Investigation of a directional warning sound system for electric vehicles based on structural vibration

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Warning sound systems for electric vehicles with advanced beamforming capabilities have been investigated in the past. Despite showing promising performance, such technologies have yet to be adopted by the industry, as implementation costs are generally too high, and the components too fragile for implementation. A lower cost solution with higher durability could be achieved by using an array of inertial actuators instead of loudspeakers. These actuators can be attached directly to the body of the vehicle and thus require minimal design modifications. A directional sound field can then be radiated by controlling the vibration of the panel, via adjustments to the relative magnitude and phase of the signals driving the array. This paper presents an experimental investigation of an inertial actuator-based warning sound system. A vehicle placed in a semi-anechoic environment is used to investigate different array configurations in terms of the resulting sound field directivity and the leakage of sound into the cabin. Results indicate that the most efficient configuration investigated has the actuators attached to the front bumper of the vehicle. Using this arrangement, real-time measurements for different beamformer settings are performed to obtain a thorough picture of the performance of the system across frequency and steering angle. [a]

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I. INTRODUCTION

The advent of electric and hybrid electric vehicles has been encouraged due to the search for sustainable transportation globally, but has also sparked concern over potential hazards in road safety that it may create as a new technology. With particular relevance to the field of acoustics, there have been studies focusing on the increased risk Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) may pose to vulnerable road users such as pedestrians and cyclists due to their silent operation[1,2].

Compared to an internal combustion engine, an electric motor produces low levels of noise emissions when in operation. The internal combustion engine is the main noise source at speeds below approximately 30 km/h. Above this limit, the noise generated by the interaction between the tyres and the road and the aerodynamics of the vehicle begin to dominate[3]. Therefore, EVs and HEVs are comparatively quiet at low speeds, meaning that they offer little auditory warning of their presence and direction of travel in situations such as cornering, parking manoeuvres, and low speed city traffic[4]. This potential safety issue has led to the issuing of regulations on a global scale[5–7], which dictate guidelines on the use of artificial warning sounds, or Acoustic Vehicle Alert Systems (AVAS), that aim to ensure that EVs and HEVs can be detected aurally. The inclusion of warning sounds is mandatory for the aforementioned speeds below 30 km/h, as beyond that limit noise produced by other sources in the vehicle is considered sufficient to provide the necessary auditory warning.

This relatively new requirement has sparked research focusing on the design of such warning sounds, with the objective of generating a detectable signal that can be readily associated with a vehicle, and is also indicative of its velocity and acceleration. This information is valuable to vulnerable road users, such as cyclists and pedestrians, but particularly the visually impaired[8] . Factors such as annoyance and intrusiveness in the sonic environment are also considered in this design process[9–12], with the objective of minimizing these parameters in order to counteract arguments against the use of warning sounds citing the increase in noise pollution[13].

Balancing the warning sound requirements may lead to a decrease in their effectiveness, and therefore, it may prove beneficial to seek a solution that is able to limit the resulting noise pollution through controlling the spatial aspects of the warning sound. For example, by focusing the radiated sound field towards the direction of vehicle motion, or even individual vulnerable road users, and minimising its output in all other directions, it may be possible to provide a sufficiently audible warning whilst keeping noise pollution to a minimum. Such directional warning sound systems have been proposed and investigated, using highly directional parametric loudspeakers[14], low-cost single loudspeaker solutions[15] and loudspeaker arrays capable of beam-steering to direct sound at identified targets[16–18]. However, due to limitations in their effective bandwidth and beamforming capabilities[15], or the increased cost of production and maintenance that comes with higher performance solutions[14,16–18], so far none of the above systems have been adopted for widespread use by the automotive industry.

Loudspeaker array-based systems have been proven capable of generating highly directional, controllable sound fields across a significant bandwidth and have been implemented in hi-fidelity applications[19,20]. A difficulty to be overcome with the implementation of a loudspeaker array as a vehicle warning sound system, however, is the necessity for significant design modifications to be made to existing structures in order to accommodate the loudspeakers and enable them to radiate sound efficiently. This might significantly raise the cost of production and potentially even interfere with other systems in the vehicle. Another issue to consider is the exposure of the fragile loudspeaker cones to adverse environmental conditions such as wind, dust, water and temperature variation.

A solution to address both the cost of modifying the structure of the vehicle and the durability of an integrated system would be to replace the conventional loudspeakers with inertial actuators. These operate by forcing the structures upon which they are attached to vibrate and radiate sound, acting effectively in place of a loudspeaker cone. For example, inertial actuators are utilized in Distributed Mode Loudspeakers (DMLs), which offer a large bandwidth, an omni-directional radiated sound field[21–23], and can be seamlessly integrated into existing structures such as walls in a building or advertising billboards. Directional radiation from structural vibration has recently been investigated regarding the sound field directivity of rectangular plates and strips[24] , and the controlled beamforming achievable from systems utilizing actuator arrays attached to flat panels[25] . An actuator-based system can potentially match the directivity performance of a conventional loudspeaker array, but holds practical advantages when it comes to an in-vehicle implementation. Firstly, no structural modifications are necessary, as the actuators can potentially be simply attached to existing panels or structures. Secondly, since inertial actuators radiate via the structure to which they are attached, such an array design offers increased durability because the actuators are not exposed to the external environment. The potential downside of a structural actuator-based array is the more irregular frequency response, but this is unlikely to be extremely critical for warning sound generation.

This paper investigates the implementation of an inertial actuator-based directional sound system in a vehicle as a potential warning sound system. Different array arrangements on the body of a commercial vehicle are investigated to determine which components can be utilized to produce a controllable sound field within the frequency range from 100 Hz to 5 kHz, which is the bandwidth of warning sounds required by current legislation[5,6] . The suitability of each configuration is further evaluated by investigating the resulting sound leakage into the interior of the vehicle. Section II describes the main operating principles of the system in terms of sound radiation through the forced vibration of a structure, and a method for achieving control of the directivity. In Sec. III, the experimental methodology is presented, with an overview of the measurement set-up and the implementation of the directivity control strategy. Section IV presents the results of the investigation using different actuator configurations, an evaluation of sound leakage from the array into the cabin, and the results of the on-line measurement of the controlled sound field using the most effective array configuration. Lastly, the findings of this study are summarized and commented upon in Sec. V.

