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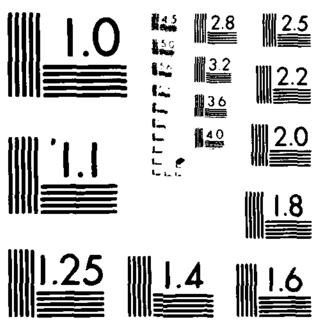

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POWER INVERSION IN A TAPPED DELAY-LINE ARRAY

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This report discusses recent studies on adaptive arrays for the Navy ITACS system. The report considers the power inversion behavior of an adaptive array with tapped delay-line processing behind each element. Typical output signals from the array are shown when a pulsed desired signal is received in the presence of a continuous interference. The effect of feedback loop gain constants on array performance is briefly discussed.

TABLE OF CONTENTS

I. INTRODUCTION

In this report we discuss recent studies on adaptive arrays for the Navy ITACS system. The goal of this research is to develop an adaptive antenna system compatible with the ITACS signaling waveform, so that a weak ITACS signal can be received in the presence of a strong interfering signal.

The work here is a continuation of earlier research on power inversion by Compton, Lee, and Schwegman [1,2,3,4]. This work differs from previous studies in that we consider here the power inversion behavior of an array with tapped delay-line processing behind the elements, rather than quadrature hybrid processing. Tapped delay-line processing allows the adaptive array to operate over a much wider bandwidth than does quadrature hybrid processing, and thus allows the array to protect a communication system from broadband interference.

In a power inversion array, no reference signal is provided, and the array feedback uses a low-pass filter to prevent weight shutdown [1,3]. This approach is especially attractive for time-division multiple access systems when the important interference threat is a continuous broadband signal. In this situation, the steady presence of the interference signal allows the array to null it effectively, while the pulsed nature of the desired signal allows one to depend on array time constants to prevent desired signal nulling.

Although our ultimate interest is in broadband interference, this report is a preliminary study in which we consider only CW interference. The more general case of broadband noise interference will be discussed in a later report.

In Section II we define the tapped delay-line array and the feedback loop under study, and discuss the problem of determining suitable values for the feedback constants. In Section III, we apply these results to a two-element array and show some typical preliminary results.

II. REVIEW OF BASIC THEORY

Figure 1 indicates the basic configuration of a 2-element adaptive array [1,3]. The feedback loop is based on a steepest-descent minimization of the mean-square error signal, $\overline{\epsilon^2(t)}$. In general, $\epsilon(t)$ is obtained by subtracting the output of the array from a reference signal $R(t)$. However, in a power inversion array, $R(t)$ is zero so that $\epsilon(t)$ is just the array output [1]. The incoming signal from each element is split in a tapped delay-line into n components. Each of these components is multiplied by a weighting coefficient w_i and then summed to yield the array output. The weights in a power inversion array are controlled by the system of equations [3]:

