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Simultaneous Multibeam Phase Compensation

XI. A RESISTIVE-ELEMENT PHASE COMPENSATOR

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THE PROBLEM

Evolve new techniques for sonars to improve low-frequency beam formation, reduce or eliminate mechanical beam steering by the application of electrical delay or phase compensation, and realize 100 per cent time utilization by simultaneous observation in all directions.

Specifically, this report deals with the design, construction, and evaluation of a phase compensator which uses resistive, rather than transformer, circuit elements.

RESULTS

1. A single-beam, resistive-element phase compensator network was designed and constructed for the 48-element array of the AN/SQS-4 Mod 3 sonar with half-wavelength spacing. Its performance was determined in the laboratory by use of Sonar Test Set TS-826/SQS-4 and Target Signal Simulator Control C-1458/SQS-4.

2. The phase compensator produced a single beam which, with its minor lobes, was essentially identical to the beams produced by the 48-beam transformer phase compensator, which was designed for the AN/SQS-4 Mod 3 sonar and was tested in the same way.

3. Satisfactory operation of the phase compensator throughout the frequency range within ±17 per cent of the design frequency was demonstrated, yielding beam patterns which were very similar to the transformer phase compensator patterns obtained in the same way.

4. Compared to the multibeam transformer phase compensator, the multibeam resistive phase compensator will be more reliable in operation. Further advantages are reductions in weight, size, and cost made possible by printed circuit or microminiature techniques. Manufactur-

ing, especially in large quantities, will be expedited, and testing and maintenance simplified. The equipment offers considerable flexibility for interchange in the event of operational or combat damage.

RECOMMENDATIONS

1. Make available the information in this report to interested contractors along with the recommendation that they consider the use of the resistive-element phase compensator for those sonar receiving systems in which the transformer phase compensator had been considered or planned.

2. Design and construct, at NEL, a multiple-beam, resistive-element phase compensator and conduct complete tests to investigate the multiple network intercoupling effects.

ADMINISTRATIVE INFORMATION

Work on the resistive phase compensator was carried out by members of the Special Research Division under AS 02101, SF 001 03 04, Task 8051 (NEL L3-2) as a portion of the sonar techniques program.

The report covers work from February 1958 to October 1958, and was approved for publication 4 December 1962.

The single-beam resistive phase compensator was designed by the authors from information on the AN/SQS-4 Mod 3 transformer phase compensator supplied by C. J. Krieger, and was constructed by J. A. Thomson.

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PREFACE

This report is Part XI in the series on Simultaneous Multibeam Phase Compensation. The other NEL reports in the series[1-11] are listed below, with brief notation of the phase compensating devices and related studies with which they are concerned. Bibliographic description of these reports, and a list of other publications containing related information, are given in the list of references at the end of this report.

NEL Report 582 (which preceded the numbered parts of the series) describes the first phase compensation device built at NEL, along with its theory, called the "Scope Presentation Array Compensator." It used synchros to provide sums of the vector components of hydrophone electrical signals for respective application to the x and y deflection plates of an oscilloscope.

Parts I and II (NEL Report 632) were the first discussion of the theory of multiple-beam phase compensation. They describe the second phase compensation device built at NEL, the "Transformer Coupled Potentiometer Compensator." This device utilized resistive elements in a high-impedance, series-summation, multiple-beam matrix with x-y scope presentation.

Part III (NEL Report 642) describes the pilot model which was the third phase compensating device built at NEL, and which was the first to utilize a transformer network with multiple secondaries to achieve multiple-beam formation. Test results are given.

Part IV (NEL Report 670) gives more detailed laboratory test results of the pilot model described in Part III. Two appendixes present the general theory of phase compensation and its application to linear arrays.

Part V (NEL Report 674) describes the fourth phase compensating device built at NEL, a laboratory breadboard for the circular array of the AN/SQS-4 Mod 1 sonar, with results of a laboratory evaluation.

Part VI (NEL Report 757) describes the fifth phase compensating device built at NEL, a phase compensator for use with the Lorad (linear array; 40 elements; 100 feet long) station-keeping system.

Part VII (NEL Report 806) describes the sixth phase compensating device built at NEL, a phase compensator for use with the AN/SQS-11 (25.5 kc/s) sonar, with results of a laboratory evaluation. In an appendix the theory of phase compensation as applied to circular arrays is presented.

Part VIII (NEL Report 851) describes the design and laboratory evaluation of the seventh phase compensating device built at NEL, a phase compensator for the AN/SQS-4 Mod 3 sonar.

Part IX (NEL Report 985) describes the receiving system for an AN/SQS-4 Mod 3 sonar designed for use with an NEL phase compensator (Part VIII). This 48-beam receiving system, with AGC beam amplifiers and video and audio displays, was installed on USS BRIDGET (DE 1024) and sea tested in April 1959. A complete system description and test results are given.

Part X (NEL Report 1009) describes a technique which enables phase compensators to operate over a wide-band frequency range by adding extra sets of secondary windings to selected transformer cores (hydrophone channels) to cover the additional frequency bands desired. Also briefly described is a three-frequency band phase compensator constructed for azimuthal beam formation for the AN/SQS-23 sonar for either receiving or low level (1 kw) transmission. This is the eighth phase compensating device built at NEL.

Part XI, the present report, describes a resistive-element phase compensator.

Part XII (NEL Report 1108) gives a very comprehensive summary of phase compensation and array design.

INTRODUCTION

The transformer phase compensator has been providing preformed receiving beams satisfactorily for several years in various experimental sonar systems at NEL, and recently it has been adopted for use to provide a complete set of horizontal azimuth beams in the AN/SQS-26 sonar. It can also be backfitted on AN/SQS-29 series sonars now in the Fleet (replacing the scanning switch system) as part of a program to improve performance. A prototype, AN/SQS-29 (XN-2), has been tested at sea on USS HANSON (DDR 832). Further tests are continuing on other ships.

The phase compensator additionally lends itself to the formation of vertical beams for either transmission or reception.

Because of its demonstrated usefulness, and also because of the increased interest in the phase compensator for use in Fleet sonar systems, the authors developed, in 1958, an analogous phase compensator which is felt to be more practical for Fleet use, in receiving systems, than the transformer type heretofore used. It is this analogous, resistive-element phase compensator which this report will describe and discuss.

DEFINITION OF SYMBOLS

d	Spacing of two adjacent array elements, in feet
E_c	Equivalent cosine generator voltage
$\bar{E}_c$	Voltage on cosine bus proportional to $\sum_{i=-N/2}^{i=N/2} \sigma_i \cos \bar{\theta}_{oi}$
E_{co}	Voltage across R_L produced by E_c
E_i	Signal amplitude at element i
E_o	Beam output voltage, resistive phase compensator
E_s	Equivalent sine generator voltage
$\bar{E}_s$	Voltage on sine bus proportional to $\sum_{i=-N/2}^{i=N/2} \sigma_i \sin \bar{\theta}_{oi}$
E_{sc}	Quadrature sum of X and Y
E_{so}	Voltage across R_L produced by E_s
E_x	A voltage introduced at a beam output, with zero input from the array preamplifiers, to establish degree of beam-to-beam cross talk. $E_x = E_o$ for any given consideration.

DEFINITION OF SYMBOLS (Continued)

e_{si}, e_{ci}	Voltages generated at i^{th} element of the resistive phase compensator. $E_i = e_{si} = e_{ci}$ in amplitude, but e_{si} and e_{ci} may be of opposite polarity (180° phase difference).
e_x	Cross-talk voltage from a given beam network across the resistance of a generator (preamp) contributing to that beam
i	Element number
K	Constant in resistive phase compensator

$$K = \frac{1}{\sum_{i=-N/2}^{i=N/2} \left| \sigma_i \cos \overline{\theta}_{oi} \right|}$$

k	$2\pi/\lambda$ (wave number)
N	Number of elements in array
N_c	Number of cosine winding turns
N_s	Number of sine winding turns
R	Quadrature sum of X and Y. $R = X - jY$
R_c	Equivalent parallel resistance of the r_{ci}
R_L	Load resistance of resistive phase compensator beam
R_o	Value of characteristic resistance in resistive phase compensator. $R_o = R_s = R_c = \omega L = 1/\omega c$

DEFINITION OF SYMBOLS (Continued)

R_s	Equivalent parallel resistance of the r_{si}
r	Radius of circle of hydrophone elements, circular array
r_g	Generator (preamplifier) resistance
r_{ci}	Cos attenuating resistor for i^{th} element
r_{si}	Sin attenuating resistor for i^{th} element
S_i	Signal vector at element i. $S_i = E_i \exp j\bar{\theta}_i$
X	Sum of cosine multiplied signals
Y	Sum of sine multiplied signals
γ_k^c, γ_k^s	Coupling correction factors
β	$180°/N$
θ	Azimuthal direction of arrival of sound measured from array normal or axis of symmetry
$\bar{\theta}_i$	Phase at i^{th} element, referred to a reference point, for any direction of arrival of sound $\theta_c = kr \{\cos[\theta - (i \mp \frac{1}{2})\beta] - 1\}$

DEFINITION OF SYMBOLS (Continued)

$\bar{\theta}_{ci}$ or $\bar{\theta}_{oi}$	Phase at i^{th} element, referred to a reference point, for sound arriving from direction of compensation (subscript c for linear array, and o for circular array)
σ_i	Shading factor of i^{th} element

$$\bar{\theta}_{oi} = kr\,[\cos\,(i \mp \tfrac{1}{2})\,\beta - 1]$$

$$\bar{\theta}_{ci} = [i - (\tfrac{1}{2})]\,kd \sin \bar{\theta}_c$$

DISCUSSION OF BEAM FORMATION

To obtain a maximum response to signals from any one direction by an acoustic array (or portion of an array) of any configuration, the electrical signals generated by each element of that array must in some manner be caused either to add together as though all elements had received the acoustic signal at the same time or, in the event that the "signal" is a periodic wave train, to add the signals from each element "in-phase" with one another for the arrival of sound from the direction of compensation. The first instance occurs naturally without compensation, for example, in a linear array as a consequence of its shape. A plane-wave signal coming from anywhere in a plane perpendicular to a straight line through the elements actually arrives at all of them at the same time. To "look" in any other direction with a linear array, the electrical signal from each element can be delayed by the proper amount and then electrically added to the last element's undelayed signal at the time that it is generated. The first situation also occurs naturally, without compensation, for circular arrays, if a plane-wave acoustic signal arrives from either direction perpendicular to the plane of the array, since it arrives at all of the elements simultaneously. Again, to "look" in any other direction, each element's electrical signal can be delayed by the proper amount of time and added to the last element's undelayed electrical signal at the time it is generated.