II. PRINCIPLES OF OPERATION

The most widely used method of generating a directional sound field is through the use of a loudspeaker array, with the relative amplitudes and phases of the individual loudspeakers controlling the direction of radiation. For the system proposed in this paper, the vibration of a panel determines the radiated sound field and this is controlled by adjusting the relative amplitudes and phases of the inertial actuators, as demonstrated in[25] for a flat panel structure. Following this previous work, this section will present the principles of operation of the actuator-based system by identifying the key parameters that affect performance and the differences when compared to conventional loudspeaker arrays. In addition, a strategy for achieving control over the resulting sound field directivity through the acoustic contrast maximization process is outlined.

A. Sound radiation from structural vibration

A vibrating structure radiates sound by causing fluctuations in the pressure field. The response of the structure in conjunction with the method of its excitation determines these fluctuations. In relation to the case study of this paper, this means that a panel forming a component of the vehicle, such as its hood, bumper, or door panel, radiates a sound field that depends on its construction and the characteristics of the excitation force. Through controlling the structural vibration, it is possible to influence the spatial aspects of the radiated sound field. This can be achieved by using multiple inertial actuators mounted to the structure.

The sound field radiated from by a vibrating structure driven by an actuator array has some key differences and additional parameters when compared to conventional loudspeaker systems. One of the benefits of using such a system is an improved high frequency limit compared to a loudspeaker array. This is due to the effective interpolation of the array sources between the actuator locations on the vibrating panel. This reduces the effects of aliasing associated with the discrete nature of a loudspeaker array[26]. At the same time, however, the resulting sound field is also likely to be affected by the modal vibration behaviour of the structure[27] and thus result in a more colored acoustic response.

The directivity capabilities of a structural vibration-based sound system have previously been investigated for a flat panel driven by an inertial actuator array[25], with the system capable of achieving a significant level of controlled directivity across a frequency range consistent with the requirements of a warning sound system. This performance is dependent on a number of parameters: the material, and physical dimensions of the panel, the number of actuators, their individual response characteristics, and their distribution on the panel. The effective upper frequency limit that is achieved has been shown to be strongly dependent on the spacing between the actuators, but as noted above is higher than expected based on standard loudspeaker array theory. The use of longer panels and a greater number of actuators in the array also provide a generally higher level of directivity control[25] .

Although it has already been shown in the literature that directional sound radiation through the control of structural vibration is feasible, the integration of the proposed system into a vehicle presents additional challenges. These are primarily related to the availability of surfaces that are suitable for the accommodation of the array, and facilitate the generation of a controllable sound field through their vibration, which may be limited by their shape and construction. Another challenge related to implementing practical on-vehicle implementation is the transmission of the generated sound to the interior of the vehicle, which is undesirable. The actuator array needs to be placed in a position that ensures that significant levels of uncontrolled warning sound are not generated inside the vehicle cabin.

B. Directivity control strategy

The control strategy used for the proposed system is the acoustic contrast maximization strategy, which attempts to maximize the difference between the average sound pressure levels within designated bright and dark zones in the far field[28]. Figure 1 depicts a configuration consisting of an array of M sensors split into a bright and a dark zone of M_B and M_D sensors respectively, and an array of I sources. The complex pressure amplitudes generated at the bright and dark zone microphones at a single frequency are given by vectors $\boldsymbol{p}_B$ and $\boldsymbol{p}_D$, which can be expressed in terms of the complex transfer responses from the array to the bright and dark zones $\boldsymbol{G}_B$ and $\boldsymbol{G}_D$, and the vector of complex input signals, $\boldsymbol{u}$ so that

$$\boldsymbol{p}_B = \boldsymbol{G}_B \boldsymbol{u} \qquad \boldsymbol{p}_D = \boldsymbol{G}_D \boldsymbol{u}. \tag{1}$$

Taking the above into account, the acoustic contrast is defined at a given frequency as the ratio of the mean of the squared pressures in the bright zone and the dark zone, which can be expressed as

$$AC = \frac{M_D \boldsymbol{p}_B^H \boldsymbol{p}_B}{M_B \boldsymbol{p}_D^H \boldsymbol{p}_D} = \frac{M_D \boldsymbol{u}^H \boldsymbol{G}_B^H \boldsymbol{G}_B \boldsymbol{u}}{M_B \boldsymbol{u}^H \boldsymbol{G}_D^H \boldsymbol{G}_D \boldsymbol{u}}, \tag{2}$$

where the ^{H} superscript indicates the conjugate transpose operator.

In addition to the acoustic contrast, it is also important to consider the electrical power requirements of the array, particularly as this can be related to the power requirements of the actuators. The array effort is a quantity that is proportional to the electrical power required to drive the array, assuming that no significant electroacoustic interactions occur between the transducers[20]. In detail, the array effort is defined as the sum of the modulus squared signals driving the array, and is commonly normalized by the modulus squared

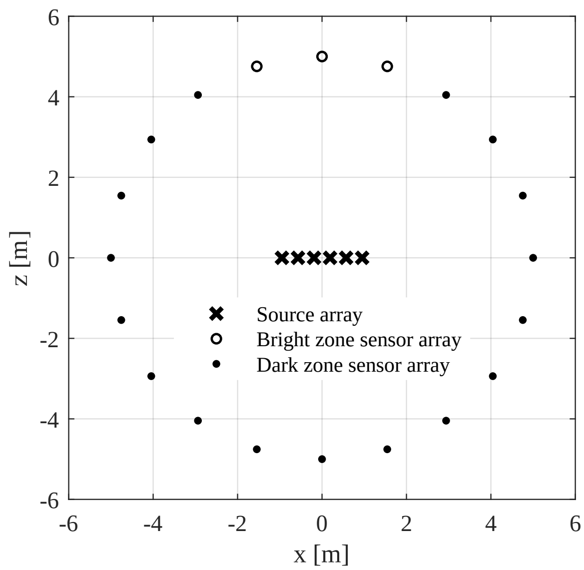


FIG. 1. Example schematic of a configuration consisting of a sound source array and an x, y planar control zone of sensors divided into a bright and dark zone.

signal required from a single element at the centre of the array to produce the same mean square pressure in the bright zone, u_m. This has the form

$$AE = \frac{\boldsymbol{u}^H \boldsymbol{u}}{|u_m|^2}. \tag{3}$$

Both acoustic contrast and array effort, as defined in Eqs. (2) and (3), are dimensionless quantities, usually expressed in decibels with their level defined as $10 \log_{10} AC$, or $10 \log_{10} AE$ respectively.

