DESIGN AND IMPLEMENTATION OF A DIRECTIVE SOUND FIELD FOR AN ELECTRIC CAR WARNING SOUND

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1 INTRODUCTION

Increasing demand from both consumers and legislators for more fuel-efficient vehicles has increased the production of both hybrid and electric vehicles[1]. When driving in electric mode at speeds below around 20 mph, where road-tyre noise is limited, these vehicles are significantly quieter than the alternative internal combustion engine vehicles[2,3,4]. This is a significant benefit for environmental noise pollution in urban areas[5]; however, the noise emitted by internal combustion engine vehicles is also an important warning signal for pedestrians and cyclists to indicate that a vehicle is approaching[4,6,7,8]. Therefore, there is currently concern that the lack of noise emissions from electric vehicles may cause a safety risk for pedestrians and cyclists and consequently legislation is being introduced to ensure that hybrid and electric vehicles are audible[9,10,11].

Although there is some debate over the need for warning sounds for electric vehicles[5,12], legislation is being introduced and there has consequently been quite some interest in developing suitable sounds for this application[13,14,15]. Conversely, there has been limited published work on the directional characteristics of the reproduced sound field. By designing the sound field reproduced by the warning system, it may be possible to reach a compromise between providing sufficient audible queues to pedestrians and cyclists and avoiding unnecessary noise pollution. This has been suggested by a number of authors[3,16] and is discussed in the context of the Halosonic system produced by Lotus Engineering[17]. The Halosonic system employs two loudspeakers, one at the front and one at the rear for when the vehicle is reversing, and is shown to achieve significant reductions in the sound radiated to the sides and rear of the vehicle compared to an internal combustion engine. However, limited details of how this directional response is achieved are provided and, presumably, it is simply a result of the baffling provided by the vehicle.

This paper investigates methods of producing a directional sound field for the generation of exterior warning sounds for electric vehicles. Initially, the potential performance achievable using arrays of separate loudspeakers is investigated and although such methods could achieve the required performance, they come at significant cost and weight. Therefore, a low-cost alternative directional sound radiator is investigated, which uses a single loudspeaker unit coupled with a passive radiating unit. The design of this low-cost directional system is described and its directional performance is validated in an anechoic chamber. Subsequently, the prototype array is implemented on a vehicle to provide an indication of the effects of the vehicle on the directivity of the system.

2 DIRECTIVE SOUND FIELD SPECIFICATION

Specifying the sound field required for an electric vehicle warning sound is a complicated task that must consider the detection distance, the need to localise the vehicle and its direction of travel and the braking distance[6,7]. Although the ability to detect and localise the vehicle via its warning sound is also heavily dependent on the warning sound itself, this will not be considered here as it is a complicated task that has been covered in the literature. It will be assumed that the warning sound has been designed to allow suitable detection and localisation and we are essentially attempting to ensure that this warning sound is reproduced in the regions where detection and localisation of the vehicle are important. For a forward travelling vehicle it is important for the warning sound to be radiated to front of the vehicle and to a certain extent to its sides. Therefore, the design of the directional sound field reproduction system will attempt to maximise the sound radiated over an angle of 90 degrees to the front of the vehicle, termed the bright zone, whilst minimising the sound radiated elsewhere, termed the dark zone, as shown in Figure 1.

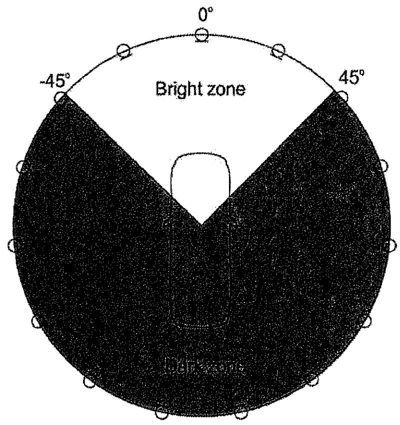

Figure 1 – The geometry and target directive sound field for the electric vehicle warning sound.

Although the design of a specific warning sound is not considered, it is important to define the frequency range over which the warning sound system will need to operate. It is generally acknowledged that low frequency warning sounds are of limited importance as they are difficult to localise[14] and the background noise in urban environments is currently dominated by low frequencies, which masks low frequency warning sounds and makes them difficult to detect[13,15]. Although higher frequency sounds are easier to localise and less likely to be masked by background noise pollution, they are generally subject to a higher level of attenuation over distance[14]. Based on these observations and the warning sound specifications of a number of authors[13,14,15,16] we have assumed a required operating frequency range of 300 Hz to 5 kHz.

