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EFFECTS OF BEAM STEERING ON THE BEHAVIOR OF PLANAR ARRAYS. (U)
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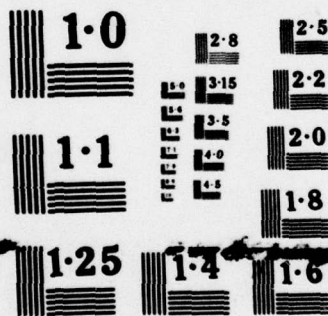
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U. S. Navy Underwater Sound Laboratory
Fort Trumbull, New London, Connecticut

EFFECTS OF BEAM STEERING ON THE BEHAVIOR OF PLANAR ARRAYS

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David T. Porter

USL Technical Memorandum No. 960-28-66

28 March 1966

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This memorandum is a continuation of reference (a), which discussed the effects of the transducer internal impedance (Z_I , or Z_{oc}) upon the behavior of unsteered planar arrays. A detailed discussion of the effects of the components of the transducer equivalent circuit upon Z_I is contained in reference (b). Results are presented in this memorandum showing the effects of beam steering and Z_I upon the behavior of 80 element planar arrays. Three main criteria will be used in evaluating the behavior of the arrays: cavitation-limited power, velocity-limited power, and the occurrence of negative radiation resistances.

ARRAYS CONSIDERED

The arrays were all 8 rows by 10 columns, as shown in figure 1.

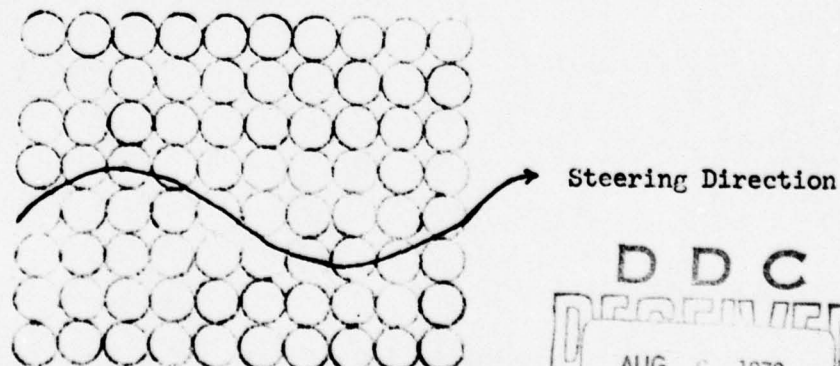
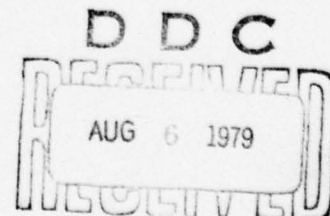


Figure 1 A Steered Array of 80 Elements



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They were composed of identical close-packed circular pistons in an infinite rigid baffle. Three values of the piston ka were used: 0.5 ($\lambda/6$ approximate diameter), 1.0 ($\lambda/3$ approximate diameter) and 1.5 ($\lambda/2$ approximate diameter). The resistive part of Z^I, R^I , was taken to be zero, but seven different values of the reactive part of Z^I, X^I , were used. The values of X^I are given in terms of the ratio X^I/X_{11} , where X_{11} is the self radiation reactance of the piston alone in the baffle. The ratio X^I/X_{11} was taken as +1, 0, -1, -2, -3, -5, and ∞ . For the j th element of an array, the Thevenin equivalent driving force (G_j), the velocity (V_j), the radiation impedance (Z_{rj}), and Z^I are related by

$$G_j = V_j(Z_{rj} + Z^I). \quad (1)$$

The driving forces were all taken equal, so that an X^I of ∞ caused equal velocity magnitudes. The arrays were steered in the direction of the longer side of the array, by keeping a constant phase difference between the driving forces in adjacent columns. Due to the mutual coupling, the velocity phases do not necessarily maintain this phase difference, so that the maximum response of the transmitted beam is not necessarily at the desired steering angle. Figure 2 shows a portion of the pattern for the case of $X^I/X_{11} = -1$, $ka = 1.0$, and θ_{st} (steering angle away from broadside) = 60° . The computer results from which figure 2 was taken show that the maximum response occurs at about $\theta = 57^\circ$, but the response at the desired steering angle is only 0.1 db down from the maximum.

CAVITATION-LIMITED POWER

Figures 3a, 3b, and 3c show the effect of steering on cavitation-limited power. With a few minor exceptions, cavitation-limited power steadily decreases as the steering angle increases. The cavitation-limited powers are normalized to the cavitation-limitation power for the unsteered case with equal velocities. As shown in reference (a) for the unsteered case, cavitation-limited power is higher for the cases with $Z^I = 0$ than for the equal velocity cases. Table I gives a summary of the advantages in cavitation-limited power of $Z^I = 0$ over the equal velocity cases.