The input signals required to achieve the maximum acoustic contrast at a specific frequency can be obtained through the solution of a constrained optimization problem[29]. In this problem, the sum of the squared pressures in the dark zone, $\boldsymbol{p}_D^H \boldsymbol{p}_D$, is minimized under the constraints that both $\boldsymbol{p}_B^H \boldsymbol{p}_B$ is held constant at a value B, and that $\boldsymbol{u}^H \boldsymbol{u}$ is equal to E, which represents a constraint on the total power of the signals driving the array. The corresponding Lagrangian has the form

$$\mathfrak{L} = \boldsymbol{p}_D^H \boldsymbol{p}_D + \lambda_1(\boldsymbol{p}_B^H \boldsymbol{p}_B - B) + \lambda_2(\boldsymbol{u}^H \boldsymbol{u} - E), \tag{4}$$

where λ_1 and λ_2 are the positive real values of the Lagrange multipliers. Seeking the minimum solution of this Lagrangian has been shown[29] to lead to the relation

$$\lambda_1 \boldsymbol{u} = -\left[\boldsymbol{G}_B^H \boldsymbol{G}_B\right]^{-1} \left[\boldsymbol{G}_D^H \boldsymbol{G}_D + \lambda_2 \boldsymbol{I}\right] \boldsymbol{u}. \tag{5}$$

The optimal solution in this case can be obtained from the eigenvector corresponding to the largest eigenvalue of the matrix, $\left[\boldsymbol{G}_D^H \boldsymbol{G}_D + \lambda_2 \boldsymbol{I}\right]^{-1} \left[\boldsymbol{G}_B^H \boldsymbol{G}_B\right]$. By using this form of the solution, the Lagrange multiplier, λ_2, not only limits the array effort, but also regularizes the matrix being inverted, which can improve the robustness of the system in practice[29].

III. EXPERIMENTAL PROCESS

This section presents the experimental method used to investigate the potential of achieving directional sound radiation using the proposed system. A number of different actuator array configurations installed on a commercial vehicle are described, and their performance is tested using the acoustic contrast control strategy.

A. Measurement set-up

The measurements have been carried out in a semi-anechoic chamber, with fully anechoic walls and ceiling and a concrete floor. A test vehicle was placed in the centre of the chamber. The directional sound system was integrated into the vehicle by attaching inertial actuators

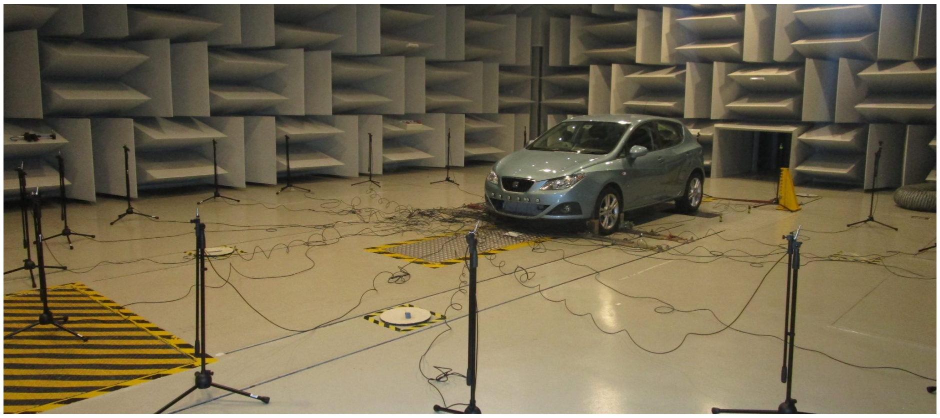


FIG. 2. Experimental set-up inside the semi-anechoic chamber.

onto its body to form an array. The actuators used (Tectonic Elements TEAX32C20-8) have an individual weight of 150 g, a diameter of 51.2 mm and a nominal rated power of 10 W. The frequency range of the actuators is between 100 Hz and 15 kHz. Up to six actuators are used simultaneously, powered by compact two-channel class D amplifiers (Sure Electronics TPA3110). The sound pressure is monitored by a circular array of twenty omnidirectional microphones (PCB 130F20), centred around the front end of the vehicle. The dimensions of the chamber limit the radius of this circle to 5m, and the microphones are placed at a height of 1.2m. Figure 2 shows the measurement set-up with the test vehicle in relation to the microphone array. As can be seen from Fig. 2, the actuators are mounted on the outside of the vehicle, which has been done for convenience of installation when investigating different array configurations on the vehicle. The intended implementation would have the actuators mounted on the inside of the vehicle structure. Nevertheless, as the direct radiation from the actuators is negligible compared to the radiation from the vibrating structure, the difference between the radiated sound fields with the actuators mounted on the interior or exterior of the vehicle structure is minimal. Control of the actuators and data acquisition are both performed by a compact data acquisition system (National Instruments cDAQ-9178), and the measurements are performed using a sample rate of 25600 samples per second.

In order to investigate how effectively different panels on the vehicle can be driven to generate a directional sound field, the actuator array is installed and tested on a number of different parts of the vehicle. Figure 3 displays the four different configurations that are considered in this study as potential practically realisable options. Specifically, the array is placed on the hood, the front door, and the front bumper of the vehicle. The spacing between actuators in each case is chosen to ensure the maximum overall array length given the available surface. This is due to previous findings[25] indicating that a larger panel, with actuators evenly distributed along its length, can achieve the highest overall contrast. As the hood offers the largest area available for actuator placement, two configurations are tested: one in a broadside arrangement, with the actuators distributed along the width of the vehicle, as shown in Fig. 3 A, and one in an end-fire arrangement, shown in Fig. 3 B, with the distribution of the actuators along its length. The spacing between actuators is 15.6 cm for the broadside, and 13.9 cm for the end-fire case. The door configuration uses only four actuators spaced at 17.8 cm, as shown in Fig. 3 C, due to limitations on their possible placement imposed by the curvature of the structure. Lastly, a six actuator array is installed along the front bumper of the car, with a 13.7 cm interval between actuators and a 68.5 cm overall length, as shown in Fig. 3 D.

