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ADAPTIVE ACTIVE EXPERIMENT TO REDUCE MULTI-TONAL NOISE IN A GENERIC COMPOSITE HELICOPTER CABIN

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Abstract

The composite materials are more and more used in helicopter domain, instead of metal structures, but lead towards a degradation of the acoustic comfort in the cabin, because of the decreasing mass and their low acoustic performances. So, active control procedures can be used in addition to passive treatments.

The paper deals with the feasibility of active noise control procedures in order to reduce the radiated noise generated in a composite helicopter cabin, through the mechanical deck. A generic composite fuselage "VASCo" is excited by four shakers to simulate the primary noise produced by the gear box beams /1/. To analyze the structural behaviour of the mechanical deck and the structure-cavity coupling, a modal analysis and structural intensity measurements are achieved on the mechanical deck. Moreover, pressure fields are acquired in two horizontal planes.

The primary excitation to control is composed of several tones representative of a realistic helicopter (792, 1012, 1068 and 1584 Hz) with a low broadband signal to simulate an "aerodynamic noise".

Four piezoelectric actuators PCB associated to four accelerometers are fixed into the cabin side as close as possible to primary sources (on the frames).

For several years, studies are led to develop algorithms specially suited to periodic signals to replace the generic adaptive LMS (Least Mean Square) algorithm /2-6/. The purpose is generally to improve the stability and the convergence speed and to reduce the computation time due to the LMS algorithm.

In our configuration, independent SISO (Single Input Single Output) algorithms for the 4 PCB / accelerometer pairs are used to reduce the vibration produced by the shakers. We compare the acceleration reduction achieved at the error sensors with the LMS algorithm and with an algorithm adapted to control multi-tones ("Multi-tone" algorithm). The acoustic pressure fields are acquired, before and after active control, with the "Multi-tone" algorithm.

1 Preliminary measurements

Four decorrelated random signals are generated to produce forces equal to about 1 N up to 3000 Hz. Pressure fields are acquired in two parallel planes located at 0.2 m and 0.5 m away from the mechanical deck (surface: 1.4 x 1.3 m^2) into the cabin (photo 1).

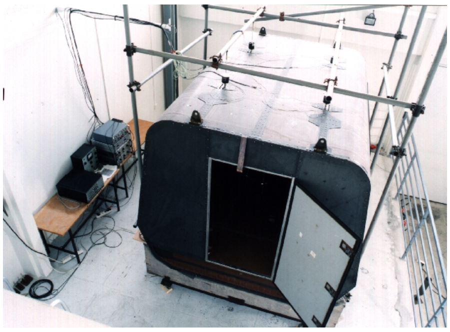

Photo 1 : VASCO cabin and primary excitations

Below 500 Hz, some modal frequencies emerge from the global spectra (figure 1). From 500 Hz, the modal density and the damping are too high to identify particular frequencies. So, the spectra are relatively flat and quite similar with only a difference of 2 dB in level due to the distance.

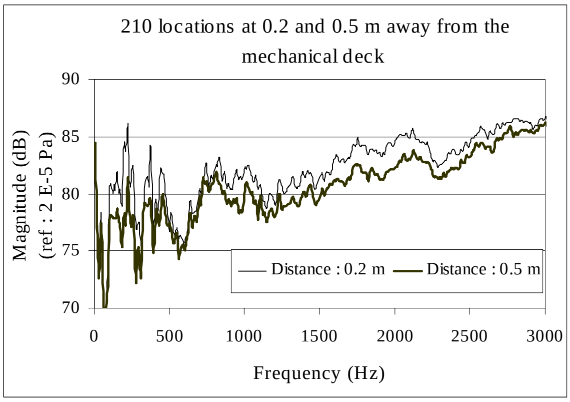

Figure 1 : Sum of quadratic pressure (dB)

Acoustic pressure simulations carried out by FEM have been compared with measurements and have allowed to show that the number of cavity acoustic modes appears rather high in low frequency band : theoretically 19 modes between 60 and 203 Hz. Moreover, a modal analysis of the mechanical deck indicates that the first 4 structural modes of the sandwich panels are located also in the previous frequency band. So, the structure-cavity coupling must be taken into account. At the gear box tones, the structural modal density is too high to use standard measurements as modal analysis. That is the reason why we have developed a method to measure the structural intensity propagated on the mechanical deck in high frequency band /7/. The figure 2 shows the propagation of energy from the 4 forces between 500 and 3000 Hz .