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~~78 08 07 227~~

Table I

Advantage in Cavitation-Limited Power (Db)
of $Z^I=0$ over Equal Velocities

ka	$\theta_{st}=0^\circ$ (Broadside)	$\theta_{st}=90^\circ$ (Endfire)
0.5	2.2	4.1
1.0	2.1	3.9
1.5	1.6	2.4

As is shown in Appendix B of reference (a), the peak pressure on a piston is closely related to the acoustic force on the piston. The acoustic force is obtained from

$$\text{Acoustic Force} = (\text{Radiation Impedance}) \times (\text{Velocity}) \quad (2)$$

Equations (1) and (2) show that when $Z^I=0$, the driving forces become equal to the acoustic forces. When the acoustic forces are equal, the pressure distribution on the array becomes nearly uniform, as is shown in figure 6b of reference (a). However, for the equal-velocity case, the acoustic forces are directly proportional to the radiation impedances, which vary considerably over the array, and will vary to a greater extent for larger steering angles. The cavitation-limited power for all values of Z^I also decreases as θ_{st} increases because the acoustic load on the pistons becomes more and more reactive as θ_{st} increases. Table II gives the average radiation resistances ($R/\rho c A$) that were computed, and Table III gives the average radiation reactances ($X/\rho c A$). Note that the average radiation reactance increases much more rapidly than the resistance as θ_{st} increases.

The cavitation-limited power index γ was presented in reference (c) by Sherman. In reference (d), Chin computed γ for some rectangular radiators with traveling waves imposed on them in such a way as to simulate steered arrays of small close-packed pistons (with velocities equal). As would be expected, Chin's graphs of γ versus θ_{st} have the same shape as the graphs given here in figures 3a, 3b, and 3c.

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VELOCITY-LIMITED POWER

Figures 4a, 4b, and 4c show the effects of steering on velocity-limited power. Straight line segments were used to connect the discrete points for which the computations were done. As would be expected, the equal-velocity cases ($X^I=00$) have the greatest velocity-limited power, as all of their pistons are at the maximum permissible velocity. The powers in figures 4a, 4b, and 4c are again normalized to the equal-velocity, unsteered cases. The $Z^I=0$ cases have much less velocity-limited power than the equal-velocity cases, as the $Z^I=0$ cases force their pistons to maintain a constant product of velocity and radiation impedance, so that many pistons will be operating far below the permissible limit. As θ_{st} increases, the variation in radiation impedances grows worse, so that the upstream end of the array has high velocities and low radiation impedances, and the downstream end of the array has low velocities and high radiation impedances, and neither end is able to radiate a large amount of acoustic power.

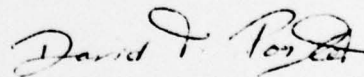
For the cases where X^I/X_{11} was -1 or -2, poor velocity control was usually present, so that velocity-limited power was low. For these cases, velocity-limited power generally continued to decrease as θ_{st} increased. However, for the equal velocity cases and the other cases where velocity control was generally good ($X^I/X_{11}=+1, -3, \text{ and } -5$), velocity-limited power reached a maximum for some sizeable steering angle. These "optimum" steering angles appeared to be near 45° for $ka=0.5$, 60° for $ka=1.0$, and 75° for $ka=1.5$. However, this optimum steering angle is mainly determined by the size of the array, not the size of the pistons in it. In reference (d), Chin also gave results for the radiation resistance for the rectangular radiator model of a steered array. When the velocity level is fixed, the radiation resistance then determines the acoustic power. Therefore, Chin's results for the radiation resistance of the steered rectangle are closely related to the velocity-limited power of a close-packed array of the same outer dimensions as the rectangle. Unfortunately, Chin did not have a rectangle of the same outer dimensions as the 80 element array in this report. However, his figures 5 and 6 do show rectangles with maximum radiation resistances at large steering angles.

OCCURRENCE OF NEGATIVE RADIATION RESISTANCES

Table IV gives the number of elements having negative radiation resistances in each of the arrays considered. Elements having negative radiation resistances are absorbing power from the rest of the array, and are evidence of badly behaved arrays. The worst of the arrays considered had 38 elements with negative radiation resistances, nearly half of the entire array. As was expected, the bad cases occurred mostly for $X^I/X_{11} = -1$ and -2 , and more often for the small ka than for the larger ka . For $ka=0.5$, negative radiation resistances occurred over a wider band of X^I/X_{11} at small steering angles than for large steering angles. However, for $ka=1.5$, the only occurrences of negative radiation resistances were at large steering angles. Looking at Table IV as a whole, negative radiation resistances occurred slightly more often at larger steering angles.

CONCLUSIONS

Cavitation limited power is maximum for broadside steering and $Z^I=0$. It grows worse as the steering angle increases. Velocity limited power is maximum for $Z^I=\infty$, and occurred at some optimum steering angle which was dependent upon the size of the array, with the larger arrays having a greater optimum steering angle. Negative radiation resistances occurred slightly more often for larger steering angles; and for $ka=1.5$, they only occurred for large steering angles.