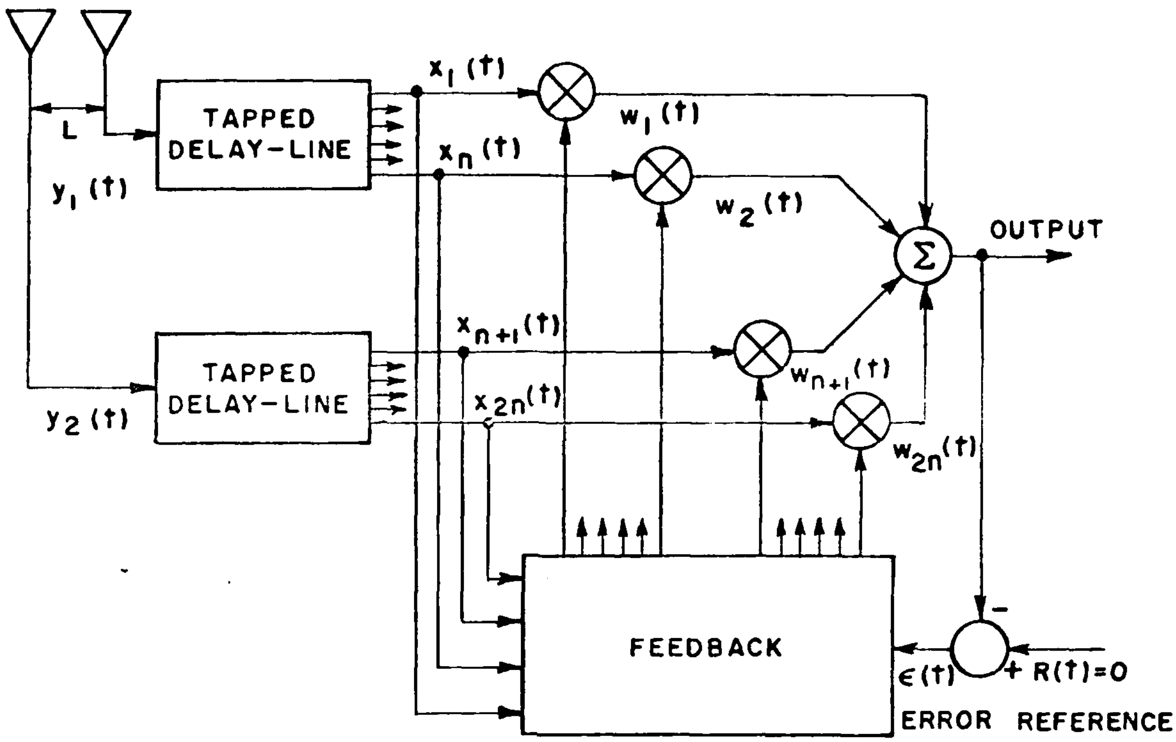

Fig. 1. Basic adaptive feedback system.

(1) $$K_2 \frac{dw}{dt} + w = w_o - K_1 \nabla_w \overline{\varepsilon^2(t)}$$

where w is a column vector whose components are the array weights,

(2) $$w = \begin{pmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_{2n} \end{pmatrix}$$

w_o is an initial offset weight vector, and $\nabla_w[\overline{\varepsilon^2(t)}]$ denotes the gradient of the mean-square error $\overline{\varepsilon^2(t)}$ with respect to the weights. K_1 and K_2 are loop gain constants that must be chosen so the array nulls a high-power interfering signal sufficiently without nulling the weaker desired signal. The dw/dt term in the equation provides the smoothing necessary to limit the frequency response of the weights, and the proportional term w_o results in steady-state weights that have the desired power inversion behavior. [1,3] The feedback loop corresponding to Eq. (1) is shown in Fig. 2.

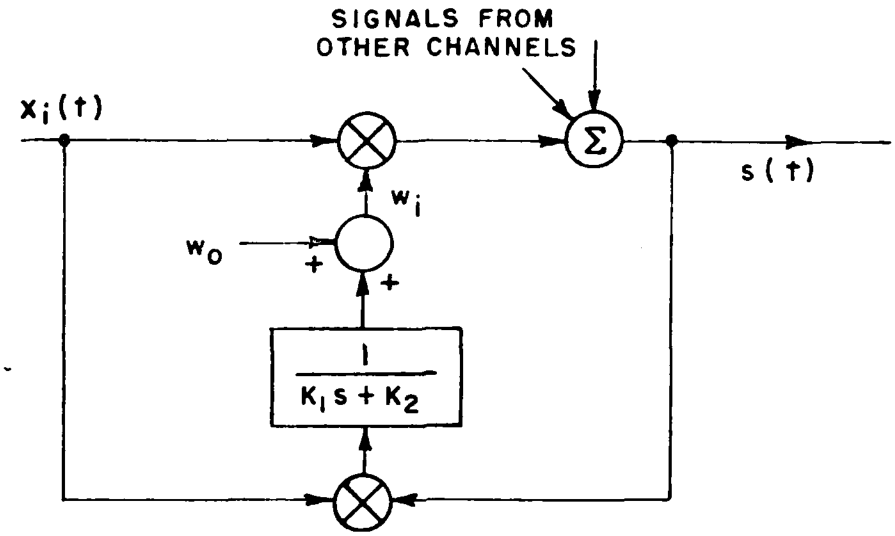

Fig. 2. The power inversion feedback loop.

