MAY 25 1962

A COLUMN LOUDSPEAKER WITH CONTROLLED COVERAGE ANGLE

JAMES F. NOVAK -- Senior Design Engineer

Jensen Manufacturing Company, Chicago 38, Illinois

INTRODUCTION

In-line loudspeaker arrays, commonly called sound columns, and broadside antenna arrays are perfectly analogous systems. Each loudspeaker in the column can be treated as a transmitting antenna that radiates acoustical energy rather than electromagnetic energy. The mathematical expressions describing radiation patterns, beamwidths, the location of nulls and lobes are identical to both systems. As a matter of fact, the directivity index, which in acoustics affords us an overall measure of the directional properties of a loudspeaker, is actually the acoustical analogue of antenna gain.

Directivity control in both antenna and acoustic arrays is based upon wave interference. Radiation takes place in such a manner that the waves oppose each other in some directions and thereby pull the radiation pattern inward. In other directions, the waves will aid each other and reinforce the radiation. A great deal of directivity (and gain) may be obtained by spacing the elements (loudspeakers) equally apart along a straight line and driving them with equal in-phase power.

The problems associated with acoustic arrays (or column loudspeakers) are considerably more complex than those in antenna arrays because the sound column is by comparison a very wide-band device. The frequency range covered is at least 10-1 or greater. These wide-band requirements cause great variations in beamwidth and are apt to give rise to a large number of side lobes, both of which may become undesirable in many applications.

From a practical viewpoint, it would appear that the ideal column should have 1) a constant beamwidth over at least a 10-1 frequency range, and 2) the side lobe level should be kept at a minimum. In order to better show the principles on which such a column is based, it is best to first consider the reasons why a conventional column falls short of the wide-band requirements.

BEAMWIDTH

A conventional column of length ℓ where all speakers are fed equal power has a directional pattern defined by the familiar function

$$R_\theta = \frac{\sin nx}{nx} \qquad (1)$$

where $x = \frac{\ell\pi}{\lambda}\sin\theta$

λ = wave length = $\frac{c}{f}$
c = velocity of sound
f = frequency of operation
θ = angle from normal to the column
n = number of speakers

Although the beamwidth is usually defined as the angle between the half-power points, it will be much simpler and no less valid for purposes of comparison to define the beamwidth as the angle subtended by the first nulls of the pattern. If the length of the column is defined as $\ell = (n - 1)d$, it can then be shown that the beamwidth is

$$B = 2 \text{ arc sin } \frac{(\underline{1 - 1/n})c}{\ell f} \qquad (2)$$

where n = number of speakers
d = distance between speakers

Equation (2) clearly illustrates that the beamwidth is dependent upon the product of column length and the frequency of operation.

The variation of beamwidth as a function of normalized frequency is shown in Figure 1. The beamwidth variation appears to be on the order of 18-1 over a frequency range of 10-1. The beamwidth variation of a single loudspeaker, Curve D, is also shown for comparison. The usefulness of this curve comes from the fact that it permits the comparison of column beamwidth to the beamwidth of a single loudspeaker. Consider, for example, a 5 speaker column 30" long with 6" loudspeakers and a frequency such that $\ell/\lambda = 10$. The corresponding D/λ would be 2. Figure 1 shows that the beamwidth of the column (as defined here) to by 9.5° while the beamwidth of a single speaker in the column is 75° at this frequency. Looking at it another way, the total beamwidth variation in this column is about 18-1 while the beamwidth variation of any of the individual speakers in the column is about 2.5-1 over the same frequency range!

RADIATION PATTERN - SIDE LOBES

The behavior of side lobes can best be illustrated by considering a specific example of five point sources, Figure 2. The directivity pattern as given by Eqtn. (1) is a function of n, the number of speakers, and consists of a large central maximum in the direction of principle radiation followed by three smaller maxima of alternating phase and finally by another maximum of the same amplitude as the first. The pattern then repeats itself in the same manner as frequency continues to increase. In the general case, the pattern with n point sources will be similar to this with the quantity of small maxima between the large ones being equal to (n-2).