Electrical delay lines have been the primary means of accomplishing these necessary electrical delays in the past. With the requirements of new large sonar arrays and the use of multiple preformed beams, the large number of delays and/or long delay periods necessitate almost prohibitively large, heavy, and costly delay line installations which, with their stringent requirements, approach the limit of the state of the art. Another relatively new method of accomplishing the necessary delays uses digital delay (shift registers).[12] These are more compact than delay lines and somewhat less costly. There are several other ways in which the signals can be delayed, such as by magnetic tape and drums, and by film and thermoplastic techniques. These offer promise, particularly for very large sophisticated systems.

However, if a single-frequency periodic wave train (as a "ping" from typical active sonars in the Fleet) is used, it may not be necessary to delay a particular place in the wave train by the full time of travel of the acoustic wave from the first element in the array to the last. Instead, the individual elements can have their electrical signals operated on so that they electrically add "in-phase" (coherently) for any particular direction of sound arrival. They will add in various phases for sound arriving from any other direction, so the total response of the array to the periodic signal arriving from the direction of compensation will be greater than that for arrival from any other direction. This is what the phase compensator accomplishes.

Delay lines are basically broadband, passive devices which pass both amplitude and phase (or time) information; shift registers are active broadband devices which pass quantized phase (or time) information only; phase compensators are basically passive, single-frequency, or narrowband devices which pass both amplitude and phase information.

Delay lines for low frequencies and long delays are large, heavy, and expensive; they are, however, generally reliable. Shift registers, for long delays, are much more compact than delay lines and somewhat less costly; they have a somewhat lower probability of reliability, using conventional components, since the reliability factor of at least one component, the transistor, is added relative to the delay line. Phase compensators are very compact and inexpensive, compared to both delay lines and shift registers, with a higher probability of reliability since, for the transformer phase compensator, the only circuit elements are toroidal transformers plus one or two capacitors and resistors (90° phase shifters) per beam. For the resistive phase compensator the only circuit elements are resistors, plus only one capacitor and one inductor (90° phase shifter) per beam; their main limitation is, of course, that they are intended to operate only over a narrow frequency range. An earlier report[10] describes a technique to enable basic phase compensators for circular arrays to operate satisfactorily over a wide frequency range, with slight modification. The same method is also applicable to the resistive phase compensator.

COMPARISON OF THE TRANSFORMER AND THE RESISTIVE PHASE COMPENSATORS

Phase compensators perform four basic operations to accomplish their "in-phase" addition of the hydrophone signals in an array to form a beam:*

1. Multiplication of each hydrophone signal by a quantity proportional to cos $\overline{\theta}_{oi}$, and summation of all "cos $\overline{\theta}_{oi}$" multiplied signals of the contributing hydrophones to give a resultant X component of the voltages.

2. Multiplication of each hydrophone signal by a quantity proportional to sin $\overline{\theta}_{oi}$, and summation of all "sin $\overline{\theta}_{oi}$" multiplied signals of the contributing hydrophones to give a resultant Y component of the voltages.

3. Vector rotation of the result of operation (2) through -90° to make this resultant $-jY$.**

4. Summation of X and $-jY$, where the new resultant, which is the beam response, is

$$R = X - jY \tag{1}$$

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*See ref. 5, p. 7 and ref. 6, p. 14.

**The required vector rotation could be introduced before summation, rather than after, as for example at the output of each array element, or at the completion of the multiplication of each hydrophone signal. Either of these methods, however, requires more phase shift networks than vector rotation after summation.

Transformer Phase Compensator

The four basic operations performed by the transformer phase compensator are as follows (fig. 1):

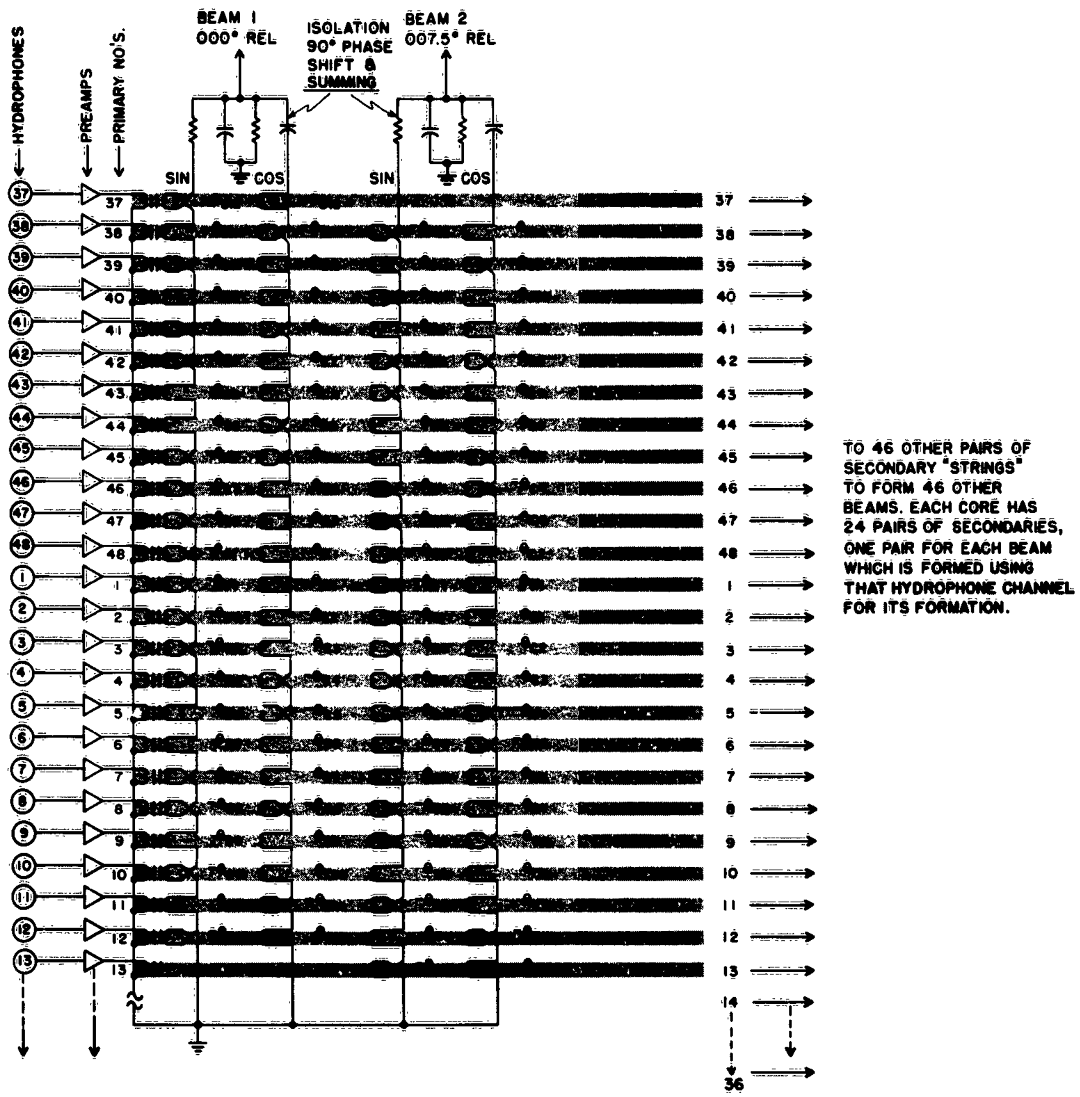
1. To multiply each hydrophone signal by a quantity proportional to cos $\bar{\theta}_{oi}$, the signal is applied to the primary of a transformer whose secondary turns are proportional to cos $\bar{\theta}_{oi}$. To sum this with the other signals which have been multiplied by their cos $\bar{\theta}_{oi}$, the secondary is connected in series with the secondaries of the other hydrophone transformers. All primaries have an equal number of turns.

2. To multiply each hydrophone signal by sin $\bar{\theta}_{oi}$ another secondary is placed on the transformer of step 1 and its turns are proportional to the sin $\bar{\theta}_{oi}$. To sum this voltage with the other signals which have been multiplied by sin $\bar{\theta}_{oi}$, these secondary turns are connected in series with the "sine" secondaries of the other hydrophone transformers.

3. Vector rotation ($-jY$) is performed with a phase shift network. Either Y can be rotated $-90°$; or X can be rotated $+45°$ and Y, $-45°$; or any other desired combination can be used, as long as the relative phase shift is 90°.

4. Summation of the two resultant vectors, X and $-jY$, is performed in a summation network. The phase shift and final summation can be suitably accomplished at one time in a single combined network.

It should be noted that the sin $\bar{\theta}_{oi}$ and cos $\bar{\theta}_{oi}$ will have either (+) or (-) values, or both. The (-) secondaries are tied in series with their winding ends reversed to obtain the (-) terms, i.e., those 180° out of phase with the (+) secondaries.



NOTE: EACH PRIMARY COUPLES INDUCTIVELY TO ITS SECONDARIES IN THE HORIZONTAL ROW TO ITS RIGHT.
(THE SHADED AREAS REPRESENT THE TOROIDAL TRANSFORMER CORES FOR THE WINDINGS SHOWN SUPERIMPOSED ON THEM.)
THERE IS ONE PRIMARY FOR EACH HYDROPHONE CHANNEL, AND ONE PRIMARY FOR EACH CORE. ALL PRIMARIES HAVE THE SAME NUMBER OF TURNS.

Figure 1. Formation of two adjacent receiving beams for the AN/SQS-4 Mod 3 sonar by use of the transformer phase compensator. Only 24 of the 48 hydrophones in the array are used for each beam. This exemplifies transformer phase compensator beam formation for any circular array. Linear arrays use all the hydrophones to form each beam.

