ACOUSTICAL ANALYSIS AIMED AT THE CHARACTERISATION OF AN ACTIVE NOISE CONTROL SYSTEM INSIDE A VAN AND THE IMPROVEMENT OF ITS PERFORMANCE.

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INTRODUCTION

In order to optimise the performance of an Active Noise Control (ANC) system that reduces low frequency noise inside a van, an exhaustive analysis of its acoustical properties has been carried out.

We determine the physical arrangement of the electro-acoustic elements by choosing the position of the error microphones where the noise must be cancelled. Four emplacements corresponding to the two front passengers' heads and the two back ones' were selected. The secondary sources are placed close to these localisations on points physically viable. The secondary path's transfer functions have been continuously monitored to avoid de presence of zeros in the frequency band of interest. We have also tried to minimise the cross terms' effect so as to simplify the algorithms.

Taking into account that the coherence function between the reference and error signals determines a bound on the reduction that can be achieved by an ANC system, we have been looking for the optimal position of acoustical and mechanical reference sensors comparing the different coherence functions obtained.

We also study the spectral distribution of the noise from the engine, for several revolution regimens. The study of the results obtained have helped us to direct the ANC system's efforts to the most annoying noise components.

Finally, we have estimated the transfer functions between the four secondary sources and the microphones located on an array homogeneously distributed at the top of the vehicle. We have developed a simulation tool to predict the power distribution when the secondary sources are fed with arbitrary signals. The same array has been used to obtain the A-weighted sound power.

DESCRIPTION OF THE ACTIVE NOISE CONTROL SYSTEM

The control system is implemented in a van (Nissan Vanette), with a four cylinder diesel engine and approximate dimensions 267x117x132 cm considering the vehicle a parallelepiped, though the volume inside the van cannot be considered to have that form. The van accepts a maximum of five or six passengers, two at the front seats and three or four at the back seats. Our ANC system can work with up to four channels, (up to two at the same time) and a local cancellation at four different points inside the van is searched. These positions correspond to the two front passengers' heads and the ones corresponding to two back passengers seated close to the windows (see figure 1). The basis of an active noise cancellation system is the generation of a secondary signal that interferes destructively with the signal produced by a primary noise source. In order to produce the proper cancelling signal the ANC system requires an amount of information that in our case, where a feedfoward system has been chosen, is a reference signal that provides information about the acoustic disturbance that we desired to eliminate at selected points and error signals that measure the level of noise presented at those points.

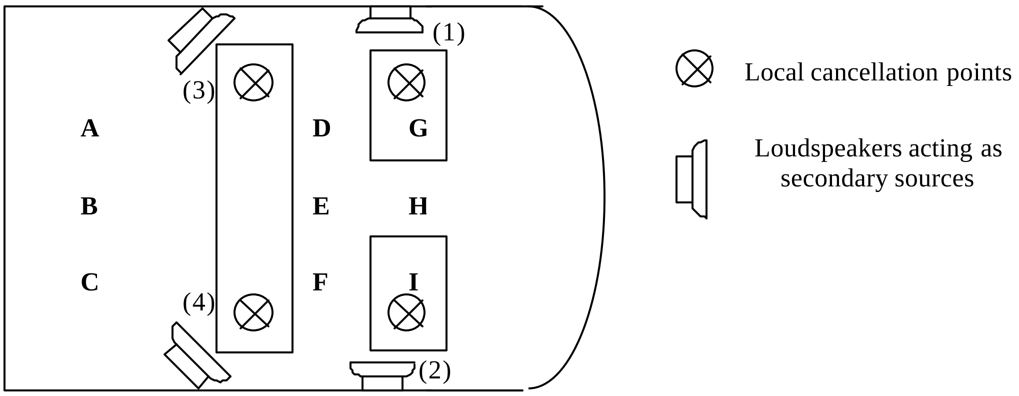


Figure 1. Schematic representation of the van where the position of the secondary sources and the points where local cancellation is aimed are marked. Every cancelling set is identified with a number from one to four. Also the positions where an acoustical reference is taken (from A to I) to evaluate coherence are shown.

Considered as single-channel the ANC system requires two inputs signals and produce just one output as is schematised on figure 2. This paper analyses the quality of these signals and if they accomplish the basic requirements to achieve an effective cancellation.

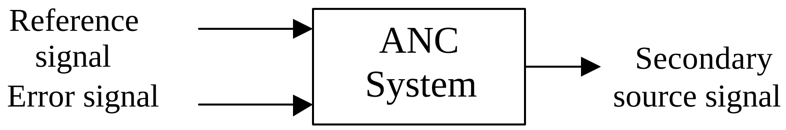


Figure 2. Inputs and outputs of the ANC system.