The curve of Figure 2 can be considered a universal directivity characteristic which can be interpreted for any particular spacing and frequency. It also points out some of the limitations of conventional columns. At low frequencies only the single central maximum will be present. This will gradually increase in sharpness as the frequency is increased and the smaller maxima (or lobes) will begin to appear. When a frequency is reached such that the spacing between speakers becomes a half wavelength (about 1250 cps in this case), the entire pattern will appear between 0° and 180°. When a frequency corresponding to one wavelength is reached (2500 cps) this entire pattern will appear between 0° and 90° and will repeat itself between 90° and 180°. This process of pattern repetition continues to occur in a smaller and smaller angle as frequency continues to increase. Figure 3 shows the measured directional patterns of a practical 5 speaker column. Although the general behavior is obviously as predicted theoretically, it is interesting to note that the side lobe level becomes increasingly less than predicted as the frequency and angle off axis are increased. This occurs because the speakers are not behaving as point sources; they are becoming directional themselves. The side lobe level will decrease as the speakers comprising the column are made more and more directional.

A METHOD FOR ACHIEVING CONSTANT BEAMWIDTH

Because the beamwidth is a function of the product of column length and frequency, a constant beamwidth would result if this product could be held constant over the entire frequency range. One method for achieving this is through the use of low-pass filters, Figure 4. The cut-off frequencies of these filters are progressively increased across the entire column length at a rate such that one-half of the remaining speakers are cut-off with each successive doubling of frequency. The starting frequency is that which yields the desired beamwidth with all speakers active: The result is that the beamwidth will not become less than the design value since column length is effectively shortened as frequency increases. The minimum frequency which will yield the desired beamwidth will depend on the length of the column and can be lowered by increasing column length. This column, as all others, will become essentially non-directional below the frequency for which the column length becomes one wavelength.

(continued on Page 7)

