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HYBRID CONTROLLER : THEORY AND PRODUCT

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ABSTRACT

The first controller NOVACS™ commercialized since 1989 is equiped with a standard digital signal processor and may process till 11 input signals and 8 output signals. With this new **Hybrid NOVACS™** version, TechnoFirst® company proposes its last innovation which has been patented in 1995 and which is now available in its products : the **hybrid control**. Hybrid control combines the advantages of feedforward and feedback control without their respective drawbacks; this is more than a simple summation of the two technologies. In this paper we make the comparison between this new technology and the two classical ones. It will appear that TechnoFirst® has defined a new way to design active noise and vibration control system.

1. INTRODUCTION

Active noise control and active vibration suppression can be separated into two broad control strategies : feedforward and feedback control.

Feedforward can be applied if a reference signal correlated to the disturbance is available; the reference signal is passed into an array of adaptive FIR digital filters, and applied to secondary sources in order to minimize an error signal from appropriate sensors. The coefficients are adapted with a multichannel Least Mean Square (LMS) algorithm called "x-Filtered LMS" in SISO configuration (Fig 1) [1-2].

The algorithm involves a large amount of real time computation which can be handled adequately by current DSP chips. Feedforward control has been applied successfully to the cancellation of narrow band disturbances, even with very short FIR filters. It also works for wide-band disturbances but longer filters are necessary.

The method does not need a precise model of the system, but only an estimate of the impulse response. Although it is fairly robust with respect to the truncation of the impulse response, the amount of computation involved in estimating the model response increases significantly for lightly damped vibrating structure, reducing the bandwidth where the feedforward acts effectively.

Feedforward control is essentially a local method in the sense that for wide-band applications where many modes may be involved, the response to the disturbance cannot, in general, be reduced uniformely over the entire domain; low amplitude response near the error sensor may be obtained at the expense of amplified ones in other parts of the system.

Feedback can also be used for noise and vibration control. If the objective is to reduce the resonant peaks in the transfer function and the settling time to transient perturbations, the feedback loop acts; it is often referred as *Low Authority Control (LAC)* [3]. These compensators have simple forms and can be implemented either in analog or digital controllers. Note that some of them consist of second order filters which must be tuned on the targeted physics caracteristics; although the stability is guaranteed, the performance of the closed-loop system depends critically on the tuning of the filter parameters on the physics systems [4].

2. THE WEAKNESS OF FEEDBACK

The feedback control is very effective in reducing the perturbations within its bandwidth, but is vulnerable to disturbances outside its bandwidth. Indeed, referring to Fig. 2 where r is the tracking demand, d the disturbance and n the sensor noise, the tracking error is

$$e = y - r = \frac{1}{1+GH}(d-r) - \frac{GH}{1+GH}n \qquad (1)$$

If we consider a regulator problem with $r = 0$,

$$y = Sd - Fn \qquad (2)$$

where $S = (1+GH)^{-1}$ is the *sensitivity function* and $F = GH(1+GH^{-1})$ is the *closed loop transfer function.*

Ideally, to achieve immunity to disturbances and measurement noise, S and F should both be small, which is impossible because $S+F=1$. Besides, the second Bode integral [5] stipulates that, for a minimum phase system, the sensitivity function satisfies

$$\int_0^\infty \ln|S| d\omega = 0 \qquad (3)$$

Thus, any decreased sensitivity ($|S|<1$) within the bandwidth is compensated by an increased sensitivity ($|S|>1$) outside the bandwidth. As a result, a disturbance d outside the bandwidth will actually be amplified by the feedback control.

To argue this phenomenon we present at Fig. 3 a result of A.N.R. given by a NoiseMaster™ A.N.R. earmuff produced by TechnoFirst®. The feedback controller uses colocated microphone, speaker and an analog fixed compensator developed for this specific application of Active Noise control [6]. This feedback controller is installed inside each earcup.

