Simulation-based design of a steerable acoustic warning device to increase (H)EV detectability while reducing urban noise pollution

Bert Van Genechten[a*], Arthur Berkhoff[b]

[a] LMS International, Heverlee, Belgium
[b] TNO Technical Sciences - Acoustics and Sonar, The Hague, Netherlands

Abstract

This paper describes the simulation-based design methodology used in the eVADER project for the development of targeted acoustic warning devices for increased detectability of Hybrid and Electric Vehicles (HEVs) while, at the same time, reducing urban noise pollution compared to conventional acoustic pedestrian warning systems. A key component of this system is an external warning signal generator capable of projecting the warning signals to a contained area in front of the vehicle where potential at-risk situations are detected. Using acoustic beam forming principles a suitable warning strategy and an initial layout for realizing such a system is defined. Starting from this information, acoustic Finite and Boundary Element models of the transducer array allow assessing more realistically the performance impact of the system integration and of the most critical changes in the acoustic environment in which the signal generator needs to operate.
Keywords: acoustic beam forming, numerical acoustic CAE, pedestrian safety, (H)EV warning system design

Résumé

Ce papier présente l'approche utilisée lors du projet eVADER pour le développement d'avertisseurs sonores visant à prévenir les piétons de la présence d'un véhicule électrique lorsqu'un risque de collision est détecté. Le but étant, par rapport aux avertisseurs conventionnels, de maximiser la détection du véhicule par le piéton (distance et direction) tout en minimisant la pollution acoustique. Un élément essentiel de l'étude porte sur la capacité du système à avertir les piétons dans des situations difficiles (présence d'obstacle…). Des éléments finis et élément finis de frontière ont été utilisés afin de réaliser cette étude. Les directivités de chaque composante ont été ainsi calculé et recombiné à l'aide d'une approche dite de « Acoustic Beamforming ». Un cas d'étude critique a été utilisé pour montrer la robustesse de l'approche.

Mots-clé: acoustique formation de faisceaux, numérique acoustique CAE, la sécurité des piétons, la conception du système d'avertissement VE(H)

* Corresponding author. Tel.: +32 16 384 533; fax: +32 16 384 350.
E-mail Bert.VanGenechten@lmsintl.com

Introduction

This paper describes a simulation-based design methodology for the development of targeted acoustic warning devices for increased detectability of Hybrid and Electric Vehicles (HEVs). This design study is part of the eVADER European project which aims at developing and demonstrating acoustic warning systems to increase the detectability of low noise vehicles at low speeds (below 35km/h) by Vulnerable Road Users (VRUs) such as bicyclists and pedestrians, while minimizing the impact on the environmental noise levels and signature. To this end, the eVADER system combines advanced VRU detection technology, carefully designed warning signals (presenting a trade-off between detectability and annoyance) and dedicated alerting strategies. A key component of this warning system is an external warning signal generator capable of projecting the warning signals to a contained area in front of the vehicle where either VRUs in potential at-risk situations are detected or where there is a high probability of dangerous situations.

This paper presents the numerical simulation based design process that has been used to develop the eVADER exterior warning generator. After a general introduction and presentation of the scope of the eVADER project, a first section discusses acoustic beam forming principles and the different approaches to realize targeted acoustic fields based on a configuration of non-directional sources (such as e.g. loudspeakers). Using these principles a suitable warning strategy is defined and an initial overall array layout is proposed. Based on this information, a second section presents the construction of numerical acoustic models of a transducer array installed on the bumper of the eVADER demonstrator vehicle. Such models allow assessing more realistically the impact of the actual system integration on the performance of the warning system. Using the acoustic responses obtained with these models, the algorithm and configuration selected in the first section are verified. Next, a sensitivity study is presented to assess the impact of the most critical changes in the acoustic environment in which the signal generator needs to operate: temperature changes, changes in the road surface properties and the influence of nearby scattering objects such as e.g. parked vehicles.

1. The eVADER VRU warning system overview and design strategy

To realize its dual goals of improved pedestrian safety and lower environmental noise, the eVADER project designs and builds a pedestrian warning system that will be integrated into a Nissan Leaf demonstrator vehicle. All aspects of the development of such a system are considered within the project ranging from the psycho-acoustic perception of artificial warning sounds to automated pedestrian detection systems, risk estimation and interior and exterior warning system design. This paper focusses on the development of a crucial component of the warning system namely the exterior warning signal generator. In a parallel TRA2014 paper (Parizet et al., 2014) the eVADER consortium presents its research on the definition of efficient warning sounds, i.e. sounds that are easily detected at a low sound pressure level. At the same time different candidate sounds are evaluated with respect to overall traffic noise annoyance thus resulting in guidelines for EV warning sound design.