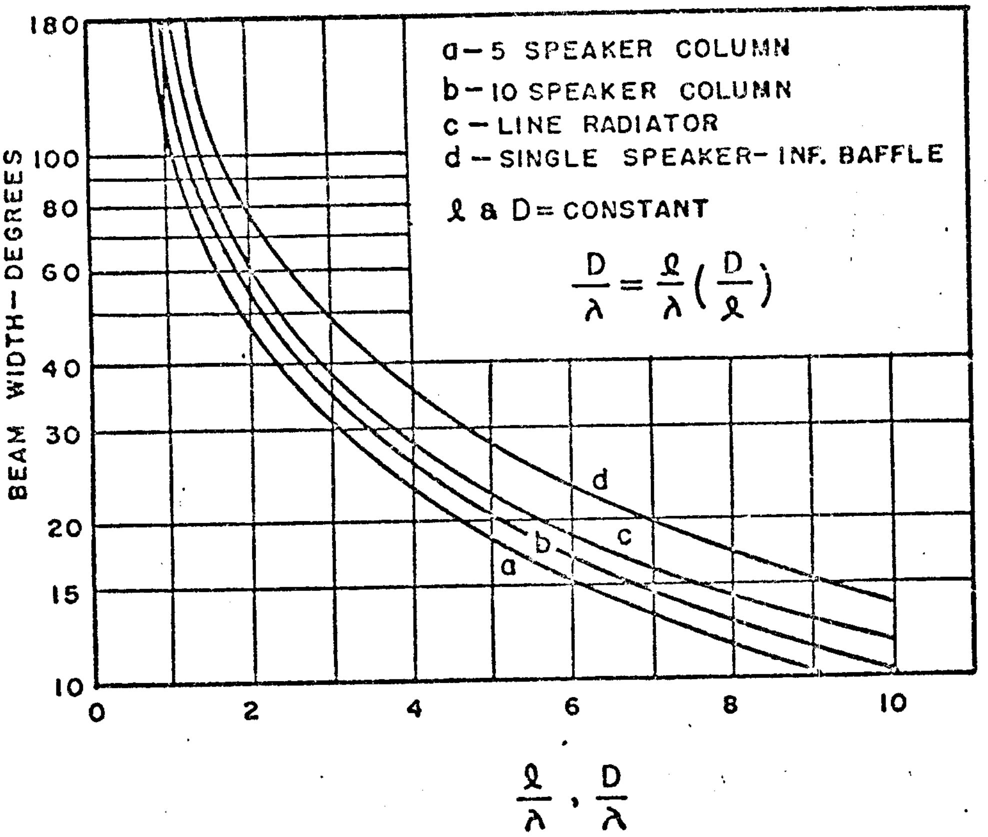

180
100
80
60
40
30
20
15
10
BEAM WIDTH– DEGREES
0
2
4
6
8
10
a – 5 SPEAKER COLUMN
b – 10 SPEAKER COLUMN
c – LINE RADIATOR
d – SINGLE SPEAKER – INF. BAFFLE
ℓ & D = CONSTANT
$\frac{D}{\lambda} = \frac{\ell}{\lambda}\left(\frac{D}{\ell}\right)$
a
b
c
d
$\frac{\ell}{\lambda}, \frac{D}{\lambda}$