David T. Porter
Mathematician

REFERENCES

- (a) D. T. Porter, Effect of Thevenin Equivalent Internal Impedance on Velocity Control, etc., USL Report No. 648, 2 April 1965.
- (b) D. T. Porter, Broadband Velocity Control, USL Tech Memo No. 960-47-65, 30 June 1965.
- (c) C. H. Sherman, "Effect of the Nearfield on the Cavitation Limit of Transducers," Journal of the Acoustical Society of America, Vol. 35, No. 9, September, 1963, p. 1409.
- (d) N. T. Chin, Radiation Resistance and Cavitation Factor of Rectangular Arrays with Beam Steering, USL Report No. 681, 6 November 1965.

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TABLE II

EXPLANATION OF TEST

AVERAGE RADIATION RESISTANCES R_{PCA}
FOR 80 ELEMENT STEERED ARRAYS

	1 R_a	2 X_{12}/X_{11}	3	BROADSIDE 0°	5°	30°	45°	60°	75°	ENDFIRE 90°	11
1	0.5	EQUAL VELOCITY ∞		776	776	822	1042	990	848	785	
2		+1		774	787	864	1032	1221	1132	1970	
3		0		752	772	852	1038	1312	1207	945	
4		-1		747	670	300	178	737	120	7049	
5		-2		637	822	418	242	293	273	264	
6		-3		769	1030	831	690	645	567	545	
7	V	-5		746	701	927	1110	809	664	621	
8	1.0	EQUAL VELOCITY ∞		789	807	864	981	1252	1110	975	
9		+1		791	813	864	982	1269	1468	1273	
10		0		789	813	866	984	1302	1718	1303	
11		-1		650	294	263	075	051	016	068	
12		-2		777	819	702	632	327	497	430	
13		-3		767	811	826	1010	1223	818	700	
14	V	-5		784	802	870	970	1322	952	823	
15	1.5	EQUAL VELOCITY ∞		724	801	839	813	1104	1165	1161	
16		+1		723	812	840	818	1111	1279	1213	
17		0		728	813	848	823	1155	1336	1200	
18		-1		734	807	857	826	1147	1501	1560	
19		-2		728	802	852	1013	918	188	379	
20		-3		724	806	850	875	1363	1360	1284	
21	V	-5		723	804	849	838	1228	1241	1194	

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TABLE III

EXPLANATION OF TEST

AVERAGE RADIATION REACTANCES X_{pca}

FOR 80 ELEMENT STEERED ARRAYS

	1 k_a	2 X_{11}^2	3	BROADSIDE 4 $\theta = 0^\circ$	5 15°	6 30°	7 45°	8 60°	9 75°	ENDFIRE 10 90°	11
1	0.5	1.0 VELOCITY		.166	.152	.176	.397	.692	.863	.908	
2		+1		.153	.159	.186	.296	.618	1.089	1.237	
3		0		.133	.145	.172	.266	.614	1.267	1.443	
4		-1		.194	.450	.338	.375	.597	.444	.455	
5		-2		.683	.485	.633	.627	.826	.802	.721	
6		-3		.268	.870	.323	1.061	.892	.822	.793	
7	V	-5		.184	.195	.7027	.619	.816	.856	.860	
8	1.0	1.0 VELOCITY		.123	.132	.156	.200	.555	1.020	1.149	
9		+1		.124	.128	.154	.211	.412	1.038	1.417	
10		0		.135	.137	.160	.221	.364	1.174	1.749	
11		-1		.211	.242	.516	.664	.485	.593	.608	
12		-2		.220	.211	.216	.543	.923	1.167	1.106	
13		-3		.139	.164	.104	.212	.626	1.107	1.083	
14	V	-5		.122	.145	.138	.200	.678	1.076	1.116	
15	1.5	1.0 VELOCITY		.209	.149	.179	.345	.680	1.492	1.714	
16		+1		.205	.145	.166	.329	.534	1.356	1.681	
17		0		.202	.153	.164	.328	.494	1.361	1.674	
18		-1		.209	.155	.174	.344	.535	1.088	1.553	
19		-2		.215	.152	.173	.236	.597	1.574	1.359	
20		-3		.213	.151	.174	.340	.638	1.598	1.729	
21	V	-5		.210	.155	.183	.363	.766	1.623	1.773	

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TABLE IV

EXPLANATION OF TEST

NUMBER OF ELEMENTS HAVING NEGATIVE
RADIATION RESISTANCES IN 80 ELEMENT
STEERED ARRAYS.