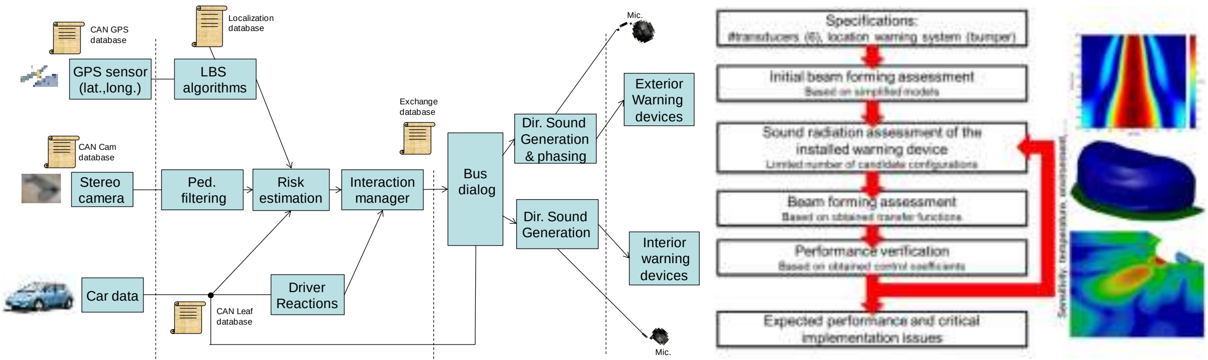

Fig. 1.Overall eVADER warning system layout (left) and exterior warning device design strategy (right)

The full eVADER warning system architecture is presented in Fig. 1. Based on the car's location, nearby detected VRUs (using a stereoscopic camera system) and the car's speed, heading etc., the risk of possible accidents is determined using a dedicated risk estimation algorithm. This data combined with any information on corrective actions taken by the driver allows the interaction manager to activate either the interior or exterior warning systems. The interior warning system aims at providing the driver a combined acoustic and visual feedback regarding the location of potential at-risk situations. At the same time, the exterior of the vehicle is equipped with a steerable noise signal generator with a high spatial directivity in the direction of any at-risk VRU. Both the acoustic signal orientation and sound level can be adjusted based on the risk assessment.

In order to optimally reduce the environmental noise impact, the design of this signal generator applies acoustic beam forming principles and follows the process shown in the right side of Fig 1:

- Starting from the functional specifications an initial beam forming assessment is performed. In order to simplify the analysis in this stage of the design the sources are modelled as monopole sources located in an infinitely extended half space.
  The outcome of this design step is a comparative assessment of different beam forming algorithms and of the impact of ground reflections and of the relative source locations on the warning system's performance.
- Based on these results, a limited subset of transducer configurations is selected whose performance as installed on the bumper of the demonstrator vehicle is studied in more detail. To this end, a FEM-based numerical model of the bumper and the separate sources is constructed.
- Using the obtained acoustic transfer functions between each transducer and a number of microphones, the best beam forming algorithm is used to determine the optimal control strategy for each individual speaker.
- To verify the system's performance, these speaker control parameters are used as inputs for an acoustic verification model. The obtained response predictions allow assessing the spatial distributions of the acoustic pressure fields in a much broader area than the microphones used in the control parameter identification.
- Once this verification of the system performance for the reference environmental conditions has been completed, a sensitivity study is performed to assess the system's robustness with respect to a wide range of relevant changes in the acoustical environment. This may require the acoustic modelling strategy to be adapted. If critical drawbacks are detected during this analysis, the system design is updated accordingly.
- Once the system has proven its robustness with respect to all relevant environmental changes, a well-founded view on the system's performance and possible critical implementation issues can be formulated.

This design study was executed as a collaboration between TNO and LMS, where TNO focussed their efforts on the study, selection and validation of the acoustic beam forming strategies and LMS looked into the numerical modelling aspects and overall process integration. In the subsequent sections of this paper the results of the different steps in this design study are presented for a transducer array of six small-sized loudspeakers (membrane radius 50mm) integrated in the front bumper of the eVADER demonstrator vehicle.

2. Acoustic beamforming strategies

The eVADER approach to increase VRU safety and reduce noise pollution is based on the use of a sound beam conveying the warning signal in the direction of the VRU, while minimising acoustic output in other directions (Fig. *2*). This section firstly describes the design of an array of acoustic sources based on simple source models. This design can be used as a starting point to generate more realistic transfer function models based on the geometry of a car or part of a car. This section starts with the definition of the initial geometry of the array, based on point source models and mirror point sources with respect to a perfectly reflecting ground plane. A comparison is given of two different beam forming algorithms. At the end of the section an example is given for a more realistic configuration showing of the influence of the ground reflection and the influence of the beam former optimisation distance.

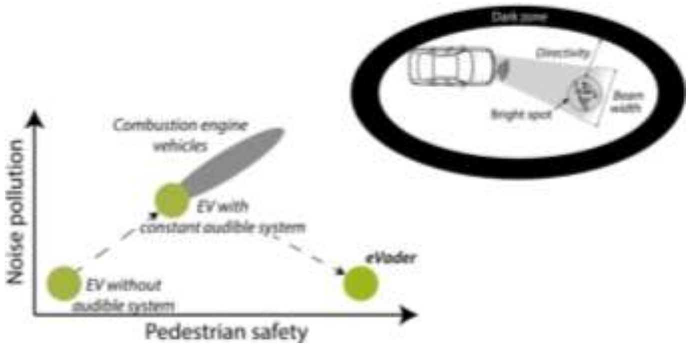

Fig. 2: eVADER approach using a directional acoustic warning system.

2.1. Specifications

The array consists of a maximum of six acoustic sources. The frequency range to be covered is 300 Hz to 1.2 kHz, which is based on several prototype sounds developed within eVADER (Parizet et al., 2014). Directivity is only required in the horizontal direction, not in the vertical one. The steering direction of the beam is between -60 degrees and +60 degrees using a a single beaming direction; multiple beams at the same time are not required. The angular tracking speed is 300º/s.