FIG. 1

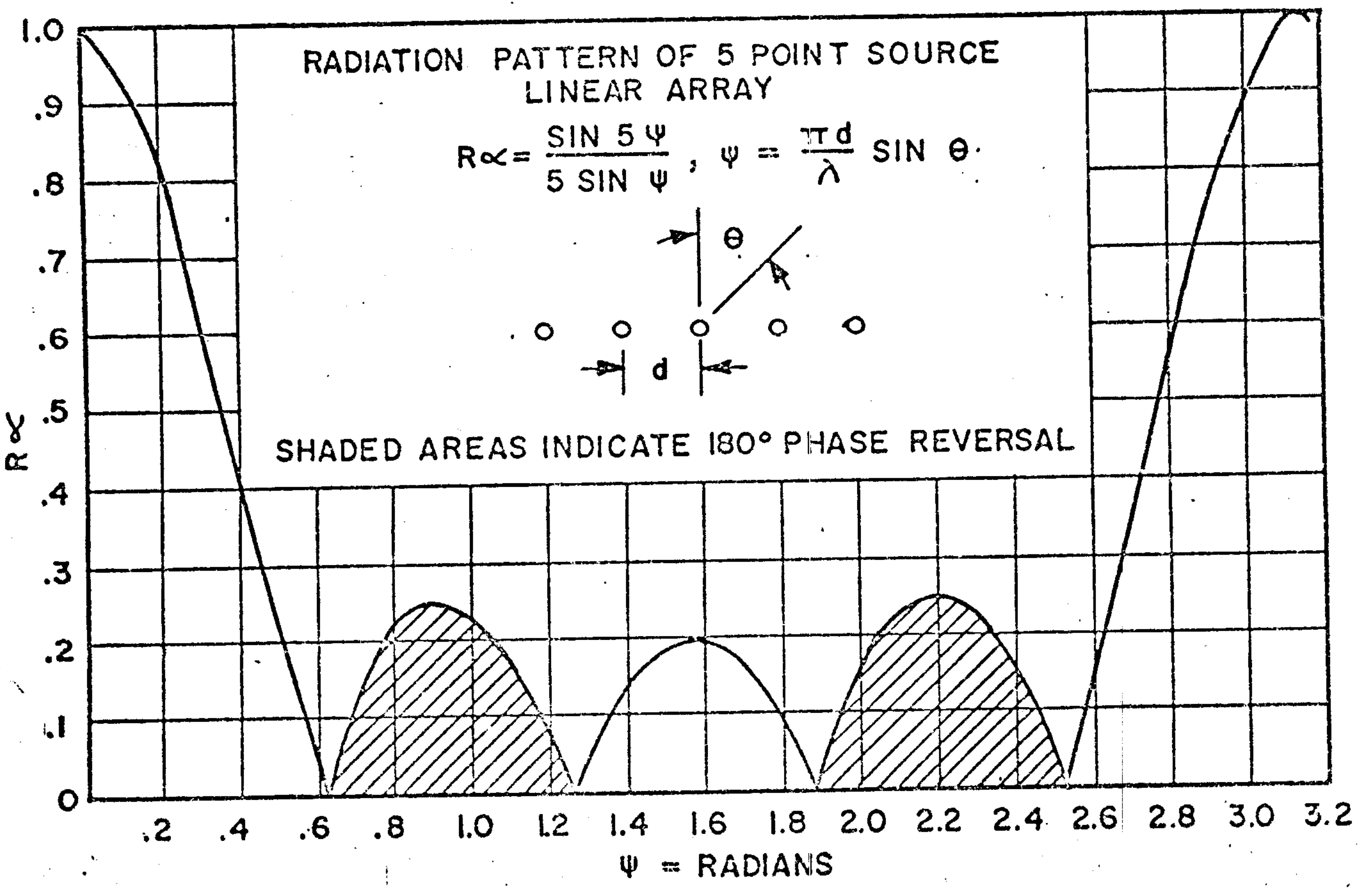
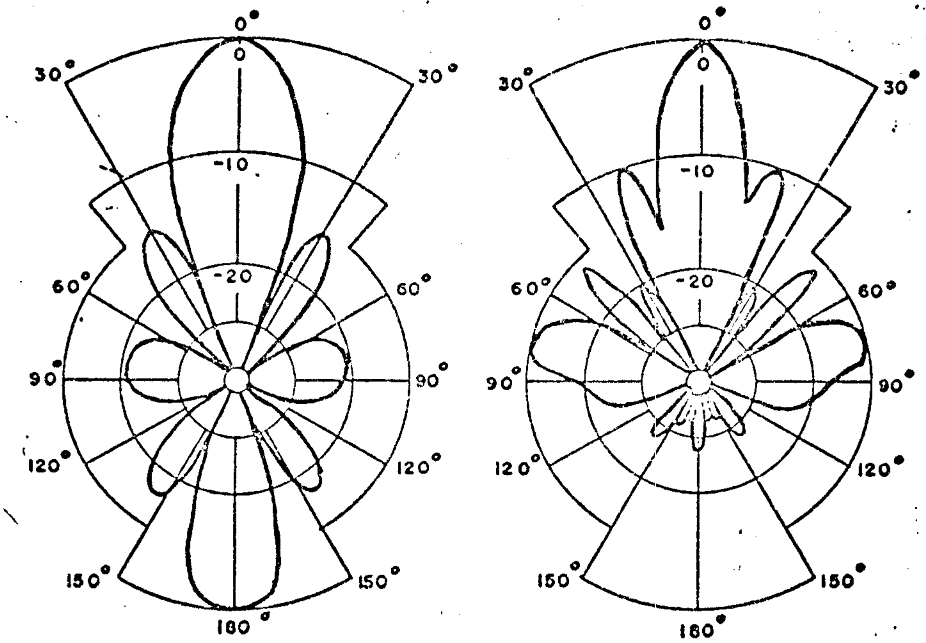

RADIATION PATTERN OF 5 POINT SOURCE LINEAR ARRAY
$R\alpha = \frac{\sin 5\psi}{5 \sin \psi}, \quad \psi = \frac{\pi d}{\lambda} \sin \theta$
θ
d
SHADED AREAS INDICATE 180° PHASE REVERSAL
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Rα
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
ψ = RADIANS