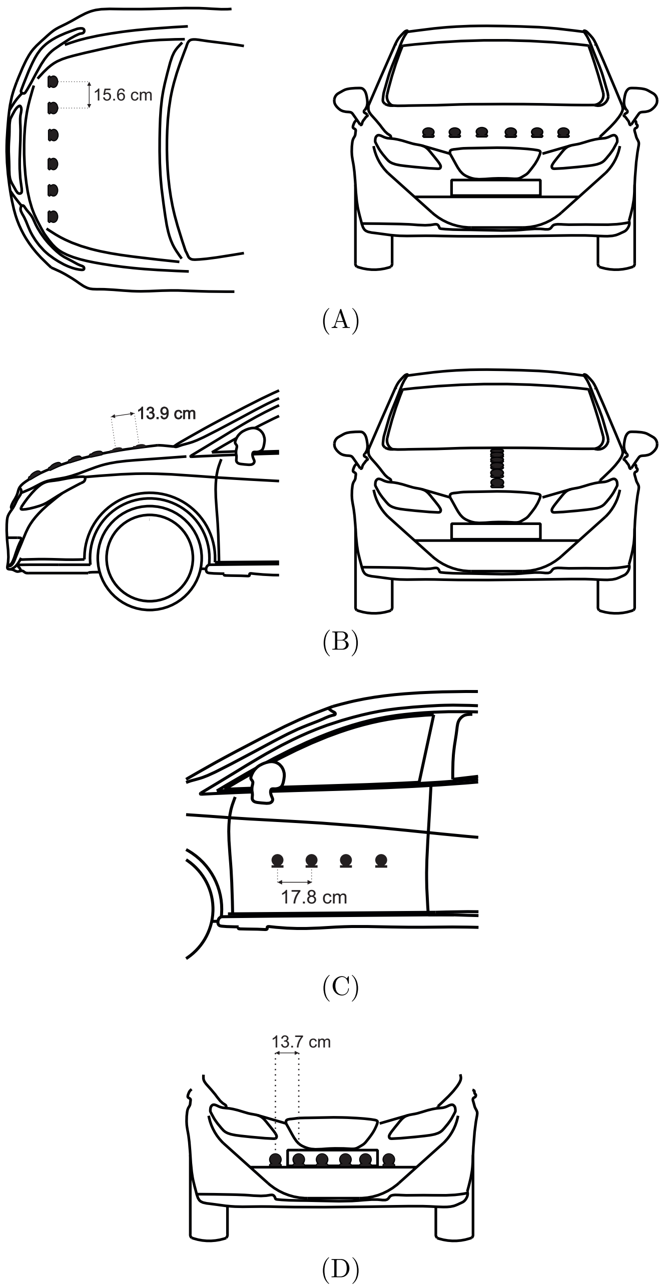


FIG. 3. Schematics of the different array configurations tested on the vehicle, with the array attached to the hood of the vehicle in broad-side configuration (A), in an end-fire configuration (B), on the front door (C) and on the front bumper (D).

B. Control strategy implementation

The directivity of the sound field resulting from the vibration of the vehicle structure is controlled by adjusting the relative phase and amplitude between the actuators of the array, two properties that are contained in the complex input vector, $\boldsymbol{u}$, introduced in Section II B. In practice, this can be achieved by filtering the base signal of the warning sound to be emitted through appropriate filters, and driving the actuator array with the filtered signals. Figure 4 presents the process of controlling the directivity of the array and measuring the resulting sound field in a four-step flowchart:

1. Each actuator in the array of I elements is driven with a test signal, such as broadband noise or a sine sweep. The resulting radiated sound pressure is measured by the sensor array, which is formed by M microphones.

2. The acoustic contrast maximization process is implemented in the next stage. The recorded data is used to calculate the matrices of transfer responses corresponding to the bright and dark zones, $\boldsymbol{G}_B$ and $\boldsymbol{G}_D$. These matrices must be calculated for the N frequency bins used in the analysis. Then, the optimal source strength vector for each actuator, $\boldsymbol{u}$, is obtained at each frequency according to Eq. (5). The regularization factor, λ_2, is chosen accordingly to ensure a relatively smooth frequency response, avoiding spikes in excess of 5 dB in acoustic contrast level to ensure robust performance.

3. These optimal source strength frequency responses are then used to calculate a set of I FIR filters that match the frequency responses of $\boldsymbol{u}$. However, in order to do this,

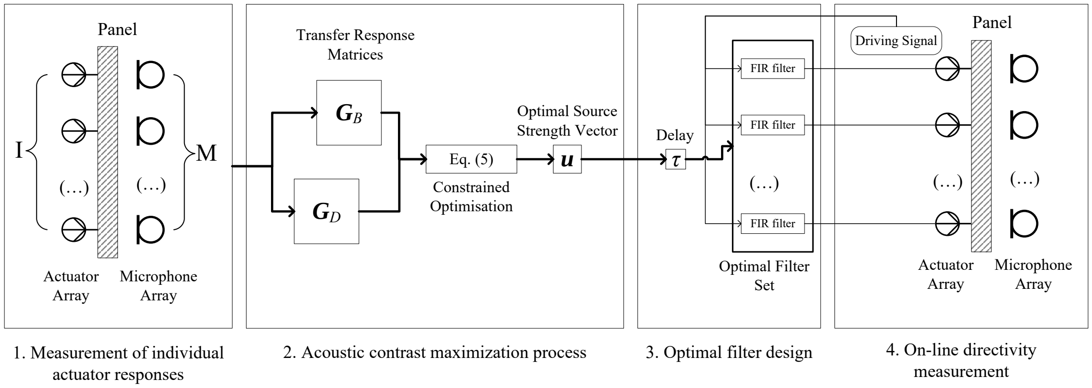


FIG. 4. Flowchart of the directivity control strategy.

a time delay, τ, needs to be introduced to the optimal source strengths in order to produce a realizable causal filter. In the frequency domain, this can be expressed as $\boldsymbol{u}\mathrm{e}^{-i2\pi f\tau}$, where f denotes the frequency. As warning sounds tend to be continuous signals, this delay does not have a significant impact on the effectiveness of the system. Considering the sample rate of 25600 samples per second, a filter order of 1024 taps and a delay of 512 samples have been assigned to realize the filters used in all presented measurements.