Resistive Phase Compensator

The four basic methods by which the transformer phase compensator operates on the signal (as described in the preceding section) are performed by the resistive phase compensator as follows (fig. 2 and 3):

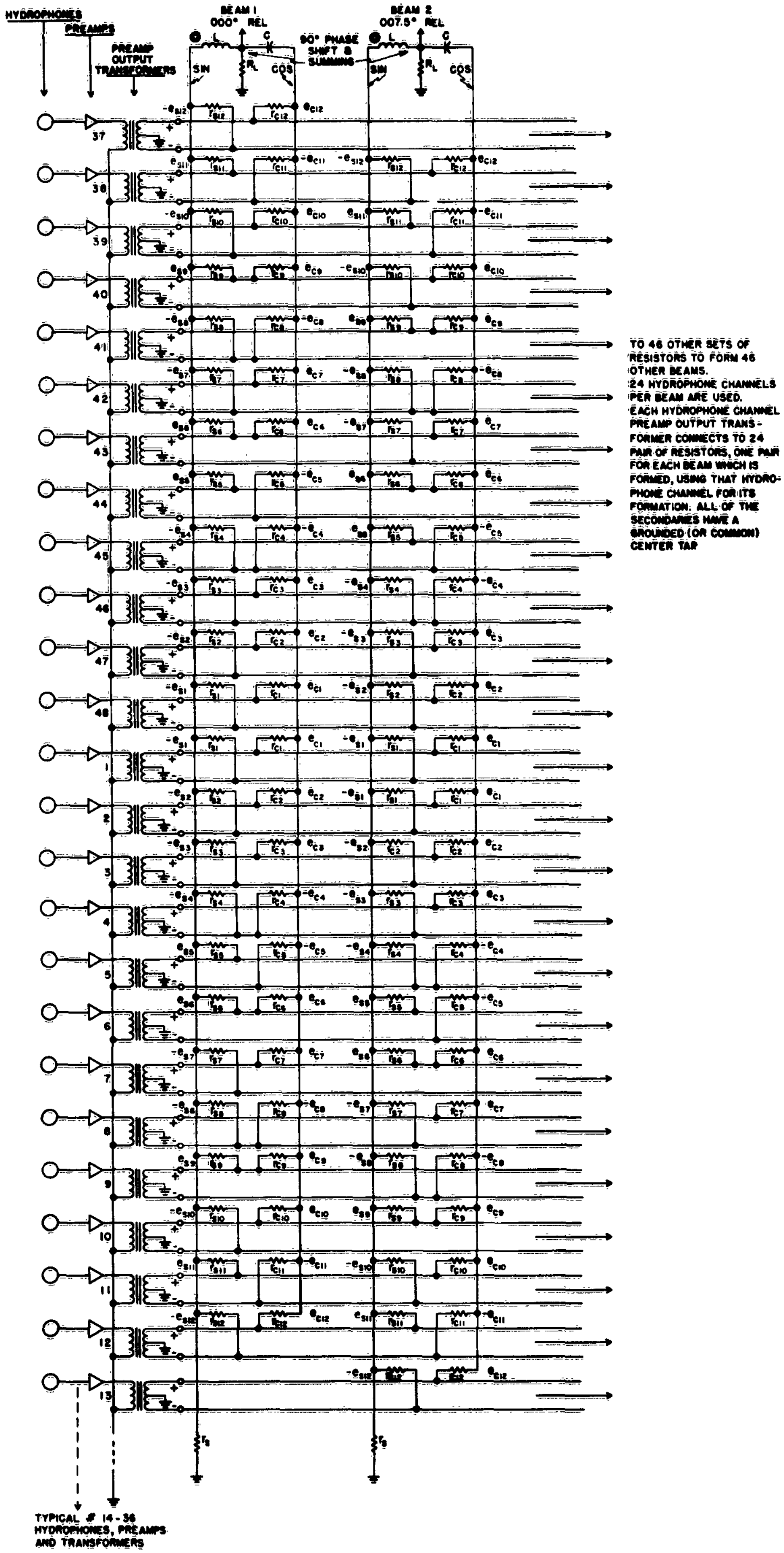
1. To multiply each hydrophone signal by a quantity proportional to cos $\overline{\theta}_{oi}$, the signal is applied to a resistor voltage divider and is attenuated to an amount proportional to cos $\overline{\theta}_{oi}$. To sum this with the other signals which have been multiplied by their cos $\overline{\theta}_{oi}$, all of the voltage dividers are designed to use a common load, which for any one divider includes also the parallel load of the other dividing resistors.

2. To multiply each hydrophone signal by a quantity proportional to sin $\overline{\theta}_{oi}$, the signal is applied to a resistor voltage divider and is attenuated to an amount proportional to sin $\overline{\theta}_{oi}$. As in step 1, the sine signals are summed into a common load.

3. Vector rotation ($-jY$) is performed in a high-Q LC network which is also simultaneously a part of all the sine and cosine voltage dividers' load. (Other types of 90° phase shift networks could be used.)

4. Summation of the two resultant vectors X and $-jY$ occurs across a common resistive load. In a sonar system this would be the input resistance of the amplifier for that beam.

Figure 2. Formation of two adjacent receiving beams for the AN/SQS-4 Mod 3 sonar by use of the resistive phase compensator. Only 24 of the 48 hydrophones in the array are used for each beam. This exemplifies resistive phase compensator beam formation for any circular array. Linear arrays use all of the hydrophones to form each beam. →


HYDROPHONES
PREAMPS
PREAMP OUTPUT TRANSFORMERS
BEAM 1 000° REL
BEAM 2 007.5° REL
90° PHASE SHIFT & SUMMING
SIN
COS
TO 46 OTHER SETS OF RESISTORS TO FORM 46 OTHER BEAMS.
24 HYDROPHONE CHANNELS PER BEAM ARE USED.
EACH HYDROPHONE CHANNEL PREAMP OUTPUT TRANSFORMER CONNECTS TO 24 PAIR OF RESISTORS, ONE PAIR FOR EACH BEAM WHICH IS FORMED, USING THAT HYDROPHONE CHANNEL FOR ITS FORMATION. ALL OF THE SECONDARIES HAVE A GROUNDED (OR COMMON) CENTER TAP
TYPICAL # 14-36 HYDROPHONES, PREAMPS AND TRANSFORMERS

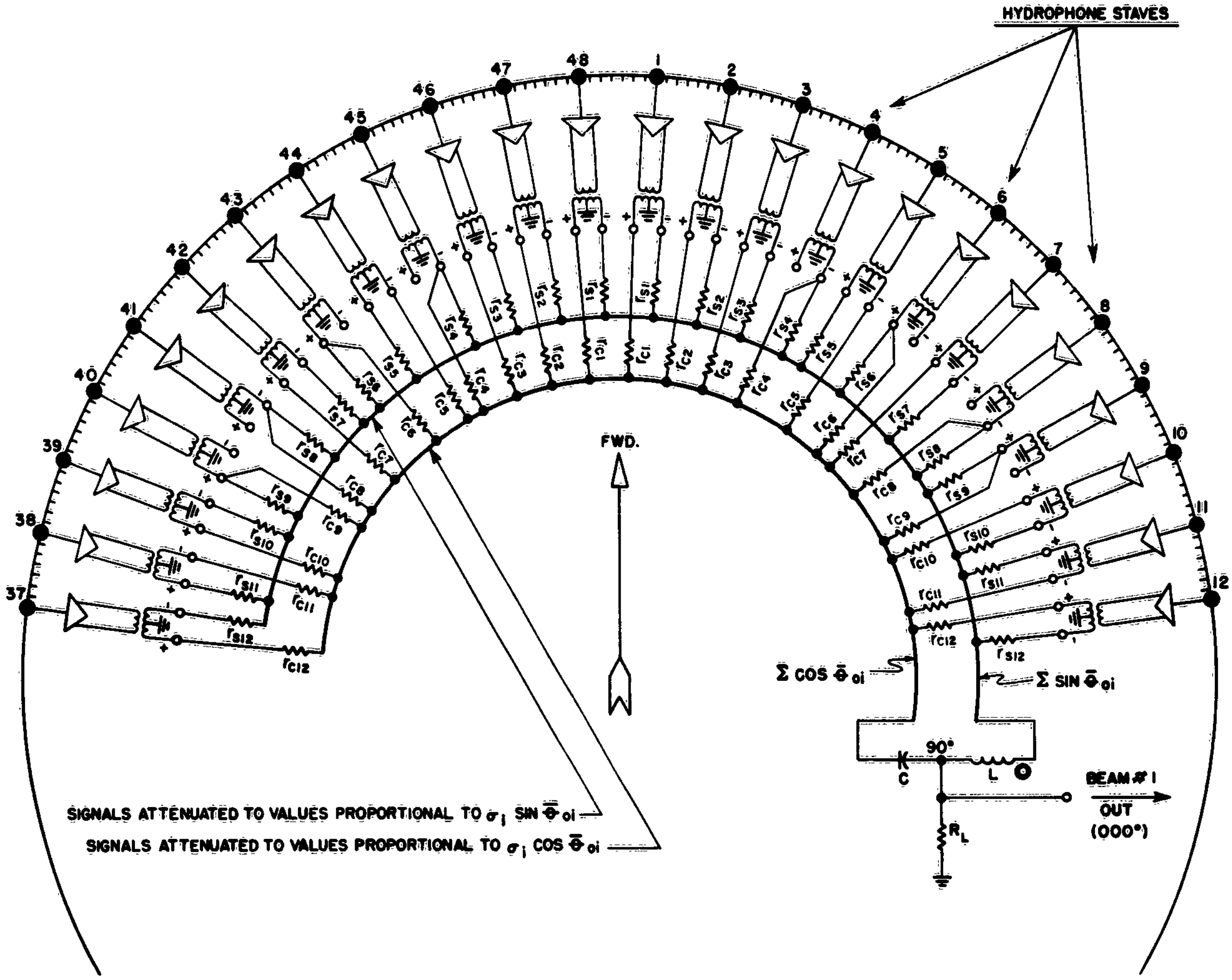


Figure 3. Formation of one beam (No. 1, 000° relative bearing) for the AN/SQS-4 Mod 3 sonar by use of the resistive phase compensator, relative to the portion of the hydrophone array used.

Other Design Parameters

Both the transformer and the resistive phase compensators must accommodate in their designs other parameters which will modify the basic response equations. In many practical arrays, directional rather than omnidirectional hydrophones are used. Each hydrophone in the array has a directivity pattern of its own which, although broader, should be considered in the array design. A second factor is the use of amplitude shading, which is employed in many current array designs and is accomplished by progressively attenuating the hydrophone channel outputs away from the center of the array (or the portion used for the beam being considered) in a particular pattern. Its purpose is to reduce the minor lobes of the directivity pattern relative to the main lobe. This factor must be included in the phase compensator design for each beam.

Only the transformer phase compensator has mutual coupling errors which reduce its performance in small degree, unless corrected in the design. These factors are tabulated on page 6 of reference 8 for the phase compensator design for a particular circular array. *

Also, in designing a phase compensator it is necessary to be able to perform the four operations in terms of the specific array configuration, namely, hydrophone spacing and arrangement in terms of the phase relations of the sound in water.** The response to sound from any direction of an unshaded circular array which has been compensated for the direction of the axis of symmetry is:

$$R = \sum_{i=-N/2}^{+N/2} E_i \exp[j(\overline{\theta}_i - \overline{\theta}_{oi})] \qquad (2)$$

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* See ref. 13, p. 43 ff.