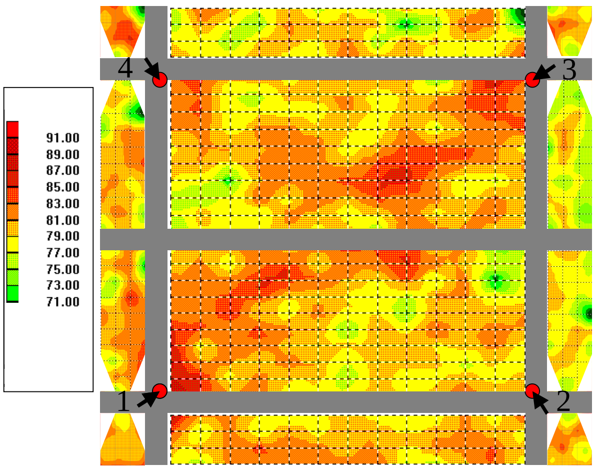

Figure 2 : Structural intensity for 500-3000 Hz frequency band - Magnitude in dB (ref : 10^{-12} W/m^2)

The energies are propagated mainly towards the middle of the mechanical deck from the excited source(s). We can notice an important decreasing of magnitude along the propagation path (due to high structural damping and the modal coupling) and some dissymmetries according to the excited shakers.

2 Feedforward adaptive algorithms

2.1 LMS algorithm

The LMS algorithm consists, for a SISO, in minimizing the cost function *J(n)* representing the square pressure $e(n)^2$ (error sensor), at each moment of the sampling n.

The total noise *e(n)* is the sum of the primary noise *y(n)* and of the secondary noise *b(n)*.

We use for that the signal of a sensor *r* (reference), correlated with the primary noise, and we identify the impulse response of the secondary source on the error sensor, *h*.

The FIR (Finite Impulse Response) control filter *W* is so adapted at the sample *n* in order to generate the secondary control *u* /8/ :

$$W_g(n+1) = W_g(n) - 2.\rho.e(n).\sum_{k=0}^{Q-1} h(k) r(n-k-g)$$

is the g^{th} coefficient of the vector *W* with ρ the convergence coefficient.

To deal with a complex signal in a wide frequency band, the filters (*W* and *h*) must include many coefficients which generate an important computation time that can be incompatible with the performances of the digital signal processing.

But, if we suppose that the primary source produces a periodic signal at ω, the reference signal *r(n)* can be written as : $r(n) = \sin(n\omega T)$ with *T* the sampling time.

In this case, *u(n)* must be written as below :

$$u(n) = W_0(n)\sin(n\omega T) + W_1(n)\cos(n\omega T)$$

if $\frac{1}{T} = 4\left(\frac{\omega}{2\pi}\right)$.

$$\Rightarrow u(n) = W_0(n)r(n) + W_1(n)r(n-1)$$

So, only two coefficients for *W* are required for the control. This is not obviously the case for the filter *h* whose the number of coefficients must take into account the complexity of the transfer function and the wished frequency accuracy.

Finally, for a signal with N tones, we need to use much more than 2 x N coefficients for *W* because of the contribution of the time-varying coefficients (for example : 64 coefficients for 3 tones /5/).

2.2 Algorithm for periodic signals

To reduce the computation time of the LMS algorithm for a periodic signal, it can be interesting to use the transfer function H at the excited frequency instead of the FIR h.

