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DIRECTIVITY PATTERNS OF A 5-ELEMENT LINEAR SUPER-DIRECTIVE ARRAY USING PRITCHARD AND BRYN SHADING METHODS.

15 Apr 63
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at NEL, and to a few persons or activities outside NEL. It should not
be construed as a report since its only function is to present informa-
tion on a small portion of the work on NEL Problem L3-2.
OBJECT

To compare two different types of shading for a linear array composed of 5 elements spaced at $\lambda/4$ intervals. One method by Pritchard(1) sets a fixed minor lobe level and determines the shading factors by using the Chebyshev polynomial. The second method was developed by Finn Bryn(2).

Pritchard's method of shading follows the procedure developed by Dolph(3) and Riblet(4) in prescribing a certain level for all minor lobes and employs the Chebyshev polynomial to determine the shading factors required to produce the desired pattern. However, Pritchard extends this method so that it may be applied to compensated or "steered" arrays.

Bryn considers the second order cross moment of noise received at two hydrophones and develops a method which implements the Neyman-Pearson likelihood ratio, thus optimizing this signal-to-noise ratio.

PROCEDURE

Comparisons were made for patterns steered in the direction of the array normal, i.e., $\theta_c = 0^\circ$; for 32.25 from the array normal, $\theta_c = 32.25^\circ$; and end fire, $\theta_c = 90^\circ$.

The Bryn method assumes electronic system noise of less intensity than the background noise, while the unshaded and shaded patterns using the Chebyshev type shading do not consider system noise.

RESULTS

The calculated patterns as shown in figures 1-15 and tables 1-3 give a comparison of the beam width and minor lobe levels.
DISCUSSION

When $\theta_c = 0^\circ$, Pritchard’s shading produces the best pattern, that is the narrowest beam width with acceptable minor lobe levels.

When the array is compensated for 32.25°, Pritchard’s method produces low minor lobe levels, but beam widths become excessive. Bryn’s method of shading narrows the beam width but the minor lobe level at $+90^\circ$ is only -3.6 db and at $-90^\circ$ is 8.7 db when a noise ratio of $10^{-5}$ is used.

At end fire operation Bryn’s method produces the narrowest beam widths with minor lobes no higher than -11 db. Pritchard’s method gives a very broad beam width, but the prescribed minor lobe levels are realized.

CONCLUSIONS

From the limited number of results, it is concluded that Pritchard’s method results in low minor lobe levels without broadening the main lobe unduly.

Bryn’s method results in narrow main lobes, but at the price of higher minor lobe levels, or an increased number of minor lobes. Also, the method of shading is sensitive to the noise ratio (system noise to ambient noise). A change in either or both may produce a substantial change in the directivity pattern.

It is not intended that these results should be extrapolated to longer arrays; each array needs to be studied individually.
REFERENCES


### Table I. $\theta_c = 0^\circ$

<table>
<thead>
<tr>
<th>Type of Shading</th>
<th>Beam Width</th>
<th>Minor Lobe Levels (db)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded</td>
<td>40°</td>
<td>-14.1 --- ---</td>
<td>1</td>
</tr>
<tr>
<td>Pritchard</td>
<td>35°</td>
<td>-15 -15 ---</td>
<td>2</td>
</tr>
<tr>
<td>Pritchard</td>
<td>34°</td>
<td>-28.6 -28.6 ---</td>
<td>3</td>
</tr>
<tr>
<td>Bryn Noise Ratio</td>
<td>10-5</td>
<td>-11 -6.8 ---</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10-2</td>
<td>-13 --- ---</td>
<td>5</td>
</tr>
</tbody>
</table>

*System noise to ambient noise.*

### Table II. $\theta_c = 32.25^\circ$

<table>
<thead>
<tr>
<th>Type of Shading</th>
<th>Beam Width</th>
<th>Minor Lobe Levels (db)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded</td>
<td>54°</td>
<td>-12 --- ---</td>
<td>6</td>
</tr>
<tr>
<td>Pritchard</td>
<td>53°</td>
<td>-15 -15 ---</td>
<td>7</td>
</tr>
<tr>
<td>Pritchard</td>
<td>64°</td>
<td>-28.6 -28.6 ---</td>
<td>8</td>
</tr>
<tr>
<td>Bryn Noise Ratio</td>
<td>10-5</td>
<td>-13.1* -15 8.7%</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>10-2</td>
<td>-12.6* -14.6* ---</td>
<td>10</td>
</tr>
</tbody>
</table>

*Left minor lobes.*

**Right minor lobe.*

### Table III. $\theta_c = 90^\circ$

<table>
<thead>
<tr>
<th>Type of Shading</th>
<th>Beam Width</th>
<th>Minor Lobe Level (db)</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded</td>
<td>100°</td>
<td>-11.6 -13.6 ---</td>
<td>11</td>
</tr>
<tr>
<td>Pritchard</td>
<td>103°</td>
<td>-15 -15 ---</td>
<td>12</td>
</tr>
<tr>
<td>Pritchard</td>
<td>112°</td>
<td>-24.6 -24.6 ---</td>
<td>13</td>
</tr>
<tr>
<td>Bryn Noise Ratio</td>
<td>10-5</td>
<td>-15.7 -18.8 -18.4 -11</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>10-2</td>
<td>-16.7 -20.7 -22.2 ---</td>
<td>15</td>
</tr>
</tbody>
</table>
APPENDIX A

Bryan Method of Shading for a Linear Array

C. J. Krieger

In the course of pattern calculations a constant attempt was made to reduce the number of operations to a minimum. The following is the method which was finally adopted.