**See ref. 7, Appendix; and ref. 8, p. 5 and 9.

The response to sound arriving from any direction, of a circular array with cosine-square law shading and allowing for the response of a single element, is:

$$R = \sum_{i=-N/2}^{+N/2} E_i \cos^2(i \mp \tfrac{1}{2})\beta \cdot \cos[\theta - (i \mp \tfrac{1}{2})\beta] \cdot \exp[j(\bar{\theta}_i - \bar{\theta}_{oi})] \qquad (3)$$

The number of secondary turns N_c and N_s, and their respective proportional voltages (for equal voltages into each primary), e_{ci} and e_{si} (fig. 1), and also the proportional attenuated voltages of the resistive compensator (fig. 2) are made proportional to the cosine and sine of $\bar{\theta}_{oi}$, respectively, in both cases:

$$N_c \text{ or } e_c \propto \cos \bar{\theta}_{oi} \qquad (4)$$

$$N_s \text{ or } e_s \propto \sin \bar{\theta}_{oi} \qquad (5)$$

The basic values above are now modified to include, for the transformer phase compensator: (1) the coupling correction factors γ_k^c and γ_k^s; (2) the shading factors, e.g., $\cos^2 (i \mp \frac{1}{2})\ 7.5°$; and (3) the maximum number of secondary turns - - chosen for the AN/SQS-4 Mod 3 to be 112:

$$N_c = \gamma_k^c \cdot 112 \cdot \cos^2 [(i \mp \tfrac{1}{2})\ 7.5°] \cdot \cos \bar{\theta}_{oi} \qquad (6)$$

$$N_s = \gamma_k^s \cdot 112 \cdot \cos^2 [(i \mp \tfrac{1}{2})\ 7.5°] \cdot \sin \bar{\theta}_{oi} \qquad (7)$$

The e_{si} and e_{ci} to be achieved for the resistive phase compensator do not include the coupling correction or the maximum number of turns and are:

$$e_{ci} \propto \cos^2 (i \mp \tfrac{1}{2})\, 7.5^\circ \cdot \cos \bar{\theta}_{oi} \tag{8}$$

$$e_{si} \propto \cos^2 (i \mp \tfrac{1}{2})\, 7.5^\circ \cdot \sin \bar{\theta}_{oi} \tag{9}$$

In general, for any array configuration, the e_{ci} and e_{si} to be achieved for a resistive phase compensator are directly proportional to the basic number of corresponding secondary turns, plus the shading factor, of a transformer phase compensator for the same array. The value of each attenuating resistor will always be related to the number of turns of each corresponding secondary winding in its transformer compensator counterpart.

The cosine resistor network is designed as a minimum loss pad for summing the signals. The sine network introduces the additional loss relative to the cosine network required by the shading factor.

DESIGN OF A RESISTIVE PHASE COMPENSATOR

Figure A-1 in Appendix A shows a resistive phase compensator in schematic form. The quantities e_{si}, e_{ci}, etc., denote the voltage outputs of the i^{th} hydrophone. They have the same amplitude, but may have opposite polarities.

The attenuating resistors r_{si}, r_{ci}, etc., are defined by equations A9 and A10 of Appendix A:

$$r_{si} = \frac{R}{K \sigma_i \sin \bar{\theta}_{oi}}$$

and

$$r_{ci} = \frac{R}{K \sigma_i \cos \bar{\theta}_{oi}}$$

where

$$R = \omega L = \frac{1}{\omega C} \qquad \text{(eqn. A6, Appendix A)}$$

and L and C are the phase-shift network elements.

$$K = \frac{1}{\sum_{i=1}^{N} |\sigma_i \cos \bar{\theta}_{oi}|} \qquad \text{(eqn. A16, Appendix A)}$$

and $\bar{\theta}_{oi}$ is the phase at the i^{th} element (also see list of symbols, p. 2). This quantity is determined by the geometry of the array.

The shading factor of the i^{th} element, σ_i, is determined by the desired minor lobe levels.

Thus all the r_{si}'s and r_{ci}'s can be found. An example of the design of a single-beam resistive phase compensator is given in the following section.

TEST RESULTS OF THE SINGLE-BEAM AN/SQS-4 MOD 3 RESISTIVE PHASE COMPENSATOR

A single-beam, 16-element, resistive phase compensator was designed (see table 1) in February 1958 and tested in October 1958 on the AN/SQS-4 Mod 3 Sonar, using Sonar Test Set TS-826/SQS-4 and the Target Signal Simulator Control C-1458/SQS-4.

TABLE 1. - Design parameters and key equations for the design of a single-beam, resistive phase compensator for the AN/SQS-4 Mod 3 sonar.

			COS					SIN				
						r_{ci}					r_{si}	
i	$\bar{\theta}_{oi}$	σ_i	$\cos\bar{\theta}_{oi}$	$\sigma_i \cos\bar{\theta}_{oi}$	$\frac{1}{\sigma_i \cos\bar{\theta}_{oi}}$	Calculated kilohms	Std. Value Used kilohms	$\sin\bar{\theta}_{oi}$	$\sigma_i \sin\bar{\theta}_{oi}$	$\frac{1}{\sigma_i \sin\bar{\theta}_{oi}}$	Calculated kilohms	Std. Value Used kilohms
+N/2 8	-522.43	0.30866	-0.95337	-0.29427	-3.3982	17.156	16.9	-0.30182	-0.09316	-10.7342	54.190	52.3
7	-400.44	0.43474	+0.76116	+0.33097	+3.0214	15.253	15.0	-0.64856	-0.28195	-3.5467	17.905	17.4
6	-291.71	0.56526	+0.37002	+0.20916	+4.7810	24.137	23.7	+0.92902	+0.52514	+1.9042	9.613	9.53
5	-198.11	0.69134	-0.95043	-0.65707	-1.5219	7.683	7.68	+0.31095	+0.21497	+4.6518	23.484	23.2
4	-121.23	0.80438	-0.51852	-0.41709	-2.3976	12.104	12.1	-0.85506	-0.68779	-1.4539	7.340	7.32
3	-62.38	0.89668	+0.46355	+0.41566	+2.4058	12.146	12.1	-0.88607	-0.79452	-1.2586	6.354	6.34
2	-22.58	0.96194	+0.92332	+0.88818	+1.1259	5.684	5.76	-0.38403	-0.36941	-2.7070	13.666	13.7
1	-2.52	0.99572	+0.99904	+0.99476	+1.0053	5.075	5.11	-0.04391	-0.04372	-22.8728	115.471	115.0
-1	-2.52	0.99572	+0.99904	+0.99476	+1.0053	5.075	5.11	-0.04391	-0.04372	-22.8728	115.471	115.0
-2	-22.58	0.96194	+0.92332	+0.88818	+1.1259	5.684	5.76	-0.38403	-0.36941	-2.7070	13.666	13.7
-3	-62.38	0.89668	+0.46355	+0.41566	+2.4058	12.146	12.1	-0.88607	-0.79452	-1.2586	6.354	6.34
-4	-121.23	0.80438	-0.51852	-0.41709	-2.3976	12.104	12.1	-0.85506	-0.68779	-1.4539	7.340	7.32
-5	-198.11	0.69134	-0.95043	-0.65707	-1.5219	7.683	7.68	+0.31095	+0.21497	+4.6518	23.484	23.2
-6	-291.71	0.56526	+0.37002	+0.20916	+4.7810	24.137	23.7	+0.92902	+0.52514	+1.9042	9.613	9.53
-7	-400.44	0.43474	+0.76116	+0.33097	+3.0214	15.253	15.0	-0.64856	-0.28195	-3.5467	17.905	17.4
-N/2 -8	-522.43	0.30866	-0.95337	-0.29427	-3.3982	17.156	16.9	-0.30182	-0.09316	-10.7342	54.190	52.3

$$\sum_{i=-N/2}^{i=N/2} \left|\sigma_i \cos\bar{\theta}_{oi}\right| = 8.4143 \qquad \sum_{i=-N/2}^{i=N/2} \left|\sigma_i \sin\bar{\theta}_{oi}\right| = 6.0213$$

Note: The values for $\bar{\theta}_{oi}$, σ_i, $\cos\bar{\theta}_{oi}$, and $\sin\bar{\theta}_{oi}$ were obtained from table 1, page 6, of reference 8. They are the values used for the design of the transformer phase compensator for the AN/SQS-4 Mod 3 sonar. Although 24 elements were used for the AN/SQS-4 Mod 3, only 16 elements were used here to form a beam.

KEY EQUATIONS

1. $R_o = 600\,\Omega$ (chosen)

2. $K = \dfrac{1}{\sum_{i=-N/2}^{i=N/2} \left|\sigma_i \cos\bar{\theta}_{oi}\right|} = \dfrac{1}{8.4143} = 0.11885$

3. $\dfrac{R_o}{K} = \dfrac{600}{0.11885} = 5048.4$

4. $r_{ci} = \dfrac{R_o}{K} \dfrac{1}{\sigma_i \cos\bar{\theta}_{oi}} = 5048.4 \dfrac{1}{\sigma_i \cos\bar{\theta}_{oi}}$

5. $r_{si} = \dfrac{R_o}{K} \dfrac{1}{\sigma_i \sin\bar{\theta}_{oi}} = 5048.4 \dfrac{1}{\sigma_i \sin\bar{\theta}_{oi}}$

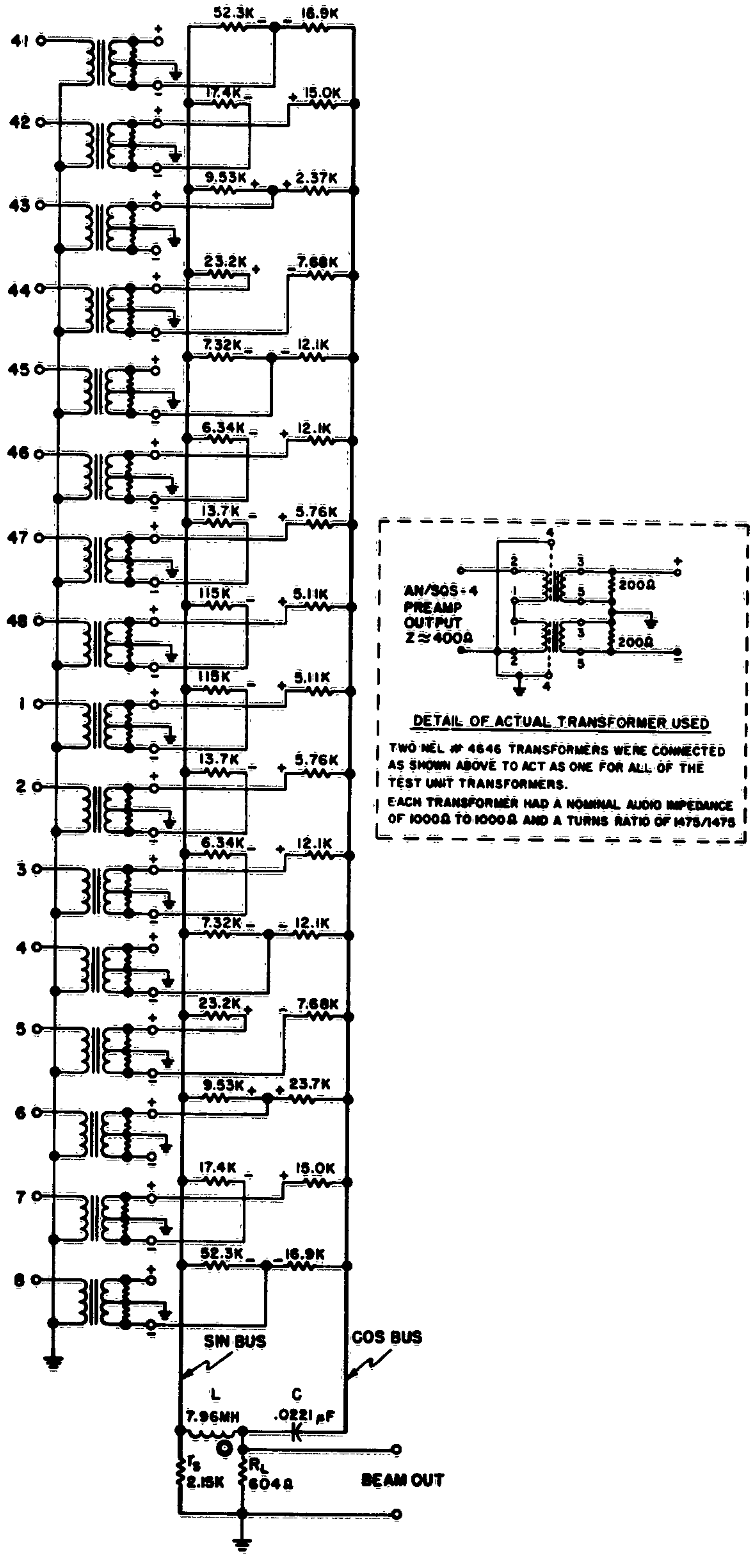
6. $r_s = \dfrac{R_o}{1 - \left[\dfrac{\sum_{i=-N/2}^{i=N/2} \left|\sigma_i \sin\bar{\theta}_{oi}\right|}{\sum_{i=-N/2}^{i=N/2} \left|\sigma_i \cos\bar{\theta}_{oi}\right|}\right]} = \dfrac{600\,\Omega}{1 - \dfrac{6.0213}{8.4143}} = \dfrac{600\,\Omega}{0.28440}$