	k_a	$\frac{x^2}{x_0}$		$\theta =$ (STEERING ANGLE)							
				0°	15°	30°	45°	60°	75°	90°	11
1	0.5	1		0	0	0	0	0	0	0	
2		0		0	0	0	0	0	0	0	
3		-1		20	24	14	24	28	38	38	
4		-2		16	10	12	22	16	8	8	
5		-3		8	6	8	8	0	0	0	
6		-5		4	4	0	0	0	0	0	
7											
8	1.0	1		0	0	0	0	0	0	0	
9		0		0	0	0	0	0	0	0	
10		-1		4	16	16	24	28	32	34	
11		-2		4	4	10	10	12	6	4	
12		-3		0	2	2	0	2	0	0	
13		-5		0	0	0	0	0	0	0	
14											
15	1.5	1		0	0	0	0	0	0	0	
16		0		0	0	0	0	0	0	0	
17		-1		0	0	0	0	0	0	0	
18		-2		0	0	0	2	8	12	4	
19		-3		0	0	0	0	0	0	0	
20		-5		0	0	0	0	0	0	0	
21	NOTE: NEGATIVE RADIATION RESISTANCES DID NOT OCCUR FOR EQUAL VELOCITY CASES										

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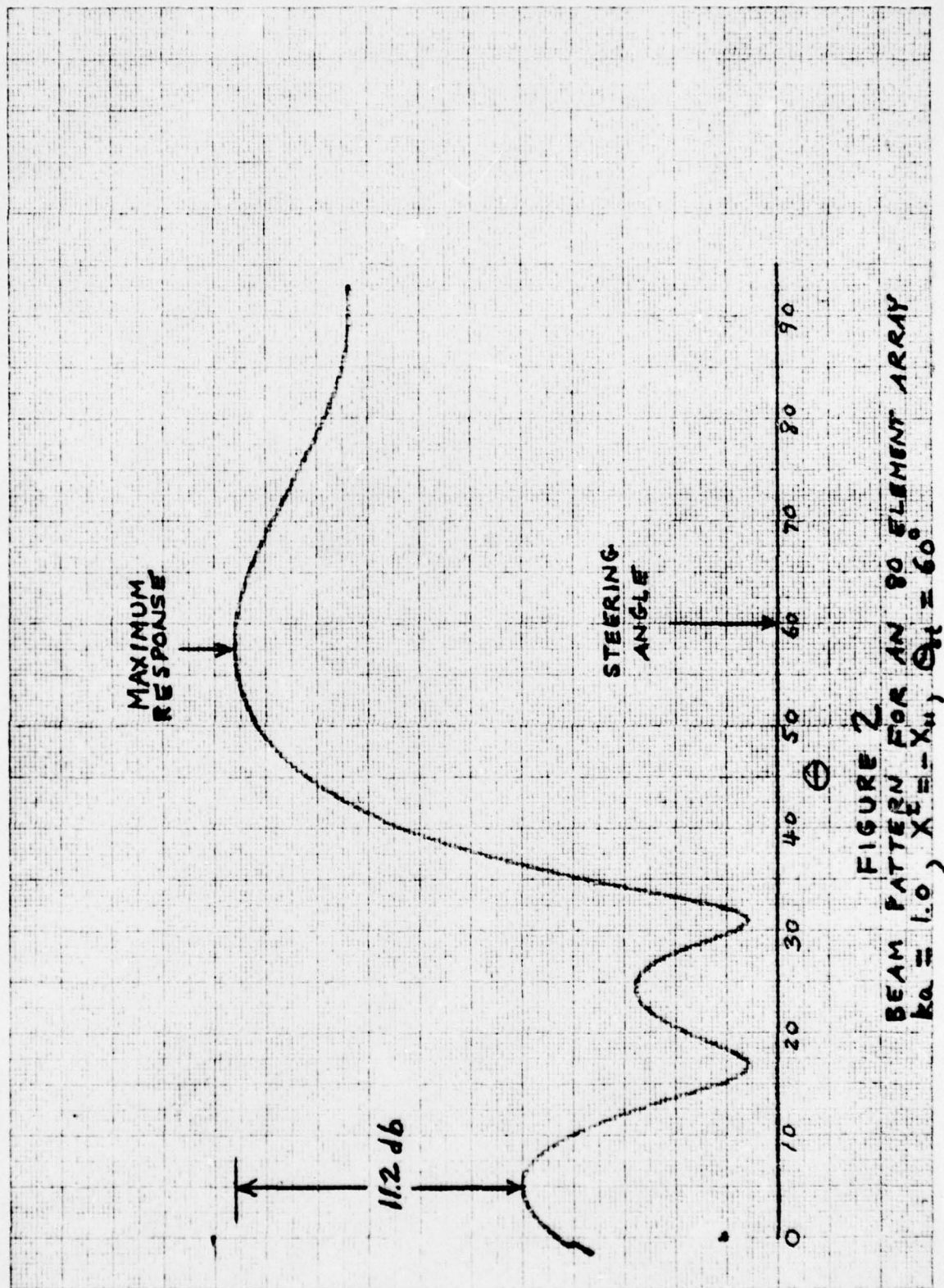
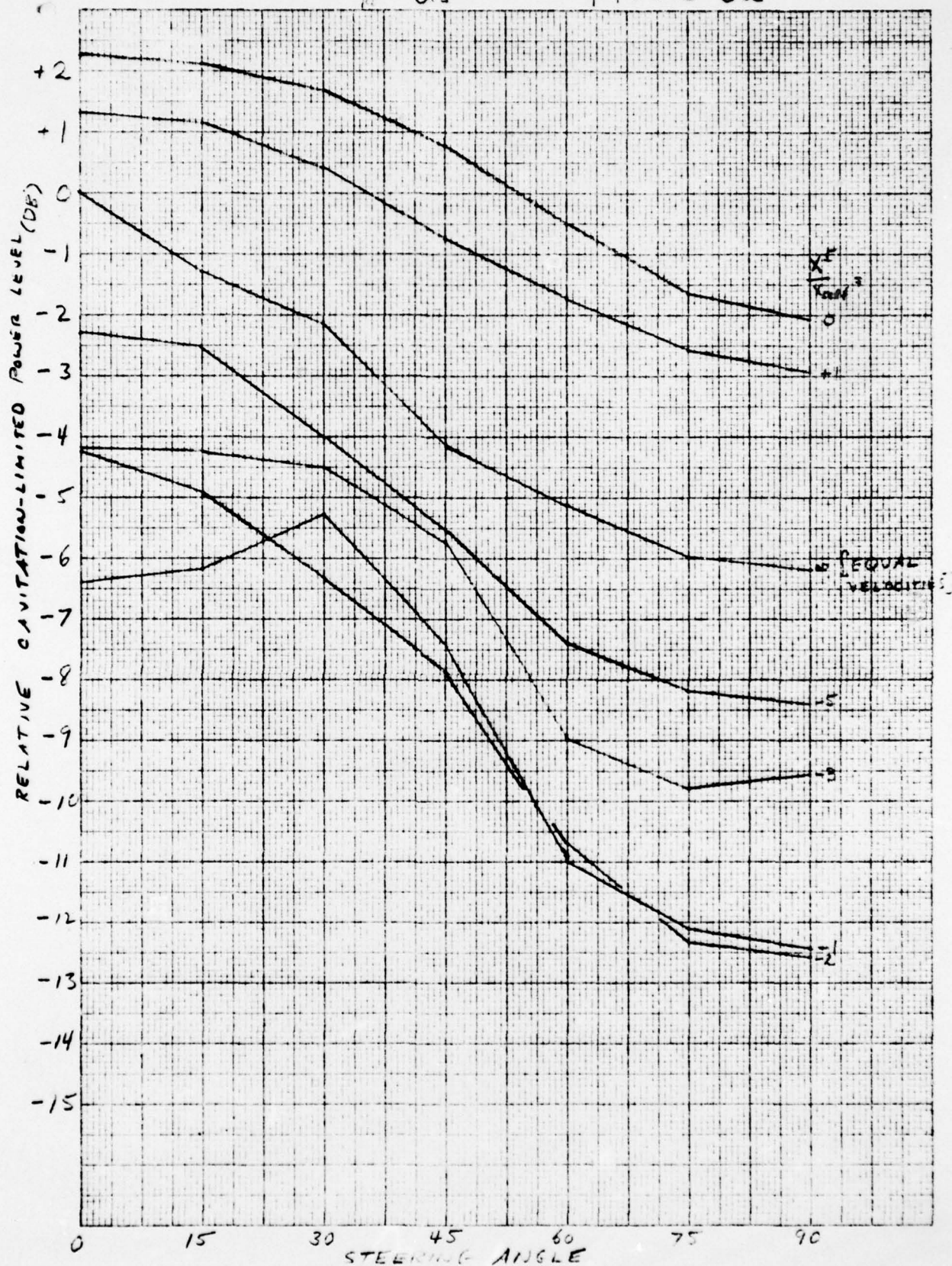


