EXPERIMENTAL STUDY OF THE NOISE DIRECTIVITY OF A HYBRID ELECTRIC VEHICLE

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Abstract

The currently increasing use of Electric and Hybrid Electric vehicles (EV and HEV) has incremented the interest of their interior and exterior NHV behaviour, as well as their interaction with the passengers, pedestrians and noise surrounding. As a matter of fact, it is widely known that the very low noise level radiated by a low-speed approaching HEV is a recognised danger for other vehicles, pedestrians and cyclists, even though this absence of sound is welcoming for the environmental regulations. In order to reduce the danger of those vehicles while moving, several manufacturers and research teams are developing and studying new external noise generators for such vehicles, however, a previous noise external characterization of an EV or HEV does not appear to have been deeply studied.
This paper describes and implements a methodology to measure the noise directivity of a Hybrid Electric vehicle using a microphone array under pass-by test conditions.

Keywords: Hybrid-electric vehicles, sound directivity, microphone array.

1 Introduction

The significant sound reduction of hybrid electric vehicles (HEV), especially when running in electric mode, seems to be a realistic solution to minimize the noise pollution of cities. However, there is still poor information about the real-world noise emission of this kind of quiet automobiles and how it is affected by the vehicle speed. At the same time, some research is currently being developed in order to propose a suitable Acoustic Vehicle Alerting Systems (AVAS) that increases the detectability of the vehicle whilst preserving the low environmental impact of these noise sources [1]. To guarantee the effective operation of the AVAS, some precise information about the sound emission of the HEV regarding the sound directivity and the frequency should be provided and carefully analysed. Noise source directivity as well as frequency radiation could help to understand better the noise behaviour of a HEV.

1.1 Directivity Index

The directivity of a noise source is defined as the distribution angle of its sound power. According to EN-ISO 3744 [2], the directivity index DI of a sound source for a hemispherical source is defined as the difference between the sound pressure level (in dB) measured in the particular direction α, and the surface sound pressure level (in dB) averaged over the measurement surface, see equation 1, both quantities are corrected for background noise. At the same time, the horizontal directivity is the horizontal angle distribution of the sound power, respectively.

$$DI_\alpha = L_{p\alpha} - \overline{L}_p \tag{1}$$

Where,

$L_{p\alpha}$ Is the sound pressure level at angle α,

$\overline{L}_p$ Is the sound pressure level averaged over the plane of emission,
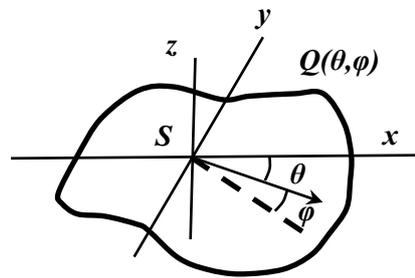
Figure 1. Directivity of an omnidirectional point source

Some of the first reference of the Directivity in a noise moving source was developed by Favre [3,4], who defined $Q(\theta, \varphi)$ as the directivity of a sound source, radiated on angles θ and φ, see figure 1.

If it is analysed the emission of a point noise source, the sound pressure measured at a distance *r* can be related to the power of the source by equation 2,

$$p^2(t) = \frac{Q(\theta, \varphi) w(t) \rho \, c}{2\pi r^2(t)} \tag{2}$$

Where *w(t)* is the sound power of the sound source, *ρ* is the air density, and *c* the speed of the sound.

In logarithmic form, taking into account the definitions of sound pressure level L_p, and sound power level L_w, equation 3 is obtained,

$$L_p(t) = L_w(t) - 20\log r(t) + 10\log Q(\theta, \varphi) - 8dB \tag{3}$$

Assuming that during a pass-by test it is measured the sound pressure level of a vehicle on a fixed height, the directivity of the source can be referenced to the plane of emission during the test, being the directivity changing over the angle of radiation *α*, $Q(\alpha)$. Additionally, it can be related the noise pressure level of an angle of radiation *α*, $L_p(\alpha)$, and the average noise pressure level for the noise source, $\overline{L}_p$, see equation 4.

$$L_p(\alpha) = \overline{L}_p + 10\log_{10} Q(\alpha) \tag{4}$$

So, clearing the directivity of the noise source, it can be related to the Directivity Index for the different angles of radiation, equation 5.

$$Q(\alpha) = 10^{(L_{p\alpha} - \overline{L}_p)/10} = 10^{DI_\alpha/10} \qquad (5)$$

