Canadian Acoustics / Acoustique Canadienne 18(2) 25-31 (1990)

THREE DIMENSIONAL ACTIVE NOISE CANCELLATION USING SPHERICAL ARRAYS OF CARDIOID SOURCES

Nigel Maybee
56 Foreht Cres.
Aurora, Ontario
L4G 3E8

Lars Rogers
Box 214
Sointula, B.C.
V0N 3E0

ABSTRACT

Computer modelling is used to design a two element loudspeaker system ('tripole') capable of generating an accurate cardioid radiation pattern for frequencies below 500 Hz. The model is used to assess the effectiveness of various spherical arrays of such tripoles at cancelling a spherical sound field. One cancelling tripole array is built and found to behave in accordance with the model predictions.

SOMMAIRE

La modelisation par ordinateur est employe dans le concept d'un systeme (tripoles) a deux elements capabale de generer un profil cardioide precis de radiation pour des frequences inferieures a 500 Hz. Le modele est employe pour evaluer l'efficacite des etalages spheriques de telles tripoles afin de reduire le champs spheriques de sonorite. Un etalage tripoles d'annulation est construit et il est trouve que son comportement suit le modele de prediction.

Introduction

The potential for active noise cancellation (ANC) in the area of low frequency noise control has long been recognized (1). ANC is a logical complement to passive noise control methods which are highly effective in middle and high frequency ranges but require unacceptable material bulk to absorb low frequency sound.

Jessel (2) has developed an approach to ANC based on Huygen's principle, in which an array of secondary sound sources is used to generate a sound field which cancels the field of a primary source. The optimum radiation pattern of the individual secondary sources is related to the characteristics of the primary field. For the case of a spherical primary field, the appropriate radiation pattern for the secondary sources is a cardioid (3). A cardioid can be created by the superposition of suitable monopole and dipole fields. An approximate realization of a cardioid field has been achieved using two closely spaced loudspeakers, forming a so called 'tripole' radiator (4). In the present work, a computer program was used to model and study a physically realizable tripole radiator. Spherical arrays of such tripoles were then modelled and their effectiveness at cancelling a tone monopole primary source was evaluated. Finally, a test system with one primary and eight secondary sources was built and its performance compared with predictions from the model.

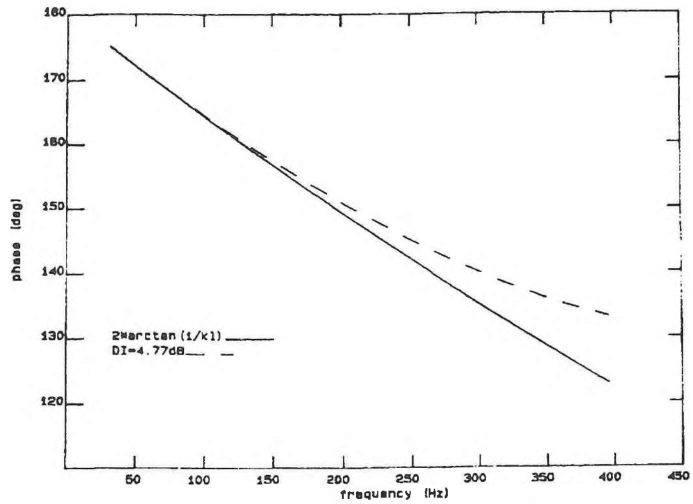

Figure 1. Tripole Phase angle

Computer Modelling Program

The computer model is based on the solution of the wave equation for spherically symmetric sinusoidal waves, and simulates the sound field generated by any collection of monotonic point sources in an inviscid freefield space. Input parameters include the position, frequency, acoustic pressure amplitude and phase of each source. The model calculates for these initial conditions, the amplitude and relative phase of the sound field at any point in space. Ancillary computer model programs calculate sound power (using 40 far field measurement points as per ANSI S1.35-1979), directivity index, and intensity of the generated sound fields. The output data are available in tabular or plot format, or as three dimensional colour contour pictures on a graphics workstation. All computer work was performed using a Syntronics "General Development Tool" (GDT) computer.