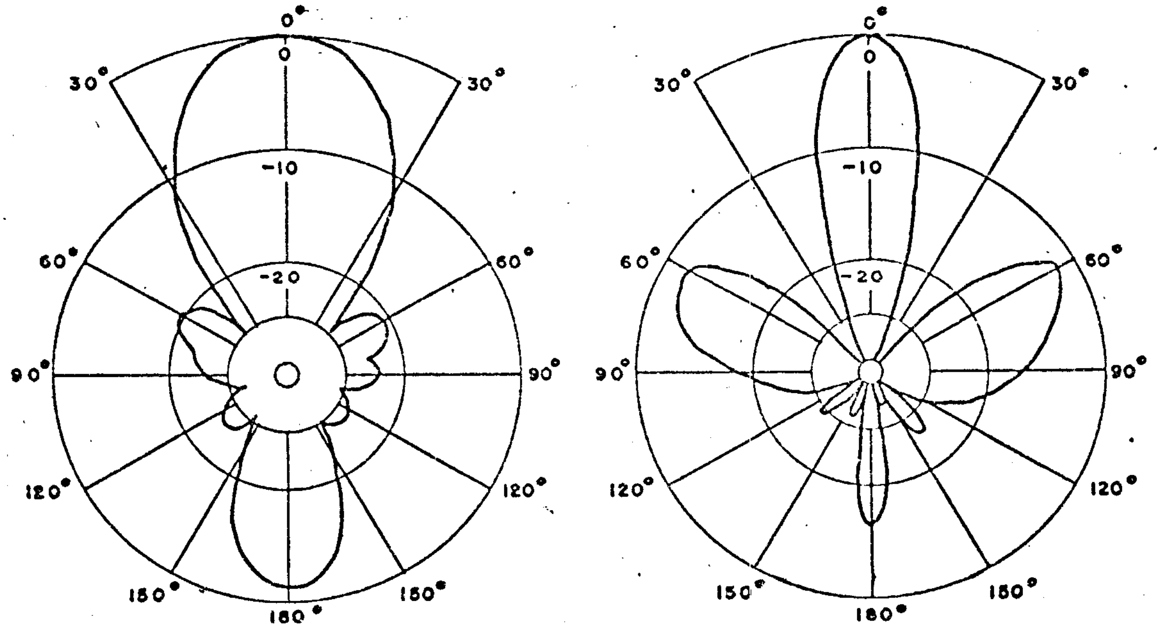
FIG. 2



$\frac{d}{\lambda} = \frac{1}{2}$ $\frac{d}{\lambda} = 1$

5 SPEAKER COLUMN – UNIFORM EXCITATION

FIG. 3



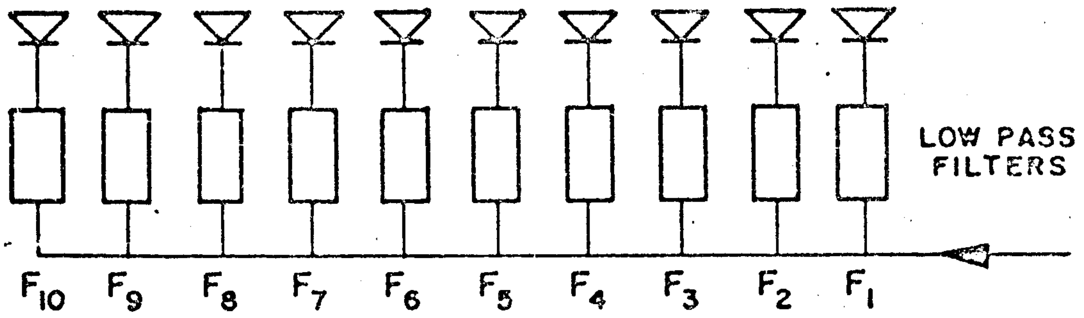
$\frac{d}{\lambda} = \frac{1}{2}$ $\frac{d}{\lambda} = 1$