1.2   State of Art

The study and characterization of a vehicle as a noise source has been a priority target for the automotive industry, moreover after being labelled as main urban noise source [5].
As it was previously shown, the directivity of a noise source describes the characteristics of the noise radiation, and it can be used to determine the effect over a potential receiver, for instance, on traffic noise prediction models [6].
Despite the potential importance of the source directivity in the characterization of a noise source [7], there is no standardised way to measure the directivity patterns of each individual vehicle moving within an overall road traffic stream. It is possible to find measurement techniques for determining the stationary vehicle directivity [8], or even some studies about vertical directivity for moving sources, trains [9-11], aircraft [12-13], and road vehicles [14], and also some initial studies of horizontal directivity of road vehicles [15], but there is no comprehensive investigation that proposes a methodology to measure the horizontal noise directivity of vehicles in movement.

1.3   Objective

The main objective of this contribution is to define and prove a testing methodology for the characterization and the assessment of an HEV under Pass-by testing conditions, using a microphone array to determine the horizontal noise directivity.

2   Methodology

The all-direction radiation of a moving noise source is an experimental challenge in most cases, but if the source emits sound levels near or under background noise, it is even more complicated [16]. Some previous research has been developed to justify the use of uniform linear microphone arrays (ULA) in order to detect the position of a moving noise source [17], as well as the noise Sound Pressure Level (SPL) and Directive Index (DI). In accordance with this, the tool used was composed of 9 omnidirectional microphones (B&J Type 4958), working together and connected to a multi-channel data acquisition system, as well as 2 position photocells, see figure 2.

Figure 2– A. ULA Microphone array and analyzer used during the tests. B. Photocell used to determine the location of the vehicle.

All microphones capture the source signal which is delayed according to the position of the source and the distance to the microphone. They are then processed in a Double Cross-Spectrum (time-frequency domains) in order to detect the angle of emission of the noise source and the sound pressure level of the different angles of emission [17].

During the signal processing, two important assumptions have been made:
- Due to the distance between the source and the microphone array, the HEV can be considered as a point source. To guarantee this assumption, it is considered the distance between the vehicle and the microphone array to assess the accuracy of the results.
- The EV is moving along a known track with some reference points (achieved by photocells, see figure 1-B) at a steady speed. This assumption is considered during the data filtering to determine the speed and radiation angle of the noise source.

Thus, all tests were developed on a conventional dense asphalt track (2 layers G-20 and S-20). The array was located perpendicularly to the track and 3 meters away from the axis of it, according to the distribution of figure 3. Photocells were distributed along the track, see figure 4.

Figure 3 - Photograph with the distribution of elements during the test.
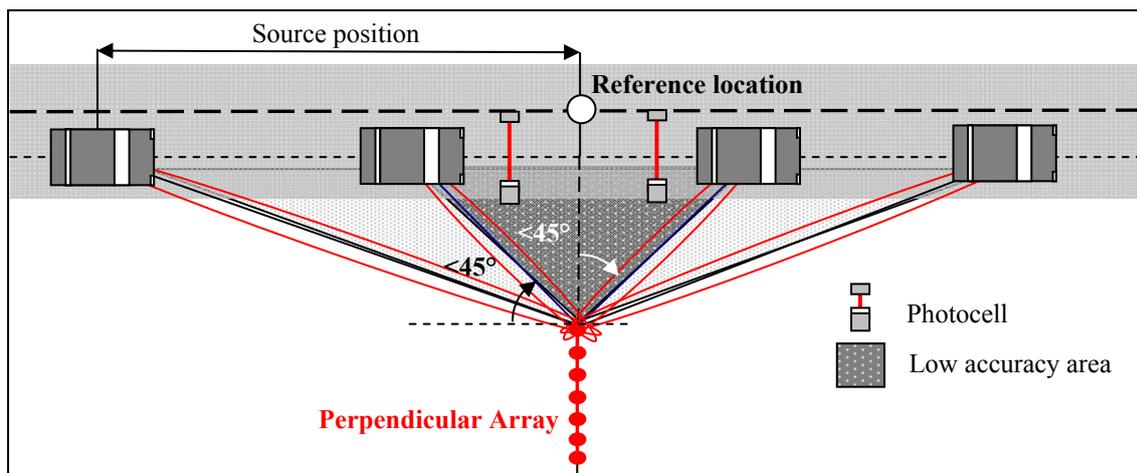
Figure 4 - Draft with the distribution of elements during the test.