The algorithm can be described as follows :

$$e(n) = y(n) + H \otimes u(n)$$

The control filters $W_0(n)$ and $W_1(n)$ are so adapted at each sample n by a gradient method in order to generate the secondary control $u(n)$:

$$W_k(n+1) = W_k(n) - \rho \frac{\partial J(n)}{\partial W_k(n)} \text{ for } k \in \{0,1\}$$

So :

$$\begin{cases} \dfrac{\partial J(n)}{\partial W_0(n)} = 2\,e(n)\left|H\right| \sin(n\omega T + \varphi) \\ \dfrac{\partial J(n)}{\partial W_1(n)} = 2\,e(n)\left|H\right| \cos(n\omega T + \varphi) \end{cases}$$

where $\left|H\right|$ et φ represent the magnitude and the phase of the transfer function at ω.

$$\begin{cases} \dfrac{\partial J(n)}{\partial W_0(n)} = 2\,e(n)\left|H\right| \begin{pmatrix} \sin(n\omega T)\cos(\varphi) \\ + \cos(n\omega T)\sin(\varphi) \end{pmatrix} \\ \dfrac{\partial J(n)}{\partial W_1(n)} = 2\,e(n)\left|H\right| \begin{pmatrix} \cos(n\omega T)\cos(\varphi) \\ - \sin(n\omega T)\sin(\varphi) \end{pmatrix} \end{cases}$$

That implies :

$$\begin{cases} W_0(n+1) - W_0(n) = \\ -\rho \left(2\,e(n)\left|H\right| \begin{pmatrix} \sin(n\omega T)\cos(\varphi) \\ + \cos(n\omega T)\sin(\varphi) \end{pmatrix} \right) \\ W_1(n+1) - W_1(n) = \\ -\rho \left(2\,e(n)\left|H\right| \begin{pmatrix} \cos(n\omega T)\cos(\varphi) \\ - \sin(n\omega T)\sin(\varphi) \end{pmatrix} \right) \end{cases}$$

Finally, these two coefficients can be expressed with the reference signal r :

$$\begin{cases} W_0(n+1) - W_0(n) = \\ -\rho_t\, e(n)\, \big(r(n)\cos(\varphi) + r(n-1)\sin(\varphi)\big) \\ W_1(n+1) - W_1(n) = \\ -\rho_t\, e(n)\, \big(r(n-1)\cos(\varphi) - r(n)\sin(\varphi)\big) \end{cases}$$

with $\rho_t = 2\,\rho\left|H\right|$

We can notice that only φ must be identified before the active control procedure.

The method, closed to /6/, has the following advantages :

- stability : the algorithm converges on the optimal solution if $\left|\varphi_{measured} - \varphi_{real}\right| < \frac{\pi}{2}$

That means that, if ω fluctuates, φ used for the algorithm will be valid if the phase variation is lower than π/2. So, we shall need only to measure the phase at the central frequency.

- fast computation due to the low number of operations that allows to increase the sampling frequency.
- in practice, the convergence is assured even if $\frac{1}{T} \neq 4\left(\frac{\omega}{2\pi}\right)$.

We can set also $\frac{1}{T} \approx 4k\left(\frac{\omega}{2\pi}\right)$ with k integer >1. In that case, $u(n) = W_0(n)\,r(n) + W_1(n)\,r(n-k)$

- This algorithm is adapted to control multi-tones : we must only filter numerically the reference signal by a bandpass filter for each tone (with Bessel filters for example) and to use a separated algorithm and convergence coefficient by frequency band.

3 Active control experiments

3.1 Preliminary experiment

We have compared the acceleration reduction achieved at 1 or 2 error sensors with the two types of algorithms.

The figures 3 and 4 show the result of active control with one SISO configuration (PCB 1 / acc. 1 to control the primary source 1). The potentiality of the used active control system allows to control 4 tones with a sampling frequency fixed at 6000 Hz. The tones are totally reduced below the broadband noise (about -10 dB) whatever the algorithm.

