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Methodology of Selecting the Reference Source for an Active Noise Control System in a Car

Zbigniew Dąbrowski

Warsaw University of Technology, Warsaw, Poland

Bartosz Stankiewicz

Industrial Research Institute for Automation and Measurements (PIAP), Warsaw, Poland

At the end of the 20th century, a significant development in digital technologies of signal processing made it possible to apply active noise control methods in new domains. A proper selection of the reference signal source is a main problem in implementing such systems. This paper presents an estimation method based on an indicator of the coherent power level. It also presents a simple system of active noise control in a car, operating according to the proposed method of optimising the positioning of reference sources. This system makes it possible to considerably increase the comfort of work of drivers in various kinds of road transport without a great increase in cost. This is especially significant in the case of trucks and vans. Passive barriers are considerably more expensive in them, which results in a higher level of noise than in passenger cars.

active noise control car vibroacoustics drivers

1. INTRODUCTION

The beginnings of active noise control (ANC) date back to the early 1930s. However, it was only when digital technologies intensely developed in the 1970s that there have been practical solutions. The end of the 1980s brought first attempts at including active methods for silencing interiors of all kinds of vehicles, including cars. A significant progress in signal processing and treatment methods meant that this limit could be shifted and their applications, previously impossible, became realistic. This fact makes it possible to apply ANC methods in new domains. Manufacturers are already equipping luxury cars with "active noise suppression" systems. In fact, the operation of such systems is limited to compensating engine noise, i.e., the frequency of combustions and its successive harmonics. This kind of system, based on an analytical synthesis of a compensating signal, overlooks essential noise sources. In the case of a car, two sound sources are overlooked: air flow and wheels rolling on a surface. However, it is now possible to approach this problem globally and attempt to design an ANC system in a vehicle. A system like that can considerably increase the comfort of work of drivers in various kinds of road transport without a great increase in cost.

Reduced exposure to noise results in better road safety. This is especially significant in trucks and light commercial vehicles, in which passive noise control systems are considerably more expensive and the noise level inside the driver's cabin is considerably higher than in passenger cars.

ANC systems are much more effective than passive ones in the frequency range of most acoustic energy emitted in the car. Simultaneously, the mass of components needed for the

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Correspondence should be sent to Bartosz Stankiewicz, Vibroacoustic Laboratory, Faculty of Automotive and Construction Machinery Engineering, Warsaw University of Technology, Narbutta 84, 02-524 Warszawa, Poland. E-mail: bartek.stankiewicz@gmail.com.

system to operate is much smaller than the mass of sound insulating materials, which should be installed in a car to achieve similar acoustic comfort. Because of the vibroacoustic characteristics of a car, to be effective, such materials must have a relatively high mass. There are many components in a car, which have other functions in addition to acting as a sound insulator or damper. However, there are many parts whose sole purpose is to improve the acoustic conditions in a cabin. The mass of these parts, in the presently manufactured cars, ranges from 30 kg in small cars to 60 kg in executive-class cars [1]. Luxury vehicles, such as Mercedes S-Klasse, weigh as much as 200 kg [2].

2. ANC SYSTEMS

ANC is based on so-called destructive interference, i.e., generation of an acoustic signal, which excites the medium to vibrations opposite to those resulting from the propagated disturbance [3, 4]. The effectiveness of this method depends on the possibility to generate a compensating wave which, after reaching a point where a decrease in sound level is necessary, will fully subtract from the disturbance acting there. Because of the number and character of vibroacoustic energy sources in a vehicle and ways of energy propagation, a system able to control noises generated by various sources is necessary to obtain a noticeable effect. A digital system with feedforward is the most suitable ANC system. A finite impulse response (FIR) filter creates a compensating signal on the basis of the reference signal. The process of a digital filtration of a discrete signal in that filter is a convolution of the vector of a sample time waveform with the vector of a filter coefficients and occurs according to Equation 1:

$$y(n) = \sum_{i=0}^{L-1} w_i(n) x(n-i), \qquad (1)$$

where $y(n)$ = output signal, n = coefficient number, L = filter order, i = iteration number, $w_i(n)$ = filter coefficients, $x(n)$ = input signal.