4. A directional sound field that focuses on the assigned bright zone and minimizes the pressure in the dark zone can be produced by filtering a base signal, which would be the desired warning sound signal, through the optimal filter set, before using it to drive the actuator array.

Utilizing this method, a real-time implementation would require a number of pre-defined filter sets to be stored, each corresponding to a specific steering angle, that could be implemented in order to control the direction to which the beamformer is focused.

For the measurement set-up used in this investigation, there are twenty microphones forming the sensor array. The narrowest definable control zone with a central measuring point, and of non-zero angular width, can be defined by three of these microphones. The interval between neighbouring microphones is 18°, meaning that this bright zone has an angular width of 36°. The remaining microphones form the corresponding dark zone. Figure 5 shows the bright and dark zones used in the measurements presented in this paper. Three steering angle settings, centred at the forward direction and at angles of 36° and 72° to the side sufficiently cover the areas in which the warning sound system may need to focus in order to target a vulnerable road user, excluding the condition under which the vehicle is reversing.

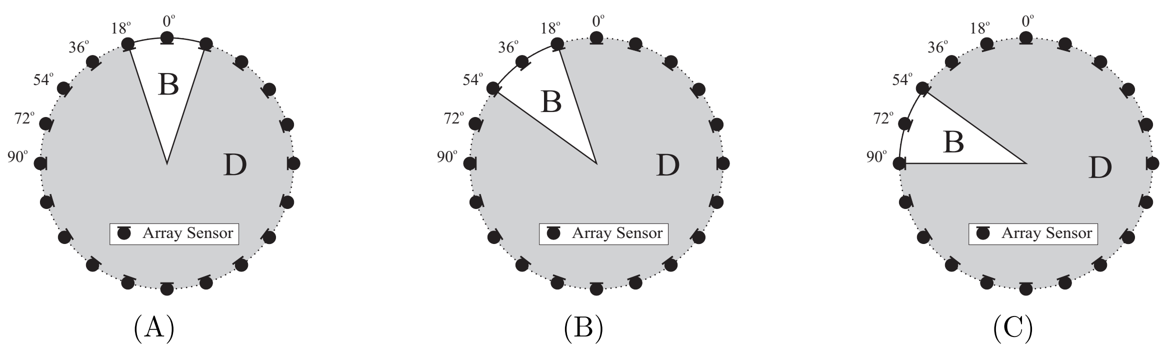


FIG. 5. Bright zones defined in the measurement set-up for different steering angles, centred forward in (A), steered by 36° in (B) and steered by 72° in (C).

IV. RESULTS

This section will present and comment on the results of the experimental investigation of the actuator-based directional sound generation system. The different configurations are evaluated in terms of directivity performance in conjunction with their efficiency and leakage of noise into the vehicle cabin, through measurements of the resulting sound pressure levels (SPL) inside and outside of the vehicle. In all measurements, the investigated frequency range over which the system will be evaluated is between 100 Hz and 5 kHz. This was chosen to cover the bandwidth used by current warning sounds as well as the guidelines on the frequency components of warning sounds set by world-wide regulations[5,6]. The array was also driven to achieve an overall on-axis SPL of around 50 dB(A), with consideration of the SPL requirements in these regulations.

A. Investigation of different array configurations

By measuring the response from each individual actuator in each of the tested configurations, the information necessary to construct the corresponding transfer response matrices is obtained, as per the process presented in Sec. III B. Using this data, the acoustic contrast performance can be estimated off-line for arrays consisting of different actuator configurations, by choosing the appropriate matrices, $\boldsymbol{G}_B$ and $\boldsymbol{G}_D$, to solve Eq. (5) and then using the resulting optimal source strength vector to evaluate the acoustic contrast as defined by Eq. (2). This allows for an off-line investigation into the effect that different numbers of actuators in each configuration have on the performance of the system. Figure 6 shows the estimated acoustic contrast, frequency averaged between 100 Hz and 5 kHz, for different numbers of actuators in each array configuration and for the three different steering angle settings. A trend apparent across all cases is that a higher number of actuators in a configuration provides a higher acoustic contrast, as expected from an understanding of the design of loudspeaker arrays, but also from the previous work on actuator-based arrays[25].

For the forward-steered setting, shown in Fig. 6 A, the bumper configuration is consistently the most effective out of the four configurations considered here, and it is capable of an average contrast above 10 dB when using four or more actuators. Due to the orientation of the bumper, the natural directivity of the bumper array is in the forward direction, leading to a higher acoustic contrast when compared to other configurations utilizing the same number of actuators. There is little difference between using a broadside or end-fire configuration on the hood, with the 10 dB mark only being approached when using all six actuators. The door configuration requires at least four actuators to achieve a positive value of acoustic contrast. This is due to the natural directivity of this configuration being towards the side of the vehicle, meaning that an array of multiple sources is necessary to generate a forward directed sound field. At a steering angle of 36°, as shown in Fig. 6 B, there is less difference between the performance of the four configurations when they are using the same number of actuators. However, the most effective configuration differs slightly depending on the number of actuators used. The highest level of contrast is achieved by the bumper configuration with 6 actuators.

For the highest considered steering angle of 72°, the door configuration becomes the most effective at achieving the desired directional control, as the bright zone in this instance is similar to the natural directivity of the array. Specifically, the system achieves a level of broadband averaged contrast over 10 dB, which is in excess of 5 dB greater than achieved by any other investigated configuration using three or four actuators for this steering angle.

Conversely to the door-mounted array, this increased steering angle is further from the natural directivity of the remaining configurations, meaning that a higher number of actuators is required to match the level of acoustic contrast. The bumper and both hood configurations all manage to reach a broadband averaged contrast of 10 dB when utilizing six actuators.

