.3. Correction

The output signal from an input the kind of which is $\phi_{cc}(f) / \left|H_i(f)\right|^2$ may differ from $\phi_{cc}(f)$ at several frequencies mainly because of the non-linearities of the structure which cannot be taken into account during the identification phase -and noises on the measurement; particularly during the vibration control session, the transfer function may change because of the modifications of the mechanical properties of the structure under test.

The schematics below illustrates the principle of the correction.

Schematic 4



The actual output density function is compared to the desired density function and the error is inputted to a digital corrector system which may be a integrator or a first order system. At the beginning, the error is zero at each frequency, so we find again the compensation system. An integrator as a corrector system insures the stability of the closed loop system because, from a feedback point of view, the transfer functions are pure gains. The above schematics apply to each frequency where the power spectral density is computed.

III.4. Randomization

The output of the digital system is a discrete power spectrum density function but the input of the physical system is an analog waveform. The randomization consists to generate a true random gaussian time series from an auto spectrum density function.

The correction and compensation produce a power density on N/2 points :

- one computes by a congruence method, N/2 random phases equally distributed between 0 and 2 .
- one forms a complex spectrum.
- one takes the inverse discrete Fourier transform, giving a periodic time series which is pseudo-random.

At this time, the time series is periodic and is not pure random. A way to get a pure random time series would be to repeat for each group of N points the above procedure by changing the N/2 random phases; but the time needed to compute the Fast Fourier Transform would decrease the bandwidth of the system; a better way is to shift the original pseudo-random time series and then overlap the blocks of N points after being weighted by an appropriate window.

IV. Multi-channel random vibration control

The passage to a multi-channel system implies some differences in the methods and architecture of the digital system to be used.

IV.1. Comparison between single and multi-channel systems

IV.1.1. Desired spectra. In the multi-channel case it is a spectral matrix with non diagonal terms in the general case.

IV.1.2. Identification. In the single-channel case it is simple because only one input is needed. In the multi-channel case, if one wishes to perform the identification in only one test, the spectral matrix of the inputs has to be regular so that the inverse matrix transfer may be computed. Problems may appear if at some frequencies the input spectral matrix is not inversible.

IV.1.3. Phase between channels. In the single-channel case, no phase is to be respected; in the multi-channel case, phases between inputs are related to the non-zero non-diagonal terms of the desired spectral matrix and transfer matrix, so the randomization has to respect the phases laws matrix.

IV.1.4. Re-identification. It is easy in the single-channel case, but difficult in the multi-channel case; if the desired spectral matrix is non regular, the input matrix is also non regular so that the inverse transfer matrix cannot be computed; if it is computable, it increases the loop time which is the time between two adjustments of the input spectral matrix of the physical system.

IV.1.5. Hardware. In the single channel case all the tasks are centralized in a general purpose computer; in the multiple channel system, computation is so heavy that a host computer is needed for the display, another processor for the mathematical computations and other processors for the input-output operations.

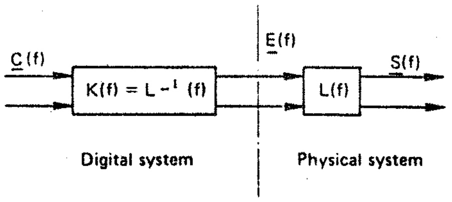
IV.1.6. System architecture. In the single-channel case, a general purpose sequential computer fits to the problem. In the multi-channel case a fast parallel oriented computer is needed; furthermore it has to be signal processing oriented.

IV.2. Realization of non-coherent responses

According as the desired spectral matrix is diagonal or not, two methods can be implemented; we will explain the case of a diagonal desired matrix.

If L(f) is the transfer matrix of the physical system, one realizes in the digital system an uncoupling of the channels according to the schematics below :

Schematic 5



Therefore it is sufficient that the spectral vector $\phi_{cc}(f)$ be equal to the desired vector, to have $\phi_{s_i s_i}(f)$ equal to $\phi_{c_i c_i}(f)$. The compensation which is so performed acts on complex spectra; the cross-coupling compensator is such that the total system between vector $\underline{C}(f)$ and $\underline{S}(f)$ is equivalent to n single-channel systems. It is therefore sufficient to apply the desired spectral matrix to the digital system as we do in the case of single-channel. As for the single-channel case, the non-linearities of the structures are corrected by correction loops, the number of which is equal to the number of uncoupled channels.