But, in the case of the LMS algorithm,

- the broadband noise is increased up to 1600Hz
- the convergence speed is slow at the 4th tone (1584 hz).

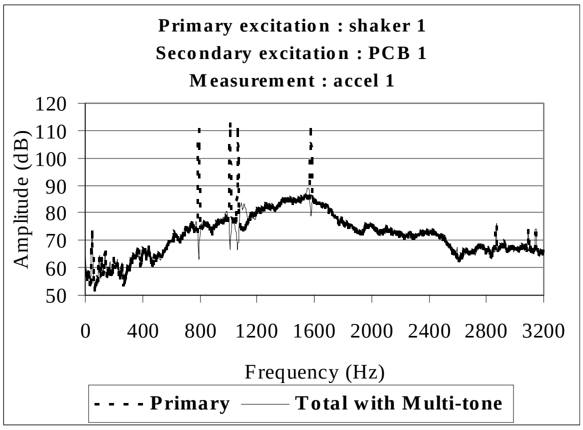

Figure 3 : acceleration measurements with / without active control - 1 SISO "Multi-tone" algorithm

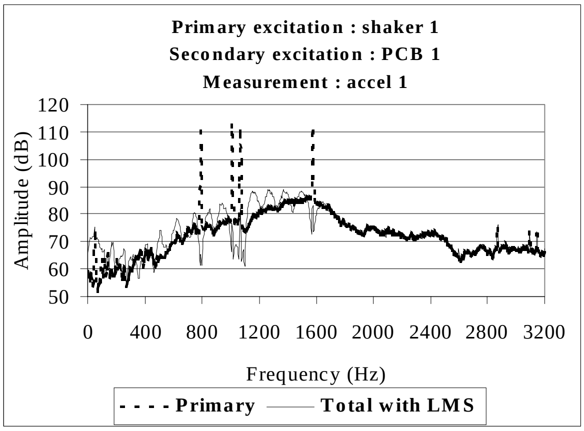

Figure 4 : acceleration measurements with / without active control - 1 SISO "LMS" algorithm

The "Multi-tone" algorithm doesn't act upon the broadband noise (outside the tonal frequencies) and the convergence speed is fast thanks to the different tonal convergent coefficients.

In a 2 SISO configuration (PCB 1 / acc. 1 and PCB 2 / acc. 2 to control respectively the primary sources 1 and 2), we set the sampling frequency at 4000 Hz (maximal value).

One can see (figure 5) that it is possible to eliminate totally only chosen tones (in our case 792, 1012 and 1584 Hz) without influencing others, which is impossible with the LMS algorithm.

In the figures 6 and 7, the analysis of a secondary transfer function (Acc. / Tension PCB) shows that the phases decreases slowly when the frequency increases, thus in a large frequency band.

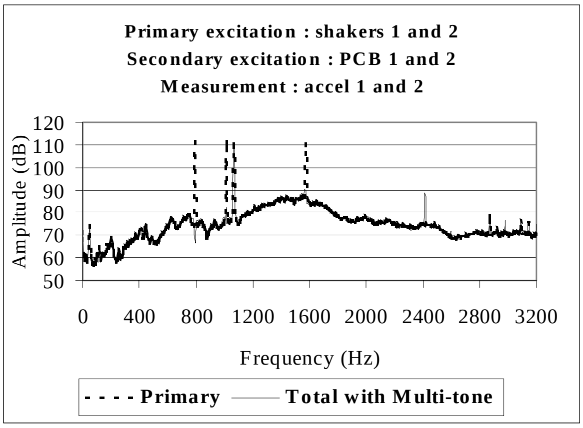

Figure 5 : acceleration measurements with / without active control – 2 SISO "Multi-tone" algorithms