Modelled Cardioid Sources

A cardioid radiation pattern can be generated by the superposition of an acoustic monopole and dipole with the following source strength relationship

$$Qm = (i/2)\ k\ l\ Qd \qquad (1)$$

where Qm and Qd are the monopole and dipole source strengths, k is the wave number, and l is the dipole separation. The source strengths are 90 degrees out of phase and simply related by wavelength and dipole separation. The normalized directional factor, $H(\theta)$ for a cardioid pattern is given by

$$H(\theta) = 1/2\ (1 + \cos\theta) \qquad (2)$$

where θ is the polar angle. This radiation pattern has a directivity index of 4.77 dB.

A practical method to implement (1) for a tripole is to drive the two speakers at equal amplitude with a phase difference given by

$$\text{phase difference} = 2\ \text{ARCTAN}(2/kl) \qquad (3)$$

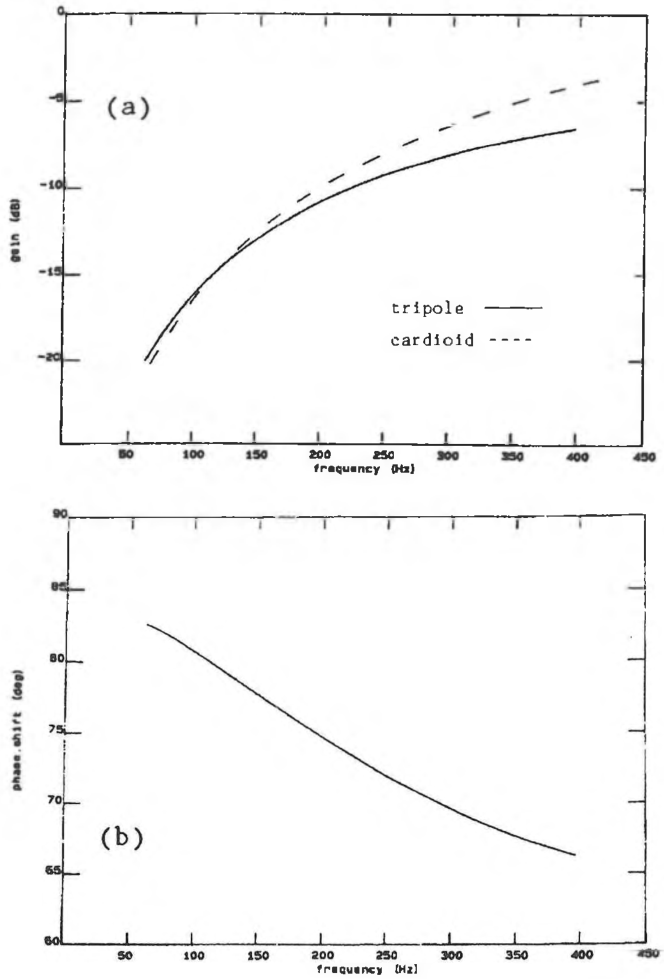

Figure 2. Tripole acoustic response (Model): (a) sound power gain, (b) farfield axial shift.