2.2. Spatial aliasing and beam width

The limited number of sources in the array necessitates a trade-off between beam width, particularly at low frequencies, and the maximum frequency determined by spatial aliasing. For the Delay and Sum algorithm the beam width BW in radians is given by $BW = 2\lambda/L$ in which $\lambda = c/f$ is the wavelength of sound in air with c the speed of sound in m/s and f the frequency in Hz, and L the size of the array in m. Other algorithms may have better performance than the Delay and Sum algorithm, so they can have a smaller beam width for a given array size and wavelength. However, practical high-resolution algorithms possess a similar relationship between array size, beam width and wavelength. So the size of the array has to be as large as possible for narrow beams. On the other hand the spacing between the array elements determines the upper frequency for which no 'aliased' beams are produced.

Spatial aliasing is determined by the spacing Δx between the sources and the spatial wavenumber k_x in the horizontal direction (Williams1999) (Note that the derivation in this reference is correct but not the conclusion regarding the condition for aliasing, which deviates by a factor 2). Spatial aliasing does not occur if the $|k_x| \leq \pi/\Delta x$. The wavenumber in the horizontal direction is defined by $k_x = \omega \sin\alpha\,/c$, in which $\omega = 2\pi f$ is the angular frequency, and in which α is the angle of the propagation direction with respect to the forward direction. For $\alpha = \pi/2$ we have $k_x = \frac{\omega}{c} = k$. The maximum frequency at which no aliasing occurs for a given spacing Δx is called the Nyquist frequency. The requirement for the spacing can be written as $\Delta x \leq \lambda/(2\,\sin\alpha)$, in which $\lambda = c/f$ is the wavelength. For a Nyquist frequency of 1.2 kHz and a maximum angle α of 60º we obtain $\Delta x \leq 0{,}165\ m$. To introduce a certain margin and to further reduce the influence of spurious beams, a Nyquist frequency of 1.5 kHz was selected and a maximum angle α of 90 º. This results in a spacing $\Delta x \leq 0{,}1143\ m$.

For sensor arrays, many beam forming methods exist (van Trees2002). For source arrays the number of methods that have been described in the literature is smaller. Some of the methods for source arrays are the Contrast Maximisation approach (Choi2002, Chang2009), the Acoustic Energy Difference method (Shin2010), and the Time Reversal approach (Guldenschuh2008). We can also define a so-called Least-Squares beam former based on a description for sensor arrays in (vanTrees2002). A method based on the reduction of the sound power with a constraint in the main steering direction is given in (Berkhoff2011, Berkhoff2013). The resulting matrix equation that has to be solved can also be found in (vanTrees2002), although the derivation that leads to this matrix equation is rather different. A comparison of five different beam formers can be found in (Berkhoff2013). From these results it can be seen that the Acoustic Energy Difference method and the Sound Power Minimization method provide the sharpest beams. An advantage of the Sound Power Minimization approach and Delay and Sum approach is that a re-computation of the source coefficients when a new steering direction is required is computationally feasible within the timing constraints and with the computing resources of the embedded hardware suggested for eVADER. Although a re-computation is not necessary for a single target direction, it is more efficient when two or more, a-priori unknown, target directions are taken into account. The Acoustic Contrast Control method and the Acoustic Energy Difference method require computation of eigenvalues and eigenvectors, and are therefore less attractive for real-time modification of the steering direction and subsequent re-computation. A selection of the results for two methods will be presented in this paper: the delay and sum beam former and the sound power minimization beam former.

An example of the beam shape for a uniform array with constant spacing between the sources is given in the left side of Fig. *3*. It can be seen that the Sound Power Minimization method gives more narrow beams than the Delay and Sum method, especially at low frequencies. A further reduction of the beam width is possible by using a non-uniform array spacing, as can be seen in the right side of Fig. *3*. The disadvantage of the high resolution methods such as the Sound Power Minimization method is that the driving levels of individual sources can be higher than with the Delay and Sum method (see Fig. *4*). A certain amount of regularisation is therefore needed, which is also beneficial for the robustness with respect to uncertainties of the transfer functions. For other beaming directions similar results can be found, possibly with somewhat wider beams at large beaming angles.

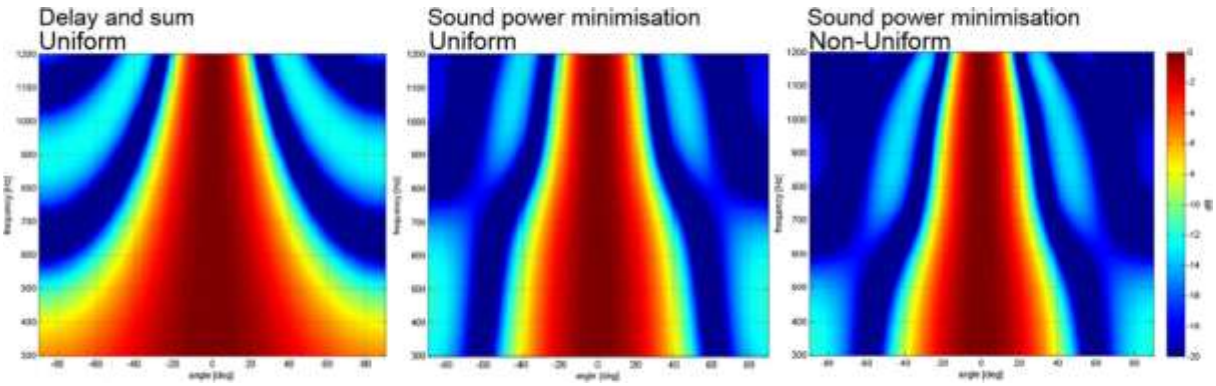

Fig. 3: Sound pressure level in dB relative to the sound pressure level in the main beam (steering at 0^{o}) for an array of 6 point sources using uniform and non-uniform array geometries and Delay and sum and sound power minimisation strategies.

