Theory And Applications Of Electrically Tapered Electro-Acoustic Arrays

An outline is given of the basic theory of arrays of linear configuration. This leads to a discussion of methods for achieving constant beam width over the working frequency range. Techniques used in the design of arrays employing acoustic and electrical frequency tapering are presented and their characteristics compared. Examples of recent applications of electrically tapered arrays are given, with particular reference to those developed for the Sydney Opera House.

1. INTRODUCTION

An important task in the design of indoor sound systems is to control the ratio of direct to reverberant sound in the listening area. This ratio may be increased by using strategically placed high-level loudspeaker systems designed for directional propagation.

The use of electro-acoustic arrays (or sound columns) for sound distribution in public areas has become increasingly widespread over the last twenty to twenty-five years. The basic theory of such arrays was developed very early in this century in the literature on radio antennae and optics [1].

The essential difference between the usual requirements for electromagnetic and electro-acoustic arrays lies in the relatively wide operating frequency range of the latter type. The problems arising from this requirement form the main theme of this paper in which techniques used in the development of directional arrays for the Sydney Opera House are described.

2. BASIC PROPERTIES OF ELECTRO-ACOUSTIC ARRAYS

The physical embodiment of practical arrays may take on a variety of forms according to their intended purpose. This paper will be confined to a discussion of linear arrays (sound columns) consisting of a number of identical small direct-radiator loudspeaker units.

The directional characteristics of an array are usually described by a series of polar response diagrams (or patterns) taken at specific frequencies and distances. The two most common patterns in the case of sound columns (mounted vertically) are those taken in the vertical and horizontal planes. It is possible, using simplifying assumptions to calculate these patterns with useful practical accuracy for any specified arrangement of elements and driving signals.

The horizontal pattern is simply that due to the directional properties of the elements and is determined primarily by their effective diameter at any frequency.

The vertical pattern of an array of separate elements is found by calculating the vector sum of the components of sound pressure due to each of the elements at a succession of test points defined by their polar co-ordinates r, θ with reference to the centre of the array and its principal axis.

For a simple linear array of n point-source elements vibrating in phase and spaced at intervals d, the normalised polar response R_θ in the far field, where $r \gg nd$, is given [1, 2] by

$$R_\theta = \sin nx / n \sin x, \tag{1}$$

where

$$x = (\pi d/\lambda) \sin \theta.$$

When $d \to 0$ and $n \to \infty$, the array becomes a continuous aperture of length $l = nd$, then

$$R_\theta = \sin u / u, \tag{2}$$

where

$$u = (\pi l/\lambda) \sin \theta.$$

At low frequencies within the "piston range" of the elements, an array of contiguously mounted loudspeaker drivers behaves approximately as a continuous aperture.

When the operating frequency of an array is increased, the pattern (originally nearly circular at very low frequencies) becomes a progressively narrowing beam. A useful measure of beam width is the angle between the "half-power" points, i.e., where the response falls to -3 dB. This has been called "opening angle" (θ_{OA}) and is found by putting $R_\theta = 1/\sqrt{2}$ in eqns. (1) and (2). The solution of eqn. (2) for $R_\theta = 1/\sqrt{2}$ is u = 1.3915, and hence

$$\theta_{OA} = 2\theta_{-3} = 2 \arcsin (1.3915\, \lambda / \pi l) \qquad (3)$$

When θ_{-3} is small, (so that $\theta = \sin\theta$), this becomes

$$\theta_{OA} = 50.8\, \lambda / l, \text{(deg.)}. \qquad (4)$$

The solution of eqn. (1) for discrete arrays may be obtained by numerical iteration for various assumed values of n and d/λ. This has been done for a wide range of practical values and the results compared with calculations using eqn. (4) when l is replaced by nd. The differences are typically quite small and decrease rapidly with increasing values of n and d/λ.

3. DESIGN TECHNIQUES

The basic requirements for an electro-acoustic array are that it provide specific polar patterns which are independent of frequency in both the vertical and horizontal planes for optimum coverage of the audience and that it exhibit minimum extraneous radiation in the form of unwanted side lobes. Techniques for meeting these requirements will now be discussed.

Vertical Pattern. Eqn. (4) indicates that the opening angle will be independent of frequency provided the effective length of the array, measured in wavelengths, is constant. To achieve this, the physical length of the array is first determined by the lowest frequency of interest, f_L. Some form of filtering must then be applied to eliminate progressively the elements from one or both ends of the array as the frequency is increased. This is called frequency tapering and may be achieved by means of either acoustical or electrical filtering. In either case, the cutoff frequencies of the filters should be increased relative to f_L in the inverse ratio of the element spacing from the centre of the array.