The least mean square (LMS) and its derivatives is the most popular algorithm of adapting the filter coefficients used in ANC. It is based on an iterative method of looking for an optimal solution, called the method of steepest descent. In the case of an ANC system, the minimum of the error signal amplitude is necessary. On the other hand, coefficients of the FIR filter are an objective function. The filter order L (number of coefficients) and the adaptation step μ are the basic parameters of a classic LMS. The normalized least mean square (NLMS) is a modified LMS algorithm; it enables reconciliation of two opposing requirements: a convergence rate and accuracy. It differs from the classic algorithm by Equation 2, which updates the vector of FIR filter coefficients:

$$\underset{i \in <0,L-1>}{\Lambda} w_i(n+1) = w_i(n) + \mu(n) \cdot x(n-i) \cdot e(n), \qquad (2)$$

where i = coefficient number, L = number of filter coefficients, n = iteration number, $w_i(n+1)$ = next iteration filter coefficient, $w_i(n)$ = filter coefficient, $\mu(n)$ = variable step factor, $x(n-i)$ = reference signal sample, $e(n)$ = residual noise signal.

The adaptation step in the LMS algorithm was substituted with the coefficient changing with time, whose value is updated in each cycle of the program. It is determined on the basis of Equation 3 [5]:

$$\mu(n) = \frac{\alpha}{L\hat{P}_x(n)}, \qquad (3)$$

where, $\mu(n)$ = LMS algorithm step factor, α = normalized step size, L = number of filter coefficients, $\hat{P}_x(n)$ = power estimate of signal in buffer, n = coefficient number.

FxLMS is the most often used structure of the system based on the LMS algorithm. The secondary path $S(n)$ is taken into account at the input of the reference signal into the controller part responsible for adapting filter taps in the form of an estimate of the secondary path transmittance, $S'(n)$. Figure 1 shows a simplified version of this structure, a delayed LMS, where the estimate is simplified to the normal delay.

Recurrent, genetic and other algorithms based on neural networks are other ways to adapt filter coefficients. However, as they are mathematically complex, these algorithms require a high calcula-

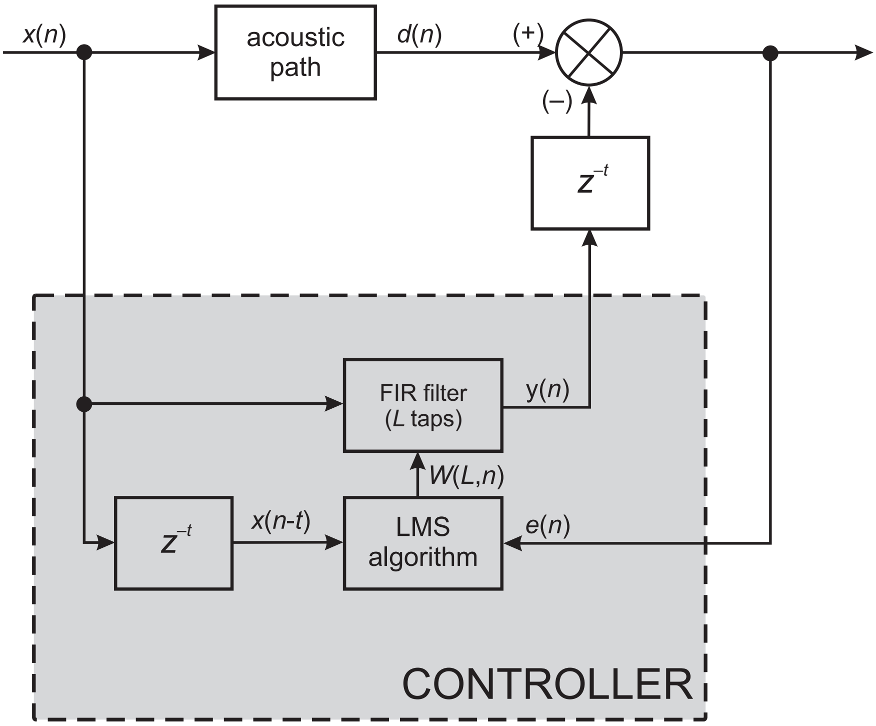

Figure 1. Structure of active noise control based on a delayed LMS algorithm. *Notes.* LMS = least mean square, $x(n)$ = reference signal, $d(n)$ = unwanted signal, Z^{-t} = discrete delay of t samples, FIR = finite impulse response filter, L = number of filter coefficients, $y(n)$ = compensating signal, $W(L, n)$ = vector of L filter coefficients in n time, $x(n - t)$ = delayed signal, $e(n)$ = residual noise signal.

tion power of controllers and are, thus, seldom used. Moreover, they are useful in few applications only. They all share one feature, they use a reference signal (the more coherent with the sound being compensated, the better).

