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APPLICATION OF ACTIVE NOISE CONTROL TO AN ELEVATOR CABIN

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Abstract: The elevators constructed today are increasingly fast and have a high level of comfort. However, this increase in speed means a higher level of noise inside the cabin, and this noise is normally compensated by passive means, that is, by improving the cabin's insulation. Low frequency noise persists, however, and it should be dealt with by active means. This article describes the practical application of Active Noise Control to an elevator cabin, greatly reducing the level of noise in the whole area. The results obtained are an advance towards the integration of Active Noise Control in elevators, and its commercialisation. *Copyright © 2002 IFAC*

Keywords: Active noise control, LMS algorithm, feedforward control, adaptive digital filters, multichannel controllers.

1. INTRODUCTION

It is a well-known fact that passive noise compensation methods are not effective for low frequency noise of less than 200 Hz, and that Active Noise Control methods are necessary for these frequencies. The combination of both methods provides the optimum solution in a large number of cases.

The development of digital signal processors (DSPs) enables adaptive filtering algorithms to be used, and these considerably improve the performance and operations of the active control systems (Kuo and Morgan, 1996). Currently, the continual advances in these processors and their decreasing cost favour the development of applications, and systems for cars (Eppli and Stroup, 1998; Finn and Stroup, 1998), airplanes, industrial environments, heating, air conditioning, etc. are now available on the market. Although most commercial applications are based on the application of Active Control to ducts (or to cases which can be considered as equivalent to ducts) due to their simplicity and the spectacular results which may be obtained, the application of Active Control to three-dimensional enclosures, generally of reduced dimensions, is being increasingly studied (Hansen, 1997).

Active Noise Control is acquiring great importance in top-of-the-range elevator applications. The elevators constructed today are increasingly fast and have a high degree of comfort. This increase in speed implies an increase in noise, and a certain reduction in passenger comfort as a result. Passive Noise Control methods have been used for some time in high-comfort elevators, and as a result the remaining noise in the cabin is mainly low-frequency noise. Active Control methods are therefore appropriate for compensating this type of noise.

IKERLAN, which is a research center located in the Basque Country, and ORONA, an important European elevator manufacturer, have been working together on the comfort improvement of elevator cabins. This article describes the application of Active Noise Control to a commercial elevator cabin. Although the tests were carried out in the laboratory,

Fig. 1. View of the ORONA's ONDDI tower.

the positive results obtained are an advance towards the commercialisation of elevators using these active methods.

2. A BRIEF SUMMARY OF ACTIVE NOISE CONTROL

ASVC (Active Sound and Vibration Control) is based on electronic cancellation in order to control an undesired disturbance. It consists of reducing an unpleasant noise by superimposing a signal containing the same frequencies and amplitudes, but 180º out of phase. To achieve this, secondary sources such as loudspeakers for sound cancellation or piezoelectric devices for the cancellation of vibrations need to be used. These secondary sources include control electronics and a data acquisition system or sensorization, such as for example microphones for the sound and acceleration sensors or strain gauges for the vibrations. High performance controllers based on DSPs (Digital Signal Processors) are necessary.

Various Active Noise Control (ANC) systems exist: Broadband Feedforward Active Noise Control, which use acoustic sensors (microphones) for input; Narrowband Feedforward Active Noise Control, using non-acoustic sensors for input; and Feedback Active Noise Control, which use only error sensors. Hybrid Active Noise Control consists of a combination of Feedforward and Feedback Active Noise Control.

The techniques mentioned are Active Noise Control systems in one dimension, referred to as single-channel systems, or may be extended to several dimensions, giving rise to multi-channel Active Noise Control systems. Adaptive algorithms based on least-mean-squares (LMS) are basically applied, being the filtered-X LMS (FXLMS) the basic algorithm that considers the secondary-path effects. Different versions of this algorithm are described in literature on the subject (Jiang, *et al.,* 1997; Kong, *et al*., 1998).

There are many situations in which irritating noise is transmitted in several spatial dimensions. Multi-channel Active Noise Control requires a control system using multiple secondary sources together with multiple error sensors in order to control the field of noise. The multi-channel systems use any of the algorithms mentioned, depending on the characteristics of the system to which the Active Noise Control is applied.

3. ACTIVE NOISE CONTROL OF AN ELEVATOR CABIN

3.1 Introduction.

The elevators constructed today are of high speed and have a high level of comfort. This increase in speed has given rise to an increase in noise level. Active Noise Control methods are applied in order to obtain greater comfort in the cabin, as the predominant noise in high-comfort elevators is low-frequency noise.