Acoustical tapering [3] is normally applied by placing wedges or slabs of sound absorbing material, such as fibreglass, in front of the loudspeakers. Electrical tapering [3, 4, 5] is achieved by driving the loudspeakers through low-pass electrical filters. In both cases, the attenuation and phase lag of the sound pressure from the array elements are increased with frequency. Acoustical tapering was investigated for the Sydney Opera House project and finally rejected [6] in favour of electrical tapering. Among the reasons for this decision were that with electrical tapering, conversion efficiency is greater, voice-coil heating less and physical bulk much less. It was also found that the dependence of the beam shape and opening angle upon listening distance were much less with electrical tapering.

Considerable economy can be effected in the cost of an electrically tapered array if the filtering is done symmetrically from the centre, so that one filter serves at least two elements. Also, because the outer elements carry only the lower frequencies, their spacing may be increased without unduly increasing the magnitude of the side lobes. It is convenient to increase the element spacing in a geometric progression from the centre of the array and then find the value of the common ratio which gives the best compromise between side-lobe amplitude and number of elements. It was appreciated early in the design process that, with electrical tapering, it is possible to do this by trial and error with a computer model before a physical model is built.

Horizontal Pattern. Control of the horizontal pattern for a single linear array at high frequencies is determined entirely by the polar pattern of the individual elements. At low frequencies, the pattern will be very nearly omnidirectional if the column is constructed as a closed-box system. If, however, the rear face of the column is provided with a resistive leak so that the rear radiation undergoes both attenuation and phase shift relative to the front radiation, destructive interference occurs, resulting in a cardioid-like pattern having two partial nulls adjacent to a greatly reduced rear lobe. Techniques for rear radiation control range from use of a fully open back [7] to a longitudinal slot or a distributed port either with or without porous filling material. This method of pattern control is similar to the two-element array technique used for broadcast antennae and has recently been described for acoustic applications by Idling [8].

Frequency Equalisation. Because, in a frequency-tapered array, the number of elements which contribute to the sound pressure within the constant opening angle decreases with increase of frequency, it is necessary to increase with frequency the signal level to these elements so as to restore a flat frequency response.

Side-Lobe Attenuation. It is well known in array theory [9] that the amplitude of side lobes can be reduced by tapering the signal level symmetrically along the array from a maximum at the centre. This is called aperture grading or amplitude tapering. In the designs described, some useful aperture grading occurs incidentally because of the progressive increase in element spacing towards the ends of the array, thereby reducing the average volume velocity per unit length of the radiating surface. No attempt was made, however, to optimise this by additional amplitude tapering.

4. PRACTICAL APPLICATIONS

Electrically tapered arrays [10] of length 4 m, 1.8 m and 1.5 m were designed and manufactured for various applications in the Sydney Opera House complex. In the highly reverberant Concert Hall [6], excellent speech intelligibility is achieved by means of the 4 m array suspended about 8 m above the stage and directed towards the rear seats. The shorter columns are used for "fill-in" purposes near the stage and for sound reinforcement or playback in other smaller halls.

Another successful application of the 1.5 m arrays is in a three-channel stereo sound reinforcement and effects system recently installed in the Music Hall, Neutral Bay (Sydney).

Finally plans are in progress to employ a pair of 1.5 m arrays in a new system being designed for the Great Hall of Sydney University, a large rectangular stone building with highly reverberant acoustics.

ACKNOWLEDGEMENTS

The author acknowledges the assistance of Donald F. Craig in the work described and thanks the Management of Amalgamated Wireless (Australasia) Ltd. for permission to present this paper.

REFERENCES

1. WOLFF, I and MALTER, L. "Directional Radiation of Sound", J. Acoust. Soc. Amer. Vol 2, October, 1930, p. 201.

2. OLSON, H.F., "Acoustical Engineering", Ch. 2, Princeton, N.J.: Van Nostrand, 1957.

3. KLEPPER, D.L. and STEELE, D.W., "Constant Directional Characteristics from a Line Source Array", J. Audio Eng. Soc. Vol 11, No. 3, July, 1963, p. 198.

4. TUCKER, D.G., "Arrays with Constant Beam-Width over a Wide Frequency Range" Nature, Vol. 180, September 7, 1957, p. 496.

5. PAWLOWSKI, R.J. "The Line Radiator", Audio July, 1961, p. 19.

6. JORDAN, V.L., "Acoustical Design Considerations of the Sydney Opera House", J. and Proc. Royal Soc. of N.S.W., Vol. 106, 1973, p. 33.

7. HILLIARD, J.K., "Unbaffled Loudspeaker Column Arrays", J. Audio Eng. Soc., Vol.18 No. 6, December 1970, p. 673.

8. IDLING, W.H., "Unidirectionally Radiating Loudspeakers". Presented at the Convention of the Audio Eng. Soc. Inc., Munich, Germany, March 1972.

9. JASIK, H., "Antenna Engineering Handbook", New York; McGraw-Hill, 1961, p. 2-26.

10. BENSON, J.E. and CRAIG, D.F., Aust. Patent Application No. 5893/73.

Reprinted with permission from IREE International Electronics Convention, 1975.