3. SELECTING THE SOURCE OF A REFERENCE SIGNAL

An ANC system based on digital filtering, in principle, modifies the reference signal only. It amplifies this signal within some frequencies and shifts in phase to resemble as best as possible the compensated signal. Therefore, the more the reference signal waveform is similar to the compensated signal, the better the system, i.e., it has similar essential components and phase characteristics. This also applies to time changes of these characteristics. An ideal reference signal has exactly the same waveform as the compensated signal; it is only shifted by the time necessary to convert the signal and to send it by a secondary source to the place being silenced. That is why, a microphone is very often used as a transducer; it is positioned in the air-track of the noise propagation between its primary source and the silenced place. This type of transducer is popular because sounds propagating in the air (in a far free-field) are damped in a predictable way: high frequencies are most damped, low frequency are least damped. Therefore, placing it in practically any point of the sound-path means a good reference signal is recorded. Since an ideal acoustic free-field is rare, the positioning of the microphone affects the effectiveness of the system.

A microphone used as a reference source often causes additional complications related, e.g., to the acoustic feedback between the secondary source and the microphone. Therefore, it is worth looking for other than acoustic reference sources [6]. In a car, these can be an ignition electric signal or vibrations of a subassembly. However, the question is which one is best. Knowing noise and vibrations propagations in a car, it is possible to indicate a group of such sources. However, it is necessary to check the best positioning of the sensor recording the reference signal [7]. Of course, it is possible to use a complete ANC system in each possible location to compare the results. However, this is a very time-consuming and difficult solution, as this system should be installed in the field. Moreover, the researcher would be exposed to high sound levels. Usually, before an ANC system operates correctly, it can be unstable. This means that the noise level increases rather than decreases (the maximum acoustic power in case of faulty operation exceeds over twofold the power of the sound source being silenced). Thus, the question is how to find a reference signal without using the whole ANC system.

One way is to use a simulator, i.e., a simulation model of the ANC system. Introducing a simulator at the input of signals recorded in the silenced object makes it possible to compare the effectiveness of the system. This is a direct method since the difference consists in substituting a real object with a simulator (see Airaksinen, Heikkola and Toivanen [8]). The entire process can thus be automated and carried out practically without a human. Sources of the reference signal can be estimated much quicker and more conveniently for the human operator. However, that approach has serious drawbacks related to modelling accuracy. In addition, a simplified procedure of looking for the best reference signal source would often be necessary (due to the large number of potential sources).

Coherence analysis is a natural technique that can help to select an optimal reference point. It enables estimating the influence of the coherence of two signals in different physical processes (including vibration and acoustic signals). Besides, the common coherence function is a dimensionless multiplier and a sum of partial coherences fulfils the dependence [9, 10]

$$\sum_{i=1}^{N} \gamma_i^2(f) \le 1, \tag{4}$$

where N = number of propagation paths, $\gamma_i^2(f)$ = square of partial coherence function in frequency domain, f = frequency. This makes it possible to separate parts of the coherent and residual signals.

However, it is difficult to use coherence as an indicator of whether the reference point is good. Coherence is a frequency function. Even if some spectrum components are coherent, the quality of the reference signal is not necessarily good, since these components can be insignificant. The value of the coherence function averaged after a given frequency range has a similar fault. There are two solutions: either to identify all propagation tracks (noise source–reference point and noise source–output) and then to create a criterion for optimising those tracks (position of the reference point) or we find an indicator of quality that combines coherence between reference points and the output, which corresponds to the energy level (power) of the coherent part of the signal.