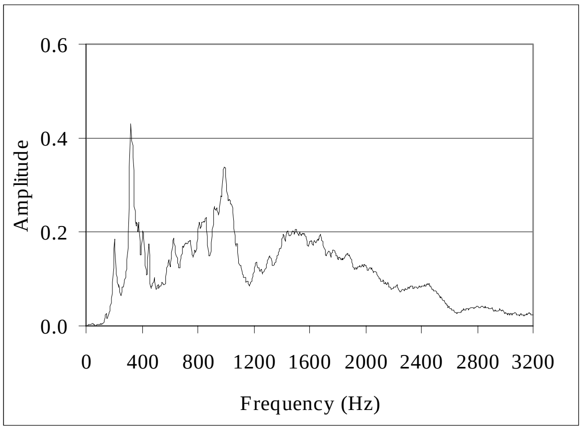

Figure 6 : Amplitude of a transfer function "Acc. / Tension PCB "

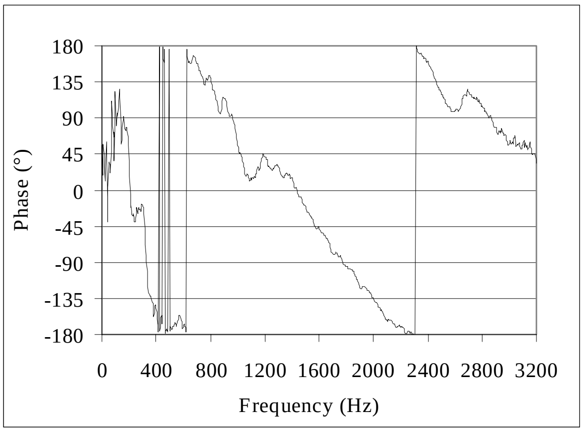

Figure 7 : Phase of a transfer function "Acc. / Tension PCB "

That allows to assure the convergence of the "Multi-tone" algorithm even if the fluctuation of the tonal frequencies is important .

That is the reason why the "Multi-tone" algorithm is chosen to reduce the accelerations produced by the 4 primary shakers at 3 tones (792 Hz, 1012 Hz and 1584 Hz), with the low broadband random noise.

3.2 Experimentation with the four primary sources

The 4 pairs of PCB and accelerometers are connected, two by two, to two independent active control systems. The figure 8 brings out the global acceleration measured at the 4 error sensors before and after control. The acceleration reductions are important whatever the studied frequency band (between 28.7 dB to 13.8 dB). The tone "1584 Hz" is less reduced on the accelerometer 4, phenomenom that affects the global acceleration.

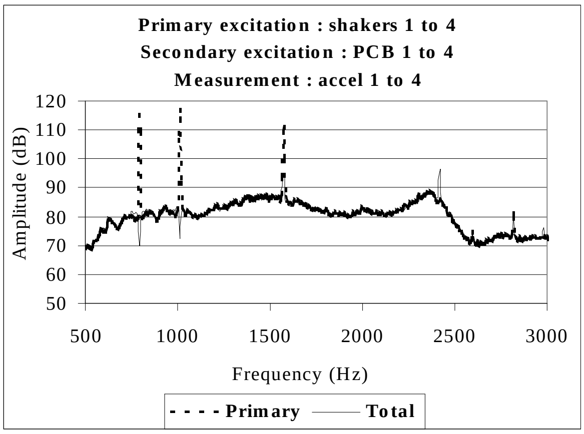

Figure 8 : acceleration measurements with / without active control – 4 SISO "Multi-tone" algorithms

The acoustic pressure is acquired, before and after active control, on the horizontal planes located at 0.2 m and 0.5 m away from the mechanical deck, on 210 measurement points (example at 0.5 m : figures 9 to 12). The fields are displayed for the 3 tones and between 500 and 3000 Hz. The blue contours show the areas where the pressure is increased after control. The tables 1 and 2 synthesize the global pressure reduction on the planes. The number of locations where the pressure is reduced is also specified.

The active control procedure is efficient to reduce spatially the pressure field (5.5 to 6.5 dB on 500-3000 Hz on almost all the locations), mainly at 0.5 m. The pressure is only increased on some areas that correspond to nodes of the primary pressure field. So, the resultant pressure level is not very high. At 1584 Hz, the pressure is not reduced everywhere (only 258 / 420 locations of the two planes), but becomes more homogeneous.