The reference signal must fulfil several requirements. Must be taken at position related to error sensors, where the causality principle accomplishes[1]. As will be explained later, this signal has to reach a degree of coherence with that second input signal of the ANC system. Besides, the reference signal must transport enough power to contribute to the cancellation algorithm. The reference signal is obtained by two different methods. Acoustically, by means of a microphone or mechanically, using an accelerometer that directly detects the vibration state of the engine. Both kind of references are taken with a sonometer RION NL-18. The sonometer is armed with a microphone ½ UC-53A and a preamplifier NH-19. The microphone can be substituted by an accelerometer so that the NL-18 can behave as a non acoustic sensor.

Four secondary sources are employed, placed near the cancellation points, as output signals. So the error sensors that provide the noise in the cancellation positions (noise that must be minimised), are also close to the secondary sources that produce the signal that cancels this noise. These error microphones are oriented to the secondary sources at a distance of 20 cm (figure 3). With these configuration, the error signal at every cancellation point pretended to be considered only dependent on the closer secondary loudspeaker.

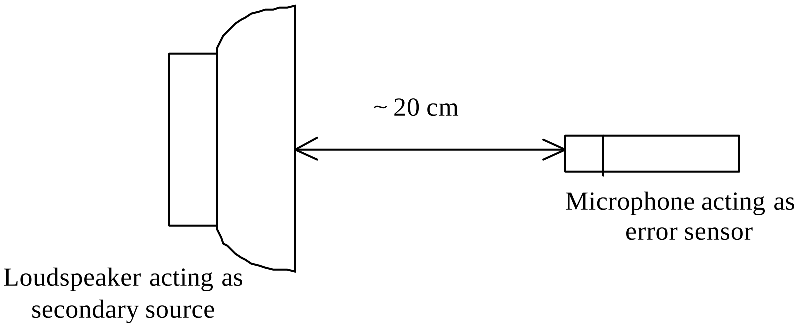


Figure 3. Relative orientation of the error sensor and the secondary source at every of the cancellation positions.

The acoustical elements placed at front and back positions are not the same. At the back seat two subwoofer loudspeakers Alpine SWS1040 are used as secondary sources. These elements work in a bandwidth from 30 Hz to 2 KHz, with a RMS power of 200 W and a maximum power of 600 W. As error sensors two microphones Falcon Type 4189 are used. They are effective between 6.3 Hz to 20 KHz, with a sensitivity of 50 mV/Pa. This type of microphones are used as error sensors at the front seats too, but at these positions different secondary sources are implemented: two T 453 Car Audio loudspeaker, with a nominal power of 25 W, maximum power of 40 W and frequency response from 90 Hz to 16 KHz. The first loudspeakers described have a better quality (are more powerful and have better frequency response) than the second ones, but their size is greater and there is a real difficulty in placing them without disturbing passengers' comfort.

NOISE SPECTRUM DISTRIBUTION

The principal source of noise in our system is the engine working at different revolution regimes. The signal produced spectrum will indicates the spectral components on that our system must mainly work. The spectral distribution of the noise generated by the engine depends on its revolution regime and also on the physical characteristics of the van where this signal propagates. We have worked with three different revolution regimes that are going to be named low, medium and high revolution regimes. To analyse the noise inside the van for each of these situations, we record the acoustic signal inside the van for a time interval of ten seconds with a sample frequency of 800 Hz what ensures the calculation of the signal spectrum till frequencies equal to 400 Hz. Our ANC system is adapted to work with these frequency range. This measurement is done with the system of acquisition and processing Symphonie 01 dB.

On figures 4 to 6 the spectrum corresponding to the high, medium and low regimes respectively are shown. These curves mainly reproduce the behaviour of our four cylinder diesel engine. The engine works in cycles of four steps. In these way, the firing frequency is the frequency related to these steps. In every cycle, two explosions take place, the revolution regime is determined by them, so the rpm frequency is just double the firing frequency [2,3].