1. Write the matrix \( \{ q \} \) whose elements are the normalized correlation coefficients \( q_{lh} \) (Eq. A 2.8 of Appendix 2 of Ref. 2). Form the reciprocal matrix \( \{ q^{-1} \} \) with elements \( r_{lh} \).

2. To compensate for a direction \( \theta_c \), multiply each \( r_{lh} \) by \( e^{-j \Phi_{bc}} \), where

\[
\Phi_{bc} = h \cdot kd \sin \theta_c \quad \text{and} \quad k = \frac{2\pi}{\lambda}.
\]

3. The filter transfer function or complex shading coefficient is

\[
Z_l e^{j\Phi_l} = \sum_h r_{lh} e^{-j\Phi_{bc}}
\]

4. To obtain the response of each filter to sound arriving from direction \( \theta \), multiply each filter function \( Z_l e^{j\Phi_l} \) by \( e^{j\Phi_i} \), where \( \Phi_i = i kd \sin \theta \).

5. The directivity function \( R(\theta, \theta_c) = \sum_l Z_l e^{j\Phi_l} \cdot e^{j\Phi_i} \)
Example:

A five-element linear array with $\lambda/4$ element spacing. System noise to ambient noise ratio $10^{-5}$.

1. The $\{q\}$ and $\{q^{-1}\}$ matrices:

$$
\{q\} = \begin{pmatrix}
1.0 & 0.6366 & 0 & -0.2122 & 0 \\
0.6366 & 1.0 & 0.6366 & 0 & -0.2122 \\
0 & 0.6366 & 1.0 & 0.6366 & 0 \\
-0.2122 & 0 & 0.6366 & 1.0 & 0.6366 \\
0 & -0.2122 & 0 & 0.6366 & 1.0
\end{pmatrix}
$$

$$
\{q^{-1}\} = \begin{pmatrix}
-24.27 & +55.41 & -68.27 & +51.83 & -21.24 \\
+26.97 & -68.27 & +87.93 & -68.27 & +28.97 \\
-21.24 & +51.83 & -68.27 & +55.41 & -24.27 \\
\end{pmatrix}
$$
2. To compensate for $\theta_c = 32.25^\circ; \bar{\theta}_{bc} = \theta - 48.02^\circ$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$Z_2$</th>
<th>$Z_1$</th>
<th>$Z_0$</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
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</thead>
<tbody>
<tr>
<td>-2</td>
<td>$11.94 \times 10^6 e^{62.05}$</td>
<td>$-2.27 e^{j62.05}$</td>
<td>$+48.77 e^{j62.05}$</td>
<td>$-21.24 e^{j62.05}$</td>
<td>$+8.97 e^{j62.05}$</td>
</tr>
<tr>
<td>-1</td>
<td>$-24.27 e^{j62.02}$</td>
<td>$+55.41 e^{j62.02}$</td>
<td>$-68.27 e^{j62.02}$</td>
<td>$+51.83 e^{j62.02}$</td>
<td>$-21.24 e^{j62.02}$</td>
</tr>
<tr>
<td>0</td>
<td>$+28.97 e^{j10}$</td>
<td>$-68.27 e^{j10}$</td>
<td>$+87.93 e^{j10}$</td>
<td>$-68.27 e^{j10}$</td>
<td>$+28.97 e^{j10}$</td>
</tr>
<tr>
<td>+1</td>
<td>$-21.24 e^{-j62.02}$</td>
<td>$+51.83 e^{-j62.02}$</td>
<td>$-68.27 e^{-j62.02}$</td>
<td>$+55.41 e^{-j62.02}$</td>
<td>$-24.27 e^{-j62.02}$</td>
</tr>
<tr>
<td>+2</td>
<td>$+8.37 e^{-j62.04}$</td>
<td>$-21.24 e^{-j62.05}$</td>
<td>$+28.97 e^{-j62.05}$</td>
<td>$-24.27 e^{-j62.05}$</td>
<td>$+11.94 e^{-j62.05}$</td>
</tr>
</tbody>
</table>

3. Filter Transfer Functions.

$Z_2 = 3.84 e^{j160.2^\circ}$  $Z_1 = 8.27 e^{j12.44^\circ}$  $Z_0 = 9.51 e^{j180^\circ}$  $Z_1 = 8.27 e^{j12.44^\circ}$  $Z_2 = 3.84 e^{j160.2^\circ}$