$= 2109.7$ Std. value 2.15 kilohms

Figure 4 shows the circuit tested. The transformers used were surplus, NEL No. 4646, with 1475 turns with a nominal audio impedance of 1000Ω to 1000Ω. Two of these transformers were connected to act as one for each of the 16 circuit transformers, with a 400-ohm, center-tapped load across each secondary. The resistors used were the nearest standard value of the RN 70 B encapsulated film type, ±1 per cent, $\frac{1}{4}$ watt. The inductor L was a small toroid wound at NEL with $L = 7.96$ mh ±1 per cent and $Q = 90$. The design value of the capacitor, C, was 0.0221 μf ±1 per cent and was obtained by paralleling several glass capacitors of nominal 5 per cent tolerance and bridging them. The internal keyed oscillator of the test set was disabled for the measurement and a steady external oscillator signal, monitored by a counter, was injected into the test set. The manual target-bearing control was rotated at a slow, constant rate (approximately 1 revolution/35 seconds) by a small motor gear box attached to the shaft. This simulated, as received by 16 of the 48 elements at a time, a plane-wave source circling around the AN/SQS-4 sonar at a constant rate.

The outputs of preamplifiers No. 41 through No. 8 were then connected to the resistive phase compensator inputs, thus forming a beam in the direction of relative bearing 000°. Any other beam could have been chosen. The individual filters in each preamplifier could not easily be removed for the tests, so it was necessary to "brute force" the signals through them while measuring response of the phase compensator at other than the design frequency. Of course this resulted in much lower signal/noise ratio at ±17 per cent from the design frequency, but the most essential information remained above the noise. The output of the resistive phase compensator was amplified by a variable gain amplifier and recorded on a Brüel and Kjaer Type 2304 logarithmic recorder as a linear plot of the directivity pattern.

Figure 4. Circuitry of the single-beam, 16-element resistive phase compensator tested in October 1958. →


41
42
43
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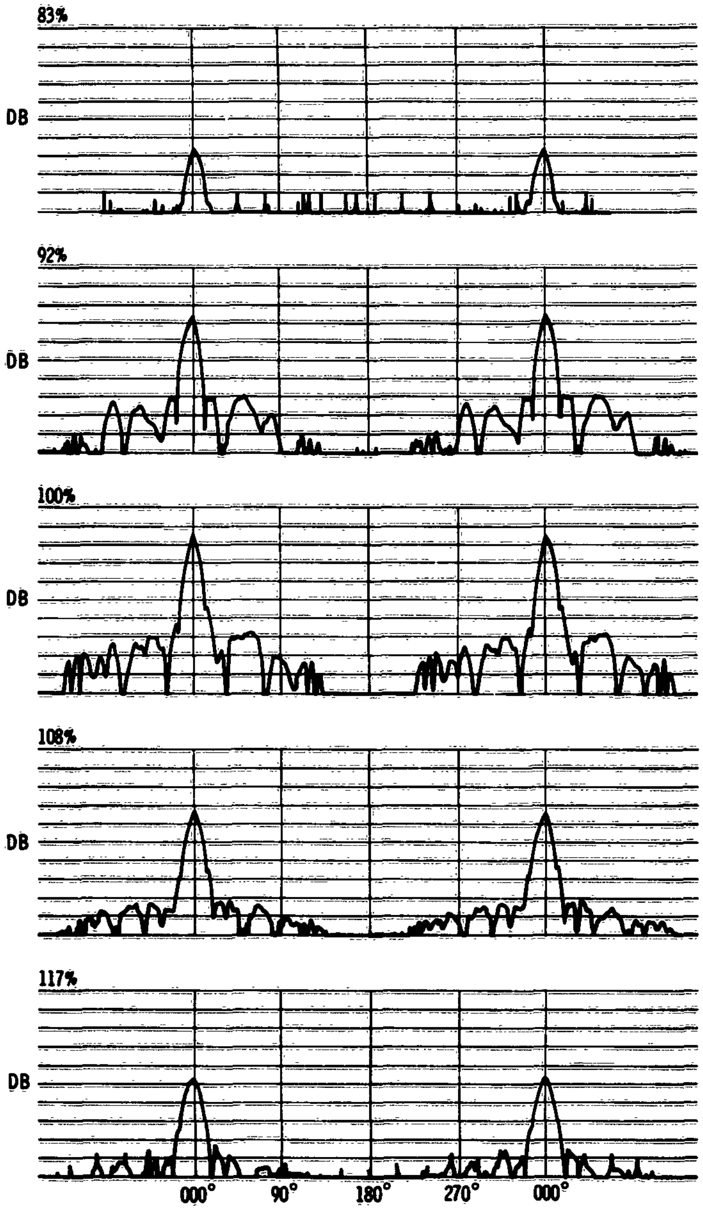
46
47
48
1
2
3
4
5
6
7
8
52.3K
16.9K
17.4K
15.0K
9.53K
2.37K
23.2K
7.68K
7.32K
12.1K
6.34K
12.1K
13.7K
5.76K
115K
5.11K
115K
5.11K
13.7K
5.76K
6.34K
12.1K
7.32K
12.1K
23.2K
7.68K
9.53K
23.7K
17.4K
15.0K
52.3K
16.9K
SIN BUS
COS BUS
L
7.96MH
C
.0221 μF
r_s
2.15K
R_L
604Ω
BEAM OUT
AN/SQS-4
PREAMP
OUTPUT
Z ≈ 400Ω
200Ω
200Ω
DETAIL OF ACTUAL TRANSFORMER USED
TWO NEL # 4646 TRANSFORMERS WERE CONNECTED AS SHOWN ABOVE TO ACT AS ONE FOR ALL OF THE TEST UNIT TRANSFORMERS.
EACH TRANSFORMER HAD A NOMINAL AUDIO IMPEDANCE OF 1000Ω TO 1000Ω AND A TURNS RATIO OF 1475/1475

Figure 5A shows several strips of the resistive phase compensator patterns recorded at frequencies above, below, and at the design frequency. Figure 5B gives three comparative patterns for the transformer phase compensator, obtained in the same manner.

Figure 5. Phase compensator patterns at various frequencies. Per cent of design frequency is indicated at upper left of each pattern.

A. Linear plot of directivity patterns of resistive phase compensator. Since these were obtained through the AN/SQS-4 preamp filters, the absolute amplitudes cannot easily be correlated at different frequencies; however, the beam shape, and amplitude relative to the minor lobes, are almost identical to those of the transformer phase compensator (and also the AN/SQS-4 scanning switch beam) at the design frequency, and they appear to remain useful (at least 18 db minor lobe suppression) at 83 to 117 per cent of the design frequency -- i.e., over a bandwidth of approximately $f_0 \pm 17$ per cent. →


83%
DB
92%
DB
100%
DB
108%
DB
117%
DB
000°
90°
180°
270°
000°

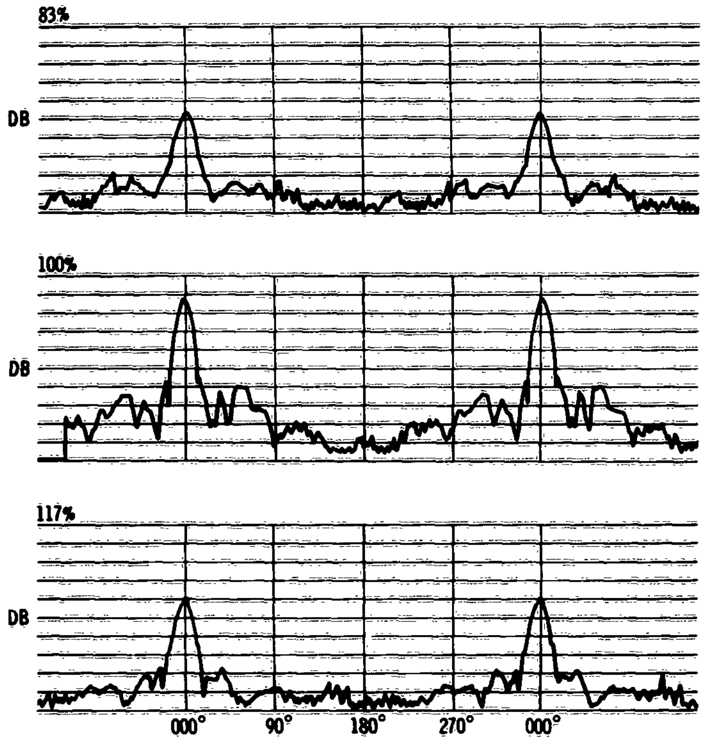


Figure 5 (Continued) B. Linear plot of directivity patterns of transformer phase compensator, shown for comparison with those of the resistive phase compensator, figure 5A. The remarks on that figure also apply here.

CONCLUSIONS

1. A single-beam, resistive-element phase compensator network was designed and constructed for the 48-element array of the AN/SQS-4 Mod 3 sonar with half-wavelength spacing. Its performance was determined in the laboratory by use of Sonar Test Set TS-826/SQS-4 and Target Signal Simulator Control C-1458/SQS-4.