Frequency band (Hz)	Global pressure reduction	Number of locations showing pressure reduction
776-808 (tone : 792)	6.6	190 / 210
996-1028 (tone : 1012)	5	177 / 210
1568-1600 (tone : 1584)	1.2	130 / 210
500-3000	5.5	202 / 210

Table 1 : Acoustic pressure reduction at 0.2 m, 4 primary sources on, control with 4 SISO "Multi-tone" algorithms

Frequency band (Hz)	Global pressure reduction	Number of locations showing pressure reduction
776-808 (tone : 792)	7.3	186 / 210
996-1028 (tone : 1012)	6.8	185 / 210
1568-1600 (tone : 1584)	1.4	128 / 210
500-3000	6.5	202 / 210

Table 2 : Acoustic pressure reduction at 0.5 m, 4 primary sources on, control with 4 SISO "Multi-tone" algorithms

4 Conclusion

Active control tests have been made in a generic composite fuselage with local secondary sources and sensors (PCB and accelerometer) to reduce the vibration and, so on, the inner acoustic pressure at several tones representative of a realistic helicopter. The pressure field has been reduced globally between 5.5 and 6.5 dB in two large planes in the band 500-3000 Hz. These experiments have been led with a feedforward adaptive algorithm suited for tonal noise. These laboratory results being satisfactory, this type of procedure will be soon tested in a helicopter in flight.

Nomenclature

e	total error signal
y	error signal of primary source
b	error signal of secondary source
J	cost function
r	reference signal
u	control input
h	FIR "secondary error signal / control input"
H	transfer function "secondary error signal / control input"
W	control filter
ρ, ρ_t	convergence coefficients

