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Testing of different types of active hearing protectors

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Abstract. — This paper presents an experimental investigation of two different types of active ear protectors: an electrodynamic earplug and a piezoelectric one. These systems require sophisticated control filters, realised using digital filtering methods. Results obtained with these digital laboratory earplugs show significant improvement of the frequency range of active attenuation compared to conventional electrodynamic headsets driven by analog filters.

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Introduction

Active ear protectors have been available on the market for several years. Various types have been proposed, mostly using electrodynamic headsets driven by simple analog filters, e.g. Carme (1988). Active attenuation is usually limited to low frequency noise components, typically less than 800 Hz.

To widen the frequency range of protection, we compare different types of anti-noise systems and actuators. We consider earplugs as an alternative to the more conventional headsets. The success of earplugs as passive hearing protectors is well known; moreover, their small size enables us to locate the active system closer to the eardrum. Piezoelectric actuators, which lead to peaked frequency responses, are also considered as part of the design of the active anti-noise system. Specifically, two types of hearing protector are investigated: an electrodynamic earplug and a piezoelectric earplug. A classical electrodynamic headset is used for comparison. In Section 1, we describe the control system, both in theory and in practical implementation. Experimental results are given in Section 2 and discussed in Section 3.

1. Description of the control system

The control system is based on local pressure amplitude minimisation, because, a priori, nothing is known about the noise to be attenuated and furthermore a compact set-up is needed. In this section we describe the theory and implementation of the system.

1.1. *Theory of local active attenuation*

The local active control system is illustrated in Figure 1: a microphone is used to measure the sum of the incident noise to be cancelled, P_i, and the anti-noise, P_s, generated by the controller. The electronic signal obtained is passed through a control filter, is amplified and then fed to the acoustic actuator.

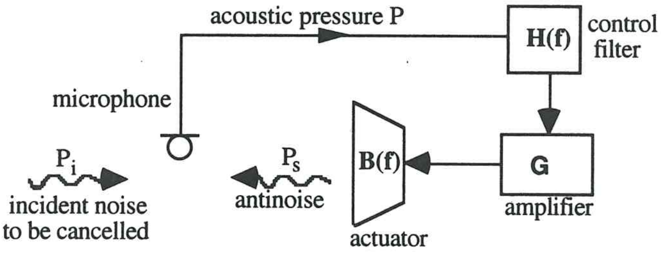

Figure 1. Principle of local active control of sound.

This system is an example of a classic closed-loop controller. In continuous operation, the attenuation is given by:

$$\frac{P_i + P_s}{P_i} = \frac{1}{1 - BGH} \qquad (1)$$

where $-BGH$ is the acoustic feedback transfer function.

The main problem with such control is that it is unstable whenever BGH is real and greater than or equal to 1. The electroacoustic frequency response of an anti-noise actuator, $B(f)$, usually shows phase variations of more than 2π radians over the audible frequency range, within which its magnitude remains significant. It follows that a control filter (GH, composed of a complex transfer function $H(f)$ and a real constant gain G) is necessary to avoid instability.

The electroacoustic response, $B(f)$, depends on the external impedance that the actuator sees, and thus can vary with protector position in the ear. These variations, which are larger for earplugs than for headsets because of the cavity size, are small in current applications. Nevertheless, they necessitate large safety-margins for both the gain and phase to preserve stability. The attenuation efficiency is of course slightly reduced, but stability must be guaranteed for the user.

Even if the control system is stable, it can nevertheless amplify certain frequency components by a process of positive feedback. In practice, this is found to be the case at mid to high frequencies and one of the criteria for judging a control system is its success in reducing such amplification within the audible frequency range.

1.2. *Implementation of the control filter*

In equation (1), the phase of BGH is severally constrained by stability and by the attenuation characteristics. In particular, if it is less than $-\frac{3}{2}\pi$ radians, positive feedback can occur for some values of the modulus of BGH. Therefore it is best to use minimum-phase filters for control. For the simplest one, proposed by Carme (1988), H is a single biquadratic cell, i.e. it is a rational function of $s = 2j\pi f$ with two conjugate poles and two conjugate zeros. Such an analog filter is currently used in commercial active anti-noise headsets. The corresponding digital system is a 5 coefficient recursive filter with the following expression:

$$y_n = b_1 y_{n-1} + b_2 y_{n-2} + a_0 x_n + a_1 x_{n-1} + a_2 x_{n-2},$$

where x_n and y_n are respectively the filter input and output at time n, and a_0, a_1, a_2, b_1, b_2 are real coefficients which characterise the control filter.