2. This phase compensator produced a single beam which, with its minor lobes, was essentially identical to the beams produced by the 48-beam transformer phase compensator, which was designed for the AN/SQS-4 Mod 3 sonar and was tested in the same way.

3. Satisfactory operation of the phase compensator throughout the frequency range within ±17 per cent of the design frequency was demonstrated, yielding beam patterns which were very similar to the transformer phase compensator patterns obtained in the same way.

4. Compared to the multibeam transformer phase compensator, the multibeam resistive phase compensator will be more reliable in operation. Further advantages are reductions in weight, size, and cost made possible by printed circuit or microminiature techniques. Manufacturing, especially in large quantities, will be expedited, and testing and maintenance simplified. The equipment offers considerable flexibility for interchange in the event of operational or combat damage.

RECOMMENDATIONS

1. Make available the information in this report to interested contractors along with the recommendation that they consider the use of the resistive-element phase compensator for those sonar receiving systems in which the transformer phase compensator had been considered or planned.

2. Design and construct, at NEL, a multiple-beam, resistive-element phase compensator and conduct complete tests to investigate the multiple network intercoupling effects.

REFERENCES

The following references include those cited in the text and others which present related information.

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2. Navy Electronics Laboratory Report 632, Simultaneous Multibeam Phase Compensation, I: Concept and Design of Transformer Coupled Potentiometer Compensator; II: Uniform Linear Array Phase Compensation Analysis, by A. A. Hudimac, 30 November 1955

3. Navy Electronics Laboratory Report 642, Simultaneous Multibeam Phase Compensation, III: Inductive Compensator Design and Operation, by F. R. Abbott, 2 December 1955

4. Navy Electronics Laboratory Report 670, Simultaneous Multibeam Phase Compensation, IV: Linear Array Inductive Compensator Output Processing and Evaluation, by C. J. Krieger, 9 April 1956

5. Navy Electronics Laboratory Report 674, Simultaneous Multibeam Phase Compensation, V: Circular Array Inductive Compensator Evaluation, by C. J. Krieger, CONFIDENTIAL, 3 April 1956

6. Navy Electronics Laboratory Report 757, Simultaneous Multibeam Phase Compensation, VI: Phase Compensator for the Lorad Station-Keeping Receiver System, by C. J. Krieger and R. P. Kempff, CONFIDENTIAL, 7 May 1957

7. Navy Electronics Laboratory Report 806, Simultaneous Multibeam Phase Compensation, VII: Circular Array Phase Compensator for the AN/SQS-11 Sonar, by C. J. Krieger and R. P. Kempff, 26 September 1957

8. Navy Electronics Laboratory Report 851, Simultaneous Multibeam Phase Compensation, VIII: Design and Laboratory Evaluation of a Phase Compensator for the AN/SQS-4 Mod 3 Sonar, by C. J. Krieger and R. P. Kempff, CONFIDENTIAL, 18 July 1958

9. Navy Electronics Laboratory Report 985, Simultaneous Multibeam Phase Compensation, IX: A Multibeam Receiving System for the AN/SQS-4 Mod 3 Sonar, by R. D. Strait and others, CONFIDENTIAL, 22 September 1960

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13. Naval Postgraduate School, Phase Compensation of Sonar Arrays, by R. C. Olson, CONFIDENTIAL, 1957

14. Navy Electronics Laboratory Report 1085, A Scanning Sonar Transmitter Employing the Matrix Phase Compensator and Silicon Controlled Rectifier Switches, by J. T. Redfern and F. R. Abbott, CONFIDENTIAL, 18 December 1961

15. Navy Electronics Laboratory Technical Memorandum 292, Proposal for the Design of a Phase Compensator for AN/SQS-4 Mod 1 Sonar, by R. P. Kempff, CONFIDENTIAL, 24 June 1958*

16. Navy Electronics Laboratory Technical Memorandum 337, AN/SQS-4 Mod 3 Sonar with Multibeam Receiving System Test Results, by C. J. Krieger, CONFIDENTIAL, 19 June 1959*

17. Navy Electronics Laboratory Technical Memorandum 351, Formation of Narrow Transmitted Sonar Beams Employing the Phase Compensator, by J. T. Redfern, 30 July 1959*

18. Navy Electronics Laboratory Technical Memorandum 388, Rotated Directional Sonar Transmission with Semiconductor Switching, by F. R. Abbott and J. T. Redfern, 10 February 1960*

*NEL Technical Memoranda are informal documents intended primarily for use within the Laboratory.

APPENDIX A: CIRCUIT ANALYSIS

Figure A-1 illustrates the circuitry for the formation of one beam with the resistive phase compensator.

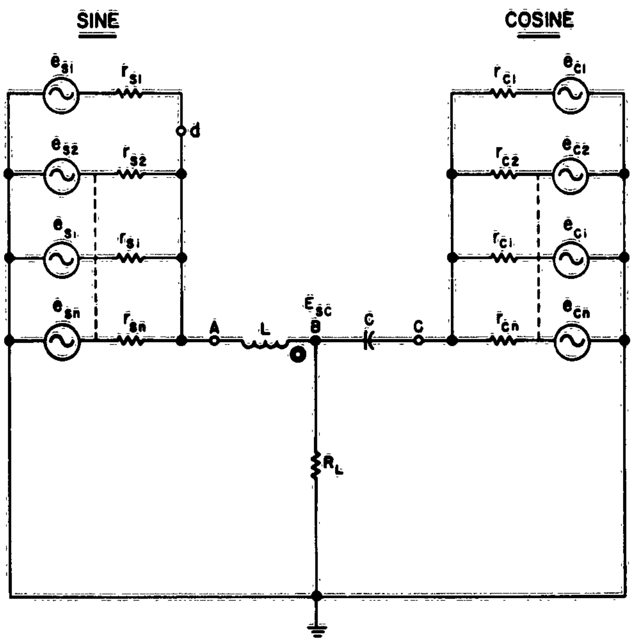


Figure A-1. Equivalent circuit No. 1.

It is desired to attenuate the signal e_{si} from hydrophone element i by means of resistance r_{si} (which is a physical resistor plus the generator resistance) to a value at point B which is proportional to $|\sigma_i \sin \overline{\theta}_{oi}|$. The same result is desired for the e_{ci} voltage. In addition we must choose the proper values of L and C so that the resultant voltage from point A is phase-shifted -45° at point B, and the resultant voltage from point C is phase-shifted +45° also at point B to give

$$E_{sc} = R = X - jY \qquad \text{(A1)}$$

To determine our relationships for this, we will put equivalent circuit No. 1 into the form of equivalent circuit

No. 2 (fig. A-2), letting R_s and R_c, respectively, be the equivalent resistances of the r_{st} in parallel, and of the r_{ct} in parallel, so that

$$\frac{1}{R_s} = \sum_{t=1}^{N}\left(\frac{1}{r_{st}}\right);\quad \frac{1}{R_c} = \sum_{t=1}^{N}\left(\frac{1}{r_{ct}}\right) \qquad \text{(A2)}$$

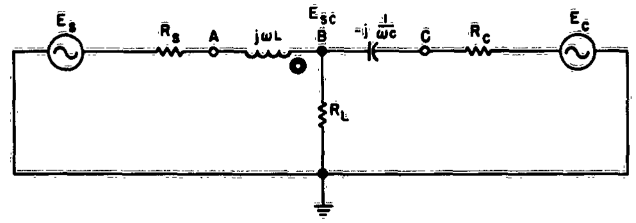


Figure A-2. Equivalent circuit No. 2.

Considering the effects of each equivalent generator separately (E_s and E_c) by superposition, we arrive at equivalent circuits 3a and 3b, for the sine and cosine sides, respectively (fig. A-3).

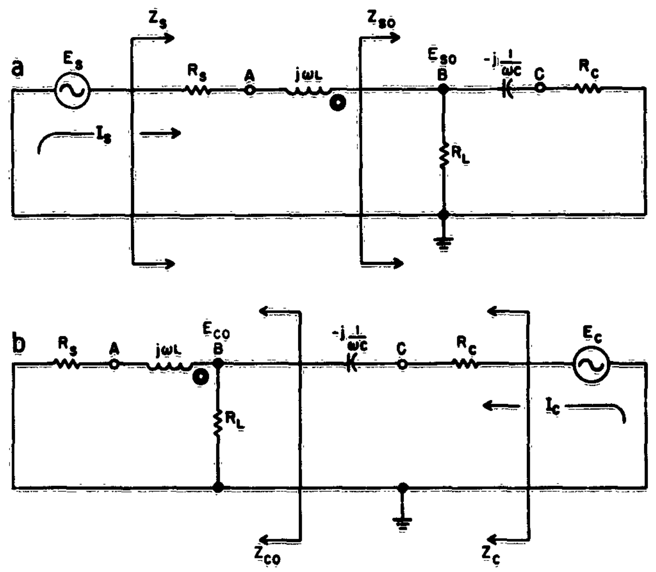


Figure A-3. Equivalent circuits Nos. 3a and 3b.

First, we will consider circuit 3a. Since we want to know the ratio of the voltage out (E_{so}) at B, to the voltage in (E_s) we will have

$$\frac{E_{so}}{E_s} = \frac{Z_{so}}{Z_s} = \frac{\dfrac{R_L\left(R_c - j\dfrac{1}{\omega C}\right)}{R_L + \left(R_c - j\dfrac{1}{\omega C}\right)}}{R_s + j\omega L + \dfrac{R_L\left(R_c - j\dfrac{1}{\omega C}\right)}{R_L + \left(R_c - j\dfrac{1}{\omega C}\right)}} \qquad \text{(A3)}$$

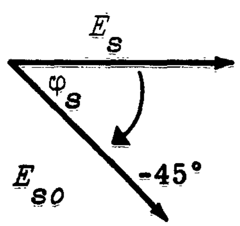
Now if we specify the condition

$$R_s = R_c = \frac{1}{\omega C} = \omega L = R_o \qquad \text{(A4)}$$

at the design frequency, we realize considerable simplification, and

$$\frac{E_{so}}{E_s} = \frac{1}{2\left(1 + \dfrac{R_o}{R_L}\right)} - j\frac{1}{2\left(1 + \dfrac{R_o}{R_L}\right)} = \frac{(1 - j)}{2\left(1 + \dfrac{R_o}{R_L}\right)} \qquad \text{(A5)}$$

The relative phase of the voltage is $\varphi_s = -45°$, as illustrated below:

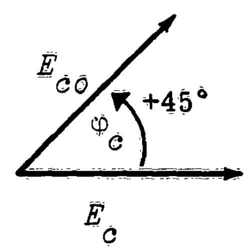


Note that the phase shift is independent of R_L. The ratio R_o/R_L will determine the total attenuation from input to output.

