NUMERICAL ANALYSIS OF THE EXTERIOR ACOUSTIC FIELD EMITTED BY AN INDUSTRIAL EV EQUIPPED WITH AVAS SYSTEM

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Abstract
One of the main environmental characteristics of an Electric Vehicle (EV) is the absence of mechanical noise while moving; the result is a significantly lower sound pressure level compared to a conventional Internal Combustion Engine vehicle (ICE). These low sound levels, together with the high traffic noise in urban areas, make more difficult for pedestrians to detect an approaching EV. In order to prevent that risk, manufacturers are working on adding warning sound systems to these quiet vehicles (Acoustic Vehicle Alerting Systems, AVAS). That is a problem not only for light passenger vehicles but also for industrial vehicles and urban buses, which can be a potential danger for the pedestrian.
In this work, the theoretical sound directionality of different configurations of loudspeakers used on heavy vehicles has been studied, by applying a frequency domain BEM formulation to simulate some different aspects related to their acoustic emission. The simulation represents the vehicle under different scenarios with changed loudspeakers configuration, allowing the comparison between them.

Keywords: Electric vehicle, warning sounds, directionality, loudspeaker, Boundary Element Method.

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1 Introduction

The growing integration of electric vehicles (EVs) and hybrid electric vehicles (HEVs) in the automotive market and urban fleets is being perceived as a potential solution to the environmental problems arisen with the use of conventional internal combustion engine vehicles (ICEs). In the one hand, they are expected to contribute to achieve the goal of reducing CO_2 and other gas emissions, which will imply to improve the quality of the air in urban areas, and to reduce the consumption of non-renewable resources. And in the other hand, they will provide an improvement in the sound quality of cities, reducing noise pollution coming from traffic flow.

However, the alternative vehicles provide new features, different from traditional vehicles' characteristics, which should be considered in order that the EVs and HEVs could be competitive in the automotive market. From the point of view of the noise, vibration and harshness (NVH), the main technical challenge comes from the different acoustical and vibrational behaviour of the EVs and HEVs [1]. The combustion engine disappears in EVs and in HEVs working on electric mode, which implies that users and pedestrians have a very different perception of those vehicles in comparison with the traditional ones. Here, new sounds and vibrations are transmitted to the vehicle's cabin, and together with the lack of noise coming from an ICE engine, entails that lower intensity noises could be now perceived as annoying by the driver and passengers. And furthermore, due to the low noise levels emitted to the exterior especially at low speeds, those vehicles are less perceived by pedestrians, cyclists and other users, what could cause dangerous situations.

Different studies can be found in the literature [2,3] reporting that the noise levels emitted by an ICE vehicle and an EV could differ up to 6 dB(A) at 10 km/h. Such reduction in the noise levels emitted by an EV could make difficult for pedestrians, and more dramatically for visually impaired ones [4], to detect an approaching EV immerse in the traffic flow due to the masking effect provided by the ambient noise. In that sense, the solution points out to improve the detectability of EVs and HEVs by means of the installation of the so-called Acoustic Vehicle Alerting Systems (AVAS). Those systems usually consist on a loudspeaker or an array of loudspeakers emitting an alerting sound, which could be mounted at different positions, as the front bumper of the vehicle, the wheel arch, under the hood close to the radiator, etc.

The installation of AVAS systems improves considerably the detectability of EVs and HEVs [5]. However, it could have the inconvenient to decrease the potential benefit in the urban acoustic environment initially provided by the quite alternative vehicles. Unless the emission of AVAS is specifically designed and controlled, it could again contribute to increase the noise pollution. In this regard, the directivity of the sound emission plays a crucial role and must be considered during the design phase of AVAS systems. Given this scenario, the main objective of the study presented in this paper is to analyse the theoretical behaviour of different configurations of Acoustic Vehicle Alerting Systems and to evaluate and compare the sound directivity of such configurations, taking into consideration the effect of the vehicle's structure on the sound propagation. The simulation represents an industrial electric vehicle under different scenarios and different loudspeakers configurations. The study has been developed using the numerical technique of the Boundary Element Method (BEM) and it has been analysed the sound propagation and the sound directivity of the AVAS sketches under static conditions of the industrial vehicle.