In order to better adapt the control filter H to the electroacoustic transfer function B, we propose to associate several filters of the above biquadratic type. Of course, the more complex the overall filter, the more numerous are the filtering parameters to be adjusted, and no analytic means is available which automatically provides values of the optimal parameters to be used. A digital signal processing system would appear to be a promising method for implementation of such filters, as suggested by Béra & Sunyach (1995).

Time discretisation generates a time delay τ, equivalent to a phase shift $\varphi(f) = -2\pi\tau f$. The digital filtering system which we have built was designed to reduce this delay as much as possible. The system is based on a digital signal processor (Analog Devices ADSP2101) working at 12.288 MHz and a parallel 1 μs analog-digital converter (Analog Devices AD7586). A sample rate of 100 kHz then leads to:

$$\varphi = a + bn,$$

where: $a = 56 \times 10^{-6}$ rad/Hz, $b = 4 \times 10^{-6}$ rad/Hz, and n is the number of biquadratic cells used in the filter. In the present application, n will be 1 or 3; at 1 kHz we then find that $\varphi = 0.06$ and 0.07 radians, respectively.

A companion computer program has been developed to calculate H for a given B and hence control the physical filter. It provides the filtering parameters and sends them *via* the serial port to the control system. More details are available in Béra et al. (1993).

2. Experiments and results

2.1. *Description of the earplugs*

Two types of earplug actuators have been investigated:

i) an electrodynamic earplug, constructed using an audio Aiwa receiver (diameter 2 cm),
ii) a piezoelectric earplug, designed using a piezoelectric actuator operating in bending mode (diameter 1.2 cm).

For comparison, measurements were also carried out using a conventional electrodynamic headset, based on a semi-open audio Sony 250.

Each of these active ear protectors has been tested on a Zwislocki artificial ear (Burkhard & Sachs, 1975). The frequency responses, $B(f)$, show acoustic and electroacoustic resonances (cf. Figure 2). The response of the electrodynamic earplug is "furry" over a large frequency range. In contrast, because the resonances are of higher frequency, the piezoelectric earplug response is relatively smooth up to 7 kHz, as is that of the electrodynamic headset, which presents highly damped resonances.

2.2. *Control filter optimisation*

In practice, optimisation of the control filter GH results from a compromise. On the one hand, the filter has to compensate the actuator response, $B(f)$, at low and mid frequencies so that the phase of the acoustic feedback is close to $-\pi$. On the other hand, it has to cut off the high frequency components to avoid instability. These two roles conflict in the present application, because ideal phase compensation for the actuator responses of Figure 2 would result in a high pass filter.

In this context, the phase behaviour of the piezoelectric earplug at low and mid frequencies is well adapted, because it decreases slowly with frequency. Consequently, the filter H only has to compensate the 10 kHz resonance peak in magnitude.

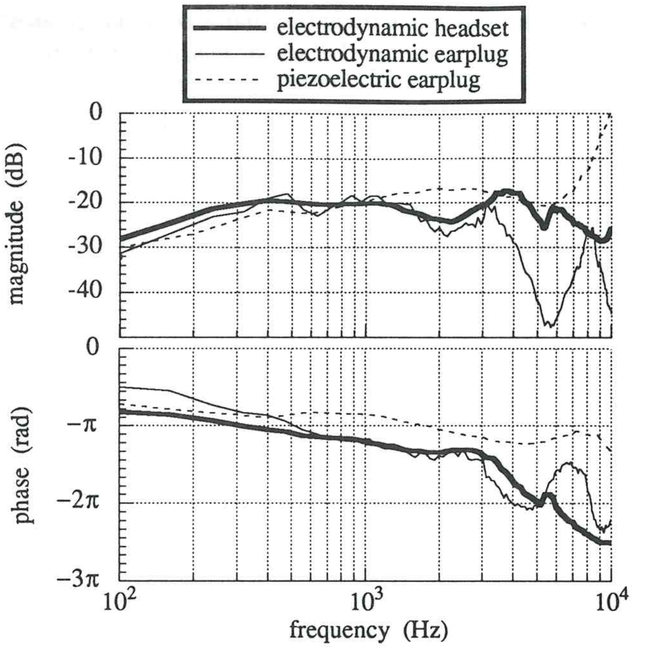

Figure 2. Frequency responses (B) of the three electroacoustic systems investigated.