ORONA is an important European elevator manufacturer, and at its central premises in Hernani is the 70m-high ONDDI tower (Figure 1), where two top-of-the-range elevators have been installed for testing and demonstration. One has a speed of 1.6 m/s, and the other a speed of 3.5 m/s. The noise signals received inside the cabins of these two elevators were measured, and it was observed that low-frequency components were those which contributed most to the noise signal, principally several harmonic of the electric frequency for the motor shunt, which is 7.92 Hz. Significant contributions from the frequency harmonics between 25 and 100 Hz appear in the spectrums.

Figure 2 shows the sound pressure level obtained inside the cabin of the elevator of 3.5 m/s. In this Figure 2, the right-hand A-weighting scale shows the total noise weighted for the human ear. It was supposed that the noise reduced 10 dB in the range 0-800 Hz, which would mean a reduction of 6 dB in the total weighted noise. As a conclusion, the application of the ANC techniques to such a cabin is quite interesting.

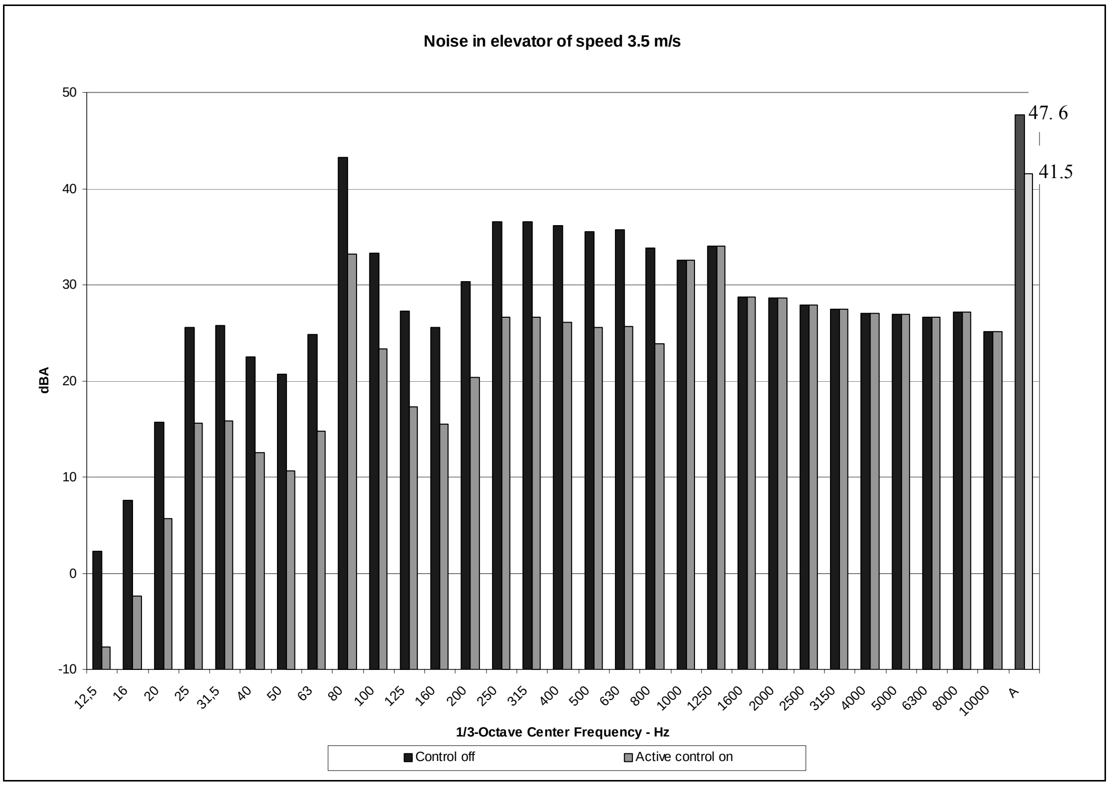

Fig. 2. One-third octave band spectra and sound level (dBA) measured in the cabin of the elevator of 3.5 m/s.

3.2 Prototype description.

On detailed analysis, it was observed that the main source of noise in the ORONA elevator cabins was the motor, the noise being transmitted from here to the cabin by the hanging ropes in particular. Owing to the difficulty of carrying out noise controls in a functioning elevator, an equivalent prototype was built in the laboratory, consisting of a normal ORONA elevator cabin plus the motor with which it is normally equipped. This prototype is shown in Figure 3, together with the positioning of the loudspeakers and error microphones.