If the reference signal R(t) is 0, the error signal becomes:

$$(3) \qquad \varepsilon(t) = -s(t) = -\sum_{i=1}^{2n} w_i\, x_i(t)$$

Hence the mean square error is

$$(4) \qquad \overline{\varepsilon^2(t)} = \sum_{i=1}^{2n} \sum_{j=1}^{2n} w_i w_j\, \overline{x_i(t) x_j(t)}$$

Differentiation of Eq. (4) yields:

$$(5) \qquad \frac{\partial \overline{\varepsilon^2(t)}}{\partial w_i} = 2 \sum_{j=1}^{2n} w_j\, \overline{x_i(t) x_j(t)}$$

so

$$\nabla_w[\overline{\varepsilon^2(t)}] = 2\Phi\, w \tag{6}$$

where Φ is a 2n x 2n matrix defined by

$$\Phi = \begin{pmatrix} \overline{x_1(t)\ x_1(t)} & \overline{x_1(t)\ x_2(t)} & \cdots & \overline{x_1(t)\ x_{2n}(t)} \\ \overline{x_2(t)\ x_1(t)} & & & \\ \vdots & & & \\ \overline{x_{2n}(t)\ x_1(t)} & & \cdots & \overline{x_{2n}(t)\ x_{2n}(t)} \end{pmatrix} \tag{7}$$

Substituting Eq. (6) into Eq. (4), we have

$$K_2\ \frac{dw}{dt} + [I + 2K_1\Phi]w = w_o \tag{8}$$

The ith component of this equation is

$$K_2\ \frac{dw_i}{dt} + w_i + 2K_1 \sum_{j=1}^{2n} \overline{x_i(t)x_j(t)}\ w_j = w_{io} \tag{9}$$

where w_{io} is the ith component of vector w_o. This is a coupled system of differential equations.

We may obtain an understanding of the effects of K_1 and K_2 on the solutions by considering a one-dimensional version of Eq. (9):

$$\frac{dw_1}{dt} + \left[\frac{1 + 2K_1\ \overline{x_1^2(t)}}{K_2}\right] w_1 = \frac{w_{10}}{K_2}\ . \tag{10}$$

If $\overline{x_1^2(t)}$ is constant, the solution for w_1 in Eq. (10) will have a final value given by:

$$w_{final} = \frac{w_{10}}{1 + 2K_1 \overline{x_1^2(t)}} \tag{11}$$

and the time constant of the transient term will be

$$\tau = \frac{K_2}{1 + 2K_1 \overline{x_1^2(t)}} \tag{12}$$

From Eqs. (11) and (12), one can see how the constants K_1 and K_2 are to be chosen. For a given signal power $\overline{x_1^2(t)}$, K_1 must be large enough so that w_{final} is sufficiently different from w_{10} to allow adequate interference nulling. After K_1 is selected, K_2 may be chosen to give a desirable array response time.

The design problem is complicated, however, by the fact that the optimum choice for K_1 depends on the signal power $\overline{x_1^2(t)}$, since it is really the product $K_1\overline{x_1^2(t)}$ that determines the loop gain. (Normally $2K_1\overline{x_1^2(t)} \gg 1$.) One must select a value for K_1 giving adequate interference nulling for the weakest interference signal for which protection is needed. Then for larger interference, the protection will be greater. However, the array will perform satisfactorily only up to the point where the time constant of the loops becomes too short. When the array time response is too fast, other problems may occur; for example, the array weights may affect the desired signal modulation.

Finding suitable compromise values for K_1 and K_2 would not be difficult for the one-dimensional weight equation in Eq. (10). However, the full array is described by the set of 2n coupled equations in Eq. (9), in which the coefficients $\overline{x_i(t)x_j(t)}$ are time varying. For this reason, the most practical method of choosing K_1 and K_2 in a computer simulation has been to use a trial-and-error approach, taking into account the effects described above.

In the next section, we examine the performance of a two-element power inversion array with tapped delay-lines.

III. RESULTS

In this section we show some typical response curves for a two-element adaptive array with tapped delay-lines when a high power interference signal and a pulsed desired signal are incident. The array is shown in Fig. 3. Each element is followed by a two-section tapped