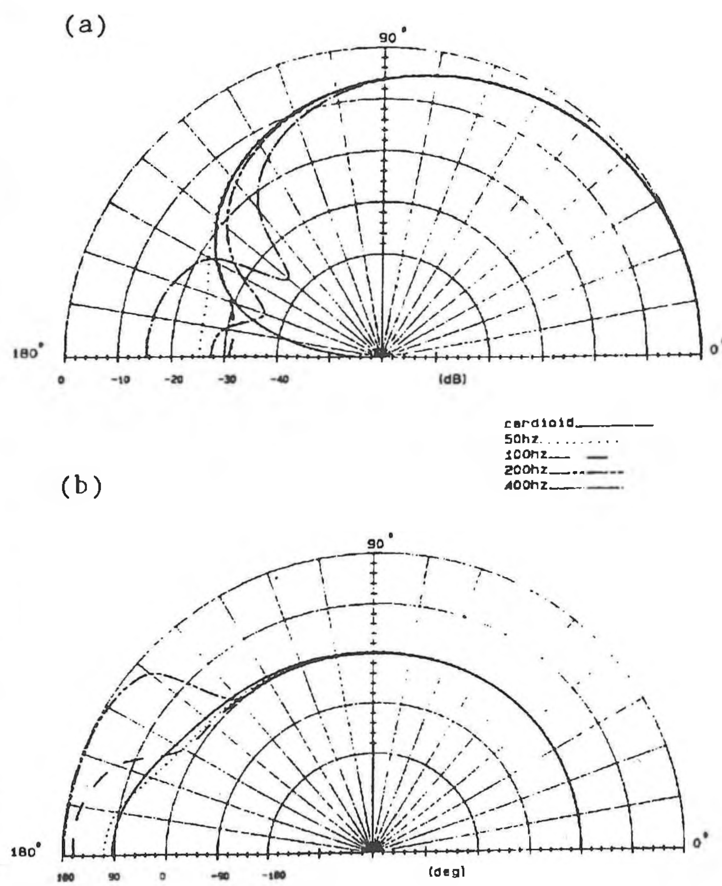

Figure 3. Farfield radiation patterns of tripoles (Model): (a) amplitude, (b) phase.

Computer simulations for a tripole of practical size (l = 0.15m) driven in this manner gave cardioid patterns only for frequencies below 100 Hz. Deviations from the 4.77 dB directivity index were found to increase with increasing frequency. The deviation was believed to arise from the separation distance l, which being non-negligible relative to wavelength at higher frequencies, resulted in distortion of the monopole and dipole field components.

To generate cardioid patterns at higher frequencies, a correction to (3) was determined using the computer model. The phase correction was chosen such that the directivity index of the field of the modelled tripole match that for a cardioid, i.e. 4.77 dB.

For frequencies above about 500 Hz a directivity index of 4.77 dB could not be obtained. The corrected phase relationship is shown in figure 1 and was used to drive both model and physical tripoles in all subsequent work.

The acoustic responses of the modelled tripole and ideal cardioid were determined relative to a monopole of equal sound power input (figure 2). The sound power amplitude of the tripole as compared to the cardioid is seen to diminish moderately with increasing frequency. Over the same frequency range, significant changes in the