As mentioned earlier, an ANC system only modifies the reference signal to obtain the required response, i.e., a compensated system. Also, the closer the reference signal to the compensated signal, the more effective the system. It follows that the digital filter in the ANC system models only the difference between the reference and the compensated signals. Thus, the lower the damping of the path (the position where the reference signal is recorded is the input, the place being silenced is the output), the more effective the system. Ideal transmittance means the signal is not modified:

$$\bigwedge_{\omega} H(j\omega) = 1. \tag{5}$$

where $H(j\omega)$ = spectral representation of transmittance of secondary path, $j\omega$ = imaginary part of complex representation of frequency, ω = pulsatance.

If the secondary path (i.e., the path of the compensating signal) does not equal one, the ideal theoretical transmittance between the reference signal and the one being compensated will be secondary path transmittance. The question is how it is possible in practice to estimate this transmittance fast and effectively? Stankiewicz proposed a coherent power level (CPL) coefficient, which is the time averaged power level of the coherent part of the reference signal [11, 12]:

$$CPL = 20 \log \frac{\int_0^{f_N} \left(\gamma_{xy}^2(f) \cdot G_{yy}(f)\right) df}{f_N \cdot 20 \cdot 10^{-6}}, \tag{6}$$

where $\gamma^2_{xy}(f)$ = ordinary coherence function between reference and unwanted signal, $G_{yy}(f)$ = power spectrum of unwanted signal, f_N = Nyquist frequency (half of sampling frequency), df = frequency interval. The reference level is $20 \cdot 10^{-6}$ W. This is the coherent power for which the theoretical ANC system compensates pink noise of 0 dB.

The function of a discrete power spectrum of the compensated signal multiplied in a scalar way by the discrete form of the coherence function can be considered the weighting function showing only these spectrum components which are essential in the damped noise (i.e., in the signal being compensated). Thus, high values of this new function indicate a useful reference source for an application of the ANC system. The average value of this scalar product in the whole range of tested frequencies enables single-dimensional estimation of the investigated frequency band. According to the definition, the CPL depends on the disturbance signal and the information concerning this disturbance in the reference signal. Therefore, it can be used in looking for the best positioning of the vibration transducer. It is also possible to select transducers of various functional characteristics for the application. This analysis can be extended to investigate various types of transducers, e.g., vibration or acoustic, at maintaining the condition of similar influencing in the feedback.

To confirm the usefulness of the proposed measure, tests were carried out in an anechoic chamber. The CPL values and the effectiveness of the ANC system were measured for various noise forms and various configurations in the room. Juxtaposing these coefficient values with the levels of the obtained damping indicates how useful they are. The first series of tests analysed the dependence of the proposed measure on the reference signal sensor. The sound of the engine operating in the parking mode, recorded in the cabin of a Nissan Micra, was generated in the anechoic chamber. The microphone (two propagation characteristics), the accelerometer situated on the casing of a loudspeaker and the sampler taking an electric signal directly from the generator were successively tested. Figure 2 shows the recorded dependence of the CPL on damping levels obtained with the FxLMS algorithm. The relation between both parameters is explicit: they are heterovalues. An increased trend of the CPL coefficient for increased effectiveness of the ANC system is clear.

Figure 3 is an example of the relation between the CPL and the effect of an ANC system, when the primary noise source emits a simple tone of a frequency of 260 Hz. The microphone situated near the primary source was the reference source; the loudspeaker was the secondary one. A change in a microphone characteristic (i.e., the noise