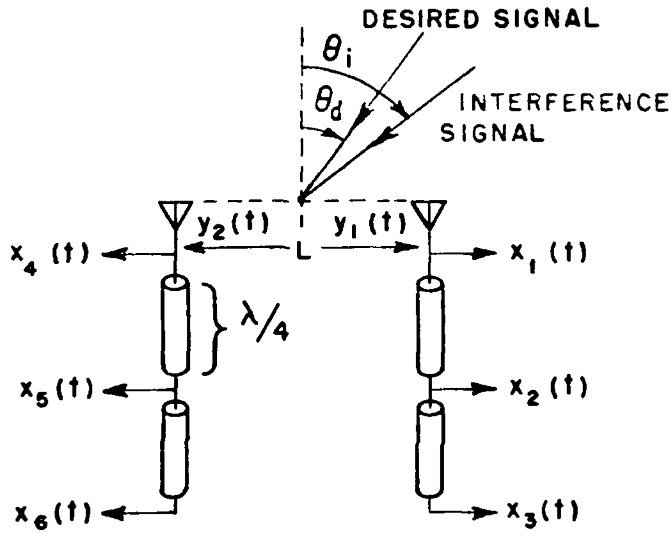

Fig. 3. Two-element array with tapped delay-lines.

delay-line* with taps spaced one-quarter wavelength at the desired signal carrier frequency. The desired and the interference signals are assumed incident on the array from angles θ_d and θ_i, respectively, as shown in Fig. 3. The two elements are spaced a half wavelength apart at the desired signal frequency ($L=\lambda_d/2$). The interface is assumed to be on a slightly different frequency than the desired signal.

The element signals are given by

$$y_1(t) = A(t)\cos(\omega_1 t) + B\cos(\omega_2 t) \tag{13}$$

*The number of delays needed behind each element depends on the bandwidth of the signals. A subsequent report will discuss this subject, and will explain why 2 delays are appropriate with the ITACS waveform.

and

(14) $$y_2(t) = A(t)\cos(\omega_1 t - \gamma_d) + B\cos(\omega_2 t - \gamma_i)$$

where A(t) is the pulse envelope of the desired signal, B is the amplitude of the interference signal,

(15) $$\gamma_d = \frac{2\pi L}{\lambda_d}\sin\theta_d = \pi\sin\theta_d,$$

and

(16) $$\gamma_i = \frac{2\pi L}{\lambda_i}\sin\theta_i = \frac{\lambda_d}{\lambda_i}\pi\sin\theta_i$$

since $L = \lambda_d/2$. We assume $B >> A(t)$.

The outputs of the tapped delay-lines are given by

(17) $$x_1(t) = A(t)\cos[\omega_1 t] + B\cos[\omega_2 t]$$

(18) $$x_2(t) = A(t-T_1)\cos[\omega_1(t-T_1)] + B\cos[\omega_2(t-T_1)]$$

(19) $$x_3(t) = A(t-2T_1)\cos[\omega_1(t-2T_1)] + B\cos[\omega_2(t-tT_1)]$$

(20) $$x_4(t) = A(t)\cos[\omega_1 t-\gamma_d] + B\cos[\omega_2 t-\gamma_i]$$

(21) $$x_5(t) = A(t-T_1)\cos[\omega_1(t-T_1)-\gamma_d] + B\cos[\omega_2(t-T_1)-\gamma_i]$$

(22) $$x_6(t) = A(t-2T_1)\cos[\omega_1(t-2T_1)-\gamma_d] + B\cos[\omega_2(t-2T_1)-\gamma_i].$$

The offset weight vector is chosen to be

(23) $$w_o = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

This choice makes the quiescent pattern of the array omnidirectional.

A computer program has been written to simulate the time behavior or the array shown in Fig. 3 with feedback loops as shown in Fig. 2. The array weights are controlled by an iterative routine that is a sampled data equivalent of Eq. (1). The program is shown in the Appendix.

Figures 4 and 5 show a typical output from the array as the weights adapt. In Fig. 4, the high power interference signal is turned on at t=0, and the array weights change with time to suppress this signal. Figure 5 is a continuation of the run shown in Fig. 4 with the vertical scale amplified, and the desired signal pulse occurs during the time shown in Fig. 5. It may be seen how the interference is suppressed (in Fig. 4), and remains suppressed when the desired signal pulse occurs (in Fig. 5). The desired signal power at the array output is higher than the interference power, even though the interference is 40 dB higher than the desired signal at the array input. The feedback loop gain constants K_1 and K_2 used in Figs. 4 and 5, which have been chosen by trial-and-error to produce a suitable response, are $K_1 = .5$, $K_2 = 1.25 \times 10^{-4}$ · $(K_1/K_2 = 4 \times 10^3)$. The effect of reducing K_1 may be seen by comparing Figs. 4 and 5 with Figs. 6 and 7, where $K_1 = .05$, $K_2 = 1.25 \times 10^{-5}$, and with Figs. 8 and 9, where $K_1 = .005$ and $K_2 = 1.25 \times 10^{-6}$. (In all three sets of curves, $K_1/K_2 = 4 \times 10^3$, so the array time constant is the same in each case.) In Figs. 8 and 9, K_1 is too small for satisfactory interference rejection; the residual interference present at the array output beats with the desired signal pulse to produce an amplitude modulation.