3 DIRECTIVE SOUND FIELDS USING LOUDSPEAKER ARRAYS

Directive sound fields can be produced using a number of different methods such as parametric arrays, gradient-type loudspeakers, phase-shift loudspeakers and beamformers[18]. Although these different methods of producing a directional sound field have varying advantages and disadvantages, beamforming loudspeaker arrays are probably the most widely employed and there is a significant amount of literature available on this topic[19,20]. Loudspeaker arrays can be designed using classical approaches such as delay-and-sum beamforming[19], or have more recently been designed using optimal or superdirective beamforming methods[20,21]. These optimal beamforming methods allow a significant increase in the directivity of an array for a given number and spacing of loudspeakers[18,20] and, therefore, are of particular interest in the automotive application where the space for such an array and the cost of employing a large number of loudspeakers are both limited.

One method of optimising the signals used to drive loudspeaker arrays is the acoustic contrast maximisation method presented by Choi and Kim[21]. This method has been used in a wide variety of applications where sound reproduction is only required within a specific region. For the electric vehicle warning sound application shown in Figure 1, the acoustic contrast method aims to maximise the acoustic contrast between the bright and dark zones. The acoustic contrast is defined as the ratio of the sum of the modulus squared pressures in the bright zone to the sum of the modulus squared pressures in the dark zone.

To assess the potential performance of loudspeaker arrays for the generation of a directional sound field for the electric vehicle warning sound we will consider the broadside and end-fire array geometries illustrated in Figure 2 for the vehicle application. The performance of these two array geometries has been simulated by modelling the loudspeakers as monopole sources and assuming free-field radiation. A source separation of 3.5 cm has been assumed and the performance of arrays employing 2, 3, 5, and 10 sources has been calculated when the driving signals have been optimised using the acoustic contrast maximisation method. To provide a practical indication of the potential performance of these arrays the electrical power, or array effort, has been limited to 20 dB relative to the power required by a single source to produce the same on-axis pressure.

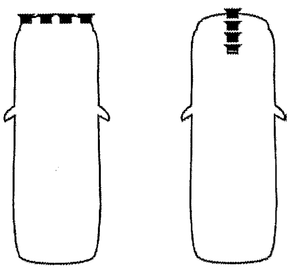

Figure 2 – The orientation and potential positioning of broadside and end-fire arrays in a vehicle application.

The acoustic contrast and array effort are presented in Figure 3 for the 2, 3, 5 and 10 source broadside arrays. From the acoustic contrast plot presented in Figure 3 it can be seen that increasing the number of sources, and consequently the length of the broadside array increases the low frequency performance limit. Using the 10 source array gives a maximum performance of around 4.5 dB over the required frequency range, but requires a 20 dB increase in the electrical power at low frequencies. The limited performance of the broadside array can be understood from the directivity plots presented for the 2, 3, 5 and 10 source arrays in Figure 4. From these plots it can be seen that due to the symmetry of the broadside array it radiates equally out of the front and rear and, consequently, struggles to achieve the required directivity performance shown in Figure 1. In a practical configuration this effect may be reduced by the baffling provided by the vehicle body, which would cause an increase in the directivity of the individual loudspeakers at frequencies where the wavelength is small compared to the dimensions of the effective baffle. The performance of broadside arrays with individual directional sources has been shown to offer an increase in performance[22].

Although the broadside loudspeaker array configuration is perhaps more straightforward to implement on a vehicle, due to the orientation of symmetry, the performance is rather limited. Therefore, the performance of 2, 3, 5 and 10 source end-fire arrays has been calculated and the acoustic contrast and array effort are presented in Figure 5. From the acoustic contrast plot it can be seen that the end-fire arrays offer a significant performance increase compared to the broadside configuration and the 2 source end-fire array largely outperforms the 10 source broadside array. Figure 6 shows the corresponding directivities for the 2, 3, 5 and 10 source end-fire arrays and from these plots it can be seen that this array orientation allows a directive sound field close to the target specified in Figure 1 to be achieved.