FIGURE 2
 BEAM PATTERN FOR AN 80 ELEMENT ARRAY
 $ka = 1.0$, $X_E = -X_H$, $\Theta_H = 60^\circ$

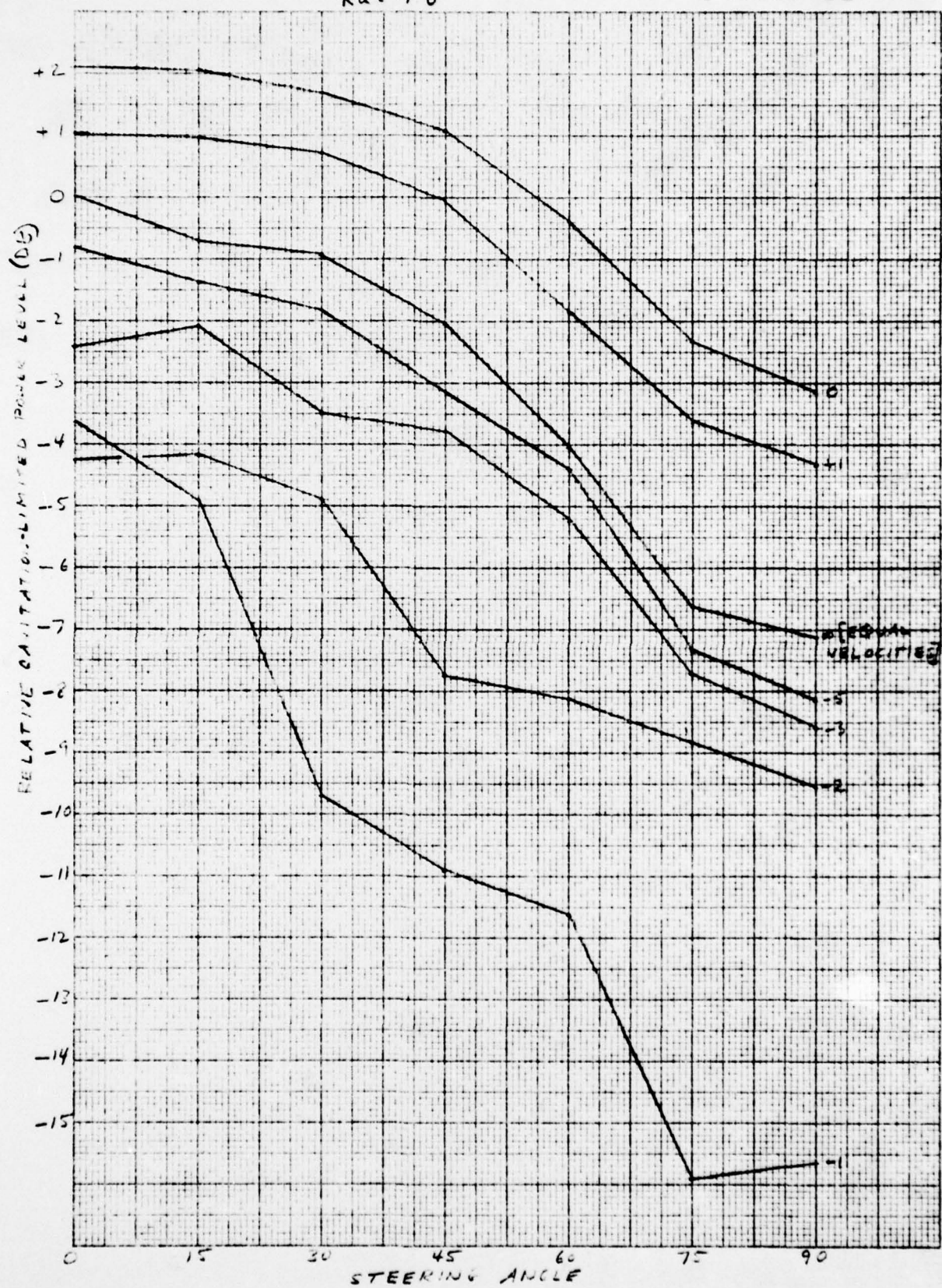
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FIGURE 3a