This NoiseMaster™ #1010 provides an active noise reduction about 20 dB from 50 Hz to 500 Hz. Nevertheless a noise increasing appears from 650 Hz to 1500 Hz.

The feedback control to be efficient has to combine two antagonistics parameters for having:

- or a rapid control with a very sensitive stability,
- or a slow control with a strong stability.

At any time, by increasing one of these two parameters, it is against the second one. We have already spoken about the weakness of feedback control. For this feedback application we can write the system behavior as follows:

$$S(j\omega)/e(j\omega) = a/(1+k.F(j\omega).H(j\omega)) \qquad (4)$$

Nevertheless, when the closed loop system is stable, if the compound path is too closed to the critical point (-1 ,0), a pumping phenomenon appears and increases the level of noise outside the frequency bandwidth controlled by the feedback loop.

Once more time to obtain the maximum active noise reduction, the parameter k has to be very high which is against the stability. To control the stability and to increase the gain control, we have developed a specific filtering [7]. This filtering allows to optimize the compromize between gain and stability and can provide a good active noise control result increased in comparison with standard filtering. This optimum result is given in Fig. 4.

We can see on this Nyquist diagram that, except of the conical sector with a vertex located at the point: $(-1+\varepsilon, 0)$, avoided by this specific filtering, we can increase the parameter k in all compound plan quadrants. So all vectors for which $j\omega_i$ is near the point $(-1+\varepsilon, 0)$ inside the conical sector give an amplification of noise which is represented at Fig. 3; the frequency response starts to be increased from 650 Hz instead to be the same as the passive frequency response.

3. HYBRID CONTROL FOR DISTURBANCE REJECTION

The following table summarizes the advantages and drawbacks of the two classes of controllers. The main motivation for this study is that there are a number of applications which combine the need for feedback control in some frequency band with the rejection of steady state disturbances for which a correlated reference signal is available.

	+	-
Feedback		
• **Active damping** (LAC)	- no model needed - Guaranteed stability with collocated actuator/sensor	- effective only near resonances
• **Model based** (LQG, H_∞,...) (HAC)	- global method - attenuates any disturbance within ω_c	- limited bandwidth $\omega_c << \omega_s$ - spillover - stability robustness - disturbances outside ω_c are amplified
Feedforward		
• Adaptive filtering of reference (x-filtered LMS)	- no model necessary - wide band $\omega_c \approx 0.1\ \omega_s$ - works well for narrow band disturbances	- Needs a reference - Local method (response may be amplified in some part of the system) - Long impulse response for lightly damped system - Large amount of real time computation

Table : Trade-offs of feedback / feedforward controllers applied to vibration suppression (ω_c : bandwidth of the controller, ω_s : sampling frequency)

For example the NoiseMaster™ #1010 headset described in §2 needs for improving the ANR performances to reduce the pumping phenomenon near the crossover of the feedback control system.

By using a combination of these two technologies together, we are expecting a stabilization of feedback control near the critical point (-1, 0) to reduce the pumping phenomenon in the frequency bandwidth [650 Hz, 2000 Hz].

On the other hand, since the noise can be used as reference, a feedforward control for cancelling the effect of unbalance can be considered. This leads to the idea of combining feedback and feedforward control for reducing the disturbance of the pumping effect and saving the noise control.

One may argue that disturbance rejections could be achieved by feedback alone, but increasing the bandwidth of the control system would not be feasible in most practical situations, because the Nyquist criterion shows that the first critical point of instability increases drastically with frequency [8].

In the following, we will examine two applications in which the Hybrid NOVACS™ controller has proved very effective.

The first one combines active damping and feedforward for vibration suppression.

The second application considers the wide-band active noise control in the earmuff NoiseMaster™ .

A nice feature of this Hybrid NOVACS™controller is that the feedforward and feedback loops can use the same set of actuators and sensors.

4. EXPERIMENTS

The following describes how the Hybrid NOVACS™ controller works and how to use it. The given example is repetitive for the two experiments.