IV.3. Randomization

It is in the synthesis of the signals driving the shakers that the channels are uncoupled. We start with the n auto-power spectral densities of the n components of the $\underline{C}(f)$ vector :

- one computes n groups of independent random phases equally distributed between 0 and 2 π in order to build a complex vector $\underline{C}(f)$,

- one performs the product of vector $\underline{C}(f)$ with matrix $L^{-1}(f)$ which gives vector $\underline{E}(f)$,

- n inverse Fourier Transform give n pseudo-random time series,

- a time mixing equivalent to that of the single channel case is then performed on each time series, but in order to keep the phase relations between the channels, the value of the time shifting has to be the same for each channel.

IV.4. System architecture

In the case of the dual-channel vibration control, the digital system can be summarized as shown in schematics n°6.

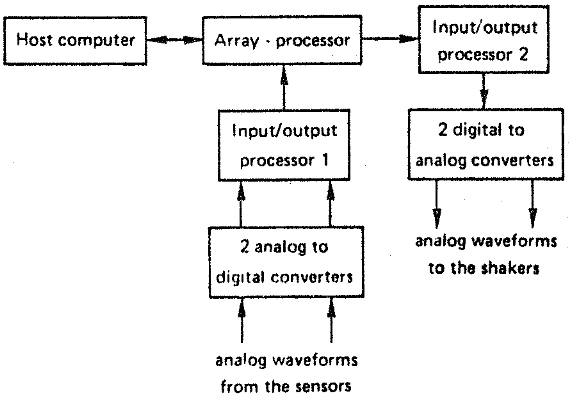
IV.4.1. Sharing of the tasks. The tasks devoted to each processor are described below :

IV.4.2. Host computer. -It insures the acquisition of the parameters of the system :

- bandwidth
- sampling frequency
- number of discrete frequencies on which the spectra are computed.

-It initializes the array-processor and the input-output processors.

Schematic 6



IV.4.3. Array-processor. It is devoted to the high-speed floating-point mathematical computations while insuring the handling of the real-time control of the input-output processors. It insures :

-the harmonic analysis that is the computing of the short-term and long-term spectra after weighting the data by an Hanning window.

-the computing of the inverse transfer matrix; this computation is not performed in real time but after data acquisition.

-the correction by applying the corrector system to the error between measured and desired spectral matrices.

IV.4.4. Input-output processor 1. It insures the data acquisition and performs some treatments on the raw data; typically it insures :

-the acquisition in its memory of the interleaved samples from the channels connected to the output of the sensors.

-the conversion of the integer values into floating-point values in the array-processor compatible format.

-the demultiplexing of the channels, i.e. the samples on a same channel are sent in consecutive locations in the main data memory of the array-processor.

IV.4.5. Input-output processor 2. The function of this processor is the handling of the digital to analog converters. It insures :

-the handling of the address of the converters; when a converter needs data; it sends its address which is acquired by the processor and tested to compute the address of the buffer where to read the right data.

-the handling of the communications with the array processor by means of flags and interrupts; when a buffer is empty the processor needs to be aware that a new buffer is ready to be read; this handling is done in conjunction with the randomization.

In a first step, the system will implement a dual-channel vibration control on 256 frequency channels in the bandwidth 0 to 2000 Hz.

V. Conclusion

The size of launchers such as ARIANE is such that the acoustic tests need more and more important and voluminous facilities. Furthermore, these test do not take into account the modelling, if it exists, of the acoustic field. The proposed simulation system which should run in the four-channel case, permits to realize simulation in the factory by moving the testing system.

The other applications are also very numerous in non aerospatial industry, especially in the seismic field and in car industry. The technics developed in the system make it available for high speed data acquisition, harmonic analysis and more generally for signal processing.