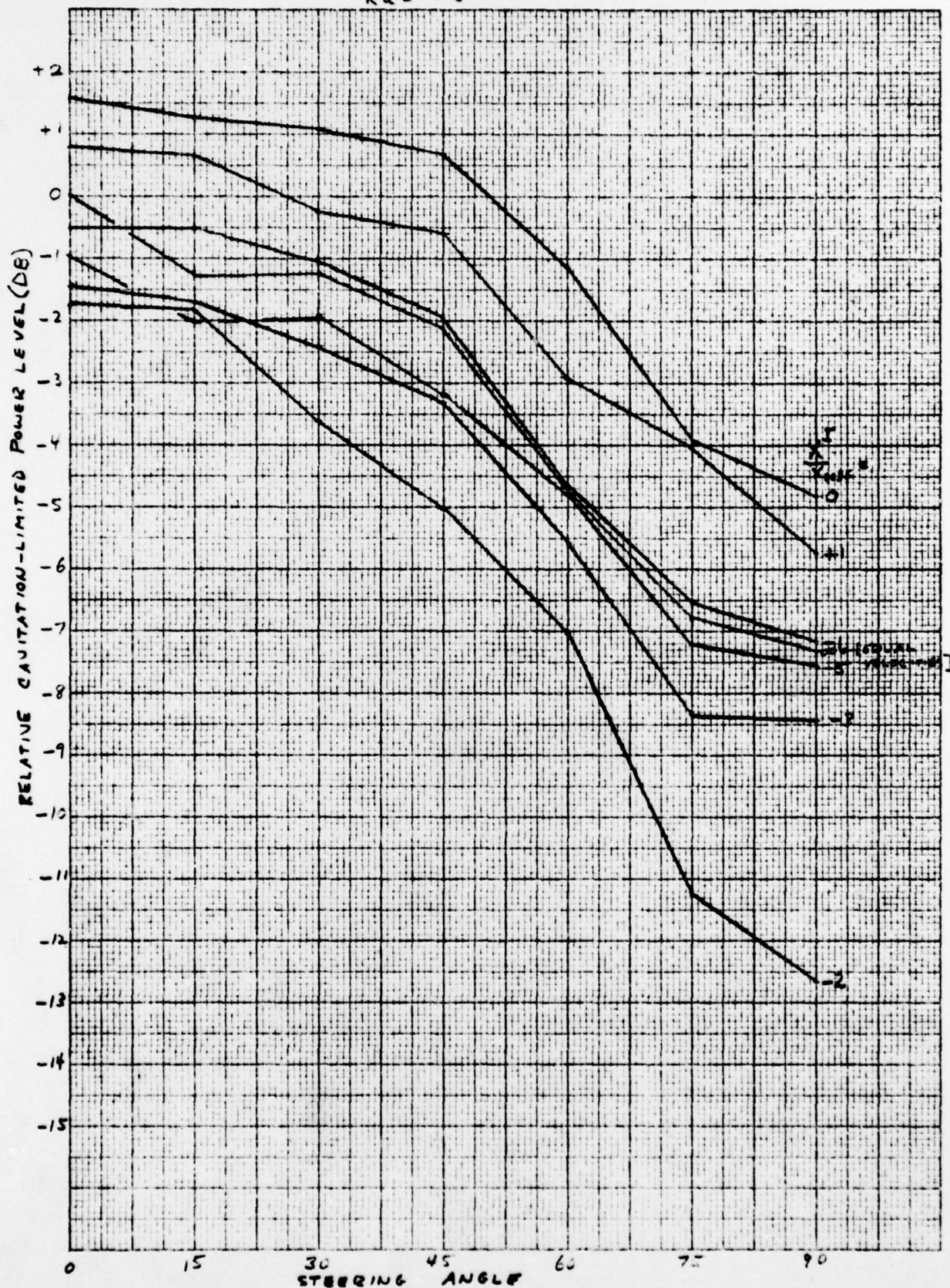
$ka = 1.0$

FIGURE 3b



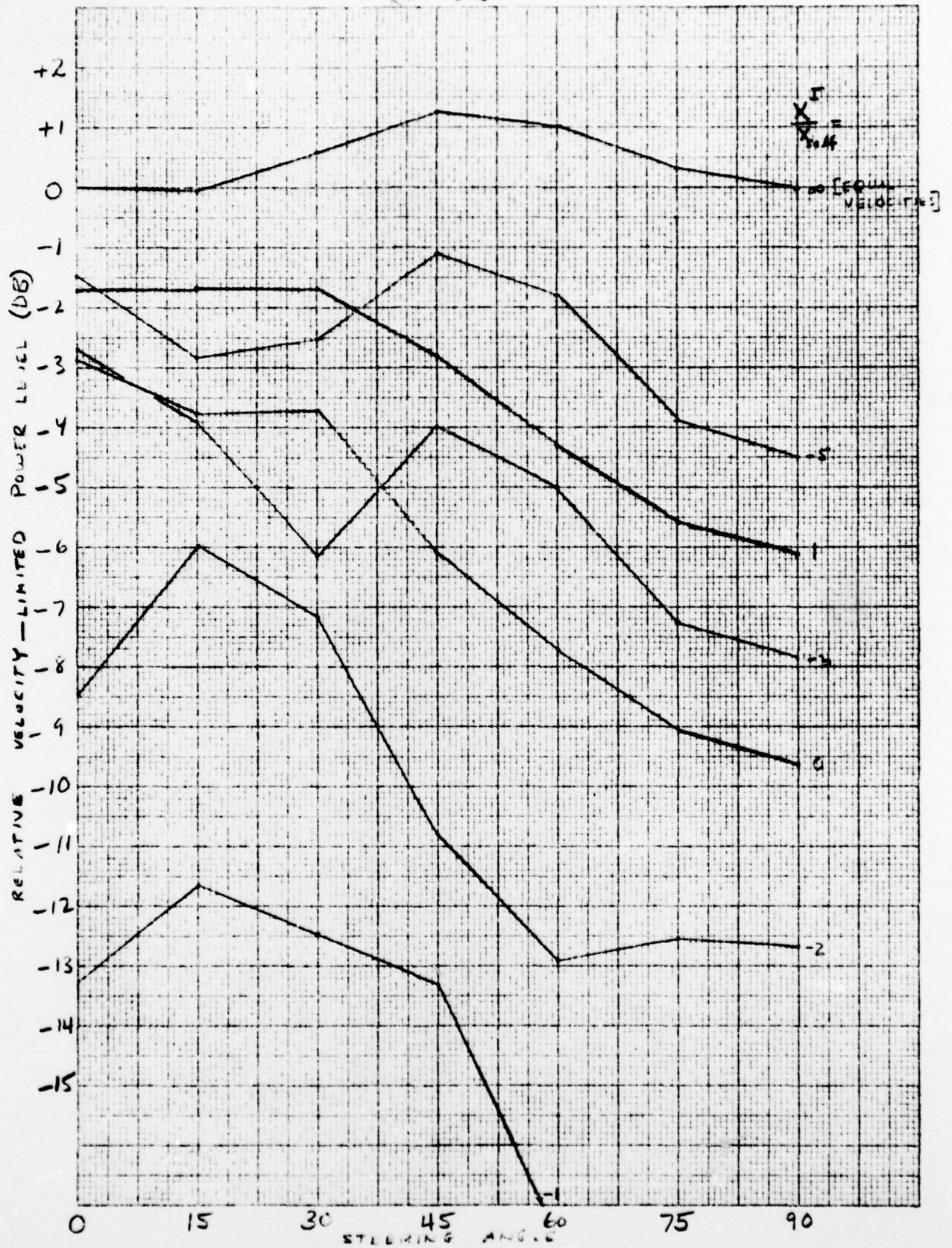
$ka = 1.5$