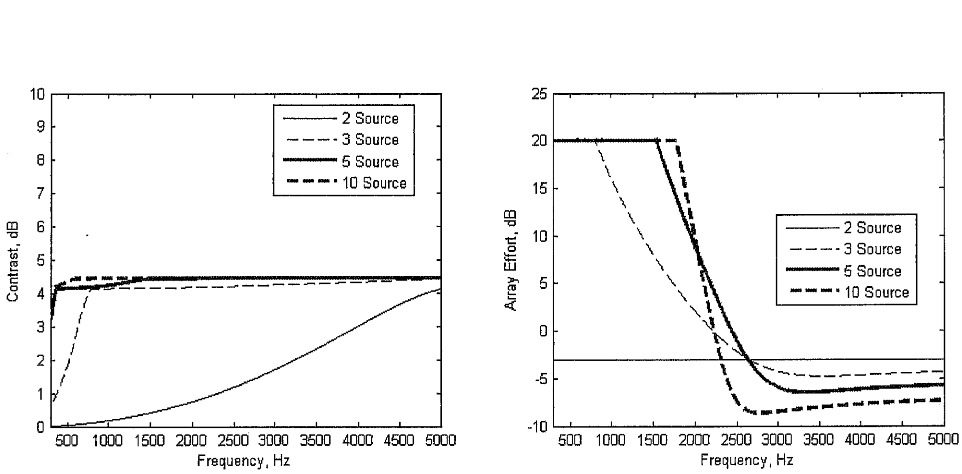

Figure 3 – Acoustic contrast and array effort for the 2, 3, 5 and 10 source broadside arrays

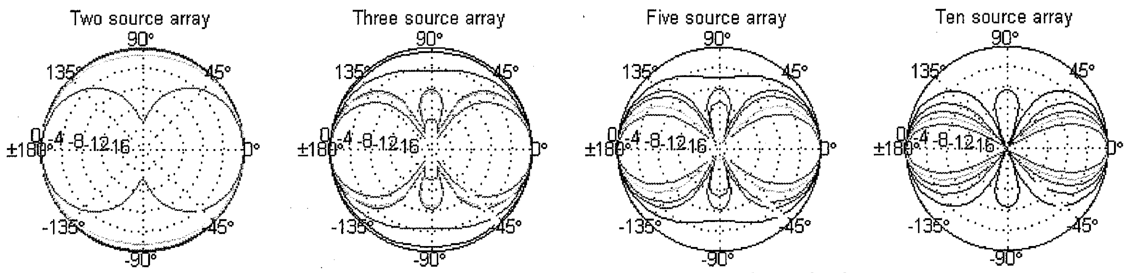

Figure 4 – Directivity of the 2, 3, 5 and 10 source broadside arrays

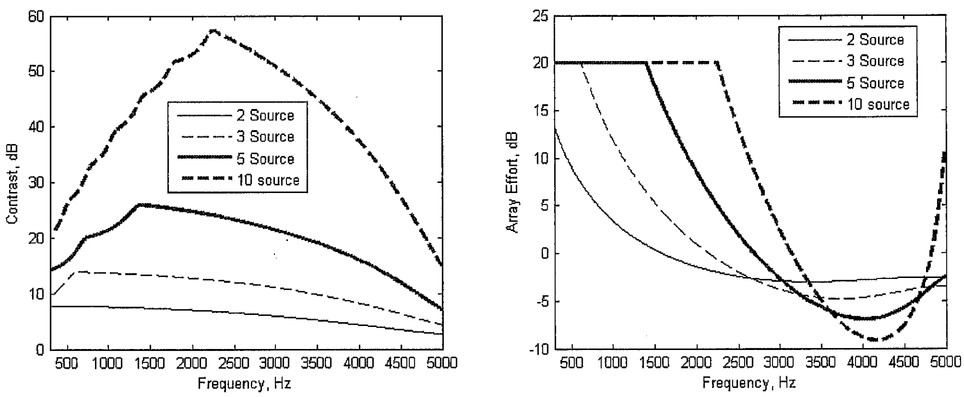

Figure 5 – Acoustic contrast and array effort for the 2, 3, 5 and 10 source end-fire arrays