For the electrodynamic earplug, the overall low-pass electroacoustic response allows us to treat the mid-frequency phase loss. As expected, the flat response of the electrodynamic headset does not require any resonance compensation. Its control can be simply performed using a low-pass filter with a limited phase shift, but, as we shall see in the next section, the attenuation condition cannot be implemented at mid-frequencies. A one-cell filter therefore appears able to compensate the headset response, while three-cell filters are required for both types of earplugs. The frequency response of these filters is depicted in Figure 3, and the corresponding open-loop responses $BGH(f)$ in Figure 4.

2.3. *Active attenuation results*

The measured attenuation levels corresponding to the closed-loop responses of Figure 4 are presented in Figure 5. Attenuation of more than 10 dB is observed up to 900 Hz for the electrodynamic and piezoelectric earplugs. In contrast, an upper frequency limit of only 450 Hz is obtained for the electrodynamic headset. In these systems, feedback amplification, which as usual cannot be completely suppressed, has in all cases been shifted towards higher frequencies, to around 2 kHz for the electrodynamic headset and the electrodynamic earplug, and to 3.5 kHz for the piezoelectric earplug.

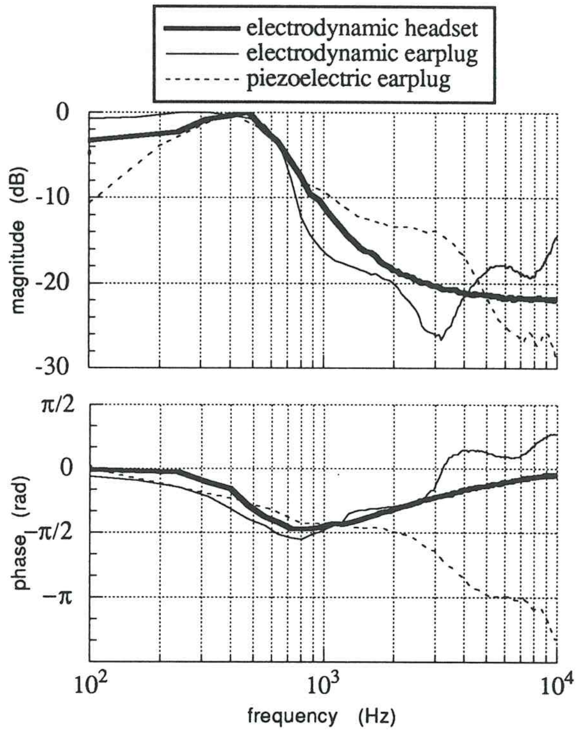

Figure 3. Frequency responses (H) of the filters optimised for each of the three electroacoustic systems.

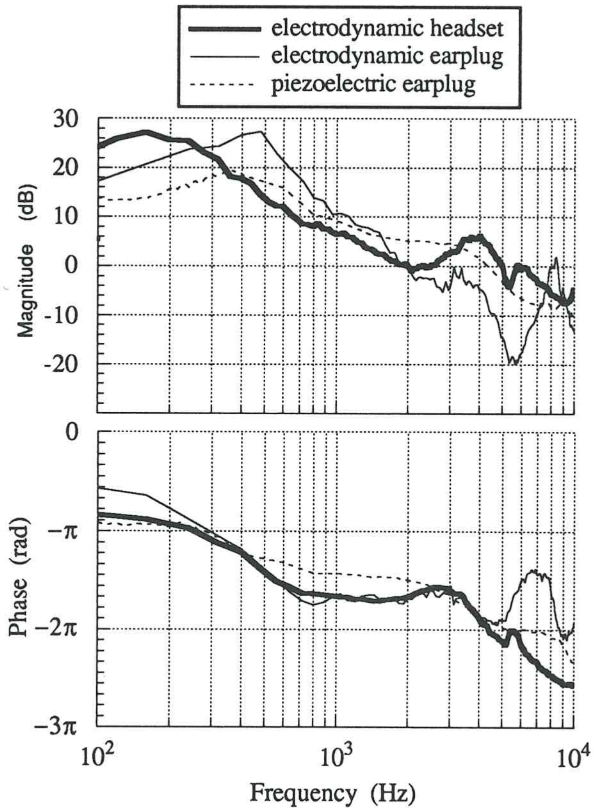

Figure 4. Open-loop frequency response (BGH) of each active protector considered.