The effect of changing K_2 without changing K_1 may be seen by comparing Figs. 4 and 5 with Figs. 10 and 11 and with Figs. 12 and 13. In all cases $K_1 = .5$. In Figs. 4-5, $K_2 = 1.25 \times 10^{-4}$, in Figs. 10 and 11, $K_2 = 5 \times 10^{-4}$, and in Figs. 12 and 13, $K_2 = .5 \times 10^{-4}$. The larger K_2, the longer the transient during which the interference is being nulled out, as predicted by Eq. (12).

IV. CONCLUSIONS

This is a preliminary report on power inversion in a wideband adaptive array using delay-line processing. The power inversion concept in a tapped-delay line array has been discussed and a computer program written to simulate array behavior. Some typical results for CW interference and pulsed desired signal have been shown, and the influence of the feedback loop constants on the performance have been illustrated. A subsequent report will discuss the power inversion characteristics of such an array in more detail and will show system performance with wideband interference signals.

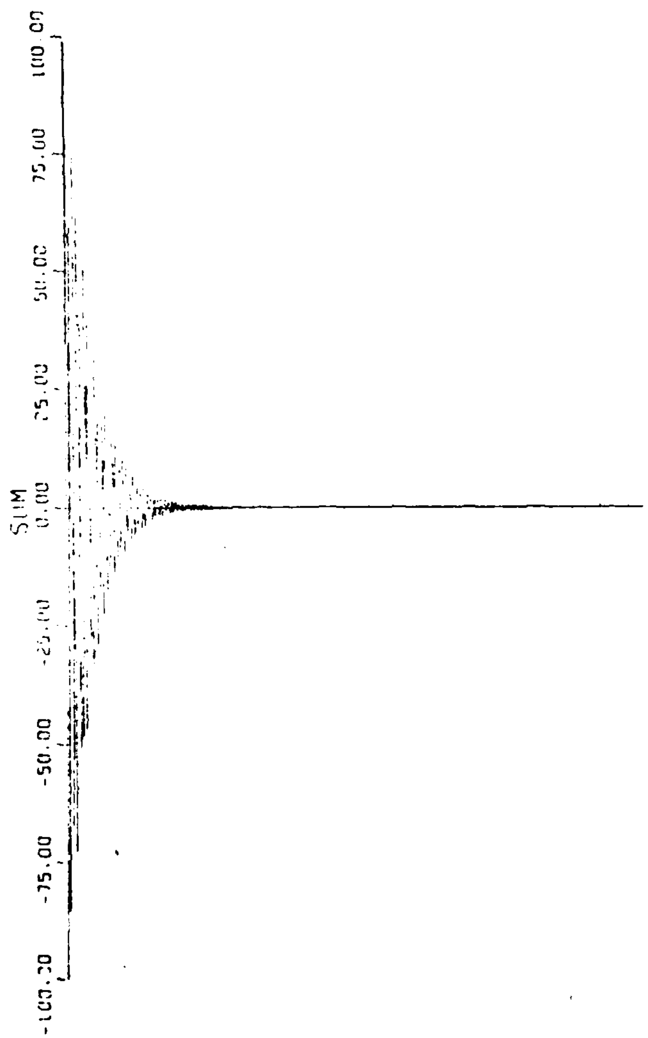

Fig. 4. Transient response of the adaptive array for $K_1=.5$, $K_2=1.25\times10^{-4}$.