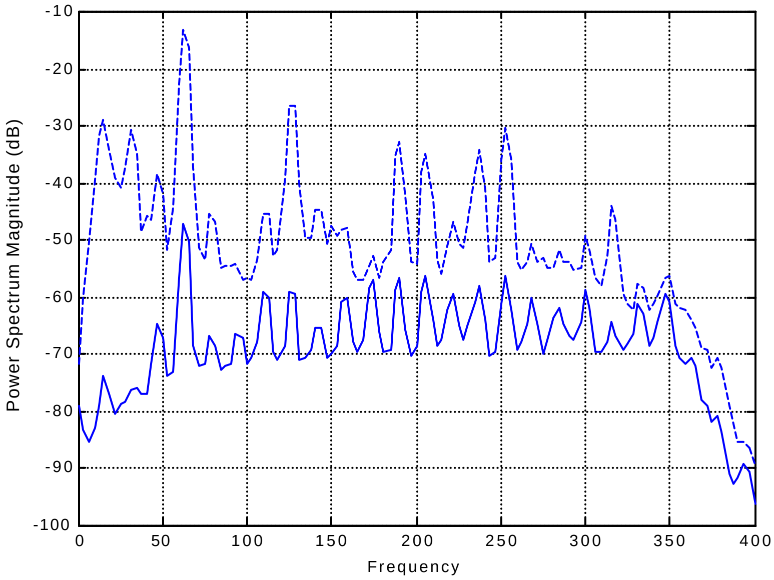


Figure 4. Power spectrum distribution of the acoustic reference (dashed line) and the mechanical reference (solid line) at high revolution regime, 1890 rpm

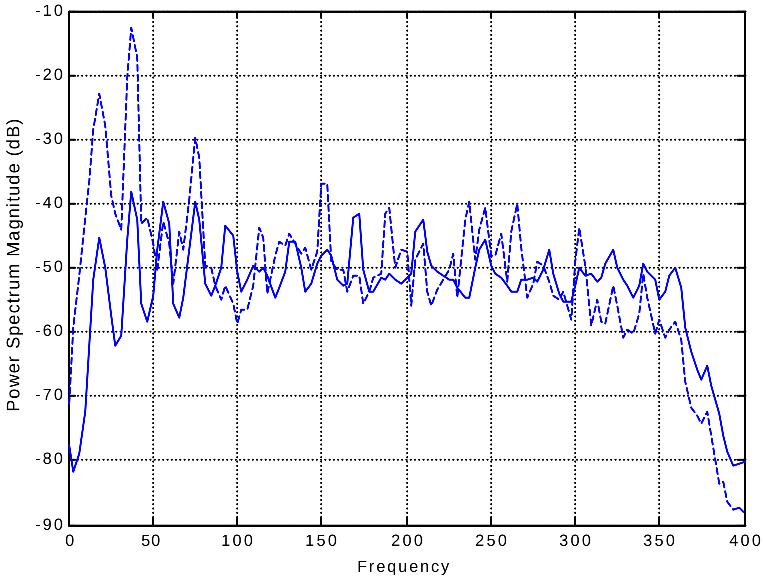


Figure 5. Power spectrum distribution of the acoustic reference (dashed line) and the mechanical reference (solid line) at medium revolution regime, 1140 rpm

The fundamental harmonics for these three regimens are 1890 rpm for high revolution regime, 1140 rpm for medium revolution regime and 800 rpm for low revolution regimen. Figures 4 to 6 show how the second harmonic is the predominant frequency on the spectrum and the 2N multiples also present important contributions. However the energy on these component varies along the set of measurements and different components become important in some occasions. These components are always multiples of the fundamental harmonic of the engine or, in some occasions, of the firing frequency.

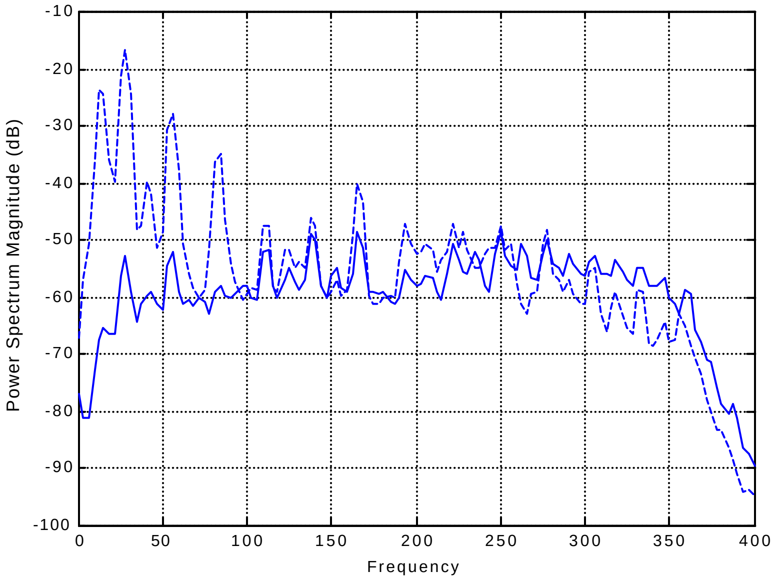


Figure 6. Power spectrum distribution of the acoustic reference (dashed line) and the mechanical reference (solid line) at low revolution regime, 800 rpm