FIGURE 3a



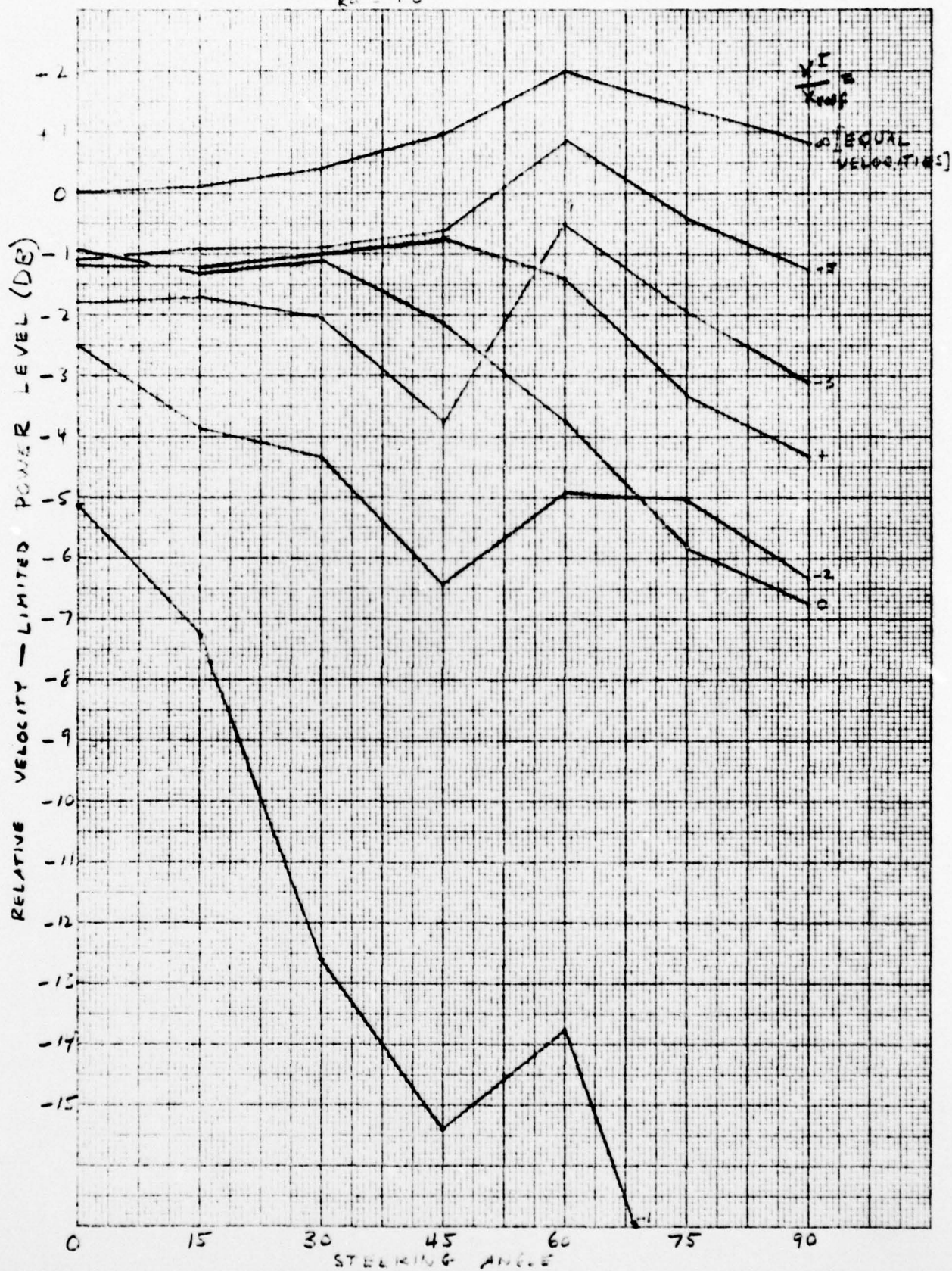
R 0.5

FIGURE 40



$$k_a = 10$$

Figure 46



Rm 15

FIGURE 4C