Considering that the bumper-based array achieves the highest contrast when it is steered in the forward direction and at low steering angles, and the door configuration achieves the highest performance at high angles, a system incorporating actuators on both doors and the bumper would potentially be capable of the highest overall directivity control. However, based on the off-line results, at least four actuators would be required on the bumper to achieve an average contrast of over 10 dB in the forward direction (Fig. 6 A), and three or four actuators would be required per door to yield a relative improvement in performance (Fig. 6 C) at higher steering angles. Such a configuration would employ ten or twelve actuators in total, and would be ultimately outperformed by a six actuator bumper array, which is capable of higher contrast in the forward direction, and similar levels at higher angles. Moreover, the cost of implementing more distributed systems with higher numbers of actuators is unlikely to be acceptable for the automotive application.

Overall, it has been shown that the most efficient configuration, when taking into account the number of actuators used, has the array placed on the front bumper of the vehicle. Although the hood has enough area to accommodate larger arrays, its orientation in relation to the vehicle's plane of movement makes it unsuitable when attempting to generate the desired directional field. In the case of the door, there is neither sufficient space for a large

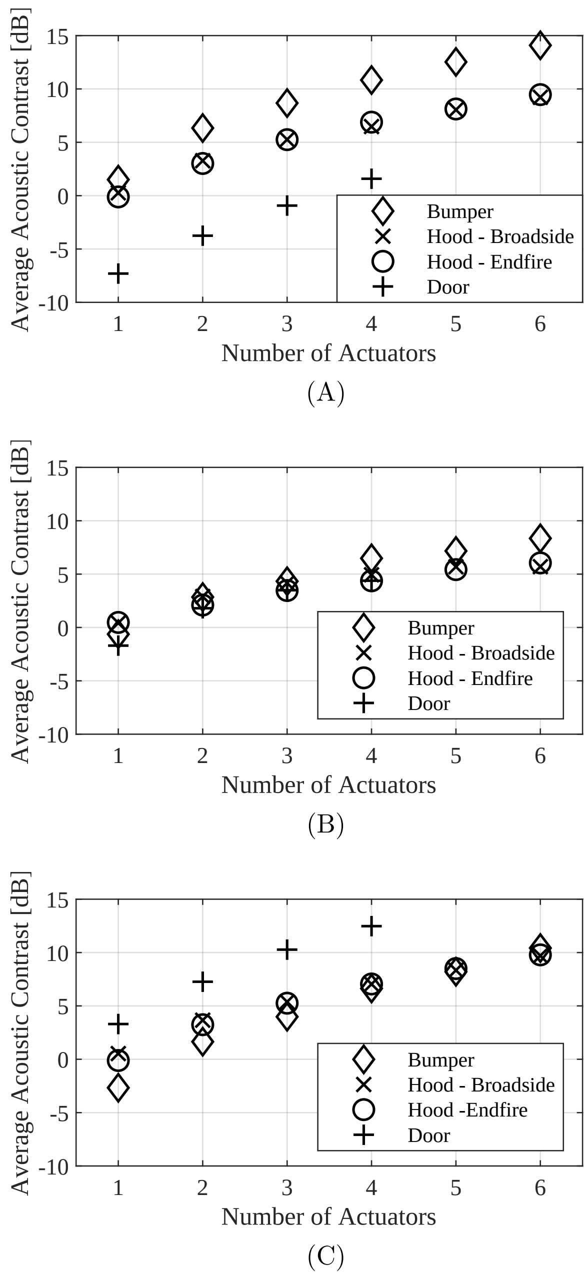


FIG. 6. Frequency averaged acoustic contrast between 100 Hz and 5 kHz, as estimated for different array configurations at forward (A), 36° (B) and 72° (C) steering angle settings.

array, nor is the orientation appropriate for a forward aimed sound field, which is expected to be the most commonly required steering angle.

B. Sound leakage into the vehicle interior

Another factor that is key to evaluating the suitability of the proposed system for practical implementation, and can be readily investigated in this study, is the separation between the resulting external and internal sound fields. The system is intended to convey a warning sound to vulnerable road users in the path of the vehicle, but it should not be intrusive to the driver and passengers. Therefore, it is important to ensure that the sound radiated from the rear of the structural actuator array into the car cabin is sufficiently attenuated by the construction of the vehicle. If this is not the case, then it may be necessary to modify the construction of the vehicle to provide higher levels of attenuation or utilize more complex array designs that minimize the sound radiated from the rear of the panel. However, both of these measures will clearly increase the cost of implementation and, therefore, the appeal of the proposed system.

Figure 7 provides insight into the sound leakage into the vehicle cabin in the form of the attenuation achieved across frequency for the different configurations, when they are all steered towards the forward direction. The level of attenuation across frequency is defined in this instance as the difference in level between the SPL in each frequency bin measured by a microphone placed at the driver's car seat headrest and the SPL measured at a microphone placed 5 m in front of the vehicle, defining the centre of the bright zone. Furthermore, the calculated attenuation has been scaled using octave bands to provide a convenience of comparison, as the frequency response would normally be characterised by peaks and notches that may be caused by ground reflection and car-body diffraction effects. It is evident that

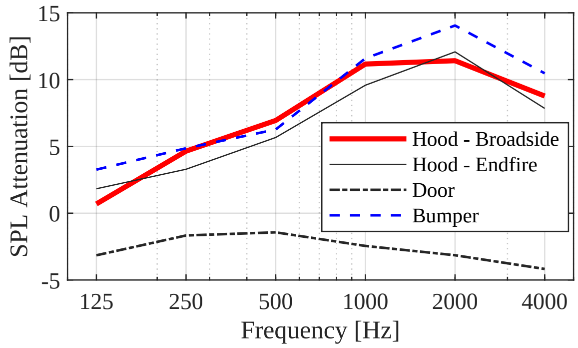


FIG. 7. Attenuation expressed as the difference between the SPL measured at the position of the driver's car seat headrest in the cabin of the vehicle, and at an external point 5 m in front of the vehicle, for arrays on the hood in broadside and endfire configurations, on the door, and on the bumper. In all cases the array has been driven for a forward-facing bright zone.

the bumper configuration displays the highest level of attenuation between the externally and internally generated sound pressures. This is probably due to the presence of the engine compartment between the array and the cabin and the significant levels of attenuation that this provides. For both hood configurations, the attenuation achieved approaches a level of around 10 dB at frequencies above 1 kHz, however, it is significantly lower at lower frequencies. The results obtained for the door configuration indicate that the placement of the array on the door results in similar sound levels at the target exterior position and in the interior of the vehicle. The lack of attenuation between the door panel vibration and the interior sound field is perhaps not surprising, given the lightweight nature of modern vehicles and the low levels of noise transmission loss typically required through the door panel.