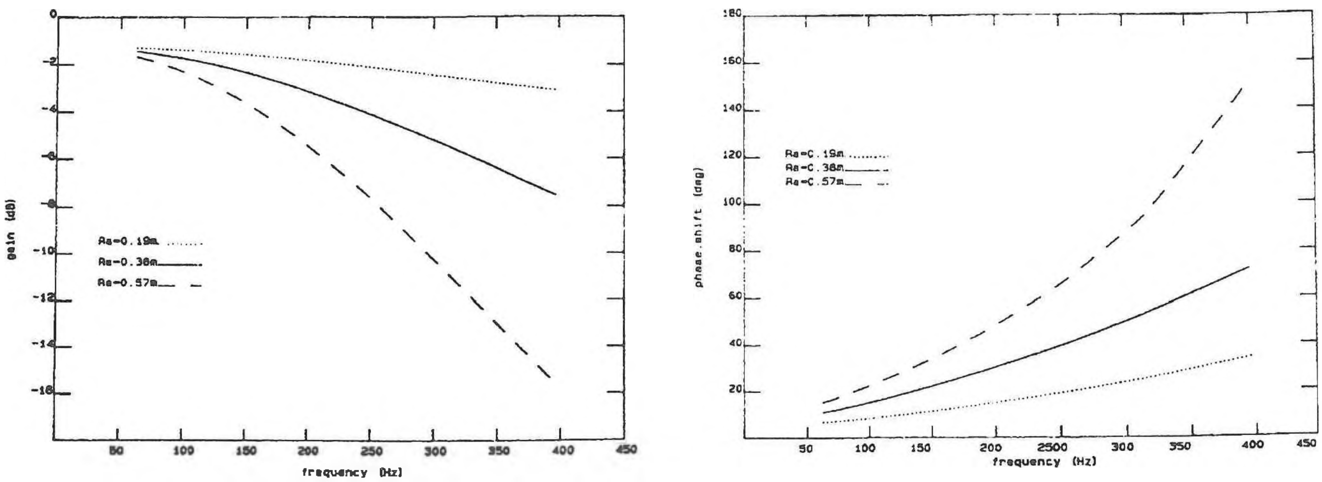

Figure 4. Tripole array response, N= 60 (Model): (a) sound power gain, (b) phase shift at cancellation point.

axial phase of the tripole sound field occur, reflecting the diminishing strength of the dipole component of the tripole relative to the monopole component, with increasing frequency.

The spatial distribution of amplitude and phase of computer modelled tripole sound fields were compared with the ideal cardioid radiation pattern in the frequency range of 50 Hz to 400 Hz. These fields are axisymmetric and are shown in figure 3. It is clear that quite good correlation with the cardioid pattern is achieved for frequencies up to 200 Hz over a polar angle of about 135 degrees. For frequencies up to 400 Hz the sound field in the 'forward' tripole hemisphere is cardioid.

Modelled Arrays of Tripoles

Twelve computer modelled tripole arrays were generated and their resulting sound field amplitude gains and phase shifts investigated. Each array consisted of N tripoles (N = 8,12,20,60) distributed on a spherical surface of radius R (R = 0.19m, 0.38m, 0.57m). The tripoles were located at the vertices of a cube, icosahedron, dodecahedron, and 'football' (a quasi-regular solid with 60 vertices). The amplitude gain was measured as the total sound power output of the array relative to the sum total sound power output of the individual tripoles. The results for the 60 tripole array type are given in figure 4a. For kR less than 2.1, identical results were obtained for all the other array types tested. The array phase shift was measured relative to the axial phase of the individual tripoles. Phase shift results for the 60 tripole array type are given in figure 4b. For kR less than 1.2, the phase shift results for the other tripole array types were identical to the N = 60 case shown. The amplitude gain and phase shift of the spherical tripole array is therefore found to be independent of N when the array radius is less than approximately 1/4 wavelength.

Modelled Active Cancellation of a Spherical Sound Field

The set of twelve tripole arrays described above were used to investigate active cancellation of a spherical sound field. An acoustic monopole was placed at the geometric centre of each tripole array. A cancellation point was selected ten