The signal captured with the accelerometer presents a similar frequency distribution. The mechanical sensor is placed just on the sheet above the engine. The main difference between the acoustic and the mechanical signals is the energy at low frequencies. The low components are acoustically emphasised by the structure of the van. So, only if the acoustic reference is employed, information of primary noise at low frequencies is obtained. This range of frequencies are not perceived by human ears and it is not indispensable to cancel them. It is even searched not to operate on these frequencies in order to optimise calculations[4]. But these components are captured by the error sensors placed at the front seats, and so are included on DSP calculations. If no reference signal is obtained about them, the output signal can diverge at that frequencies. Another important difference between the two kind of reference signals is that in the mechanical one the amplitudes of the spectral components have closer values. The acoustical signal clearly reveals what frequencies are enhanced by the structure of the van.

Our study let us determine the frequencies that can have significant energy in the noise signal, though the distribution of the energy between them changes. The spectral components of the analysed noise are mainly periodic and so they can be cancelled by means of the ANC algorithm. But only a few spectral terms have always enough energy, those that correspond to the low predominant frequencies. The higher ones are not stationary as a real time monitoring reveals. So they are more difficult to cancel. Only at high revolution regime, the predominant frequency is above the sensibility limit of the human ear.

COHERENCE FUNCTION.

The ANC system only provides cancellation of the portion of noise that keeps correlated as it gets the error microphone. This degree of correlation is measured by the coherence function $\gamma_{xd}(\omega)$ determined by the spectral spectrum of the reference signal at the position of the reference sensor, $S_{xx}(\omega)$, at the position of the error sensor $S_{dd}(\omega)$, and the cross-power spectrum between them, $S_{dx}(\omega)$, as indicated on equation [1]:

$$\gamma_{dx}(\omega) = \frac{S_{dx}(\omega)}{\sqrt{S_{dd}(\omega) S_{xx}(\omega)}} \qquad [1]$$

The coherence at every frequency depends on two factors, the energy present at that frequency and the relative linearity of the reference signals captured at the two position described above. Coherence close to its maximum value equal to 1 is necessary to achieve a good cancellation. We are going to study the coherence of the ANC systems as a function of the position of the acoustical reference sensor. It is placed at 9 different positions inside the van. These position are labelled from A to I and are localised on figure 1. The position of the reference sensor is 52 cm above the vehicle floor. We measured at the same time the noise produced by the engine at the selected reference position and at each error sensor. The measurement are 15 seconds long and sampled at 800 Hz. On tables 1 to 3, we present the degree of noise reduction that can be reached at the error sensor number 3 for the three revolution regimens considered. This degree of reduction in decibels depends on the coherence as expressed on equation [2]:

$$-10\log_{10}\left[1-\left|\gamma_{dx}\right|^{2}\right] \qquad [2]$$

As it is implicit on the definition of the coherence function, only at frequencies with enough energy the coherence and also the maximum reduction attainable, can be high. So the results are shown for the predominant frequencies of the noise spectrum. The second harmonic of the engine and its first and second 2N multiples have been represented.

As a conclusion, the measurements reveal that the coherence is generally greater at back positions A, B, C (except for the low revolution regime). However, at these positions the causality principle is not certain because the error sensor is nearer the primary source than the reference microphone. If the primary noise is periodic the causality principle is not strictly necessary and these positions can be chosen for the reference microphone. Also the degree of noise reduction is greater at low harmonic components because these frequencies transport more energy.

Coherence with mechanical reference is also obtained. The accelerometer is again placed above the engine. Tables 4 shows the degree of noise reduction for the three regimens analysed. The degree of noise reduction limit is lower with this kind of reference for the frequencies presented.

High revolution regime (1860 rpm)			
Reference sensor position	63 Hz	126 Hz	189 Hz
A	36.5 dB	26.46 dB	25.18 dB
B	31.77 dB	11.46 dB	24.7 dB
C	24 dB	15 dB	11.2 dB
D	12.72 dB	3 dB	3.18 dB
E	19.84 dB	11.37 dB	12.71 dB
F	16.1 dB	14.97 dB	16.43 dB
G	23.72 dB	22.67 dB	14.52 dB
H	29 dB	18.8 dB	12 dB
I	27.12 dB	15.5 dB	15.57 dB

Table (1)

Medium revolution regime (1080 rpm)			
Reference sensor position	37.5 Hz	75 Hz	112.5 Hz
A	30.28 dB	13.28 dB	18.4 dB
B	38.07 dB	18 dB	10.15 dB
C	40.5 dB	14.1 dB	5 dB
D	19.3 dB	11.06 dB	11.7 dB
E	32.17 dB	6.4 dB	14.34 dB
F	26.18 dB	12.78 dB	15.41 dB
G	23.1 dB	2dB	15.37 dB
H	29.12 dB	24.6 dB	14.7 dB
I	19.88 dB	5 dB	10.92 dB