We can, in the same manner, evaluate equivalent circuit 3b and find that

$$\frac{E_{co}}{E_c} = \frac{1}{2(1+\frac{R_o}{R_L})} + j\frac{1}{2(1+\frac{R_o}{R_L})} = \frac{(1+j)}{2(1+\frac{R_o}{R_L})} \qquad \text{(A6)}$$

and that the relative phase of the voltage is $\varphi_c = +45°$:



Thus the sum of the attenuated sine voltages will be phase-shifted -45°, and the sum of the attenuated cosine voltages will be phase-shifted +45° with respect to the input reference. The sum of the attenuated sine voltages will then be effectively phase-shifted -90° with respect to the sum of the attenuated cosine voltages. This will perform the rotation through $-j$, and $R = X - jY$.

We can now establish conditions which will allow us to find the values of each of the attenuating resistances, r_{si} and r_{ci}.

First we will consider the sine resistors by redrawing equivalent circuit 3a so that we may show a different impedance that will be useful.

As shown in equivalent circuit 4 (fig. A-4), we should note that, at point A, we look to the right into impedance Z_{s2} and to the left into the resistive impedance R_s, which we have already specified as equal to ωL, $\frac{1}{\omega C}$, and R_c. Equivalent circuits 5a and 5b (fig. A-5) show how we can consider each r_{si} in turn by allowing all of the r_{si} in parallel, except the one being considered, to be represented by a new equivalent resistance $R_s{}'$.

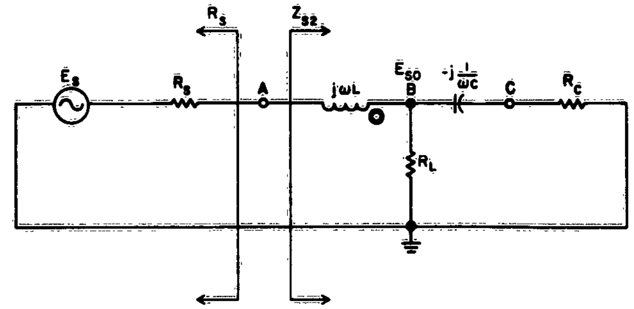


Figure A-4. Equivalent circuit No. 4.

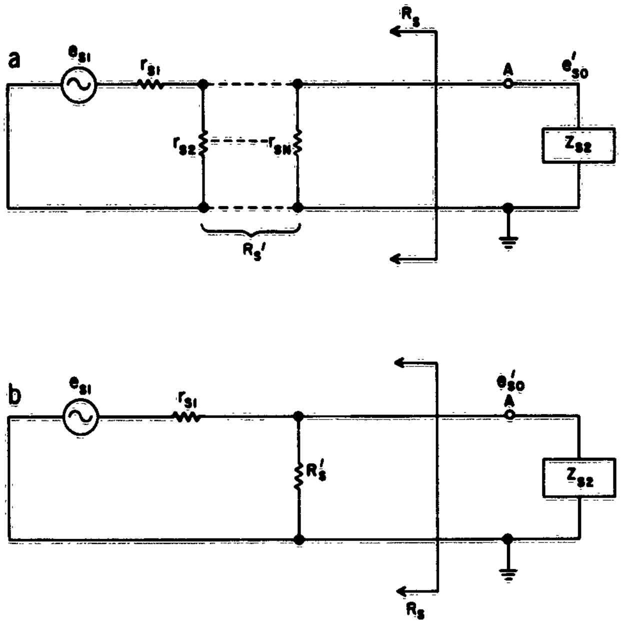


Figure A-5. Equivalent circuits Nos. 5a and 5b.

Of course, each R_s' corresponding to each r_{si} will be different, but the impedance looking left at point A will always be R_s, and looking right at point A will always be Z_{s2} so the impedance at point A will be constant for consideration of each of the r_{si}'s.

Since we wish the i^{th} attenuated voltage e_{so}' to be proportional to $\sigma_i \sin \bar{\theta}_{oi}$, we write from equivalent circuit 5b

$$\frac{R_s'}{r_{si} + R_s'} = K \left| \sigma_i \sin \bar{\theta}_{oi} \right| \tag{A7}$$

where K is a constant of proportionality.

We also see that $$\frac{1}{R_s} = \frac{1}{R_s'} + \frac{1}{r_{si}}$$

or

$$\frac{1}{R_s'} = \frac{r_{si} - R_o}{R_o \; r_{si}} \tag{A8}$$

Substituting into equation A7, we find

$$r_{si} = \frac{R_o}{K \left| \sigma_i \sin \bar{\theta}_{oi} \right|} \tag{A9}$$

and similarly

$$r_{ci} = \frac{R_o}{K \left| \sigma_i \cos \bar{\theta}_{oi} \right|} \tag{A10}$$

Using equation A2, we have

$$\frac{1}{R_s} = \frac{K}{R_o} \sum_{i=1}^{N} \left| \sigma_i \sin \bar{\theta}_{oi} \right| \tag{A11}$$

and

$$\frac{1}{R_c} = \frac{K}{R_o} \sum_{i=1}^{N} \left| \sigma_i \cos \bar{\theta}_{oi} \right| \tag{A12}$$

Since our circuit design rests on the assumption that $R_s = R_c$ (eq. A4) and since $\sum_{i=1}^{N} \left| \sigma_i \sin \bar{\theta}_{oi} \right|$ is not necessarily equal to $\sum_{i=1}^{N} \left| \sigma_i \cos \bar{\theta}_{oi} \right|$, principally because of shading, $1/R_s$ and $1/R_c$ can be equalized by introducing a resistor r_s in parallel with the other r_{si}'s (fig. A-6). This resistor can be considered as an additional sine generator, but with zero signal.

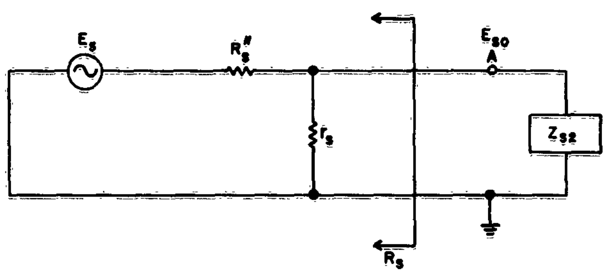


Figure A-6. Equivalent circuit No. 6.

If, for example, $\frac{1}{R_s''} < \frac{1}{R_c}$, then $\frac{1}{R_s''}$ can be increased to equal $\frac{1}{R_c}$ by means of $\frac{1}{r_s}$:

$$\frac{1}{R_s} = \frac{1}{r_s} + \frac{K}{R_o} \sum_{i=1}^{N} |\sigma_i \sin \bar{\theta}_{oi}| \tag{A13}$$

$$= \frac{1}{R_c} = \frac{K}{R_o} \sum_{i=1}^{N} |\sigma_i \cos \bar{\theta}_{oi}| \tag{A14}$$

But from equation A6, $\frac{1}{R_o} = \frac{1}{R_c} = \frac{1}{R_s}$

so that

$$\frac{1}{R_o} = \frac{K}{R_o} \sum_{i=1}^{N} |\sigma_i \cos \bar{\theta}_{oi}| \tag{A15}$$

We can now solve for

$$K = \frac{1}{\sum_{i=1}^{N} |\sigma_i \cos \bar{\theta}_{oi}|} \tag{A16}$$

and substituting into equation A13 we find

$$r_s = \frac{R_o}{1 - \frac{\sum_{i=1}^{N} |\sigma_i \sin \bar{\theta}_{oi}|}{\sum_{i=1}^{N} |\sigma_i \cos \bar{\theta}_{oi}|}} \tag{A17}$$

If, as a special case,

$$\sum_{i=1}^{N} |\sigma_i \sin \bar{\theta}_{oi}| = \sum_{i=1}^{N} |\sigma_i \cos \bar{\theta}_{oi}|$$

then $r_s = \infty$ and no shunt resistor is required.

If $\frac{1}{\bar{R}_c''} < \frac{1}{\bar{R}_s}$, then $\frac{1}{\bar{R}_c''}$ can be increased to equal $\frac{1}{\bar{R}_s}$.

APPENDIX B: MULTIBEAM COUPLING EFFECTS

In 1957 a study of cross-talk suppression in an inductive phase compensator was made by R. C. Olson,* but these multiple coupling effects in a resistive phase compensator have not been analyzed rigorously with experimental verification. However, a qualitative approach will be indicated here which should yield a workable solution with a moderate amount of time and effort.

There are several different cross-talk-effect voltages which may be considered; these will be combined with the generator (preamplifier) signal voltages in a manner largely determined by the nature of the sound received by the hydrophone array. The nature of this sound can be considered to be in one or more of the following three categories:

1. Essentially plane-wave coherent noise (listening passively, received from other ships, torpedoes, etc.), or signal echo which may arrive either from (a) the compensated bearing of a given beam under consideration, or (b) from some other direction which, for purposes of practical significance, will be confined to bearings close to the compensated bearing. Some types of reverberation as well as multipath returns from other causes would be a source for these returns from other directions.

2. Semi-coherent self noise from all ship sources, including machinery noise, screw noise, turbulent water and bubble noise, flow noise, and transducer fairing excitation noise.

3. Ambient sea noise comprising marine life noise, surface noise, etc. Except for nearby fish noise, the ambient noise will probably be largely incoherent, depending on the local environment.

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*Reference 13, p. 47, fig. 39, and Appendix III.

Additionally, electrical circuit noise will add itself, but its contribution to cross talk will probably be negligible, even under very quiet listening conditions.

The foregoing factors should be considered for a full analysis of multiple-beam cross-talk effects. However, it appears that category (1) will give the cross-talk effect which has the most practical significance, since the voltages generated by categories (2) and (3), as well as circuit noise, will approach random phase summation on the sine and cosine busses. This would tend to give only the same type of beam-degrading effect as incoherent sound noise received directly by the hydrophones used to form any given beam.

Since the output voltages of the beams are of prime concern, it appears that a useful criterion of cross talk can be the amplitude relationship of the outputs of several beams adjacent to the one on which a compensated coherent signal is being received. This may be visualized, as well as simulated for practical measurement, by the injection of a continuous signal voltage into a beam output at a known level and calculating or measuring the adjacent beam output voltages, while at the same time insuring that there is no appreciable contribution by signal or noise voltages from the preamplifiers (such as zero input to all preamplifiers).