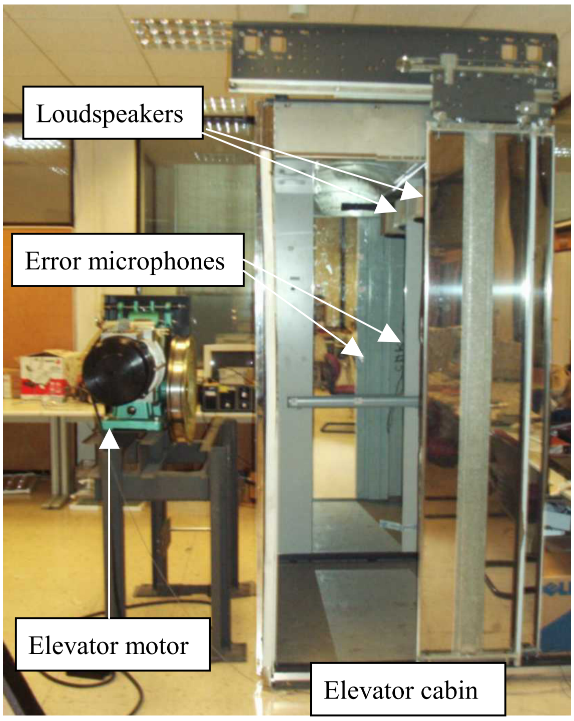

Fig. 3. Prototype in which ANC was applied.

The motor is Three-phase Asynchronous with nominal characteristics of 5.5 HP and 1360 rpm. As it is located beside one of the walls of the cabin, the noise is polarised, and after several tests the secondary loudspeakers were therefore located on the ceiling, near the opposite wall. Normally they would be placed centrally on the ceiling.

With this arrangement, the spectrum of the noise in the cabin generated by the motor was measured. Figure 8 shows the sound pressure level (noise signal without any compensation), and it can be observed that although high frequency components appear, basically owing to the existence of air-borne transmission paths, low frequency noises also appear, at frequencies which are multiples of the motor speed, those of 25 Hz and its multiples up to 200 Hz being the most significant. In short, the type of noise problems in this prototype, and their compensation, were considered to be the same as for ORONA elevators with a normal arrangement and functioning normally, both in the case of the standard models and those at the high end of the range.

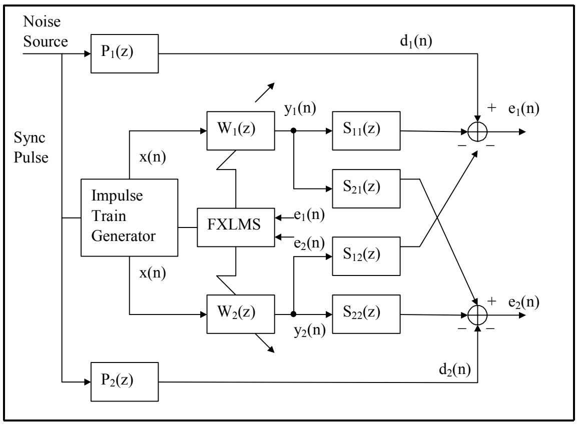

Fig. 4. Structure of the Waveform Synthesis Method with the FXLMS algorithm.

3.3 Control Hardware and Software.

As has already been indicated, inside the cabin the most significant low-frequency components correspond to the frequency of the motor rotation and of its harmonics, that is, at 25 Hz and multiples of this frequency. Special cancelling loudspeakers, that is, subwoofers, were therefore necessary as secondary sources. Two 120 w subwoofer loudspeakers were used as actuators and two microphones as error sensors: microphone 1, ICP with a sensitivity of 53.9 mV/Pascal and microphone 2 with a sensitivity of 15.2 pC/g. A 200 w dual channel power amplifier was also used.

As the noise in the cabin was of a frequency proportional to the speed of the motor, a reference signal was needed. The motor had no tachometric output and so a photoelectric proximity sensor was incorporated, so that a synchronisation pulse was generated at each turn of the motor. This was used as a reference signal.

For control hardware, the dSPACE DS1103 control card was used. An 8^{th} order active analogue low-pass filter with a cut-off frequency of 1 kHz was applied to the controller output signals, in order to avoid a heavy influence of the sampling period on the signal obtained, and to correct the resolution of the output card.