C. On-line directivity measurements using the bumper configuration

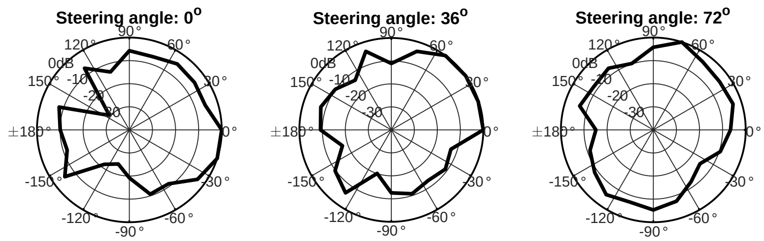
The investigation into different practical array configurations presented in Sec. IV A shows that the most effective arrangement in terms of performance and practical application would be the bumper-based configuration. The performance of this system has thus been investigated further by implementing the control strategy defined in Sec. III B to drive the actuators in real-time and produce a measurable directional sound field. A photograph of the bumper system installed on the vehicle is shown in Fig. 8. The resulting directional performance is presented in Fig. 9, where the measured SPL, averaged at four different frequency bands, is presented as a function of angle for the three investigated steering settings. From these plots it can be seen that the sound field is effectively focused on the central angle of the corresponding bright zone for each setting; however, the directivity performance is dependent on the steering angle as well as the frequency emitted. The highest directivity is achieved within the 1 to 2 kHz range, for a forward directed bright zone. Aliasing effects can be observed, particularly within the 1-2 kHz bandwidth when the array is steered to 72°, where a grating lobe is generated at around the complementary angle of 18°. Nevertheless, it should be noted that the effect of aliasing is generally reduced in the structural actuator-based array, due to the effective interpolation between the sources as previously noted in[25], and therefore the grating lobes are less intense or focussed compared to a loudspeaker-based array.

In order to obtain a more in-depth view of the performance of the system, it is useful to examine the directivity as a function of frequency. Figure 10 shows the acoustic contrast frequency response of the six actuator bumper array for a forward steered setting, as estimated

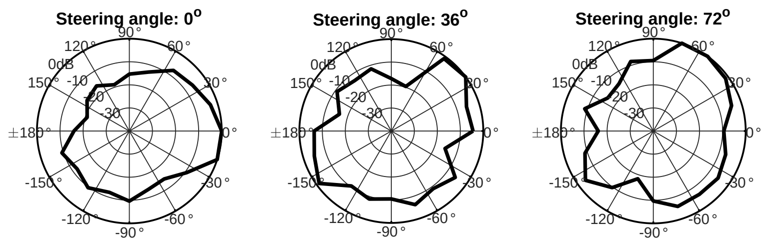
FIG. 8. Six-actuator array attached to the front bumper of the vehicle.

off-line using the measured responses of the individual actuators, and as calculated using the measured sound pressure when the array is driven in real-time. From these results it can be seen that the real-time system matches the off-line prediction, except for frequencies below 200 Hz, where the performance of the actuators is limited.

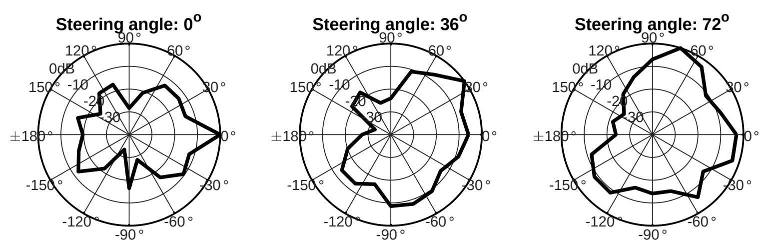
The array effort across frequency for the bumper configuration is shown in Fig. 11. These values have been calculated using Eq. (3) with a reference signal, u_m, corresponding to the signal required for a single loudspeaker driver to produce the same mean square pressure in the forward bright zone. The single loudspeaker driver is used as the reference, since this is the configuration currently used in most warning sound systems. The calculated array effort shown in Fig. 11 in this instance offers a view of the power required to drive the array compared to a single loudspeaker. As previously mentioned, the array has been optimised to generate an A-weighted overall SPL of 50 dB, and levels in the specific third-octave bands in line with the standards set by[6]. The level of effort is highest at frequencies below 200 Hz, which is consistent with the characteristic of loudspeaker arrays[20,29]. In the region between



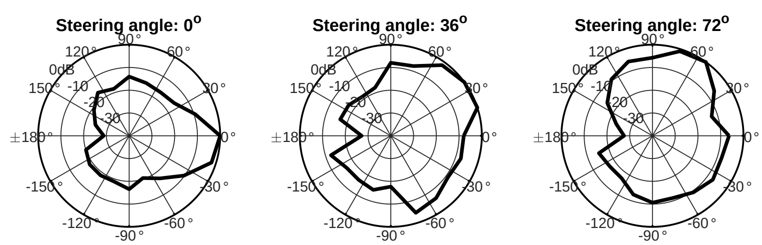
(A) 250 Hz - 500 Hz



(B) 500 Hz - 1 kHz



(C) 1 kHz - 2 kHz



(D) 2 kHz - 4 kHz

FIG. 9. Directivity patterns for the array steered towards the forward direction and at angles of 36° and 72°, from measurements using the six-actuator bumper configuration. The normalized SPL displayed has been frequency averaged between: 250 Hz and 500 Hz (A), 500 Hz and 1 kHz (B), 1 kHz and 2 kHz (C), 2 kHz and 4 kHz (D).