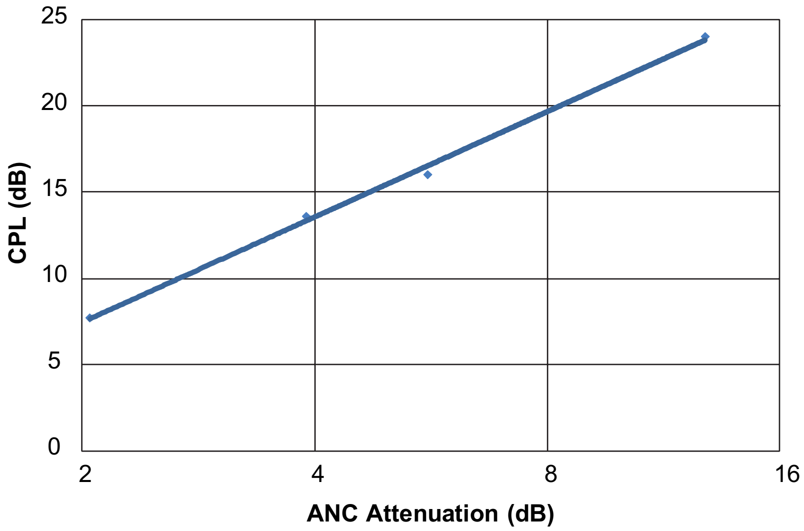

Figure 2. Coherent power level at noise excitation recorded in a cabin of a car (various reference sensors). *Notes.* ANC = active noise control, CPL = coherent power level.

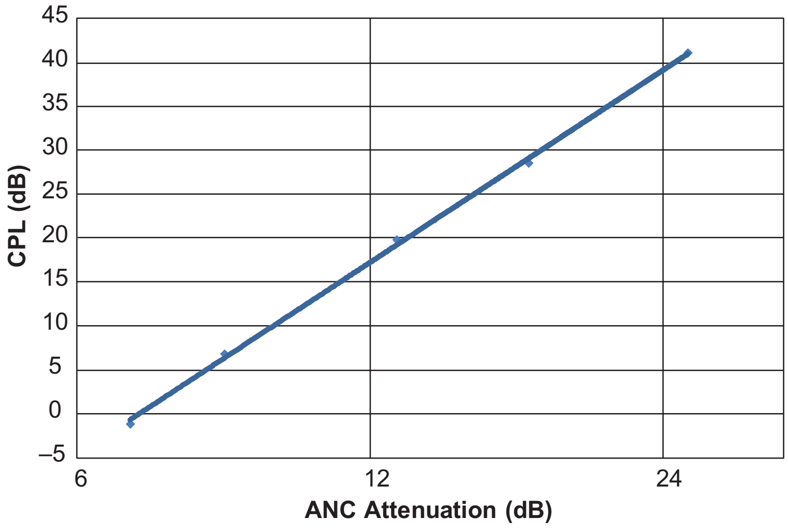

Figure 3. Change in coherent power level and active noise control (ANC) results at various efficiency of the reference sensor. *Notes.* CPL = coherent power level.

fraction in the useful signal, SNR, recorded by the sensor) is responsible for the curve. There was a similar dependence when the accelerometer was the reference sensor. So, the CPL coefficient value, measured before launching an ANC system, makes it possible to estimate the effectiveness of its operation after the launch (i.e., enables selecting the best configuration). In particular, it makes it possible to compare reference sources related to various physical processes generating the signal (with invariable feedback).

3. VERIFYING ANC IN A CAR

The effectiveness of the method of selecing the reference source was verified in a car. To this end, the algorithm for determining the CPL during measurements was implemented in LabView[1] version 8.6. The sensor of the compensated signal (the microphone) was positioned in the place being silenced (near the head of the back-seat passenger), while the reference sensor was fixed in various places of the vehicle. When the measuring conditions were stable, the results were read. First, the best reference signal sensor was selected. The choice was narrowed down to the accelerometer (vibration acceleration sensor) and the microphone (acoustic pressure sensor). The accelerometer was positioned on various elements of a car (including the engine chamber), while the microphone was always in the passenger cabin. Table 1 presents sample results. They show that both a vibration sensor and a microphone are effective reference sensors.

However, as an acoustic sensor is always burdened with the problem of feedback, it turns out that an ANC system with an accelerometer is more effective than a system with a microphone. A directional microphone did not perform well at all; the CPL was much lower than for the remaining reference sources. Therefore, successive analyses focused on vibration transducers only.

There was still the problem of the position of the sensor. Several configurations and models of sensors were tested; using the CPL coefficient simplified work. Table 2 presents places with the highest coefficient values during driving; the CPL was highest when the accelerometer was on the side wall of an engine compartment and on the front radiator support. The former position is better, due to the slightly better results at higher rotational speeds of the engine. That position of the sensor was verified in examinations in a car, where it was acting as the reference source for a simple ANC in the cabin of a Ford Fusion (Figure 4).