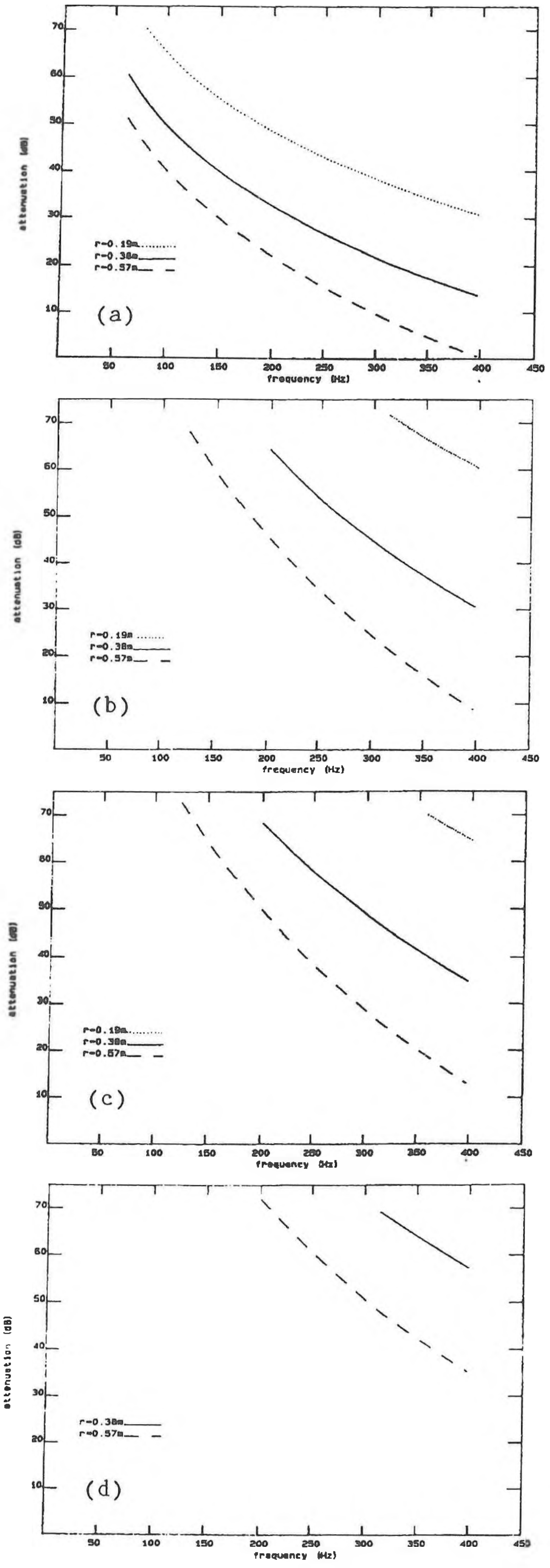

Figure 5. Sound power attenutation of a monopole by tripole arrays (Model): (a) cube, N=8, (b) icosahedron, N=12, (c) dodecahedron, N=20, (d) 'football', N=60.

metres from the monopole. At this point the monopole and tripole array sound fields were compared. Amplitude and relative phase adjustments were made so that the fields were exactly equal in amplitude and opposite in phase at the cancellation point. With the primary and cancelling fields superposed, sound power reductions were measured on a test sphere of radius 100 metres (figure 5). Sound power reductions due to cancellation were found to increase with increasing N and decreasing kR. For kR less than 1.2, reductions were greater than 70 dB for all array types and radii except for N = 8, where reductions for all radii increased from 35dB. The worst test case for each array type occurred for R = 0.57m and f = 400 Hz (kR = 4.2) where sound power reductions ranged from 0dB (N = 8) to 36dB (N = 60).

Recently Nelson, Curtis, Elliott and Bullmore [5] determined the maximum sound power reductions for a monopole field using secondary monopole sources for cancellation. They provided an example of a single cancelling monopole in close proximity to the primary source which gave considerably less attenuation than that for the cubic tripole array. A further example for a tetrahedral array of cancelling monopoles (four secondary sources) also gave less attenuation, however the results were more consistent with those for tripole array cancellation.

Experimental Cubic Cancelling Array

An experimental test system was built and the cancellation results compared to the predictions of the model. The lab system consisted of a cubic array of tripoles (N = 8) mounted on a spherical surface of radius 0.38m at whose centre was an acoustic monopole.

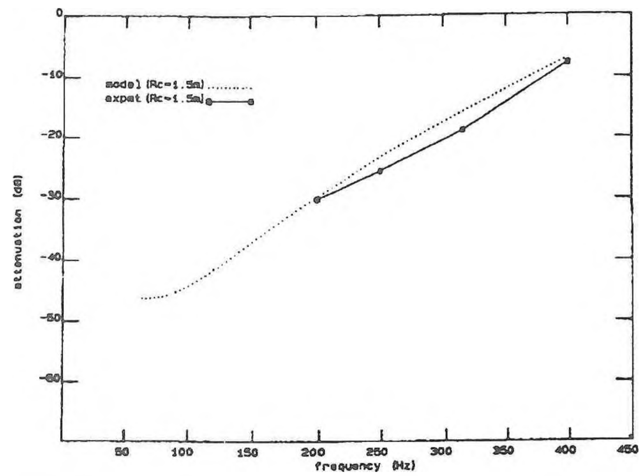

Figure 6. Experimental sound power attenuation of monopole by cubic tripole array.