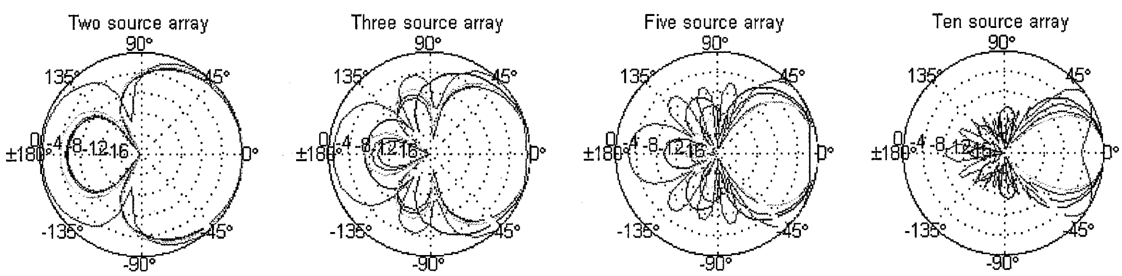

Figure 6 – Directivity of the 2, 3, 5 and 10 source end-fire arrays

4 A COST EFFECTIVE END-FIRE ARRAY SYSTEM

Although significant performance can be achieved from an end-fire loudspeaker array, the implementation of such a system in a vehicle comes at the expense of significant increases in cost and weight. It may also be difficult to package such a system within the standard vehicle due to space restrictions and it is unlikely that an automotive manufacturer will make many design modifications to incorporate such a system. Therefore, an alternative low-cost solution has been investigated based on the end-fire array system proposed by Holland and Fahy[23]. This system uses a single loudspeaker unit coupled to a pipe in which a line of holes is drilled. The individual holes act as sound sources and the sound radiated by each hole is delayed due to the propagation of the sound along the pipe. The delay between each hole is dependent on the separation between the holes and by varying the size, spacing and number of holes it is possible to tune the directivity, operating frequency range and sensitivity of the array[23]. If the holes in the array are equally spaced then an end-fire type directivity response is achieved.

4.1 Design and Implementation

The design of the end-fire array system must consider both performance and practicability. For the array to be implemented within a vehicle it is important that its dimensions are restricted and, therefore, a pipe length of 1 metre was selected to ensure that the array could be implemented within the space constraints of a vehicle. To avoid higher order propagating modes within the frequency range of interest (300 Hz – 5 kHz) the diameter of the pipe was specified as 40 mm. To limit reflections from the end of the pipe which were not considered within the design process, a wedge of glass-fibre was inserted into the end of the pipe, as shown in Figure 7. To allow the loudspeaker unit to be positioned remotely from the pipe system, and thus increase the ease of implementation, the loudspeaker unit and the pipe were connected via a piece of flexible tubing, as shown in Figure 7. Finally, a compression driver was used as the source as this provides efficient coupling to the pipe.

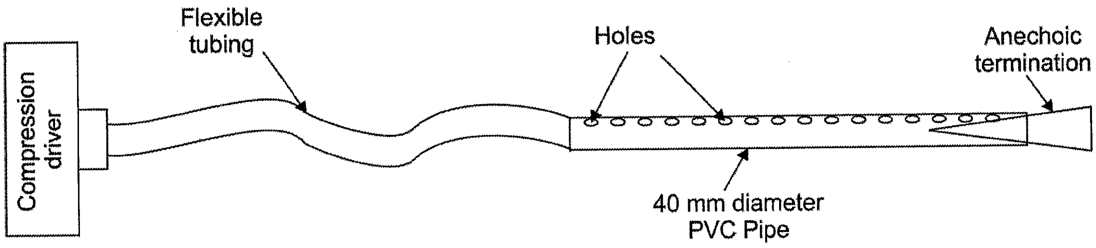

Figure 7 – Low-cost end-fire array system

To investigate the optimal hole size and spacing the system was first modelled as described by Holland and Fahy[23] using transmission line theory. This allowed a number of different system configurations to be investigated and a selection of twelve prototype systems were implemented and tested in the anechoic chamber at the ISVR[24]. These prototype systems investigated the effect of hole size and hole spacing on the performance of the system and based on this study a single pipe was selected. The final pipe design had 26 holes with a diameter of 8 mm spaced by 3.5 mm over the first 90 cm of the pipe.

4.2 System Performance

The directivity of the proposed system has first been measured in the large anechoic chamber at the ISVR and the resulting directivities, averaged over one third octave bands, are presented by the solid black lines in Figure 8. From these results it can be seen that in the first frequency band, centred at 390 Hz, the directivity of the array is quite omnidirectional and this can be related to the length of the pipe being limited. For the frequency band centred at 635 Hz the directivity of the array has increased and provides around 15 dB attenuation to the sound radiated to the rear. The directivity of the system continues to increase for the following two frequency bands, before showing a slight reduction in performance in the highest frequency band. This reduction in performance can be related to the generation of significant side lobes at high frequencies when the wavenumber multiplied by the hole spacing is greater than 2.5 [23]; for the implemented pipe this occurs at around 3.8 kHz. This could be increased to a higher frequency by reducing the hole spacing, but this has been shown to also decrease the low frequency performance of the array[24].