The tests were initially conducted at 40[1] km/h as a reference speed on both sides of the vehicle (two times left and right side of the vehicle), resulting a total amount of 4 testing records. The real speed of the vehicle during the tests was obtained with the data provided by the photocells, see table 1.

Table 1 – Real speed of the HEV during the tests, classified according to the reference test speeds.

40 km/h		
Ref.	HEV direction	Speed (km/h)
40A	Left-side	36.36
40B	Right-side	32.02
40C	Left-side	36.15
40D	Right-side	35.15

Measurements were developed at Miguel Hernandez University Campus, north access road, see figure 5. In order to test under low background noise conditions, measurements were developed on Sunday morning, from 9:00 to 13:00 am ($L_{Aeq,4h}$=47.6 dBA).
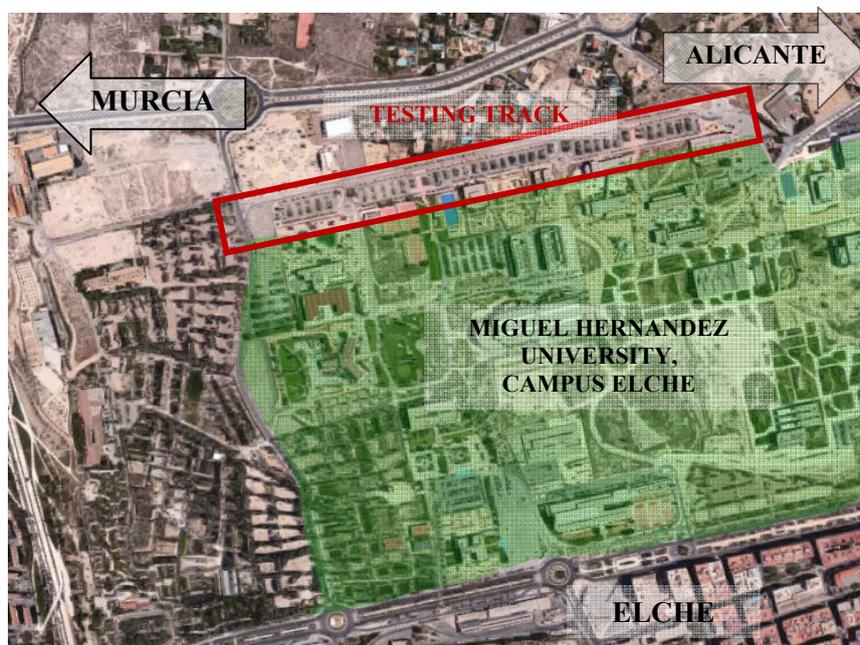
Figure 5 - Location of the testing track

3   Results

Data processing is divided into two main steps:
1. Detection of the vehicle during the test by the microphone array, calibrated by the photocells' information, resulting the angles of radiation during the test and the speed of the noise source.
2. Evaluation of the sound pressure level emitted by the point noise source, as well as ID of the HEV tested in a frequency range 500 Hz to 2000 Hz.

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[1] It is assumed that the ICE motor is connected at that speed

3.1 Source detection

Figure 6 shows the data processing diagram to determine the radiation angle during the test, $\alpha(t)$, as well as the speed of the vehicle estimated by the array and photocells signals, $v(t)$. It is important to note the importance of determinate the angular misalignment, β, which is used to significantly reduce inaccuracies during the test.

MICROPHONE ARRAY   Photocell

Noise signal of each microphone
$$S'_n(t)$$

Pass band filter: f_{min} - f_{max}
$$S_n(t)$$

k Blocks of $0.1sf$ dates
$$S_{n,k}(t), T(k)$$

Hanning window
$$S^H_{n,k}(t)$$

Array data processing
Cross Spectrum

DFT to temporal frequency   DFT to Spatial frequency
$$X_{n,k}(f) = DFT(S^H_{n,k}(t)) \implies R_k(f,d) = \sum^d X_{n,k} X^*_{n,k} \implies H_k(f,k) = DFT(R_k(f,d))$$

Angle of radiation, $\alpha(t')$

Array reference position, $C_{p,A}$ Photocell reference position, $C_{p,ph}$

Distance and time after beta correction, $D(t'')$ β

Speed of the vehicle, $v(t'')$

Figure 6 – Data processing diagram for the location of the noise source during the tests

Figure 7 shows the results of the location angle of the vehicle during the tests 40C and 40D (left and right side of the vehicle respectively). The microphone array is able to detect the vehicle during 8 and