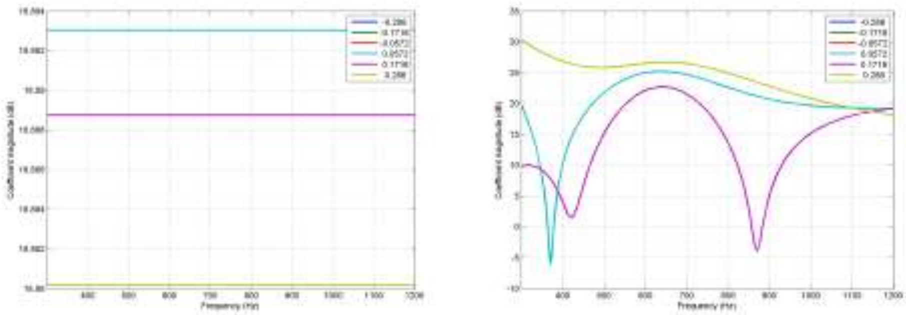

Fig. 4: Coefficient magnitude for delay and sum beam former (left) and sound power minimisation beam former (right).

2.3. Beamforming based on measured transfer functions

The methods for driving an array of sources were selected such that measured transfer functions could be used, allowing calibration with experimental data. An advantage of such an approach is that there is no need to assume that the sources are small. Such assumptions are often used in derivations for sensor arrays but for source arrays such an approximation is unrealistic. The sound power of the sources is often critical and therefore the dimension of the sources is maximized and tends to be approximately equal to the array spacing. As a consequence the sources cannot be assumed to be small. Furthermore, there is a certain coupling between the sources, due to acoustic, mechanical or electrical interaction. Since the present method is based on measured transfer functions all such factors are automatically taken into account in the design of the beam forming algorithm, but the performance of the system of course depends on the actual geometry and conditions. An example of a configuration in which 15 microphones are used at distance of 5m from the array is given in Fig. *5*.

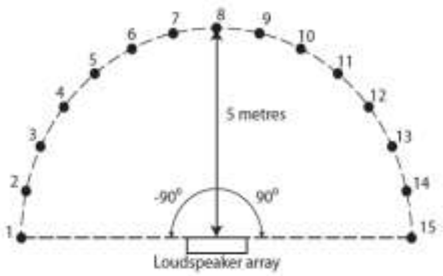

Fig. 5: Example configuration used to define the beam former showing the loudspeaker array and a number of microphones on a circle, in this case using 15 microphones at a distance of 5m from the centre of the array.

For the initial computations a simplified frequency domain point source model is used, based on the Green's function $G(x|x') = e^{-jk|x-x'|}/(4\pi|x-x'|)$ in which x is the source coordinate, x' is the receiver coordinate and $j = \sqrt{-1}$. The reflecting ground surface is an important aspect of the present application. In a first approximation, each Green's function is augmented with a contribution due to an apparent mirror source. If the algorithm is used in such a way that the sound pressure in the main beaming direction at a specified distance is constrained then the ground reflection results in a degraded beam shape at frequencies with strong destructive interference. Several strategies exist to reduce the effect of such ground reflection interference. In Fig. 6, the influence of the optimisation distance is illustrated. An optimisation of the beam at a relatively large distance from the array, in this case 40m, leads to a smooth and narrow beam at the identification distance. However, if the beam is optimised at a relatively short distance from the array, in this case 5m, then the beam shape in the far field is degraded in the frequency range affected by the ground reflection (650-750Hz). Similar degradations are observed at other evaluation distances with other corresponding frequencies. Additionally, Fig. 6 shows that this degradation can be reduced by optimising the array for the far field. The effect of the ground reflection is still apparent at the shorter distances as an attenuation of the sound at specific frequencies, but it does not lead to widening of the beam. Moreover, attenuation of the sound at specific frequencies caused by the ground reflection is the normal situation for sources and receivers at a specific location. Optimisation of the beam former for the far field leads to a more natural behaviour, albeit with possible dips in the spectrum at certain receiver locations.