4. For sound arriving from $\theta = 90^\circ; \bar{\theta}_4 = 190^\circ$

<table>
<thead>
<tr>
<th>$k$</th>
<th>$Z_2$</th>
<th>$Z_1$</th>
<th>$Z_0$</th>
<th>$Z_1$</th>
<th>$Z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>$3.84 e^{j160.2^\circ}$</td>
<td>$8.27 e^{-j12.44}$</td>
<td>$9.51 e^{j180^\circ}$</td>
<td>$8.27 e^{j12.44}$</td>
<td>$3.84 e^{j160.2^\circ}$</td>
</tr>
<tr>
<td>-1</td>
<td>$e^{-j180^\circ}$</td>
<td>$e^{-j190^\circ}$</td>
<td>$e^{j190^\circ}$</td>
<td>$e^{j190^\circ}$</td>
<td>$e^{j180^\circ}$</td>
</tr>
<tr>
<td>0</td>
<td>$e^{-j180^\circ}$</td>
<td>$e^{-j190^\circ}$</td>
<td>$e^{j190^\circ}$</td>
<td>$e^{j190^\circ}$</td>
<td>$e^{j180^\circ}$</td>
</tr>
<tr>
<td>+1</td>
<td>$8.27 e^{j12.44}$</td>
<td>$9.51 e^{j180^\circ}$</td>
<td>$8.27 e^{j12.44}$</td>
<td>$3.84 e^{j160.2^\circ}$</td>
<td></td>
</tr>
<tr>
<td>+2</td>
<td>$3.84 e^{j160.2^\circ}$</td>
<td>$8.27 e^{-j12.44}$</td>
<td>$9.51 e^{j180^\circ}$</td>
<td>$8.27 e^{j12.44}$</td>
<td>$3.84 e^{j160.2^\circ}$</td>
</tr>
</tbody>
</table>

5. $R(90^\circ, 32.25^\circ) = -2.99$ (units)

Repeat for other values of $\theta$. 
Acknowledgment

Various helpful discussions with Burwell B. Goode are gratefully acknowledged. He also made available to the author computer results which were used in the preparation of this memorandum.
Figure 1. 5-Element Linear Array. λ/4 Spacing. θ = 0°. Unshaded. Beam Width 42°. Highest Minor Lobe Level -14.1 dB.
Figure 2. 5-Element Linear Array. λ/4 Spacing. $\theta_e = 0^\circ$. Pritchard Shading. Beam Width 30°. Highest Minor Lobe Level -15 db.
Figure 3. 5-Element Linear Array. \( \lambda/4 \) Spacing, \( \theta_c = 0^\circ \).

Figure 4. 5-Element Linear Array. $\lambda/4$ Spacing. $\theta_c = 0^\circ$. Bryn Shading. Noise Ratio $10^{-8}$. Beam Width 28°. Highest Minor Lobe Level -6.8 db.
Figure 5. 5-Element Linear Array. $\lambda/4$ Spacing, $\theta_c = 0^\circ$. Bryn Shading. Noise Ratio $10^{-2}$. Beam Width $32^\circ$. Highest Minor Lobe Level -13 db.
Figure 6. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( \theta_c = 32^\circ.25. \)
Unshaded. Beam Width 54\(^\circ\). Highest Minor Lobe Level -12 db.
Figure 7. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( \theta_c = 32.25^\circ \).
Pritchard Shading. Beam Width 53\(^\circ\). Highest Minor Lobe Level -15 db.
Figure 8. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( \phi_c = 32.25^\circ \).
Pritchard Shading. Beam Width 64°. Highest Minor Lobe Level -24.6 db.
Figure 9. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( a_c = 32.25 \), Bryn Shading. Noise Ratio 10\(^{-6}\). Beam Width 29\(^\circ\). Highest Minor Lobe Level -3.6 db.
Figure 10. 5-Element Linear Array. $\lambda/4$ Spacing. $\theta_c = 32.25^\circ$.
Bryn Shading. Noise Ratio $10^{-8}$. Beam Width $35^\circ$.
Highest Minor Lobe Level -12.6 dB.
Figure 11. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( \Phi_c = 90° \).
Unshaded. Beam Width 100°. Highest Minor Lobe Level -11.8 db.
Figure 12. 5-Element Linear Array. $\lambda/4$ Spacing. $\phi_c = 90^\circ$.
Figure 13. 5-Element Linear Array. $\lambda/4$ Spacing. $\theta_c = 90^\circ$. Pritchard Shading. Beam Width 112°. Highest Minor Lobe Level -24.6 db.
Figure 14. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( \theta_c = 90^\circ \). Bryn Shading. Noise Ratio 10^{-6}. Beam Width 42^\circ. Highest Minor Lobe Level -11 \text{ db}. 
Figure 15. 5-Element Linear Array. \( \lambda/4 \) Spacing. \( \theta_C = 90^\circ \).
Bryan Shading. Noise Ratio 10^{-2}. Beam Width 50^\circ.
Highest Minor Lobe Level -16.7 db.