200 Hz and roughly 1.5 kHz, the response maintains a level above 0 dB, and displays an increasing trend, but is below 5 dB. The array is shown to be most efficient at frequencies of 1.5 kHz and above, as the effort level drops to values around 0 dB for the remainder of the investigated frequency range. It can thus be concluded that the required array effort is not significantly greater than that required for a single loudspeaker and in fact the individual actuator driving signals are well within the capabilities of the low-cost actuators used in the array.

The acoustic contrast across the investigated frequency range for different steering angles is presented in Fig. 12 for the six-actuator bumper array. Excluding the low frequency region up to 200 Hz, these results demonstrate that the system is capable of high directivity performance for different steering angles. Particularly within the 1 kHz to 2 kHz region, the acoustic contrast is calculated to be greater than 15 dB, although it drops to 10 dB when steered at a high angle. This is consistent with the off-line simulations presented in Sec. IV A. The average contrast achieved within the 200 Hz to 5 kHz bandwidth is consistently above 10 dB, which is comparable to the performance of loudspeaker-based systems[17].

This bandwidth sufficiently covers the frequency requirements set by regulations[5,6], with the exception of the 160 Hz and 200 Hz one-third octave bands allowed by ECE[6], within which the system is not sufficiently directional. However, these low frequency bands are generally not opted for in the design of warning sounds, as documented AVAS-compliant sounds in current use[30] do not typically contain frequency components below the 315 Hz third-octave band. Therefore, the bandwidth offered by the actuator array can be consid-

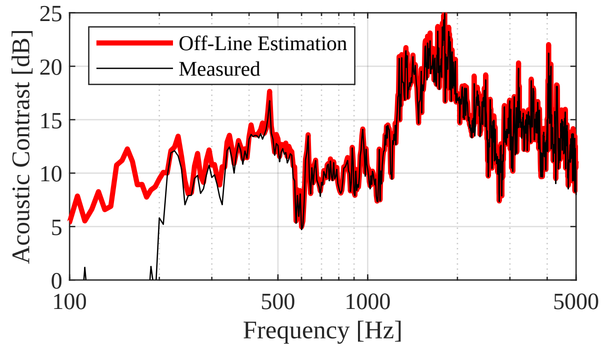


FIG. 10. Acoustic contrast frequency response for the actuator array attached to the front bumper of the vehicle. Displayed in red is the optimal frequency domain result, calculated off-line using the estimated transfer matrices, and in black the directly measured response produced by driving the array using the designed FIR filters.

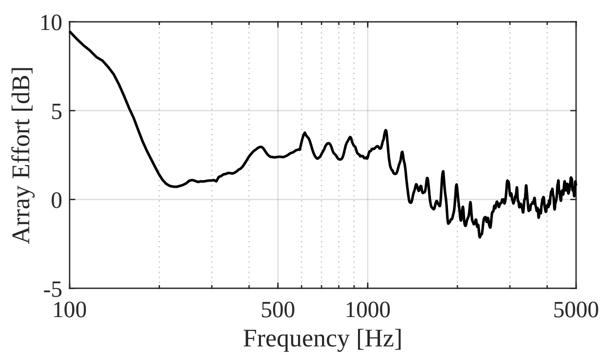


FIG. 11. Array effort frequency response for the actuator array attached to the front bumper of the vehicle. The array effort has been calculated with respect to the effort required for a single loudspeaker driver to produce the same mean square pressure in the forward bright zone.

ered sufficient to accommodate the components of an AVAS sound, including the shifts in frequency that are used to simulate acceleration of the vehicle.

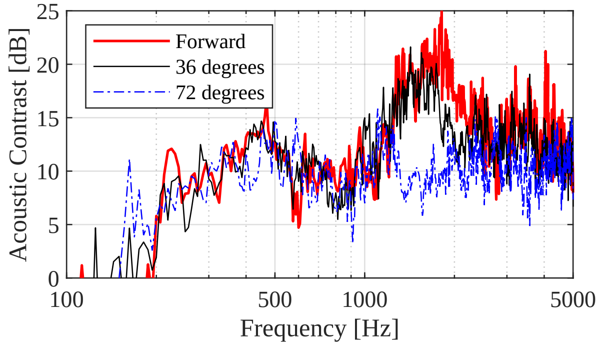


FIG. 12. Measured acoustic contrast frequency response achieved by the six-actuator bumper configuration, for bright zone centred forward and at angles of 36° and 72°.

V. CONCLUSIONS

This paper presented the concept and experimental evaluation of a directional warning sound system for EVs and HEVs, based on controlling the structural vibration of the vehicle body. The system comprises of an array of inertial actuators, attached to an existing panel on the vehicle. By controlling the vibration of the panel using the actuator array, it is possible to generate a directional sound field, which can be steered towards the potential location of vulnerable road users, maximizing effectiveness while lowering unnecessary noise emissions to the environment. The proposed system was physically evaluated by installing the actuator array in a test vehicle and performing measurements in a semi-anechoic environment. Control over its directivity was achieved through the implementation of filter sets corresponding to different steering angles, constructed using the acoustic contrast maximization process.

Different arrangements of the actuator arrays on the vehicle were tested to obtain information on the most efficient placement for such a system. Apart from the directivity performance across the investigated frequency spectrum, the sound leakage from the array into the vehicle cabin was considered to determine the suitability of the system. A six-actuator array, positioned on the front bumper, was shown to hold the overall best performance out of the configurations tested. Measurements of the real-time performance of the bumper array showed that the system can be successfully controlled to focus its radiated sound field towards the defined bright zones, maintaining an acoustic contrast level of over 10 dB throughout the 200 Hz to 5 kHz frequency range.

Overall, it has been shown that the proposed system can offer an efficient and realizable solution to the problem of conveying auditory warning while at the same time minimizing environmental noise emissions. Provided that in-depth information on the components of a vehicle would be available during its development, such a system could be further optimized in a simulation environment in terms of its array distribution and characteristics, to achieve even higher performance. Future work on the development and evaluation of the proposed system could consider the effects on performance and beamforming capabilities that different environmental conditions might have. Such examples include changes in temperature, humidity, and general prolonged use.

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