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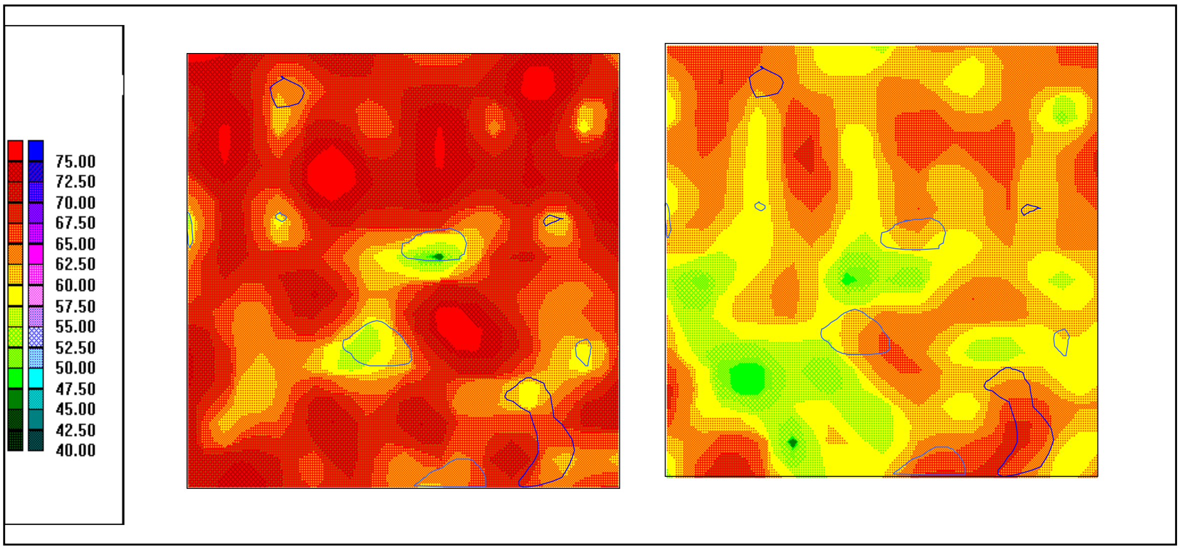
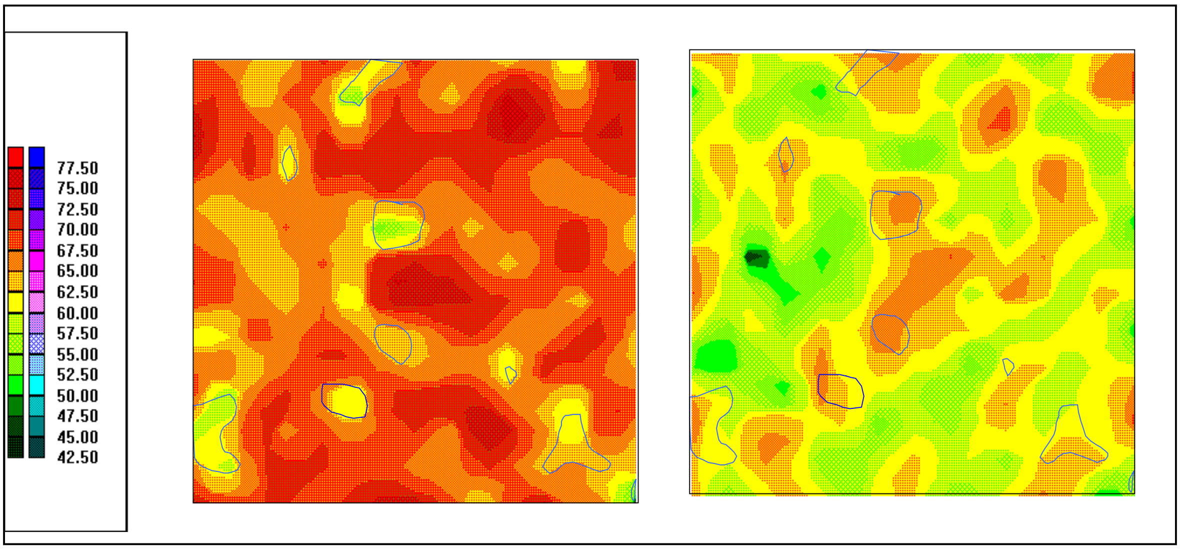