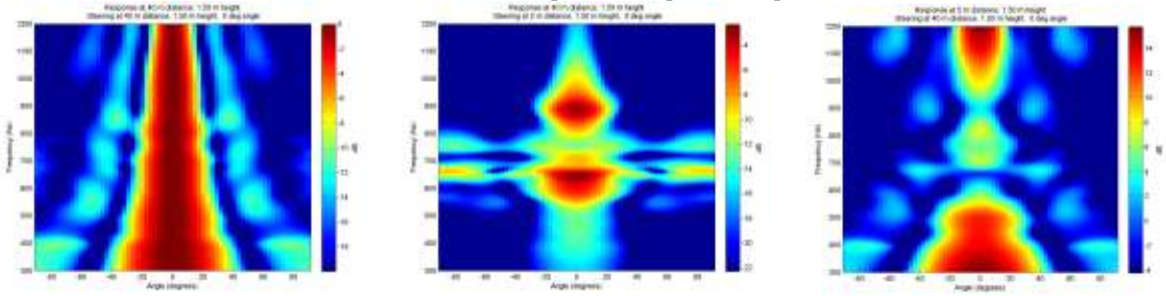

Fig. 6: Beam shapes for more realistic car geometry with reflecting ground surface; steering at an angle of 0 degrees. Beam optimisation at 40m distance, beam evaluation at 40 m distance (left), beam optimisation at 5m distance, beam evaluation at 40m distance (middle), beam optimisation at 40m distance, beam evaluation at 5m distance (right).

3. Advanced acoustic CAE in support of VRU warning system design

In the scope of the eVADER exterior warning system design, the use of acoustic virtual prototypes presents very attractive perspectives on the one hand to quickly gather realistic input data needed to assess the potential strengths and weaknesses of different acoustic beam forming algorithms and on the other hand to assess the algorithms' and design robustness by varying a wide range of environmental conditions. This section presents the construction of suitable acoustic CAE models of the warning system and their use in the design and verification of the signal generator. The versatility of advanced CAE approaches in the context of (H)EV acoustic analysis has also been shown in (Van der Auweraer et al., 2011) and (Van der Auweraer et al., 2012).

3.1. Selection of suitable predictive CAE tools for modelling VRU warning systems

Whenever virtual prototypes are used to support a design process or to assess the performance of a specific system, the selection of a suitable discretization approach and analysis type is of key importance. When considering acoustic radiation problems, which involve solving an uncoupled exterior acoustic problem with imposed normal velocity boundary conditions in the frequency domain two families of numerical modelling approaches are frequently used in the current engineering practice:

- The Boundary Element Method (BEM) (VonEstorff2000) is based on a boundary discretization of the problem domain and is hence very suited to model acoustic radiation problems since the infinite nature can be easily and exactly incorporated. Moreover, since its conception a number of decades ago significant advances have been made to increase the BEM's computational efficiency and relax its limitations in terms of model size. Examples of recent enhancements are the Fast Multipole BEM methods (Gumerov2005) and the Hierarchical Matrix (or H-Matrix) solvers (Hackbush1999).
- The Finite Element Method (FEM) (Zienkiewicz2005) has become the standard solution approach for solving interior acoustic and vibro-acoustic problems. The main challenge for applying it to unbounded problems originates from its inherent domain discretization nature. This prohibits the method to be directly applied to infinitely extended volumes. Different strategies for coping with this limitation have been devised, mostly based on the introduction of fictitious outer FEM boundaries where appropriate absorbing conditions such as infinite elements (Astley1994) and perfectly matched layer (Bérenger1994) approaches are applied.

Based on an in-depth comparison of strengths and weaknesses of the different modelling approaches a combination of different numerical strategies is proposed for this design study:

- For scenarios where only the bumper itself needs to be considered, the FEM-AML technique which is based on the perfectly matched layer approach is selected.
- In the settings where also the complex acoustic environment in which the warning signal generator needs to operate (road surfaces, nearby objects etc) are considered BEM-based approaches present an attractive alternative. More specifically, in the current study the H-Matrix approach is used.