2 Numerical set-up

The theoretical study of the propagation of the sound emitted by the AVAS system has been carried out by using the BEM numerical technique. That method has become one of the major numerical techniques used for sound propagation analysis, particularly in domains involving unbounded or semi-infinite media. However, the technique could address problem size limitations when studying cases with a large number of elements. In order to avoid that, an Adaptive-Cross-Approximation algorithm described in [6] and previously applied in [7] has been used.

In the algorithm used, the Helmholtz partial differential equation was performed to represent the spatial propagation of the sound in the frequency domain. Then, the fundamental solution for the sound pressure was calculated after including a point source located into the propagation space, considering also other features in the propagation field as plane reflecting surfaces [8].

3 Model features

The analysis of the theoretical behaviour of different AVAS configuration, the comparison of its sound directivity and the study of the sound propagation taking into consideration that the effect of the vehicle's structure was carried out by means of a two-dimensional model that collects the vehicle geometry and the area around the vehicle under study. The vehicle geometry was simplified to a rectangle with the following dimensions: 12m length and 2.5m width. The calculations are done considering the vehicle located over a reflecting plane, corresponding to the ground surface. The absorption coefficients assigned to the surfaces are: 0.01 for vehicle surfaces and 0.2 for ground surface. The size of the area under study around the vehicle is 24m length and 16m width; the vehicle is geometrically centred in that area.

In order to achieve the objectives of the study, three AVAS configurations were analysed. All of them are composed by different arrangement of point noise sources representing the loudspeakers boarded on the vehicle, lined up with the exterior surface of the vehicle, as seen in Figure 1. The first configuration, Case 0, is composed by just a sound source located in the front part of the vehicle. The second arrangement, Case 1, corresponds to two sound sources located in the front part of the vehicle and one in the rear. Both sources in the front part are located close to each other, and the distance between them is 10cm, what corresponds to the distance between the membrane centres of loudspeakers. The final case, Case 2, is an array consisting of two sound sources in the front and also one in the rear part of the vehicle. In that case, sources are located at both edges of the front part, and the distance between the source emission axis and the side of the vehicle equals to 10cm, what corresponds to the radio of the membrane of the loudspeakers. The Case 0 will be considered as the reference case, and it will be used for further comparisons developed in the study with the rest of cases.

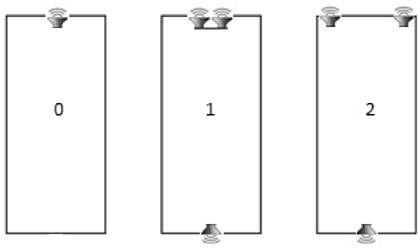

Figure 1 – Three cases of AVAS configurations

The emission of the noise sources has been defined in accordance with the specifications collected in the standard from the National Highway Traffic Safety Administration (NHTSA) [9]. In the NHTSA document, it is recommended that the AVAS systems should emit alerting sound in the frequency bandwidth comprising the 1/3rd octave bands from 315 to 500Hz and from 2 to 5kHz, and with a minimum sound level to be emitted per each 1/3rd octave band. Table 1 summarises the sound pressure levels (SPLs) collected in the regulation and the ones used for the present study.

Table 1 – Sound pressure levels used for the study

Band frequency (Hz)	315	400	500	2000	2500	3150	4000	5000
SPL acc. NHTSA (dB(A))	42	43	43	42	39	37	34	31
SPL used in the study (dB(A))	43	44	48	43	43	38	38	37

4 Analysis of results

The evaluation of the sound propagation and the sound directivity of the AVAS configurations was done considering two different situations: the vehicle is located in an open area with no reflecting obstacles, and the effect of a reflective wall located close to the vehicle for the Case 2 of AVAS configuration.

The sound pressure distribution in the area of study around the vehicle was calculated for each one of the 1/3rd frequency bands indicated in the NHTSA regulation. The Figure 2, as an illustrative example of the results – in this case for AVAS configuration Case 0; a) 315Hz and b) 2000Hz -, represents a plan view of the vehicle and the surrounding area under study. The surface in white colour represents the area occupied by the industrial vehicle, where the upper zone corresponds to the front part of the vehicle. The acoustical field produced by the emitting AVAS system around the vehicle has been illustrated in a colour scale from 0 to 45dB.