Table (2)

Low revolution regime (800 rpm)			
Reference sensor position	27.34 Hz	54.68 Hz	82.02 Hz
A	15 dB	12.82 dB	18.15 dB
B	23.29 dB	16.26 dB	24.02 dB
C	29.44 dB	15.6 dB	21.25 dB
D	28.4 dB	10.1 dB	9.91 dB
E	38.25 dB	22.22 dB	30 dB
F	30 dB	21.34 dB	30.88 dB
G	11.83 dB	14.02 dB	23.14 dB
H	14.87 dB	12.72 dB	26.53 dB
I	25.66 dB	11.48 dB	19.54 dB

Table (3)

Mechanical reference					
Regimen high		Regimen medium		Regimen low	
Frequency	Reduction	Frequency	Reduction	Frequency	Reduction
63 Hz	19.91 dB	37.5 Hz	14.15 dB	27.34 Hz	6.4 dB
126 Hz	8.34 dB	75 Hz	9.6 dB	54.68 Hz	7.38 dB
189 Hz	8.37 dB	112.5 Hz	---	82.02 Hz	---

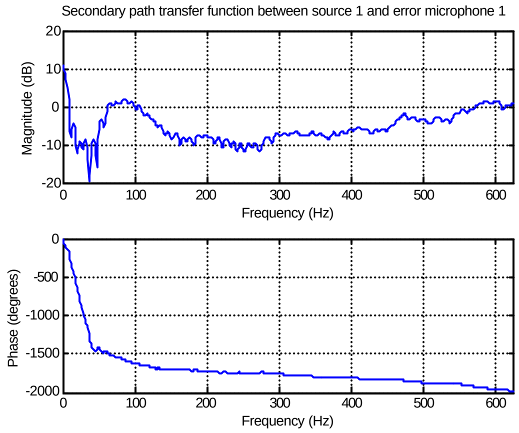
Table (4)

SECONDARY PATHS

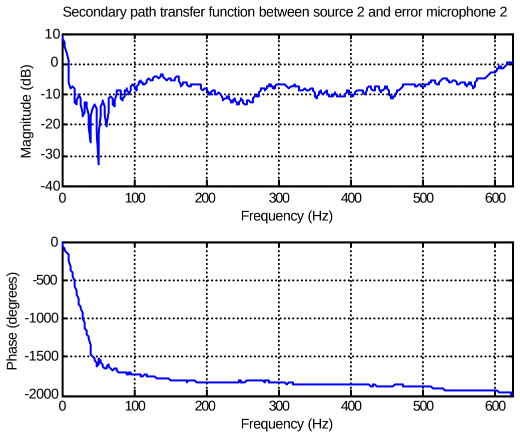
The FXLMS algorithm used requires an off-line estimation of the secondary path between the secondary signal and the error signal. This secondary path comprises the transfer function between the digital calculated output and the digitally captured error input signal, so it depends on the characteristics of the analogical-digital and digital-analogical converters, the features of the loudspeaker source and the error microphone and the acoustical path between these elements.

To obtain the secondary path between a secondary source and an error microphone, a white noise signal is emitted by the output. The transfer function is digitally calculated by the DSP following the LMS algorithm. The input information required is the white noise ejected and the signal captured at the error position [1]. As a single-channel system is pretended, the secondary paths between each secondary source and its related microphone sensors are calculated and presented on figures 7. A sample frequency of 1250 Hz is used, so information from 0 to 625 Hz is presented.

The knowledge of the secondary path transfer function indicates us if there is any uncontrollable frequency. If this function is null for a frequency, it means that we have no information about it and the control system can be unstable at that frequency. The measurements done indicate that the physical features of the secondary source determine these potentially unstable frequencies. Figures 7 (a) and 7 (b), corresponding to cancellation positions 1 and 2, show a limitation below 90 Hz that corresponds to the low limit of the frequency response of the associated loudspeakers. Figures 7 (c) and 7 (d), that provide information of points 3 and 4 reveal that the system can be problematic at frequencies below 30 Hz. This value correspond to the low limit of the loudspeakers employed at these points.