The monopole unit was constructed of two 5 inch cone type loudspeakers mounted face to face and separated by a cylindrical spacer 0.035m long. The loudspeaker inputs were connected in phase so that a pulsating sphere was approximated when the unit was driven. Each tripole was made of two 5 inch loudspeakers mounted face to face, and separated by a cylinder 0.15m long which was partitioned in the middle to form a separate small cabinet for each speaker. The test system was driven by the GDT computer, one of whose array processors was programed as a multi-channel waveform generator capable of providing the necessary individual amplitude and phase control over the 17 audio signal channels used by the array. The array was tested in a hemi-anechoic room of dimensions 4.9m x 3.8m x 2.6m and cutoff frequency approximately 250 Hz. Sound fields were measured and analyzed with a B&K 4133 1/2 inch condenser microphone, B&K 2032 spectrum analyzer and the GDT computer. Cardioid radiation patterns for the tripoles were generated using the corrected relative phase difference between speakers discussed above. A cancellation point 1.5m from the centre of the monopole was selected and a test sphere of 2.0m was used to measure the sound power reduction of the cancelled monopole field. Tests were conducted using discrete tones at 200 Hz, 250 Hz, 315 Hz, and 400 Hz. The same cubic array, cancellation point and test sphere were run on the computer model. Good agreement between the experimental data and computer simulation were obtained (figure 6), the difference in no case being greater than 3dB.

Conclusion

A good degree of correlation between computer simulation and experiment for active cancellation of a spherical sound field by a tripole array was obtained. This suggests that computer modelling could provide a powerful and practical tool for further investigation in this area. A simple two loudspeaker tripole unit was found to be effective at generating the required cardioid radiation pattern, providing it was used below a critical frequency related to its physical dimensions. A strategy for driving the tripole speaker elements, based on directivity index measurements, has been found to be effective in generating an accurate cardioid radiation pattern. The acoustic response of a spherical array of tripoles was found to be essentially independent of the number of tripoles when the array radius was less than about 1/4 wavelength. Cancellation of a spherical sound field in such circumstances was very effective. It is suggested that the acoustic wavefront generated by the tripole array spatially modulates about a mean shape which is spherical, and the degree of overall cancellation is controlled by the variance of the spatial modulations. This emphasizes the importance of perfect reproduction of the primary sound field by the cancelling array. There are significant practical limitations to the use of tripole arrays for active noise cancellation. Tripoles are not efficient radiators at low frequencies where active cancellation is most effective. Consequently, high gains required at low frequencies to compensate for this inefficiency could result in difficulties avoiding significant distortion of the drivers. Also, it is clear that exact reproduction of the primary sound field is necessary to achieve the noise reduction potential offered by three dimensional active control methods. However, for all but the most simple noise sources, spatial duplication of the resultant sound fields by an array secondary sources would probably be difficult to achieve.

References

1) G.E.Warnaka, "Active Attenuation Of Noise - The State Of The Art", Noise Control Engineering, vol 18, no 3, 1982.

2) M.J.M.Jessel, "Secondary Sources And Their Energy Transfer", Acoustic Letters, vol 4, no 9, 1981.

3) G.A.Mangiante, "Active Sound Absorption", J.Acoust. Soc. Am., vol 61, no 6, 1977.

4) O.L.Angevine, "Active Acoustic Attenuation Of Electric Transformer Noise", Proceedings of Inter-Noise 81, 1981.

5) P. A. Nelson, A. R. D. Curtis, S. J. Elliot and A. J. Bullmore, "The Minimum Power Output Of Free Field Point Sources And The Active Control Of Sound", J. Sound & Vib., Vol. 116, No. 3, pp. 397-414, 1987.