We have used the transducers placed in a classical feedback system : a colocated sensor and an actuator. The colocated sensor is also in fact the control microphone of the feedforward system. We have used an external microphone for the reference signal. The feedforward control signal is added to the feedback filtering control signal. The resulting signal is amplified and is entered in the earphone.

The feedback control allows a very fast control even for an impulse noise. The transfer function between the control microphone and the earphone is measured throught the existing feedback control. The result is a shorter impulse response, and means less datas and time computing for the feedforward system.

4-1 Vibrations suppression

Consider the lightly damped beam of Fig 5; it is representative of numerous stiff supporting structures used in many applications (test bench, machine tool,...). We seek to eliminate the micro vibrations produced by unknown impulsive loads and steady state disturbances with a known reference (such as unbalanced loads).

The effect of transient disturbances can be attenuated by introducing some active damping in the system; this problem was considered in [9]. The active damping also attenuates the effect of steady state disturbances in the vicinity of the natural frequencies of the structure, but is unable to attenuate them away from the resonances. If a reference signal is available, the proposed hybrid controller can be implemented, combining the active damping with a

feedforward controller operating over a broad frequency range [10]. In Fig 6, we observe a substantial attenuation of the response up to 150 Hz.
It is important to observe that the active damping actually improves significantly the performance of the feedforward controller by reducing the length of the impulse response, which is quite long for lightly damped structure (Fig 7).

4-2 Noise application : ANR Earmuff

The second experiment concerns the ear protection NoiseMaster™ produced by TechnoFirst®. The system consists in a feedback control of the sound field at the entrance to the ear canal [8]. The ANC system provides an active noise reduction of about 20 dB from 50 Hz to 500 Hz, but some noise amplification appears from 650 Hz to 1750 Hz as a result of the phenomenon as explained before.
Once again, the situation can be improved by using the Hybrid NOVACS™. Experimental results have shown that the hybrid controller increases considerably the bandwidth of the noise reduction for narrow band steady state disturbances.

Fig. 8 shows the improvements of noise attenuation obtained with hybrid control at 700 Hz frequency. Actually, we can observe this result for each frequency included in the hybrid bandwidth processing [50 Hz, 2000 Hz].

5. CONCLUSION

This paper evaluates a hybrid feedback-feedforward controller for noise and vibration suppression. The synergy between the two types of controllers is pointed out. The feedforward control extends the bandwidth of the controller for steady state disturbances with a correlated reference, while the feedback control reduces drastically the impulse response of lightly damped structures, avoiding the problems associated with truncation. The Hybrid NOVACS™ controller does not require additional actuator and sensor. In each example presented the theoritical advantage of the hybrid controller is confirmed by experiments.
The feedback control allows a very fast control even for an impulse noise. The transfer function between the transducers is measured throught the existing feedback control. The result is a shorter impulse response, and means less datas and time computing for the feedforward system. This has been pointed out in the vibration suppression application.
The precision pointing and the ANC applications show that feedforward control can deal with stationnary disturbances which are outside the bandwidth of a model-based feedback controller, and more generally over a wide range of frequency, limited only by the sampling period and the hardware available.
The hybrid control can be used whenever the system is subjected to impulsive and stationnary disturbances provided that a reference correlated to the disturbance is available; there is no detrimental interaction between feedback and feedforward, and they can be used with the same set of actuators and sensors.