The software consists of a control program containing the Active Noise Control algorithms written in C language, which receives the input signals, processes them in DSP and calculates the output signals. The control loop closes every 0.5 ms. The LabWindows/CVI environment was used for monitoring purposes.

4. CONTROL ALGORITHM

The low-frequency noise corresponds to the harmonic frequencies of the motor speed, which is periodic,

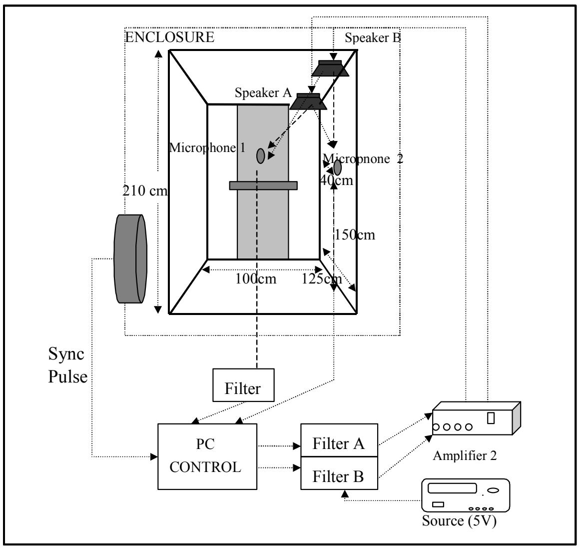

Fig. 5. Control scheme used in the elevator cabin.

and so a narrowband algorithm had to be used. Although different narrowband algorithms were tried and applied in the prototype, this paper presents the results obtained with the waveform synthesis method, where the synchronisation pulse is a reference signal.

This technique assumes that the next cycle will have the same wave form as the present one and it is appropriate for a wide range of low-frequency problems associated with machinery, vehicles, ships, airplanes, etc. An Active Noise Control using this algorithm is equivalent to an adaptive FIR filter with a pulse train as a reference signal.

In this context, a Narrowband Multi-channel Feedforward algorithm was used, the algorithm WSM 1x2x2 (Waveform Synthesis Method with the FXLMS algorithm, 1 reference source, 2 secondary sources and 2 error sensors) (Kuo and Morgan, 1996), completed with the on-line modelling of the secondary paths. Figure 4 shows the algorithm structure: y_1(n) and y_2(n) are the cancelling signals generated by the adaptive filters W_1(z) and W_2(z) respectively; e_1(n) and e_2(n) are the error signals measured by the two error sensors; P_1(z) and P_2(z) are the primary paths from the noise source to the two error sensors; S_{11}(z), S_{12}(z), S_{21}(z) and S_{22}(z) are the secondary paths from the cancelling signals to the error sensors. The block FXLMS includes, as well as the LMS algorithm, the transfer functions $\hat{S}_{mk}(\mathrm{z})$, which are estimates of S_{mk} (z) for m=1,2 and k=1,2.

The FXLMS algorithm (Kuo and Morgan, 1996) is typically expressed as:

$$\boldsymbol{W}(\mathrm{n}+1) = \boldsymbol{W}(\mathrm{n}) + \mu \cdot \boldsymbol{X}'(\mathrm{n}) \cdot \boldsymbol{e}(\mathrm{n})$$
$$\boldsymbol{X}'(\mathrm{n}) = \hat{\boldsymbol{S}}'(\mathrm{n}) \otimes \boldsymbol{x}(\mathrm{n})$$

where $\boldsymbol{x}$(n) is the reference signal, $\boldsymbol{e}$(n) is the error signal vector, $\hat{\boldsymbol{S}}'(\mathrm{n})$ is an estimate of the secondary