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[1] http://www.ni.com

TABLE 1. Comparison of Selected Sources of Reference Signals: Acoustic and Vibrational

Source of Reference Signal	CPL (dB)
Accelerometer, side wall of engine compartment	20.5
Accelerometer, front radiator support of car	22.0
Microphone, above front seat	19.8
Directional microphone, between front seats	–5.4

Notes. CPL = coherent power level.

TABLE 2. Average Coherent Power Level (CPL) During Driving and the Position of the Accelerometer

Position	CPL (dB)
Right-hand side window, at mirror	10
Engine bonnet, inside	9
Side wall of engine chamber	12
Right-hand bracket of engine mounting	6
Front radiator support of car	12

Figure 5 is a schematic presentation of an ANC system in a car. An accelerometer on the side wall of the engine compartment was the reference signal, whereas the usual location of the head of the back-seat passenger was the quiet zone. This was verified when driving at 58 km/h. Figure 6 shows the spectrum of the acoustic pressure level. The loudspeaker in the right-hand back doors was the secondary source. The measured sound level, at the ANC system switched off, was 67.3 dB(A). At the ANC system switched on, there was a total reduction in discrete harmonic components and the total sound level decreased by 3.3 dB. The sound reaching the passenger's ears seemed "lighter", without rambling bass. However, there was a certain increase in noises, for which the increase in the noise level visible in the diagram, is responsible. The controller was operated by the algorithm of the delayed NLMS (the transmittance of the secondary path was considered), where the FIR filter was $L = 512$ and the adaptation step $\alpha = 0.001$.

The example proved the methodology with the CPL is successful in practice. It helped to select the best sensor and position in a car when implementing an ANC system. Finally, the ANC system decreased the noise level around the passenger's head (measured in the whole range of the audible spectrum). Attention should be drawn to the factory soundproofing of the car, for which the standard value is only 67.6 dB.

4. CONCLUSION

To operate effectively, common algorithms of the ANC require a reference signal strongly coherent with sounds audible in the planned quiet zone.

Figure 4. Positioning a vibration sensor, acting as the reference source in the engine compartment of a Ford Fusion.