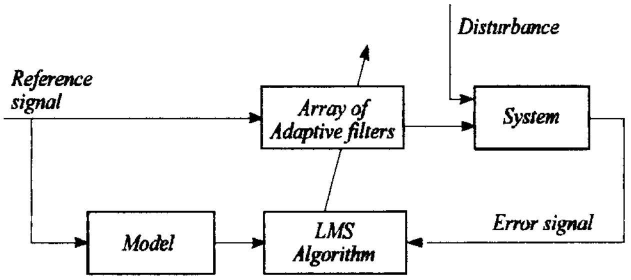

Figure 1 . Principle of the x-filtered LMS feedforward controller

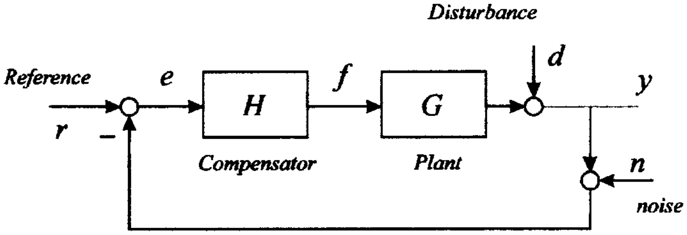

Figure 2 . Feedback system

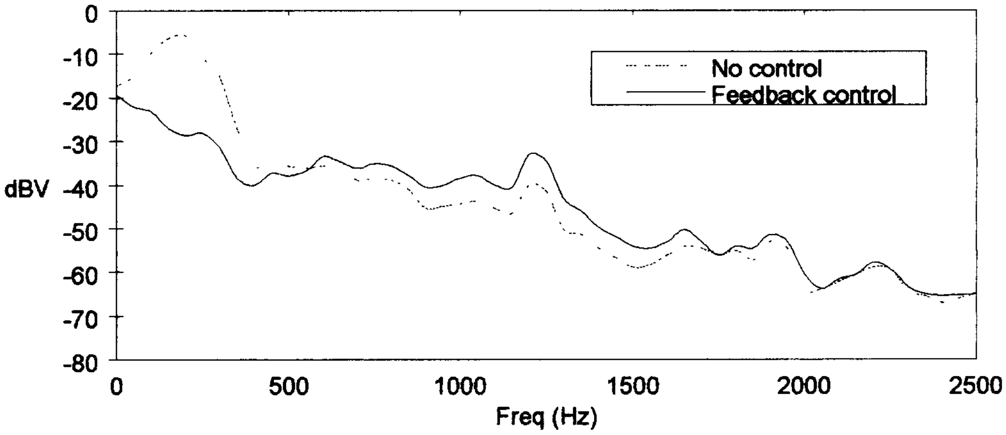

Figure 3 : ANC wide-band noise reduction using feedback control

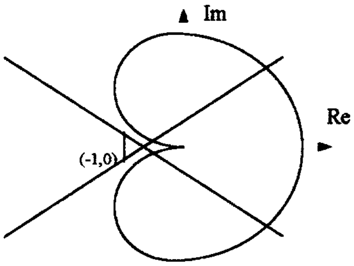

Figure 4 : Nyquist diagram of the optimum filtering

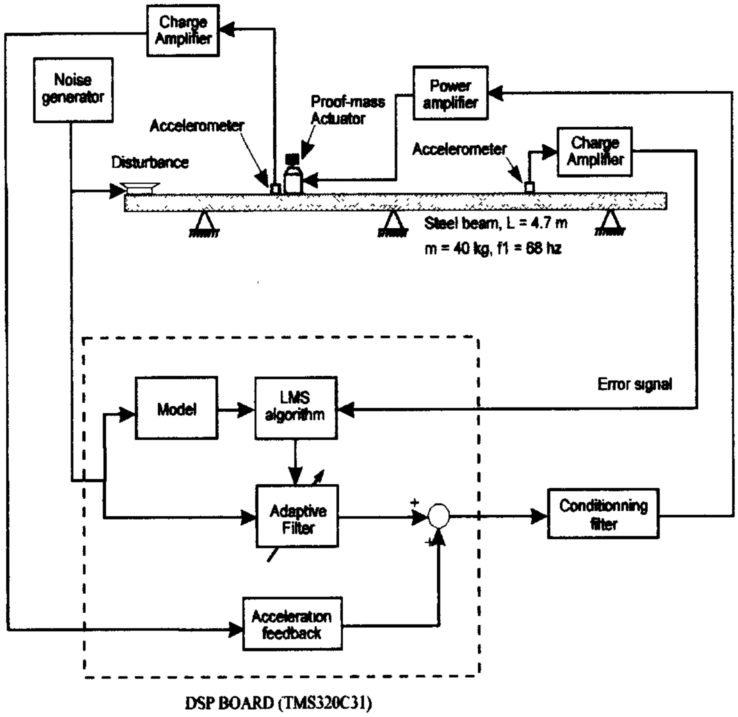

Figure 5 : Test structure for vibration suppression