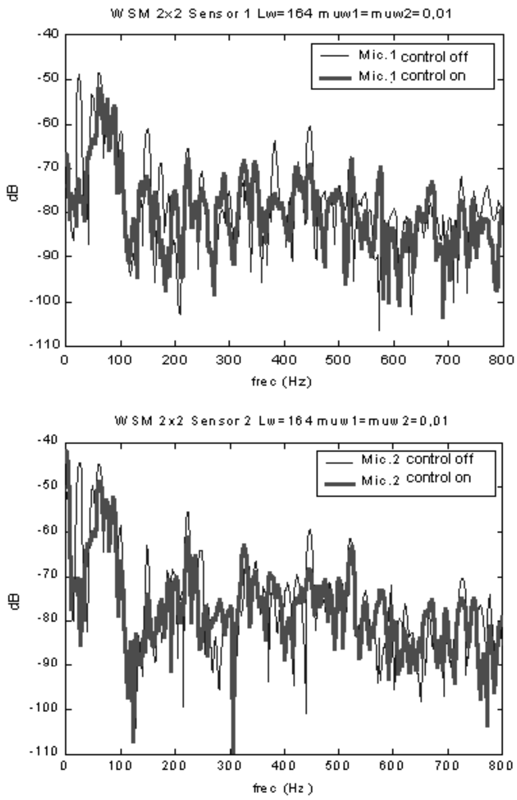

Fig. 6. Signal spectrums in microphone 1 and microphone 2 without control and with control.

paths, μ is the step size and $\otimes$ denotes a Kronecker product convolution.

The case of 3 error sensors was also considered, where an error plane or zone is better defined, but although the algorithm is more complex, the results obtained were analogous.

The control scheme carried out with the hardware components described above is shown in Figure 5. The two error microphones were placed at a height of 150 cm from the cabin floor, attempting to define a reference zone in which the noise was to be reduced. The results were mainly evaluated on three horizontal planes: on the horizontal plane at which the error microphones were placed, on a higher parallel plane situated at a height of 170 cm from the floor, and on a lower parallel plane at a height of 90 cm from the floor. A microphone with a sensitivity of 3.63 mV/Pascal was used as a test sensor and was placed at the different points of each plane.

5. EXPERIMENTAL RESULTS

When the secondary paths were correctly estimated, using an order of 164 for the digital control filters and a step size of 0.01, the results shown in Figure 6 were obtained. It is shown in the upper part the spectrum of the noise signals in error microphone 1 before and after convergence is reached. In the lower part the spectrum of the signals in error microphone 2

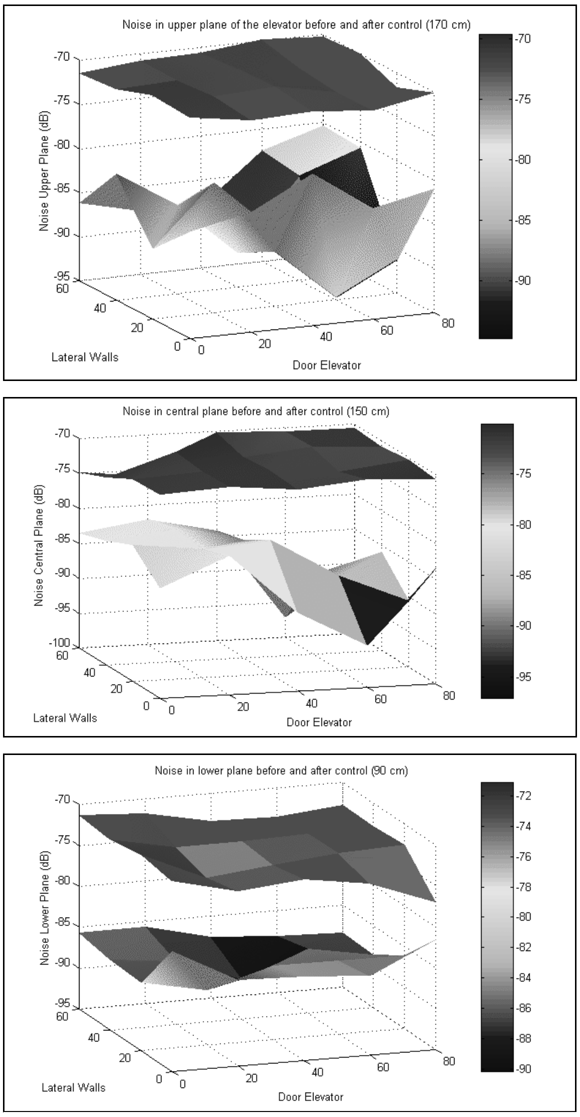

Fig. 7. Noise level in signal of 25 Hz in three reference planes, without active control and with active control.

appear as well. It can be observed that the system succeeds in reducing the signal for the fundamental frequency (25 Hz) and also for most of the harmonics.

Measurements were also taken at the different points of the elevator using the test microphone, before and after applying the control algorithm. The results shown in Figure 7 were obtained for the three reference planes considered, with only the noise at a frequency of 25 Hz being evaluated. A considerable noise reduction was obtained, not only on the plane at which the error microphones are situated, but also on the higher and lower planes, the average reduction being of around 10 dB.