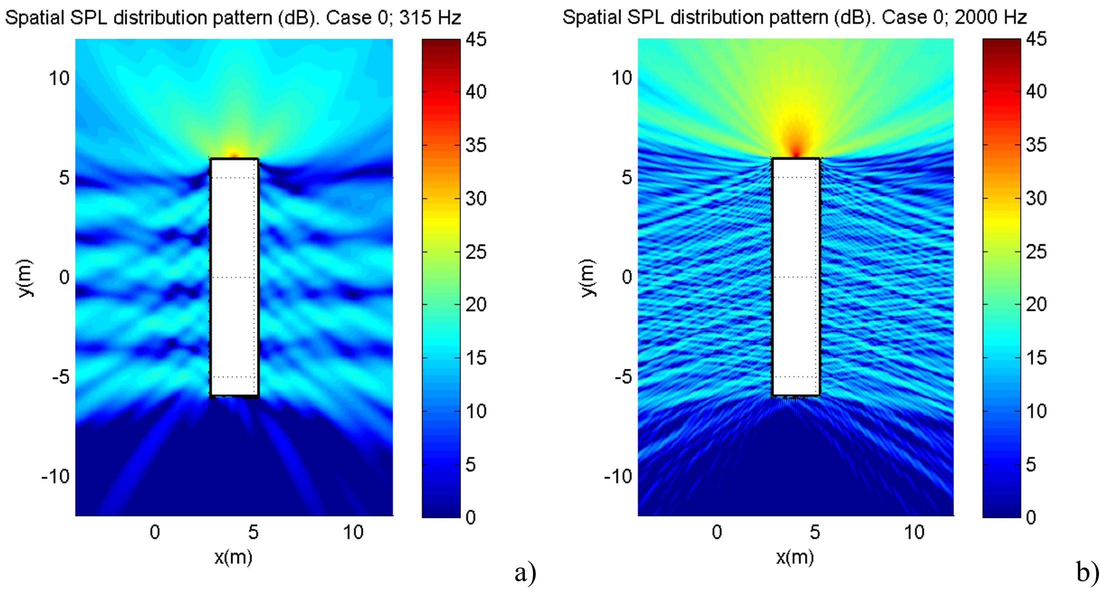

Figure 2 – Sound pressure field. a) Case 0, 315Hz; b) Case 0, 2000Hz.

In the plot, it can be observed that the area located in the front part of the vehicle is where the higher sound pressure levels are obtained since the sound source is located on the front surface of the vehicle. The propagation in the side areas of the vehicle presents a more complex pressure map, due to the effect of reflections caused by the vehicle surface and the ground plane. The body of the vehicle plays an important role in the sound propagation, as it creates a barrier effect that avoids sound to propagate to the rear area. Similar results can be observed for all cases.

In Figure 2 it is also noted the effect on the directivity pattern depending on the frequency emitted. Generally, for all cases, higher frequency emissions are more directional than lowers, as observed in the front area of the vehicle, but also the wave's interaction and the reflection effects create more complex sound maps in the rest of areas under study. This can be especially observed in Figure 2, where the single speaker considered for the AVAS Case 0 creates a radiation pattern in front of the vehicle.

Figure 3 shows the results for the same frequency, 2000Hz, and the AVAS configurations a) Case 1 and b) Case 2, where the effect of introducing a sound source in the rear part of the vehicle can be observed. As it was expected, the amount of energy increases in the rear area of the vehicle, when comparing results in Figure 3 a) and b) with results in Figure 2 b). Such effect occurs in all frequencies analysed.

The result of including two loudspeakers in the front part of the vehicle can be also analysed in Figure 3. In the AVAS configuration for Case 1, Figure 3 a), which considers the effect of two loudspeakers in the central part of the vehicle's front, it is obtained an improvement of the directivity of the AVAS system, resulting in an increment between 3 and 6dB of the noise levels in the front area compared with Case 0. Furthermore, when the loudspeakers are located in distant positions, Case 2, Figure 3 b), a silent beam in front of the vehicle starts appearing, and this is even more noted for higher frequencies, 4 and 5 kHz, where the sound levels could decrease up to 15dB. For the 4 kHz frequency, the beam has an angle of 45 degrees with the bus axis, and near 30 degrees for the 5 kHz frequency, which reveals that the angle covered by the AVAS system in the Case 2 is greater than for the reference case.