1ST NULL AT ± 45° 1ST NULL AT ± 20°

5 ELEMENT COLUMN – TCHEBYSCHEFF EXCITATION

FIG. 5

FIG. 4


LOW PASS FILTERS
F10
F9
F8
F7
F6
F5
F4
F3
F2
F1

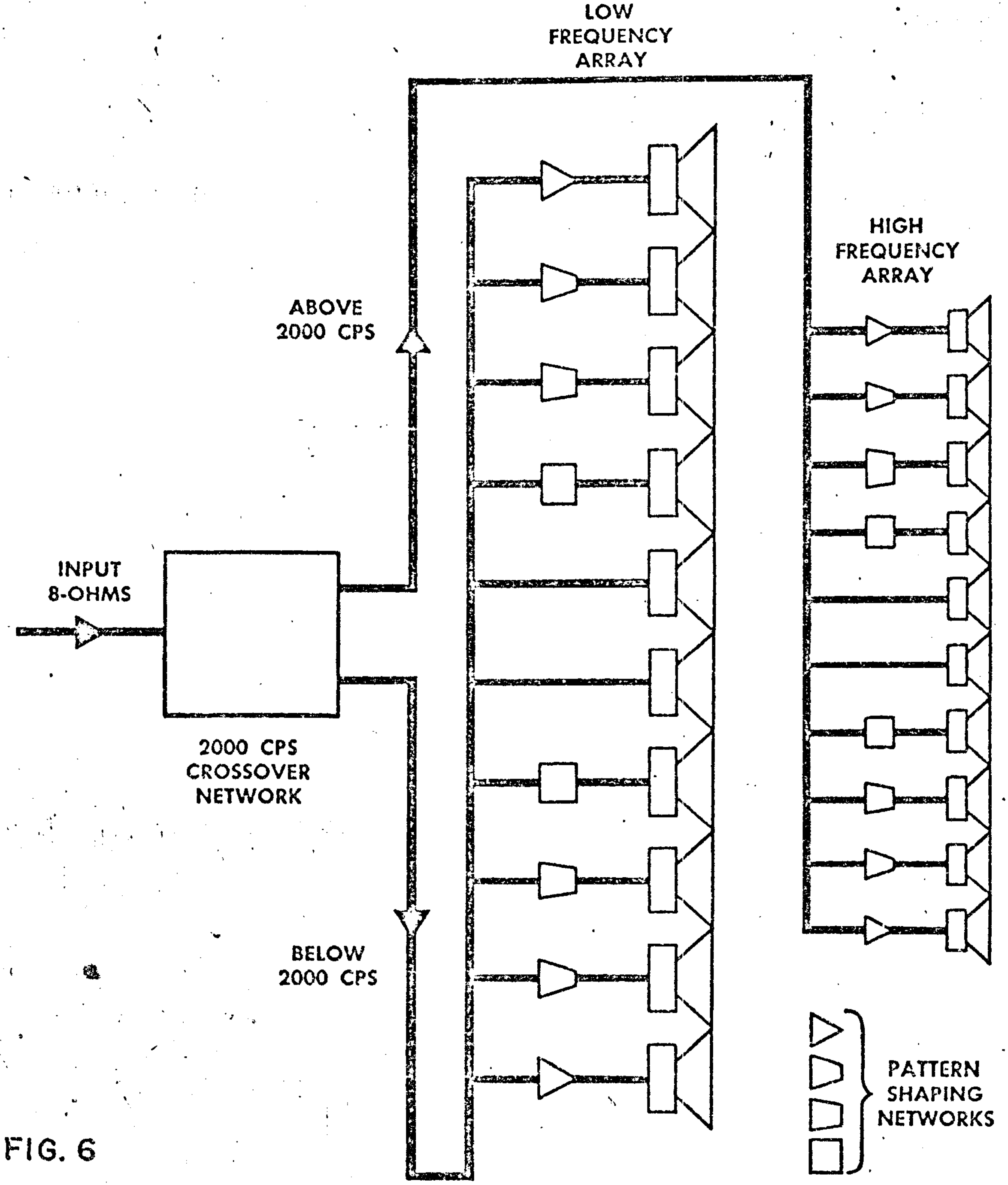
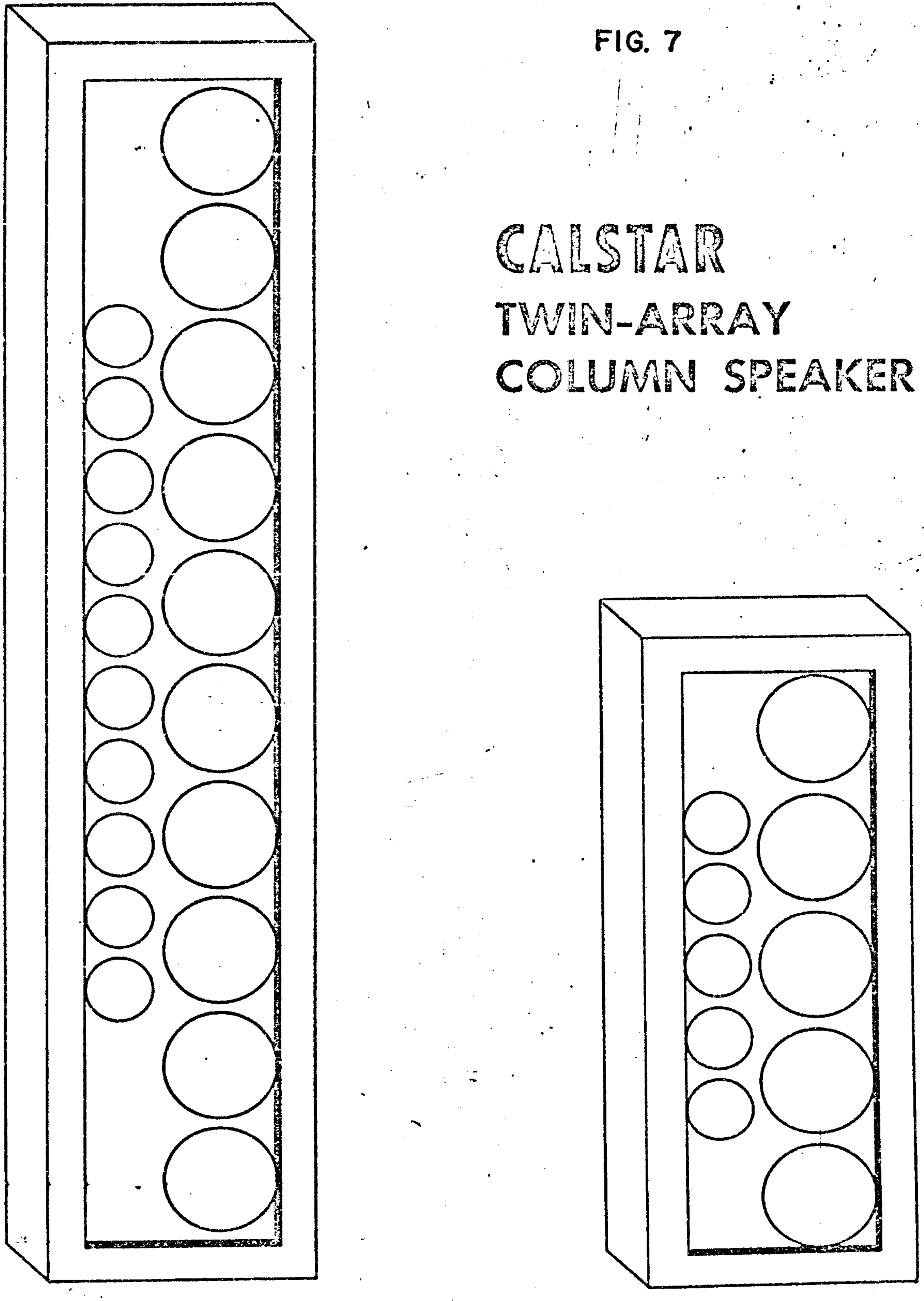