6

12 seconds as can be seen in the figure, which implies that it is providing 345º degrees of radiation in each direction (172º from test 40C and 173º from test 40D).
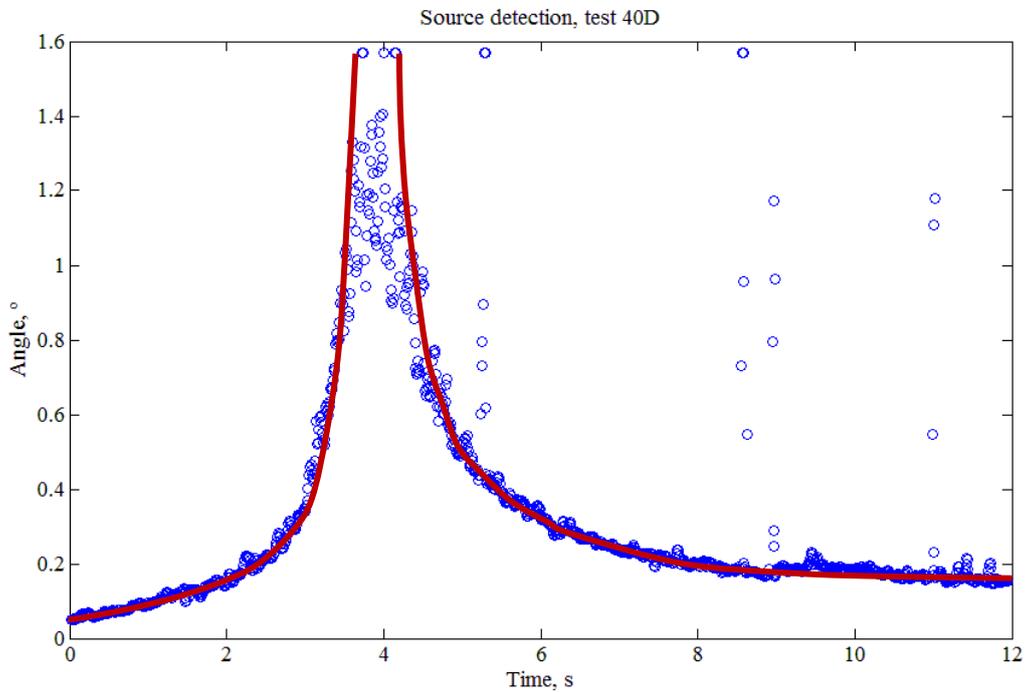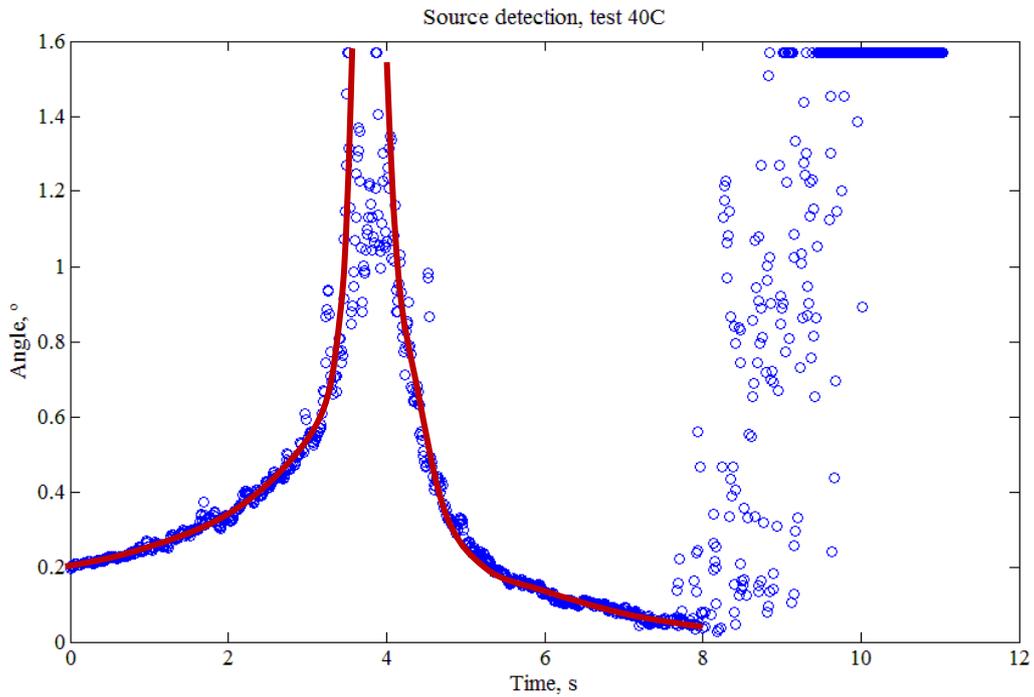
Figure 7 –Source detection during tests 40C and 40D.