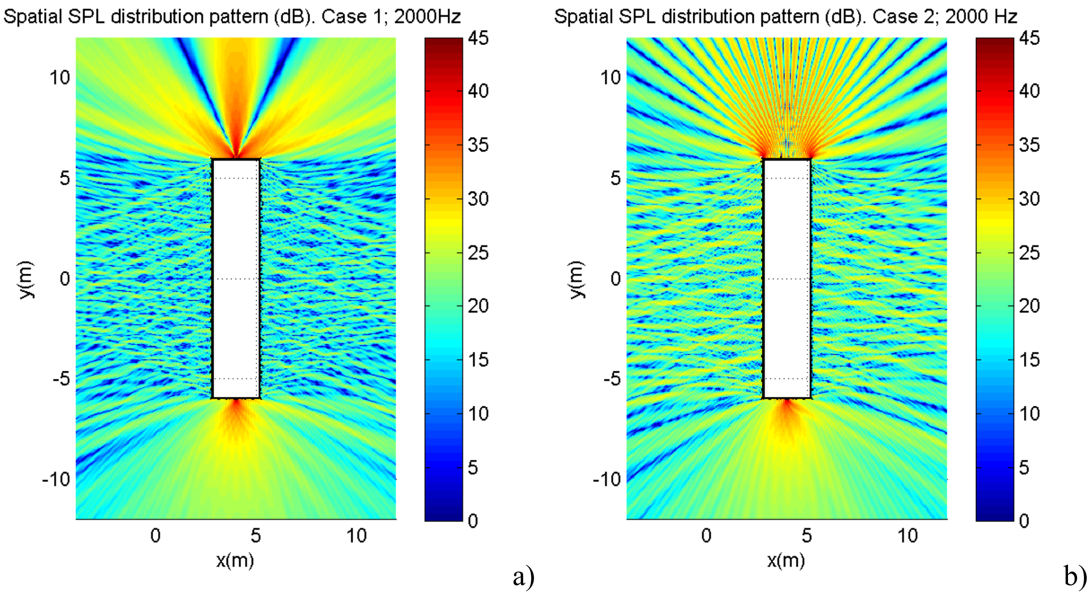

Figure 3 - Sound pressure field. a) Case 1, 2000Hz. b) Case 2, 2000Hz.

Finally, it was studied the effect of the sound pressure field of a reflective surface located close to the vehicle side, as for instance a row of parked vehicles, Figure 4. The surface is located on the left side of the vehicle, and it can be observed that it reduces the pressure levels just in the lateral area of the vehicle. However, the emission pattern in the front and rear changes significantly, as the sound propagation here is not so directive and a reverberant field is created. That effect is interesting from the pedestrian point of view, in order to distinguish the approximation of a vehicle where the visibility could be obstructed by other vehicles.

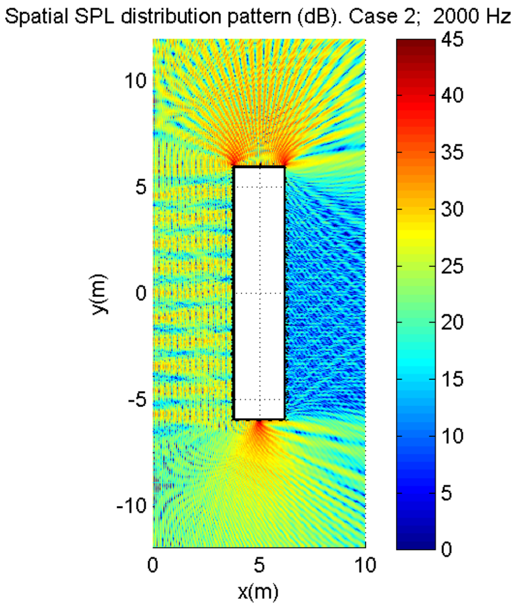

Figure 4 – Effect of a reflective wall on the sound pressure field. Case 2, 2000Hz.

5 Conclusions

The work described in the present paper presents a preliminary study of the theoretical behaviour of different configurations of Acoustic Vehicle Alerting Systems. The study, carried out by means of the ACA-BEM technique, was done with the goal to evaluate and compare the sound directivity of three different AVAS configurations, taking into account the effect of the vehicle's structure on the sound propagation, under static conditions. Eight different frequencies of emission were analysed, in accordance with the frequencies proposed by the NHTSA regulation. Future work considering a dynamic situation will provide further results on the sound pressure field, in order to obtain the better AVAS configuration from the pedestrian point of view, but without compromising the low noise emission advantage characteristic of the electric vehicles.

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