LOW FREQUENCY ARRAY
HIGH FREQUENCY ARRAY
ABOVE 2000 CPS
INPUT 8-OHMS
2000 CPS CROSSOVER NETWORK
BELOW 2000 CPS
PATTERN SHAPING NETWORKS

FIG. 6

FIG. 7

CALSTAR
TWIN-ARRAY
COLUMN SPEAKER



MODEL 1010

MODEL 55

One disadvantage of this method is that excessive beam tilting and/or beam distortion can occur since all filters have different cutoff frequencies and therefore different phase characteristics. An additional disadvantage is that the side-lobe level is unaffected although the total number of side-lobes will be decreased. Side-lobe generation in this case is dictated only by the spacing between speakers while the number of lobes depends upon the number of speakers.

TAPERED COLUMNS

A tapered column is one where the power input decreases from the central loudspeakers to the outer loudspeakers at a prescribed rate. Although an endless variety of tapers can be used, the results compared to a non-tapered column are, 1) beamwidth at any frequency is increased, 2) side-lobe levels are decreased, 3) repeated main lobe levels and widths are increased, 4) the column becomes non-directional at a higher frequency, and 5) the total beamwidth variation over any frequency range is decreased. The main disadvantages of this type of column lie in results 3) and 4).

An important feature of the tapered column is that within certain limits it is possible to obtain any desired beamwidth at a given frequency by proper choice of taper.

One particular taper is of considerable interest and importance. This taper utilizes the properties of Tchebyscheff polynomials and is based on antenna work done at Bell Laboratories. The one major advantage of this taper is that it yields a minimum side-lobe level for any specified beamwidth. Figure 5 illustrates the effects of tapering as applied to the column of Figure 3.

AN IMPROVED CONSTANT BEAMWIDTH COLUMN

An improved constant beamwidth column has been developed which utilizes the best features of the three columns just discussed. The main features of this column are:

1) Uniform excitation is employed at low frequencies because this excitation allows the specified beamwidth to occur at the lowest possible frequency.

2) The column length and spacing are decreased in the frequency range where pattern repetition would normally occur. Pattern repetition now occurs at the upper end of the frequency range normally used. The decrease in length and spacing is accomplished through the use of <u>two</u> columns each of which reproduces a different frequency range. This is basically a two channel system. The low frequency column consists of 5-1/4 inch woofers spaced 6 inches apart. These speakers operate in the range below 2000 cps. The high frequency column consists of 3 inch tweeters spaced 3 inches apart. These speakers operate in the range above 2000 cps. A conventional crossover network is used between the two columns.

3) Each column employs Tchebyscheff tapering. Minimum phase shift networks are used to cause the taper to increase as frequency increases. The rate at which the taper varies is carefully controlled so as to provide a Tchebyscheff excitation at all frequencies. The variable taper plus column length change results in a beamwidth that remains constant within 5 degrees over the range of 500 to 5000 cps--a 10-1 frequency range. The Tchebyscheff excitation keeps the side lobe level to a minimum within this range.

Two columns of this type are now available. They are trademarked as Jensen CALSTAR --- Constant - Angle - Lobe - Suppressed - Twin - Array - Radiator. The Model 55 CALSTAR consists of two five speaker columns with 60° beamwidth. The Model 1010 CALSTAR consists of two ten speaker columns with 30° beamwidth. Power ratings are 30 watts and 60 watts respectively. Total frequency range covered is 200 - 10000 cps. with a gradual rolloff above 5000 cps.

Figure 6 illustrates in block diagram form the circuitry involved while Figure 7 illustrates the physical speaker placement.

In conclusion, it must be pointed out that the sound column is not a panacea for bad architectural acoustics. Nor will the sound column render obsolete either the high-level multicellular horn installations, or the low-level installation which consists of many small speakers distributed throughout the area to be reinforced. But if properly designed and intelligently used, it can become a very useful tool in the sound installers bag of tricks.

This paper was presented at the Midwest
Communications and Sound Seminar of the
Electric Association (of Chicago), May 25, 1962

Jensen MANUFACTURING COMPANY
[illegible] COMPANY
6601 South Laramie Avenue • Chicago 38, Illinois
In Canada: Radio Speakers of Canada, Ltd., Toronto