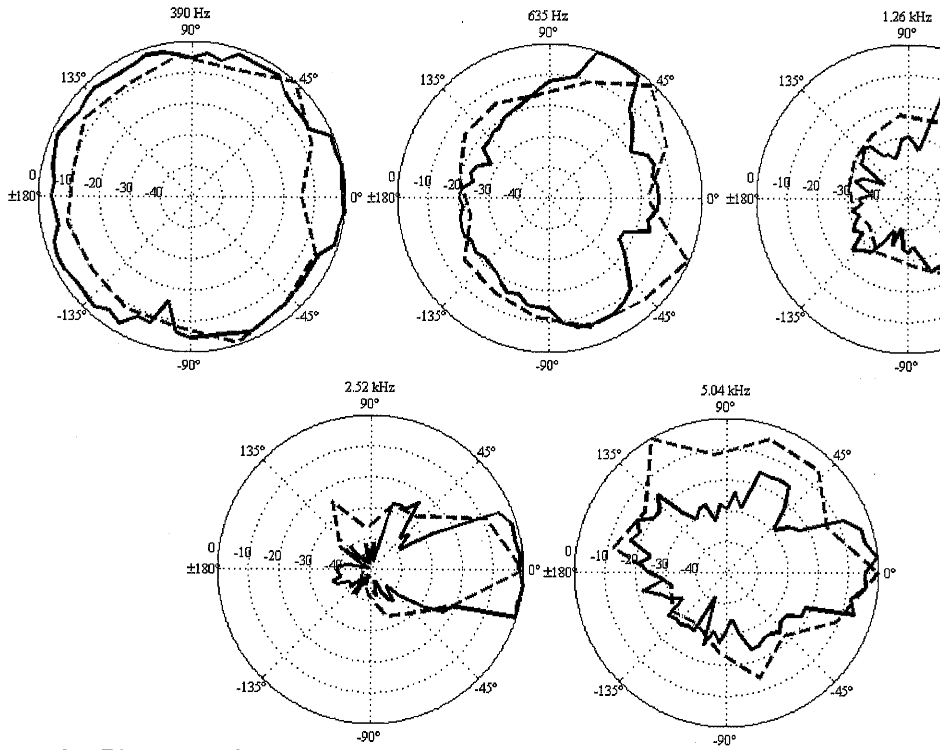

Figure 8 – Directivity of the low-cost end-fire radiator averaged over third-octave bands measured in the anechoic chamber (black solid lines) and positioned on the vehicle as shown in Figure 9 (blue dashed lines).

Although the performance of the proposed pipe array system has been validated in the anechoic chamber, it is also important to investigate the effect of positioning the array on a vehicle. The proposed array has been mounted to a vehicle as shown in Figure 9 and the resulting directivity responses are presented as the dashed blue lines in Figure 8. From these results it can be seen that for the first four frequency bands the presence of the vehicle has a limited effect on the performance of the system. However, the performance in the highest frequency band has been reduced. Although this effect could be related to the increased influence of the vehicle on the radiated sound field at higher frequencies, where the wavelength is smaller compared to the effective baffle provided by the vehicle, it is also perhaps a result of the low sound pressure levels radiated by the device in this frequency band and the resulting dominance of background noise.

Figure 9 – The low-cost end-fire radiator positioned on the test vehicle.

5 CONCLUSIONS

Electric and hybrid vehicles not only offer a potentially environmentally friendly mode of transport, but are also significantly quieter than internal combustion engine vehicles. This has significant benefits for noise pollution in the urban environment; however, the lack of noise emissions raises a potential issue of safety for pedestrians and cyclist. Therefore, in part due to legislation, there is a need for warning sounds for electric and hybrid vehicles. To limit the impact that this has on noise pollution there has been some interest in generating the warning sound using a directional sound source.

This paper has initially investigated the limitations on performance when using a conventional array of loudspeakers, optimised using the acoustic contrast method. It has been shown that, although the broadside array configuration may be more conveniently implemented within a vehicle, the end-fire array configuration provides a significantly higher level of performance. In both cases, however, the use of a number of loudspeakers and the associated amplifiers will pose a significant cost and weight to vehicle manufacturers and may be difficult to incorporate within the space limitations of a vehicle.

To overcome the limitations of conventional loudspeaker arrays a low-cost end-fire array alternative has been investigated which employs a single loudspeaker unit coupled to a pipe with a series of sound radiating holes. This system is significantly lower in cost and weight, and also benefits from the loudspeaker being able to be positioned quite freely. A number of prototype systems have been implemented to investigate the trade-offs in performance that must be met between directivity, bandwidth and sensitivity. Based on this study a system has been implemented and tested, first in an anechoic chamber and then on a vehicle. It has been shown that the performance of the array is limited at lower frequencies, but shows significant directivity performance at frequencies above around 600 Hz. The omnidirectional nature of this system at low frequencies may however be an advantage in terms of warning sound generation, since at low speeds, which are generally associated with low frequencies, it is generally necessary to provide a warning sound over a larger region of space. To confirm this observation, further work is needed to specify the required sound field for electric vehicle warning sounds.

6 ACKNOWLEDGEMENTS

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