3.2. Reference configuration FEM-AML model

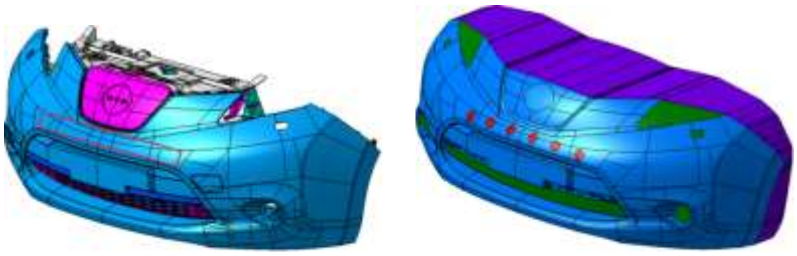

Fig. 7. Original (left) and computational (right) bumper geometry

A detailed geometrical model of the front bumper of the eVADER demonstrator vehicle is incorporated in all the numerical models in design study. To this end, Nissan provided the detailed CAD model shown in Fig 8 of the bumper itself and all components that are located in its immediate vicinity. While all this geometrical information is required for the package space analysis to define suitable transducer locations, this bumper model is far too detailed to be readily used in the acoustic FEM model for the reference configuration. As a first step, a closed surface model needed to create the FEM model discretization was obtained by filling up the remaining holes and surface mismatches. In view of an accurate assessment of the acoustic radiation of the different transducers as installed on the bumper of the test vehicle the front of the car is not taken into account (explicitly or approximately). Therefore the outer edge of the surface model was extruded in the length direction as is shown by the purple surface area in the right of Fig 8. The length of the extruded surface was selected as a trade-off between model size (the longer the extrusion the bigger the model) and the impact of the created back edge on the radiated pressure field. Due to their small size, the six individual loudspeakers are incorporated as the six red circular vibrating pistons that are incorporated in the bumper geometry shown in right side of Fig 8. To finalize the creation of the FEM-AML model, the advanced pre-processing capabilities of the LMS Virtual.Lab Acoustics Rev.12 (LMS Virtual.Lab12) suit of acoustic numerical modelling tools are used to automatically generate a suitable convex wrapper mesh around the extended bumper geometry. This mesh is created in such a way that a minimal distance between the physical boundaries and the convex mesh is respected and that the mesh runs up to and is perpendicular to a predefined perfectly reflecting plane. Fig 9 shows the final baseline FEM-AML model. The resulting mesh contains 385.000 linear 4-noded tetrahedral elements and 78.000 nodes. The average mesh size is 0.0125m, making the mesh at least valid up to 1.3kHz according to commonly used rules of thumb. The total computational cost for solving this baseline FEM model of 120.000 degrees of freedom is 9 seconds per frequency. In comparison, solving a BEM model using the H-matrix solver takes 210 seconds while providing acoustic predictions that are perfectly matching the FEM results. The large difference in computation time indicates that the FEM method was appropriately selected for this study.

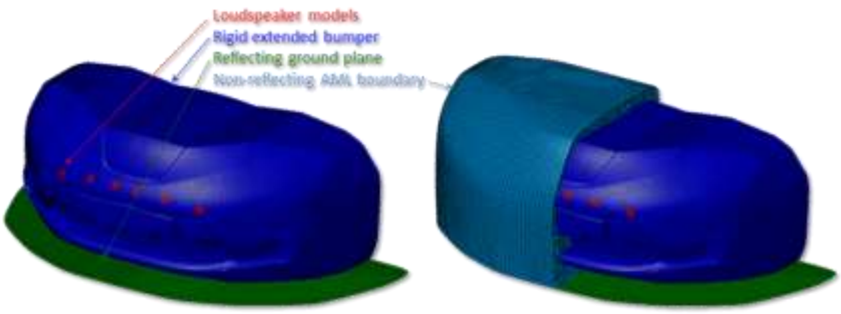

Fig. 8. FEM-AML model of the warning signal generator integrated into the front bumper

In this design study, the FEM-AML model of the warning signal generator installed on the front bumper of the demonstrator vehicle is used in two steps of the design process presented above:

- Firstly, the model is used to obtain the acoustic transfer functions between the surface velocity of each individual loudspeaker and the acoustic pressure at a number of semi-circular microphone arrays. These transfer functions can then be used as an input for the beam forming strategies discussed in section 2. An example of such a set of transfer functions is shown in the left side of Fig 10.
- Secondly, by introducing the optimal beam forming control parameters in the numerical model, the full acoustic pressure field generated by the exterior warning generator can be reconstructed. This information is very useful to assess the impact the warning generator has on environment noise landscape. The right side of figure 10 shows the acoustic pressure field at 900Hz in front of the bumper generated by an irregularly shaped beam forming array. The area considered in this picture extends up to 15m away of the bumper and illustrates the highly directive noise field that is generated. These figures clearly illustrated the suitability of the beam forming strategies selected in section 2 to derive optimal control parameters.

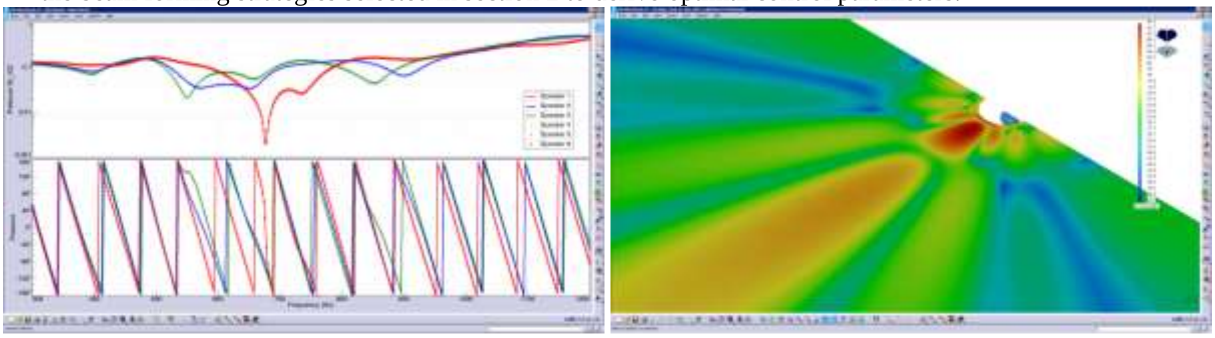

Fig. 9. Acoustic pressure responses obtained with the baseline FEM-AML model: (left) individual acoustic transfer functions for the six speakers, (right) forward-facing acoustic beam at 900Hz

3.3. Design sensitivity study

Given the high level of exposure of the exterior warning system to a wide range of environmental conditions it is paramount that the dominant parameters are taken into account during the design of the system to ensure robustness. Based on an extensive literature review ([Remillieux2012], [Zoubir2008], [Castellini2008], [Moran2007], [Omologo1998], [Castellini2010]), the following parameters have been found to influence the propagation of acoustic waves in typical traffic environments (and hence may impact the performance of a targeted acoustic warning system):

- Variations in the acoustic properties of the air (mass density and sound speed variations) that may be caused by the presence of temperature gradients or variations or changes in relative air humidity
- Aerodynamic disturbances of the propagating medium caused by wind gradients and air turbulence
- Impact of second order reflections that may interfere with the direct field generated by the array such as the presence of reflecting objects and ground reflections.
- Interference with other noise sources that can be other sound sources in the environment or incoherent background noise

In the current study, the first and third class of influencing factors are considered. The fourth impact type is implicitly integrated into the total warning system's control architecture that selects an absolute sound level to be generated by the warning system to guarantee detectability.