The study was completed with the application of passive noise control methods to the elevator cabin. In order to do this, the interior panels of the cabin were covered with insulating wooden panels. Measurements were taken of the noise signal

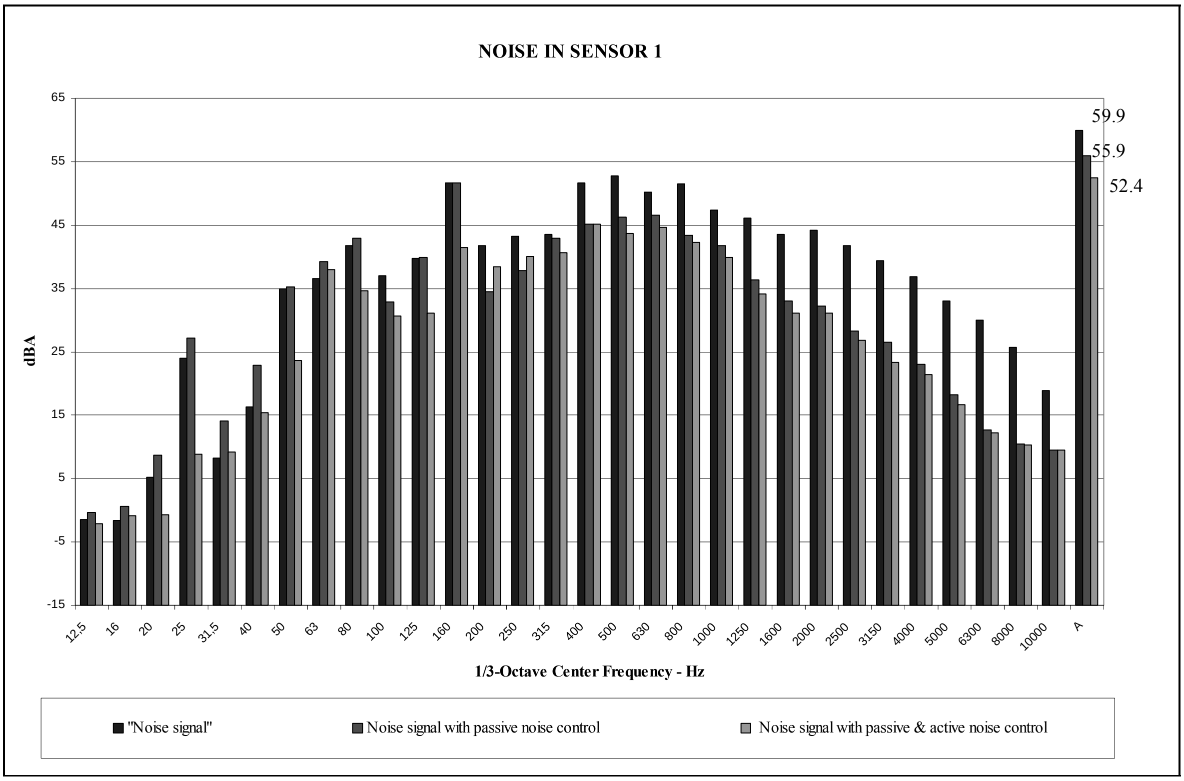

Fig. 8. One-third octave band spectra and sound level (dBA) in sensor microphone 1 without any compensation, with compensation by passive methods and with passive and active compensations.

generated by the motor inside the cabin, without the control, with the passive compensation and applying both the passive and active controls together. Figure 8 shows the results obtained in error microphone 1. It can be observed that the passive control succeeds in reducing the noise signal for the high frequencies, and the active control for the low frequency components. The right-hand A-weighting scale shows the total noise in the cabin weighted for the human ear. With the passive techniques a reduction of 4 dB is obtained, and with the active techniques an additional reduction of 3.5 dB is obtained, which can be considered a very positive result.

6. CONCLUSIONS

In spite of the system's complexity, the experimental results show that the application of Active Noise Control to an elevator cabin succeed in reducing the noise signal by over 10 dB at the frequencies of interest, not only on the plane containing the error sensors but also on several planes in the elevator cabin. In the case studied, the proximity of the noise source and the polarisation of the noise signal prevent from obtaining better results. Considering the total noise weighted for the human ear, the reduction achieved with the active techniques is 3.5 dB.

Finally, it was observed that with a combination of active and passive control methods the human ear can pick up a total noise reduction of over 7 dB in certain areas of the cabin.

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