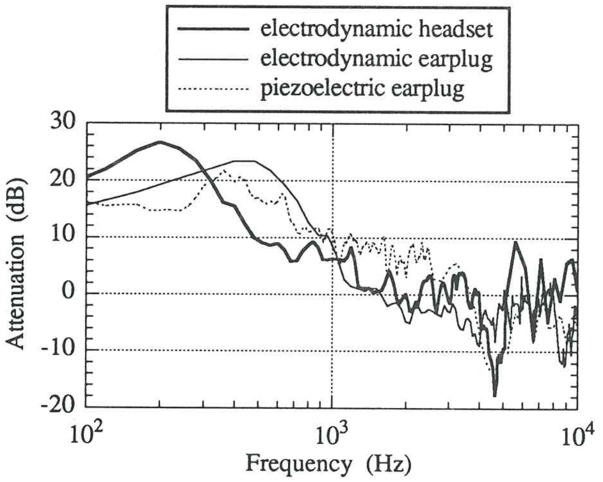

Figure 5. Attenuation-frequency curves for the three active protectors considered.

3. Discussion

3.1. *Evaluation of anti-noise efficiency*

Current active systems are often combined with passive acoustic protection, which preferentially reduces mid and high frequency noise components. Thus, when evaluating an active ear protector, the first requirement is good low frequency attenuation. The systems investigated are designed to meet this requirement but, depending on the protector, maximal attenuation occurs at different frequencies and its value varies (Figure 5).

A further concern for active protectors is feedback amplification. Because of the ear's sensitivity in the mid-frequency range, feedback amplification could have a very negative impact on subjective efficiency. Thus, for classical applications, the protection systems have to be designed to limit feedback amplification or to shift it towards higher frequencies. Of course, in some applications, a little amplification can be acceptable to increase the low-frequency attenuation: for example, such a strategy can be used for the improvement of speech recognition in a low-frequency noise environment (Béra et al., 1994).

3.2. *Comparison between the electroacoustic systems*

In terms of attenuation, the three protectors have very different behaviour. The electrodynamic protectors and especially the headset give high response at low frequencies (Figure 2), so that the reduction in noise at these frequencies is greater. The earplugs, and especially the piezoelectric one, provide significant active noise attenuation up to much higher frequency than the headset (Figure 5).

Such widening of the attenuation band is of the greatest interest. In particular, if the active hearing protector is also used to pass a communications signal, this should help to improve speech recognition in the presence of external noise.

Absolute comparison between electroacoustic systems depends on choice of an efficiency criterion. Experience shows however that, for a given electroacoustic system, the optimised control filter (H) depends only slightly on the selection criterion. Indeed, a previous study (Sunyach & Béra, 1994) has pointed out that the amplification gain G is an essential parameter which can be considered as a direct compromise between attenuation and high frequency positive feedback: attenuation and positive feedback levels both increase with G. Changes in the amplification G simply affect the open-loop response magnitude (Figure 4) and have no effect on the corresponding phase. As a result, the non-linear G dependence of the attenuation can be directly deduced from Figure 4 using equation (1). In particular, a phase greater than $-\frac{3}{2}\pi$ guarantees that for any G some positive attenuation is achieved: this occurs up to approximately 600 Hz for the headset and the electrodynamic earplug, and up to 2000 Hz for the piezoelectric earplug. The superiority of the piezoelectric earplug system is obvious here.

Conclusions

In this study we have shown that a variety of electroacoustic systems can be used as alternatives to the electrodynamic headset for active protection. Specifically, the efficiency of electrodynamic and piezoelectric earplugs has been demonstrated in laboratory tests. Moreover, these earplugs show active attenuation in a frequency range which is wider than that of a classical hearing protector. The results for the piezoelectric earplug are particularly encouraging because absence of feedback amplification can be guaranteed up to 3 kHz; the greater part of the speech frequency range is therefore actively protected in this case. Thus, the adaptation of such a system to an ergonomic earplug presenting a good passive noise attenuation, would mark a significant improvement in individual hearing protector technology.

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