Both the ambient temperature and the air's relative humidity change the acoustic wave propagation properties of the acoustic environment and hence may significantly impact the warning system's performance. In order to identify the most influential parameter, Fig 11 shows the evolution of both density and sound speed for representative temperature (-10^{o}C to +30 ^{o}C, blue curves) and humidity (0 to 100%, red curves) ranges. The curves clearly show that the temperature has the most impact. Hence only this parameter is considered. Since temperature changes only impact the acoustic material properties of the ambient fluid, the selection of the FEM-AML technique remain valid. By combining these updated models with the control coefficients computed for the reference conditions, the robustness with respect to ambient fluid property changes can be assessed. The right side of Fig 10 shows a representative example result of this study for a warning signal targeted at a 0^{o} orientation at 20^{o}C and at 0^{o}C. A very good agreement between the obtained directivities can be seen from these results.

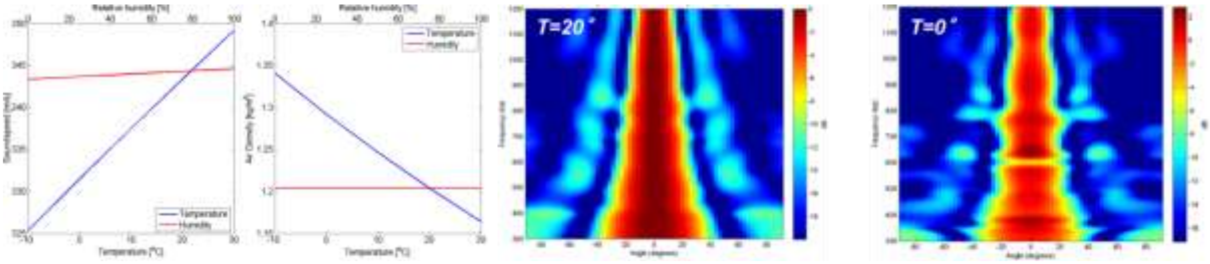

Fig. 10. Impact of air temperature and humidity on speed of sound and density (left) and on beam forming (right)

A second parameter with a major impact on the warning system's performance are the acoustic absorption properties of the road surface. Apart from attenuating acoustic waves, the acoustic impedance of the road surface may also introduce asymmetry or may even fully scatter the warning signal. In order to incorporate these effects a suitable description of the frequency-dependent acoustic normal impedance is incorporated in a discretization of the road surface. Many models exist in literature to describe the acoustic behaviour of porous asphalt layers and Hamet et al (1993) have developed a theoretical model in which the acoustic surface impedance depends on the ambient fluid properties of the air but also on the air flow resistivity of the asphalt, the porosity, the so-called structural factor and the thickness of the asphalt layer. Typical values for these quantities were taken from literature and are used to obtain the acoustic normal impedance values shown in this study. Since the exterior warning system is designed to warn at-risk VRUs up to large distances in front of the vehicle, the road surface absorption properties should be appropriately modeled. Hence, the area where the road surface is located is modelled explicitly for a scenario where the vehicle is driving along a 20m long straight road which is two lanes wide, as is shown in the left of Fig 11. Additionally the impact that scattering objects in the vicinity of the warning signal generator is considered. To this end, the BEM model is extended by adding a model of two vehicles parked on the side of the road 5m in front of the approaching demonstrator vehicle. The vehicles themselves are considered to be perfectly reflecting and their additional impact on the spatial distribution and directivity of the acoustic warning signals generated by the exterior warning system will be assessed. The increased extent and complexity of the problem setting significantly impacts the choice of the modelling approach to be used. Based on the model size (around 190.000 degrees of freedom for the road surface and 250.000 when including the parked cars) the H-matrix BEM was selected. Due to the increased computatonal cost (around 13-25 min per frequency of interest), the acoustic responses are only computed every 25Hz.