(a)



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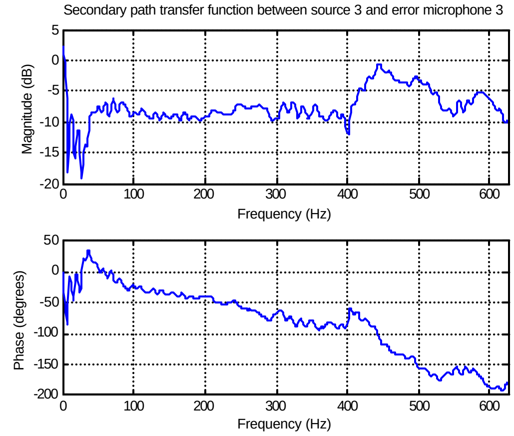
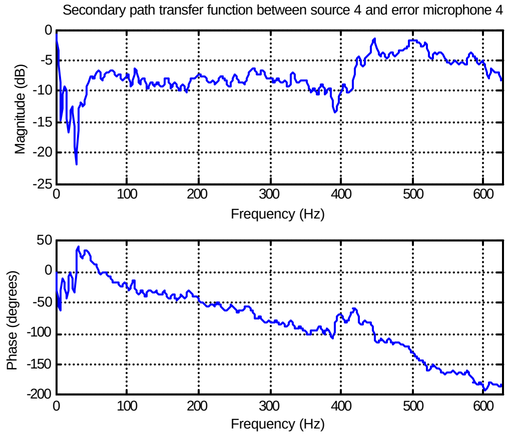


(c)



(d)

Figures 7. Magnitude and phase of the transfer function of the secondary paths between loudspeaker and error microphone 1 (a), 2 (b), 3 (c) and 4 (d).

SOUND DISTRIBUTION CREATED BY THE FOUR SECONDARIES SOURCES.

In order to obtain the influence of every secondary source at the whole van volume, the transfer function between these sources and an array of 20 microphones homogeneously distributed along that volume is calculated following the same method to estimate the secondary paths. All the microphones are placed at the same height, that coincides with the position of a passenger's ears. These positions are shown on figure 8.

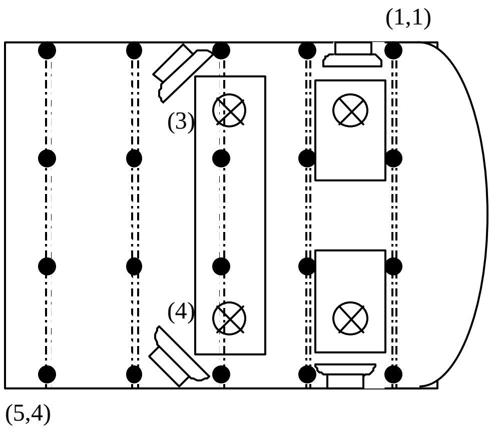


Figure 8 (a). The rings shows the points where a microphone is situated to calculate the acoustical map distribution of the signal emitted by every secondary source. Figure 8 (b) The position of the 20 microphones related to the points of local cancellation is schematised. This points are treated as a 5x4 matrix, the elements (1,1) and (5,4) are indicated.

On figure 9 the power sound level, normalised to the maximum power measured, on the surface considered is represented when white noise is emitted by each secondary source. On figure 10 the distribution is A-weighted and so, adapted to the sensibility if the human ear. These figures show that the influence of any secondary source cannot be despised at the positions of all the error microphones and that the ANC system is advisable to be designed as multiple-channel. Nevertheless, this influence is greater if all the frequencies are equally treated. When the distribution is A-weighted, the acoustical pressure created by a source is almost concentrated near that source. If a filtering of the signals is done, eliminating low frequencies components, the single-channel system will produce good results.

With the transfer function calculated, a simulation program has been done to predict the acoustical distribution inside the van when an arbitrary signal is ejected by any of the sources. Figure 11 shows the results experimentally measured and theoretical estimated with our program when a tone of 160 Hz is emitted by secondary source 3. The discrepancies between both representations can be attributed to the differences between the experimental input signal (where energy at the first harmonic of 160 was remarkable) and the theoretical one, a pure tone. Possible displacements of the acoustical sensors between measurements must also be considered.