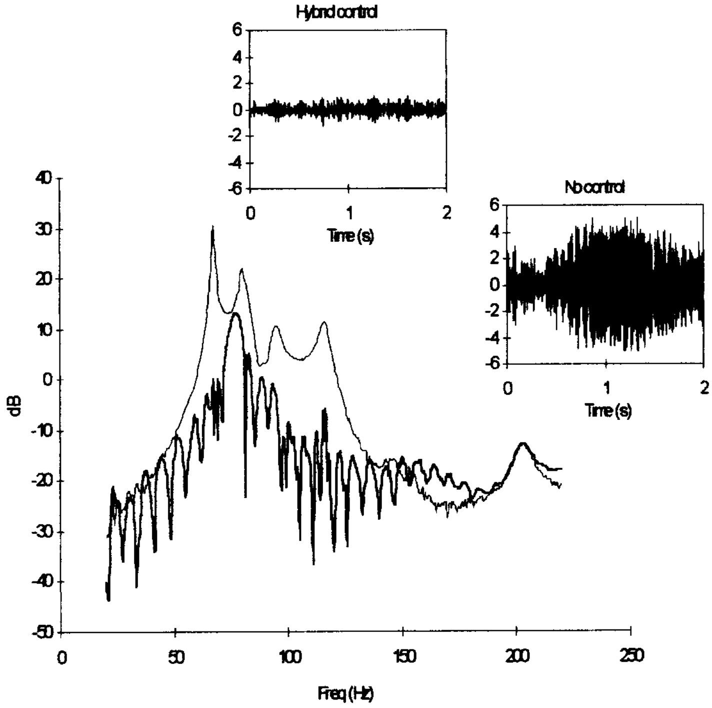

Figure 6 : Response of the beam to a broad band disturbance (band-limited white noise) Transfer fonction between the disturbance and the error signal. Typical samples of the error signals are also displayed.

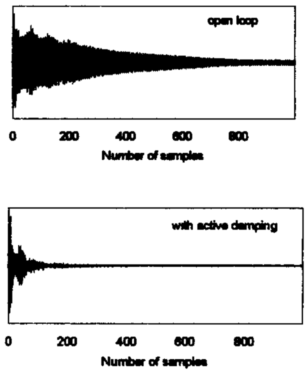

Figure 7 . Impulse response with and without active damping

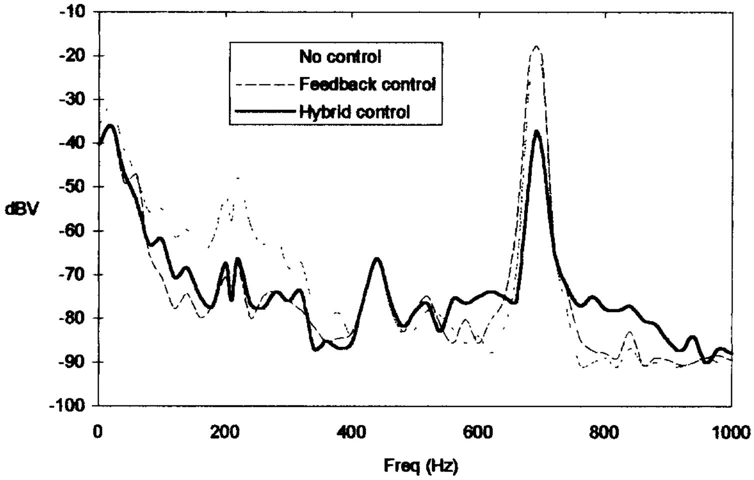

Figure 8 : ANC narrow-band noise reduction using hybrid control

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