The differences between the before-array slope and after-array slope are due to the angular misalignment between the track and the array position.

3.2 Directivity Index

Figure 8 displays the DI of the vehicle running at 40 km/h. As it is shown, the vehicle is radiating a uniform directivity probably due to the connection of the ICE engine during the tests. The contribution of tyre/road noise can be detected in the high radiation of the vehicle in its front and rear.
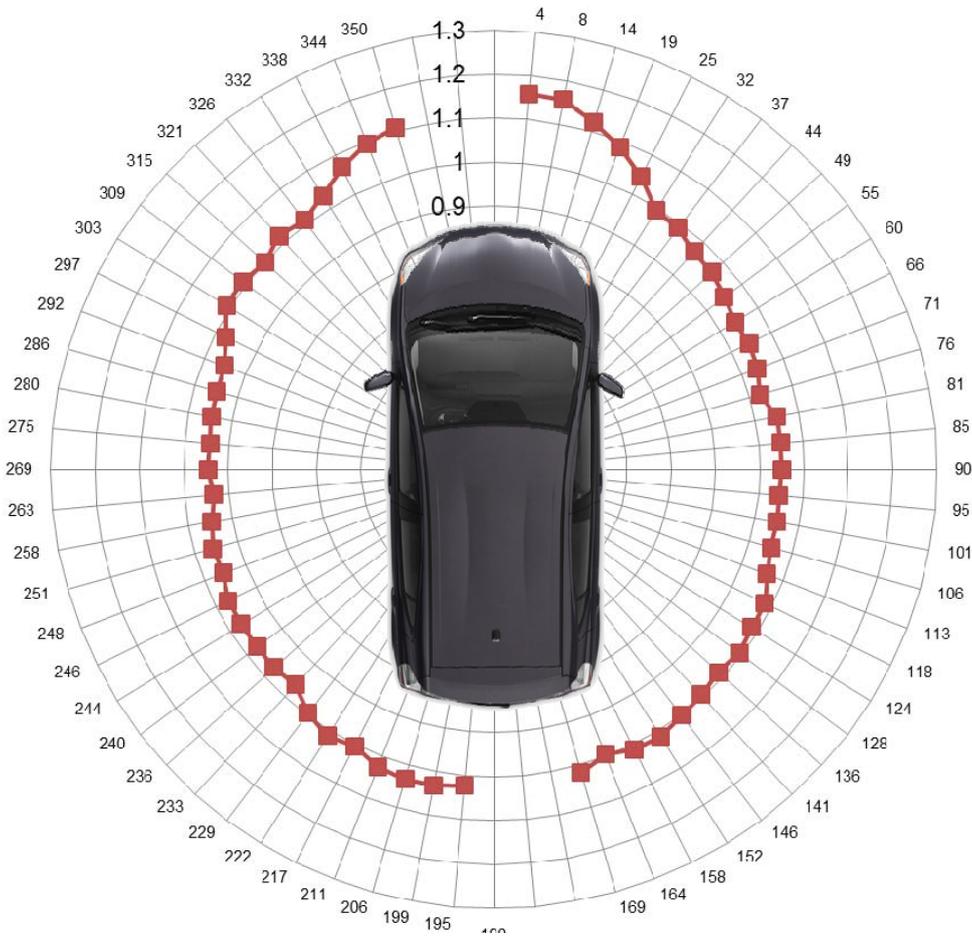
Figure 8 – Overall Directivity Index of a HEV at 40 km/h (average level 500-2000Hz).

4   Conclusions

Assuming the sound directivity of a noise source as an important characteristic to determine the effect of its radiation, it was proposed and developed a testing methodology to measure the Directivity Index of a Hybrid Electric Vehicle. The connection of ICE engine during the tests delays significant conclusions about the real directivity of an electric vehicle, but it was possible to reach the objective of the study of verifying the proposed methodology. In the near future, the suggested methodology will be implemented on pure electric vehicles, as well as electric vehicles provided with Acoustic Vehicle Alerting Systems.

Acknowledgements

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