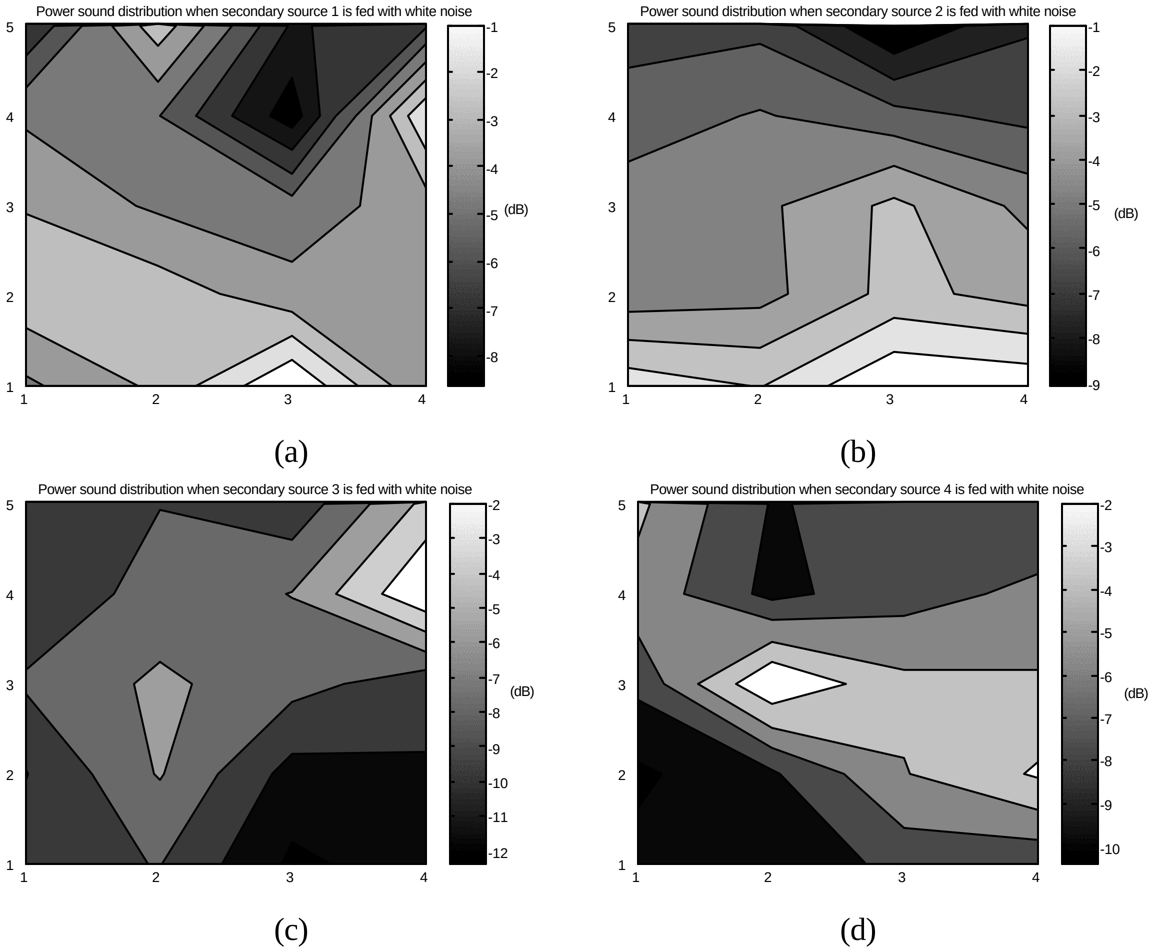


Figure 9 Acoustical power distribution normalised to the maximum power measured, when secondary sources 1, (a), 2, (b), 3, (c) and 4, (d) are fed with white noise. The axis co-ordinates represent the indexes of the microphones in the measurement matrix. Frequencies till 625 Hz are considered.

CONCLUSIONS

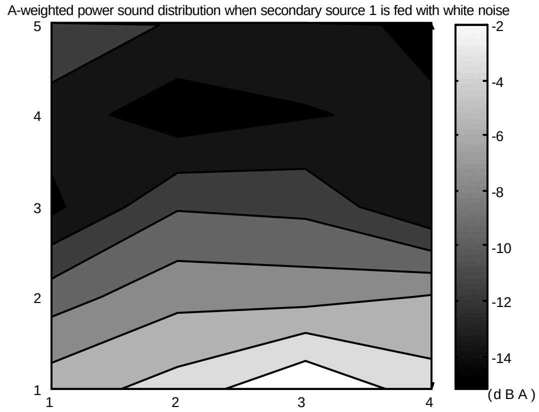
An acoustical characterisation of an ANC system is done in order to determined the best way to captured the necessary input signals related to the primary noise source and the position of the secondary sources that are considered fixed because of space considerations.

An analysis of the spectral distribution of the primary noise reveals that every revolution regime is defined by a fundamental frequency. All the predominant components are an integer multiple of this value. When the reference is taken with a mechanical sensor, all these components show similar magnitudes except for the lower ones. An acoustical reference reveals which of those frequencies are emphasised by the vehicle structure. Higher harmonics can present high amplitudes but not in a stationary way. So these components are more difficult to cancel.