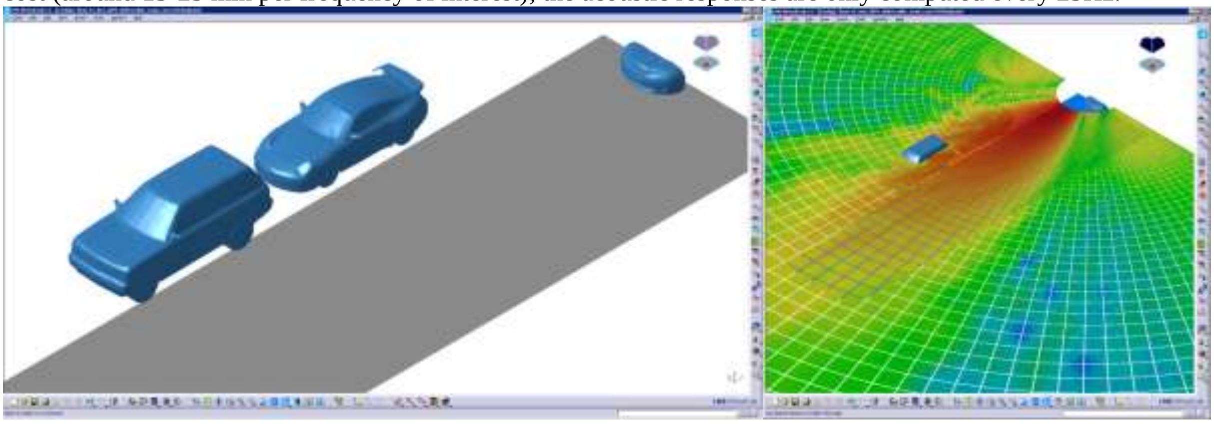

Fig. 11. Impact of road surface impedance and nearby scattering objects on beam forming performance: (left) H-matrix BEM model discretisation, (right) spatial distribution of the acoustic pressure field at 600Hz

The right side of Fig 11 shows the spatial distribution of the acoustic pressure amplitude generated by the warning system at 600Hz for a steering angle of 0^{o}. This case is considered as the worst possible mode of operation since the central acoustic pressure amplitude lobe of the warning signal impinges directly on both stationary vehicles. As can be seen in the contour plots in Fig. 11, the presence of the two vehicles shields the areas behind them. From the point of view of VRU safety this is however not an issue since there is no danger of these people being hit by the moving vehicle. The sound waves that are scattered by the parked vehicles do interfere with the central lobe of the warning signal but do not significantly alter its shape nor do they generate areas of very low acoustic pressure amplitude. The conclusions above for the spatial pressure distributions at discrete frequencies are confirmed by the warning signal directivity analysis presented in Fig 12. On the left side of the figure the directivity obtained for the baseline problem setting is given. This image is compared to the directivity for a 0^{o} steering in the case where only the road surface impedance (middle) and where both the road surface and the two parked vehicles (right) are included in the analysis. In both cases, the directivity pattern becomes slightly asymmetric due to the asymmetric positioning of the vehicle with respect to the road (it is occupying the right lane). Additionally the interference between the directly radiated acoustic field and the acoustic waves scattered by the parked vehicles is clearly visible in the image on the right but as was observed in Fig. 12 these interferences do not interfere with the overall directionality and hence they do not impact the system's intended operation.

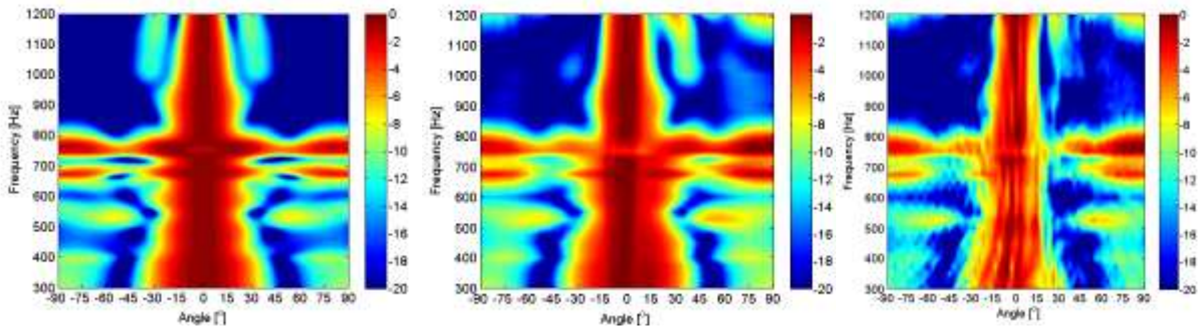

Fig. 12. Impact of road surface impedance and nearby scattering objects on beam forming performance: (left) reference configuration, (middle) impact of 20m long asphalt road, (right) impact of asphalt road and parked cars

4. Conclusions

In this paper, a CAE-based analysis and evaluation process is proposed to support the design of the eVADER acoustic exterior warning system. In this process, advanced acoustic beam forming algorithms are linked to suitable high-fidelity numerical models for the assessment of the acoustic radiation of the different transducers as installed on the vehicle. In this way, a thorough and realistic assessment of different configurations for the final warning system layout can be executed in a flexible and efficient manner. The choice of a suitable modeling technique is based on the problem setting itself, the problem geometry and the expected computation times for different types of modeling approaches. Both FEM and BEM models are considered.

Based on the control coefficients derived to realize a localized warning signal targeted at different angles with respect to the forward direction of travel of the demonstrator vehicle, a verification study was performed to analyze the spatial distribution of the acoustic pressure amplitude that is generated by the warning system. In a subsequent analysis step, the use of detailed numerical models allows to incorporate various parameter changes in the problem setting to assess the robustness of the proposed design. In this sensitivity study, three key types of changes in the acoustic environment of the warning system are considered: changes in the fluid properties of the ambient air, impact of acoustic absorption by the road surface and disturbances by scattering objects.

For all types of parameter changes their effect on the spatial pressure distributions and warning signal directivity is assessed. Based on the results of this study the proposed transducer configuration was proven to be robust with respect to environmental changes and hence the design is deemed to be ready to go into prototype testing and integration into the eVADER demonstrator vehicle.

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