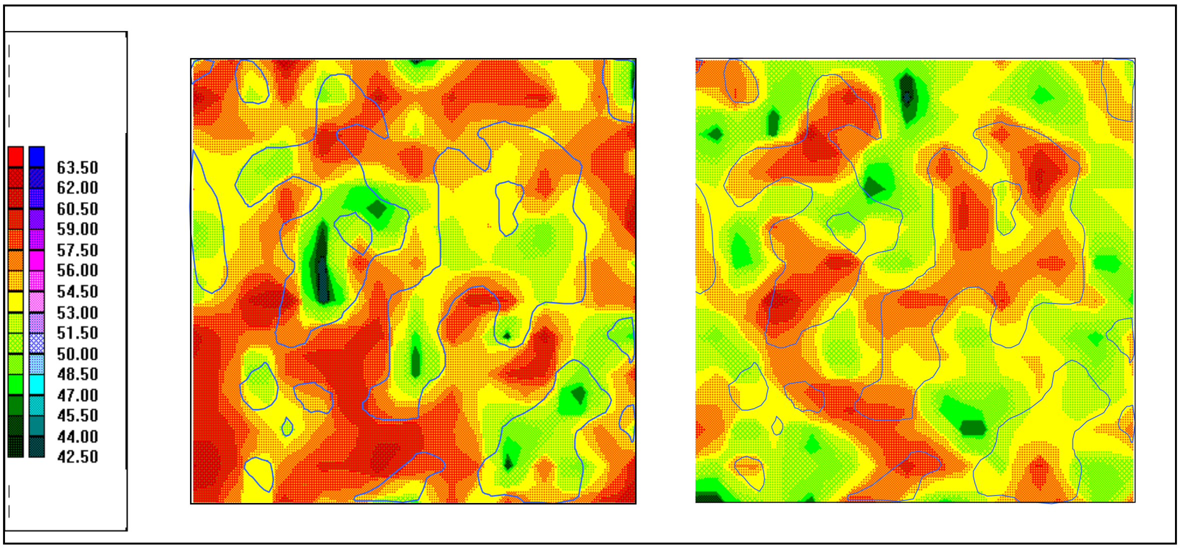
Primary field Total field

Figure 9 : Control with PCB 1 to 4 / accel 1 to 4 - 4 SISO "Multi-tone" algorithms - Measurement of acoustic pressure field at 0.5 m away from the mechanical deck around 792 Hz (surface : 1.3 x 1.4 m^2) - Global pressure reduction = 7.3 dB



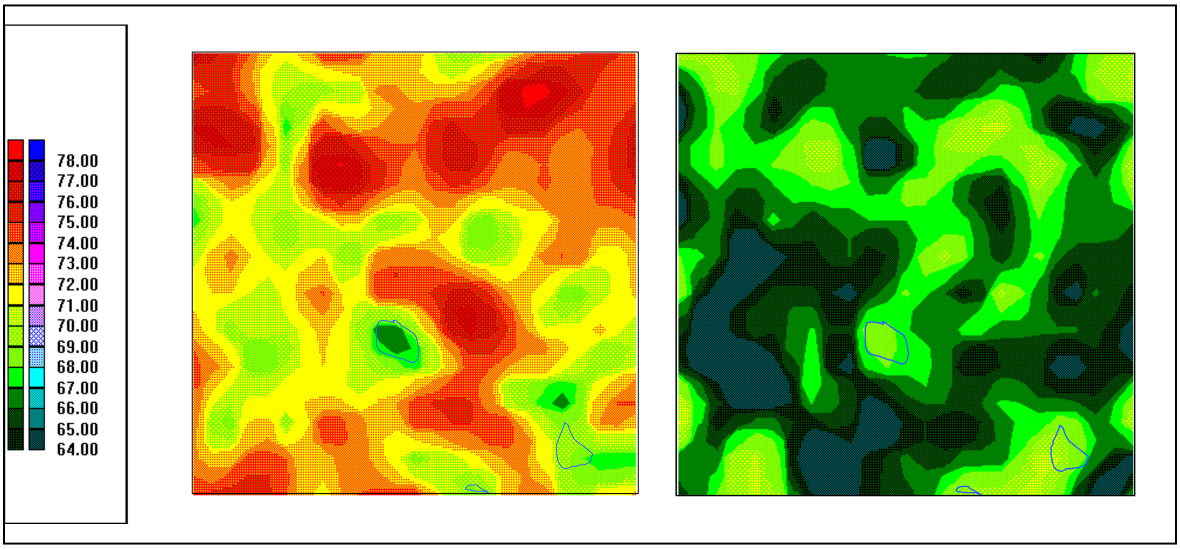
Primary field Total field

Figure 10 : Control with PCB 1 to 4 / accel 1 to 4 - 4 SISO "Multi-tone" algorithms - Measurement of acoustic pressure field at 0.5 m away from the mechanical deck around 1012 Hz (surface : 1.3 x 1.4 m^2) - Global pressure reduction = 6.8 dB



Primary field Total field

Figure 11 : Control with PCB 1 to 4 / accel 1 to 4 - 4 SISO "Multi-tone" algorithms - Measurement of acoustic pressure field at 0.5 m away from the mechanical deck at 1584 Hz (surface : 1.3 x 1.4 m^2) - Global pressure reduction = 1.4 dB



Primary field Total field

Figure 12 : Control with PCB 1 to 4 / accel 1 to 4 - 4 SISO "Multi-tone" algorithms - Measurement of acoustic pressure field at 0.5 m away from the mechanical deck between 500 and 3000 Hz (surface : 1.3 x 1.4 m^2) - Global pressure reduction = 6.5 dB