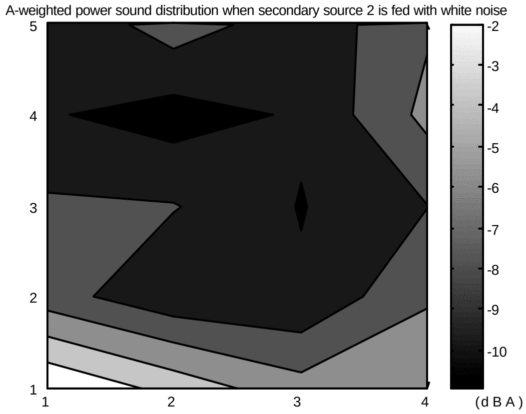
The coherence between the primary noise at the reference and error positions is greater at points where the causality principle is not achieved. But it is not a problem when the primary noise is strictly periodic. The coherence is greater for the spectral components with more energy, twice and four times the fundamental frequency of the engine. The coherence for the predominant components of the primary noise, can be considered acceptably high at all the positions tested.

The analysis of the secondary paths is necessary to detect frequencies potentially no controllable. The measurements reveals that only frequencies out of the frequency response of the secondary sources can present problems.

Finally a power sound map distribution simulation has been done for arbitrary signals ejected by the four secondary sources. This calculation shows that if low frequencies are considered a multiple-channel ANC system should be implemented. When the distribution is A-weighted, a single-channel system can be implemented.



(a)



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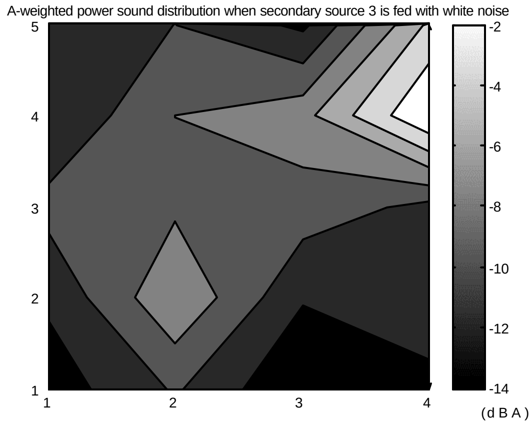
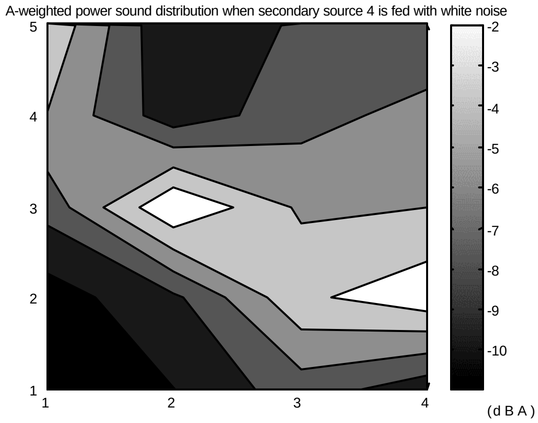


(c)



(d)

Figure 10 Acoustical A-weighted power distribution normalised to the maximum power measured, when secondary sources 1, (a), 2, (b), 3, (c) and 4, (d) are fed with white noise. The axis co-ordinates represent the indexes of the microphones in the measurement matrix. Frequencies till 625 Hz are considered.

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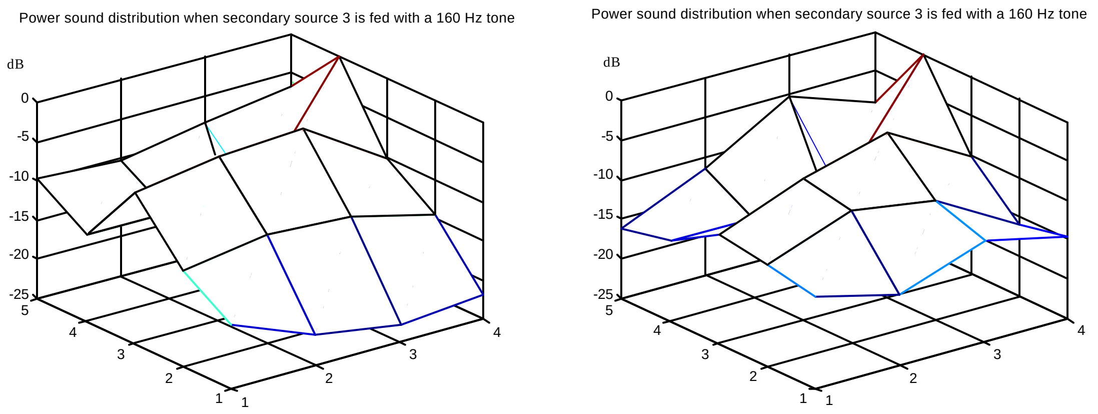

Figure 11. Power sound distribution when a 160 Hz tone is injected through secondary source 3. (a) experimental results, and (b) theoretical results.

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