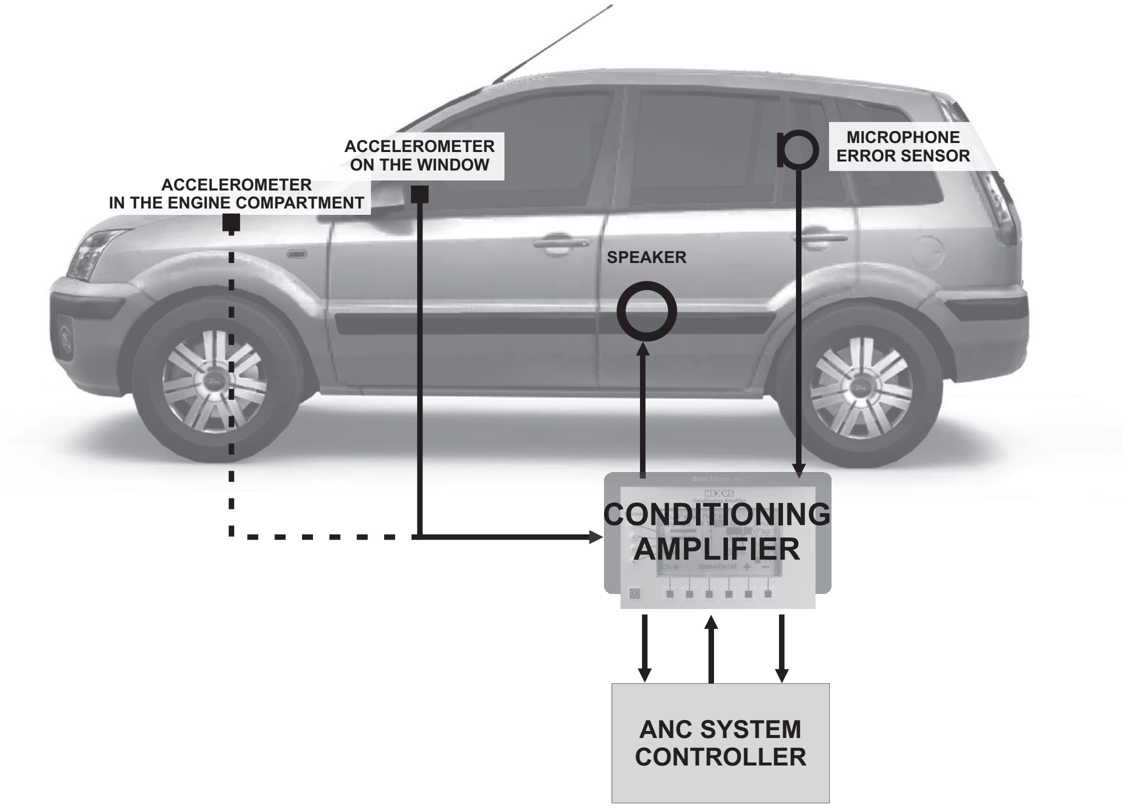

Figure 5. Block diagram of an active noise control (ANC) system in a Ford Fusion.

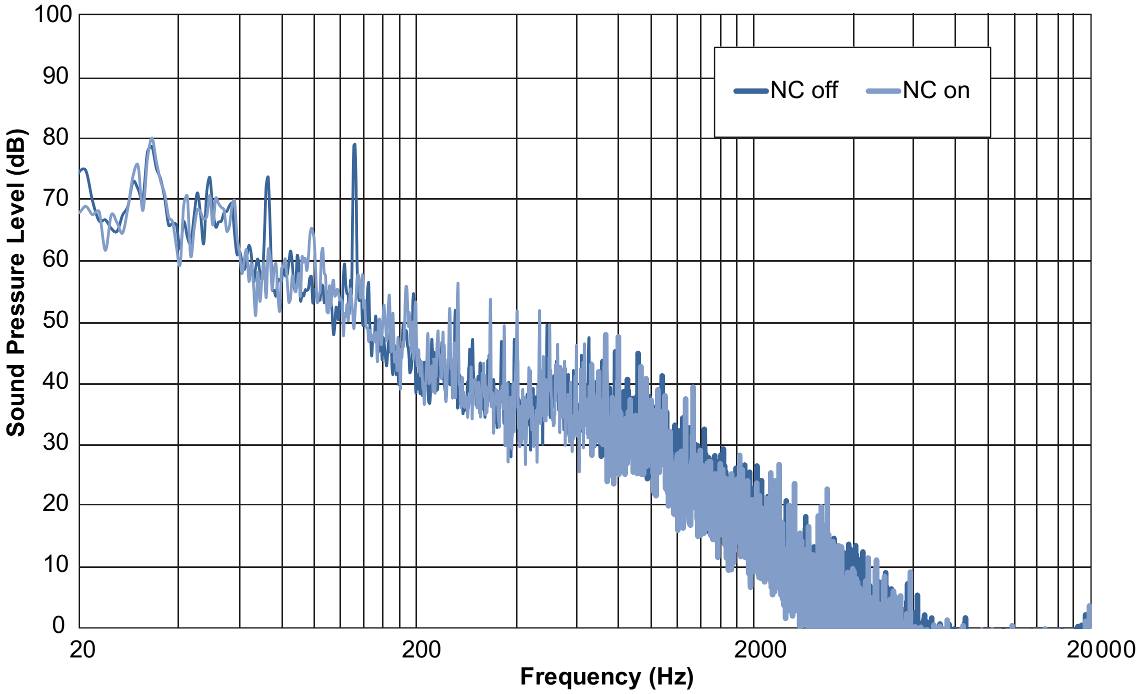

Figure 6. Effectiveness of an active noise control (ANC) system in a Ford Fusion cabin, during driving.

Finding the best reference source is the most time consuming stage of implementing such systems. This used to be a tedious, ineffective task. The ANC system had to be launched for each case. Because of time constraints, potentially useful sources of the reference signal were often not analysed. Researchers often selected the acoustic source (a microphone), since it guaranteed high coherence. However, at the same time, they had to consider feedback between the secondary and primary sources.

The proposed methodology simplifies selecting the source and makes it possible to compare sources based on transducers with very different physical effects. Moreover, it is also possible consider transducers that do not seem to be related to the emitted noise. Additionally, it is possible to optimise the position of the transducer. A good source must be, first of all, characterised by the high coherence with the sound being compensated.

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