Figures B-1 and B-2 illustrate the fact that the multiple generators contributing to the network of each beam combine their multiple voltages into two single voltages which are the summed "sine" and "cosine" voltages respectively, on the "sine" and "cosine" busses. The current from these summed voltages will flow back through the parallel combination of any given generator resistance and the "other beam" impedances to which it normally contributes. Therefore, the attenuation of the cross-talk voltage from a given beam, via the path of one of its contributing generators, is determined by the ratio of the particular "sine" and "cosine" resistors to the parallel generator resistance and "other beam" impedances which it feeds. Obviously, the smaller the generator resistance, the smaller will be

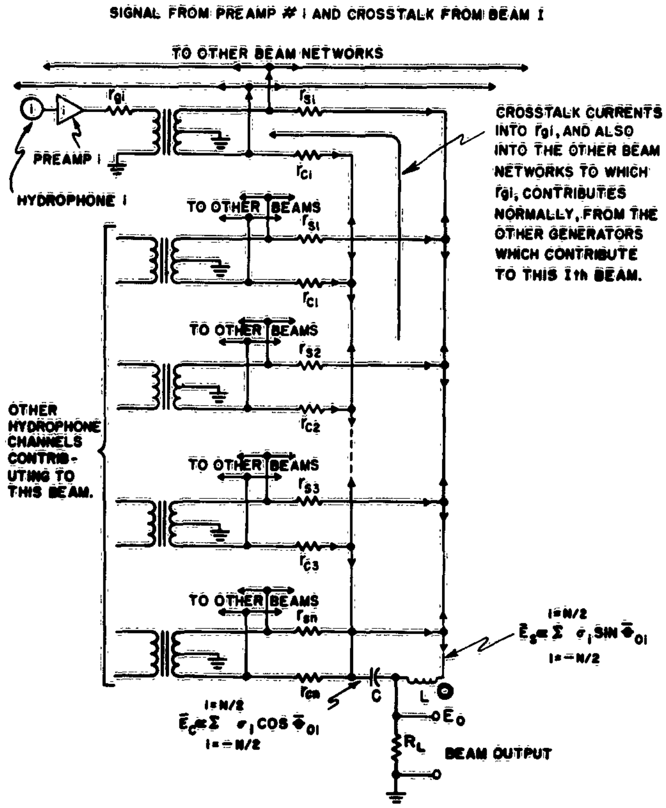

Figure B-1. Illustration of cross talk, showing the manner in which the summed beam quadrature voltages ($\overline{E_s}$, $\overline{E_c}$) can be considered single generators contributing cross-talk voltage to adjacent beams by means of inducing current flow back through a given generator (preamp) resistance.

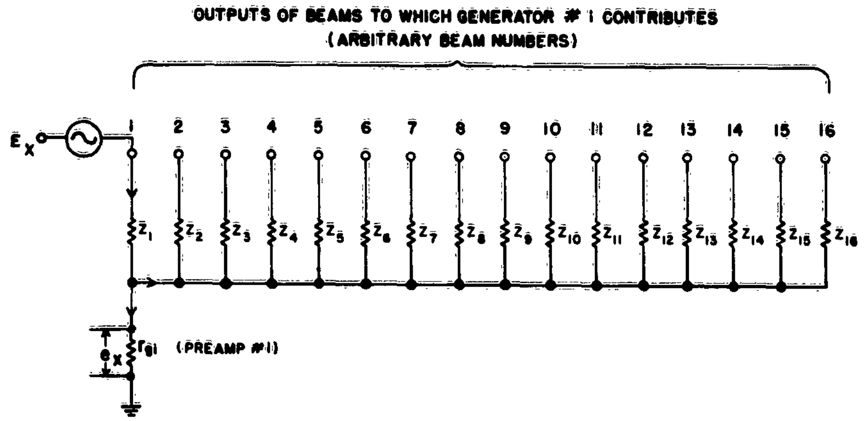

Figure B-2. An equivalent circuit, illustrating that a voltage (E_x) introduced at a beam output (with zero input into all preamplifiers) will feed an equivalent current back through a given generator resistance, creating a cross-talk voltage (e_x) which simulates the normal cross-talk voltage (for single-frequency considerations) from the other beam networks ($Z_1 \ldots Z_{16}$) to which generator i normally contributes a signal.

the cross-talk voltage across it to be imparted to the other beams to which it contributes. The preamplifier output impedance (design value), therefore can control the cross talk between beams, since by going down to zero as the limiting generator impedance, the cross-talk voltage would be zero. However, it is desirable to design the preamplifier output impedance for maximum power transfer to the multiple beam circuits it feeds. If the generator design impedance for maximum power transfer is not sufficiently low to minimize the cross talk to an acceptable level, a compromise between the two factors will be necessary.

APPENDIX C: OTHER USES OF THE PHASE COMPENSATOR

Basically, the phase compensator simply shifts the phases of the signals from various elements of an array of hydrophones (and the principle can also be applied to electromagnetic antenna elements) so that they add in-phase electrically for acoustic (or electromagnetic) signals from particular directions. The first use of the principle was to provide a simple, reliable, and compact package which would give multiple, preformed sonar beams. However, it may be advantageous to utilize this concept in a variety of other phase-shifting applications.

The technique can provide the formation of single or multiple phased outputs from single or multiple phased inputs anywhere that lumped (or determinable) constant circuit elements can be used, and where circuit restrictions are acceptable; and it is applicable with the use of transformer, resistor, or capacitor circuit elements. This can be done in one of two general ways:

1. In a phase compensator designed to provide receiving beams from an array of elements by phasing and summing the individual element voltages, the process is reversible; and by introducing a voltage signal into any beam output, a resulting group of voltages of various phases will appear at the (normal) inputs to the phase compensator. It is in this manner that some transformer phase compensators have been designed and constructed specifically to form transmitting beams for sonar arrays.[14] If, in the receiving array above, two or more voltage signals of the same or different phases were applied into the outputs of two or more beams having array elements in common, the resulting group of voltages appearing at the (normal) inputs to the phase compensator would have phases and amplitudes different from those with only one "beam" input. Of course, the specific values would depend on the design values of the phase compensator, as well as on the amplitude and relative phases of the voltages introduced into the "beam" outputs. Almost any combination and number of input/output voltages for a variety of circuit applications can be obtained in this general way.

2. One or more signal inputs may be considered as analogous to the array element inputs to the phase compensator when it is used to "form" receiving beams; and the desired phased outputs may be considered as analogous to the "beam" outputs. Thus an almost limitless number of different combinations of input/output voltages and phases may be obtained: two-phase to four-phase; two-phase to three-phase; one-phase to six-phase, etc.

Figures C-1 and C-2 indicate the general circuit configuration to obtain three-phase voltages from a single phase input. This is analogous to a phase compensator for a one-element "array" forming three "beams" for predetermined angles of compensation. There is only one signal input to "sum" its voltage on the sine and cosine beam busses in the resistive phase compensator, so an additional shunt resistor, to ground, is necessary to allow the LC 90° phase shift network to look "back" into the "R_o" impedance that will not in general be the same as that of each attenuating resistor used. By either using a different 90° phase network, or modifying the original circuit constants, these shunt resistors might be eliminated. The transformer version does not generally impose this requirement with its RC 90° phase shift network.

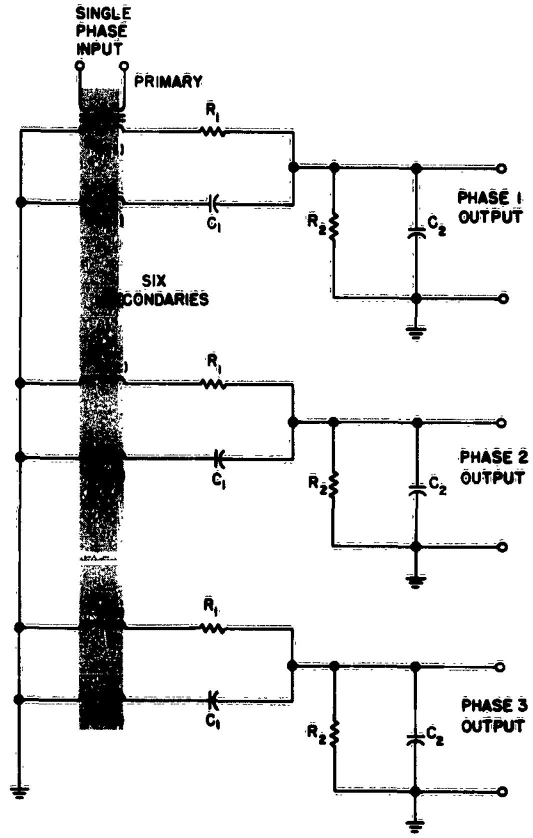

Figure C-1. Typical one-to-three phase network using transformer elements.

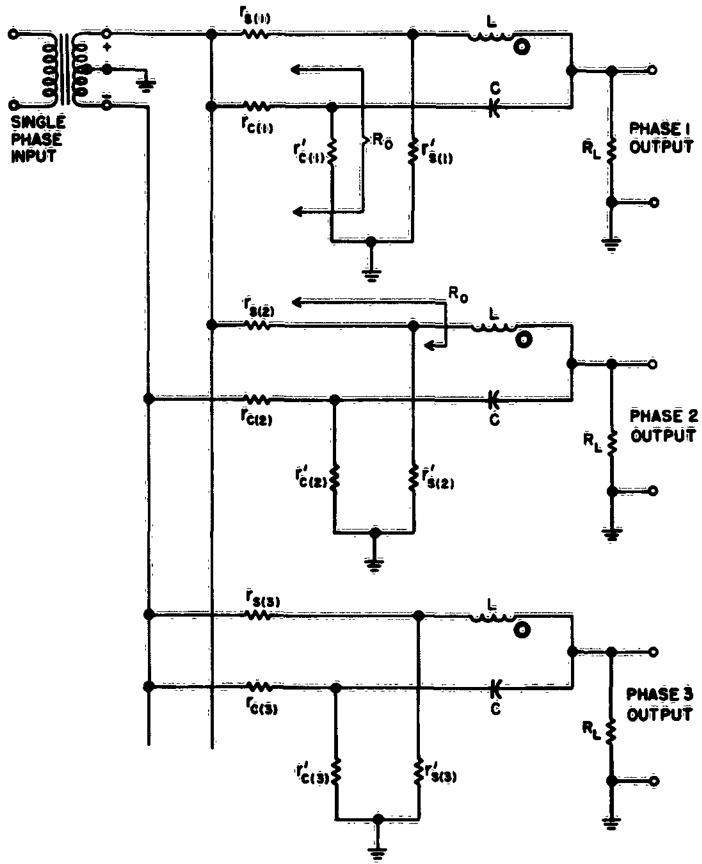

Figure C-2. Typical one-to-three phase network using resistor elements.

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XI. A RESISTIVE-ELEMENT PHASE COMPENSATOR, by
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UNCLASSIFIED

A single-beam, resistive-element phase compensator network was designed and constructed for the 48-element array of the AN/SQS-4 Mod 3 sonar with half-wavelength spacing. It demonstrated satisfactory operation throughout the frequency range within ±17 per cent of the design frequency, yielding beam patterns similar to the transformer phase compensator patterns obtained in the same way. Theory and design details are discussed fully.

1. Model AN/SQS-4 Mod 3
2. Phase compensators

I. Morgan, L. D.
II. Strait, R. D.

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