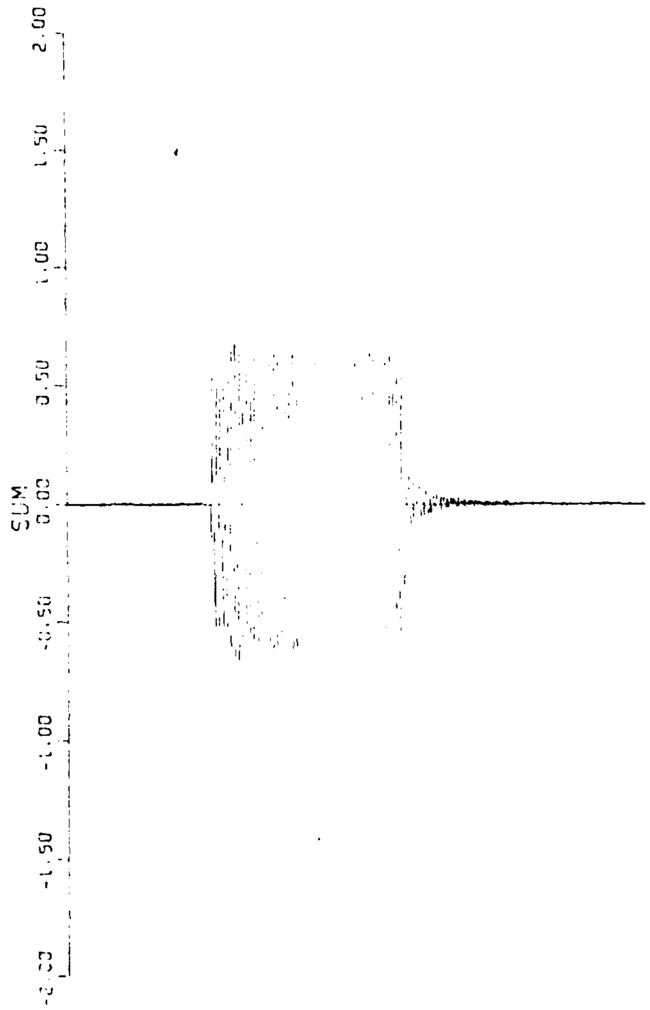

Fig. 5. Transient response of the adaptive array for $K_1=.5$, $K_2=1.25\times10^{-4}$.

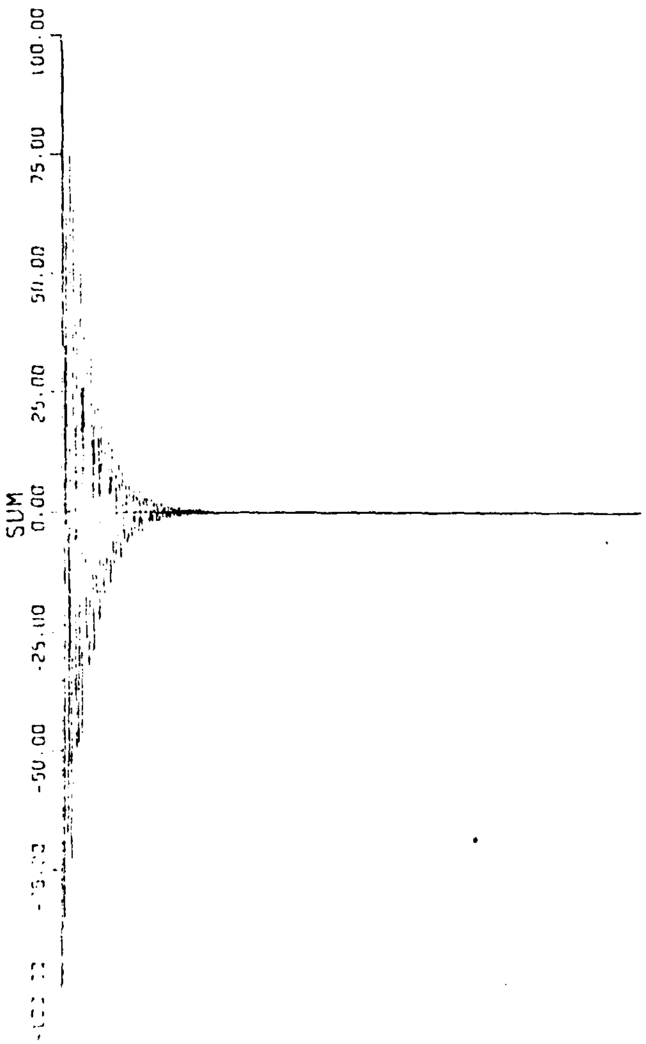

Fig. 6. Transient response of the adaptive array for K_1=.05, K_2=1.25x10^{-5}.

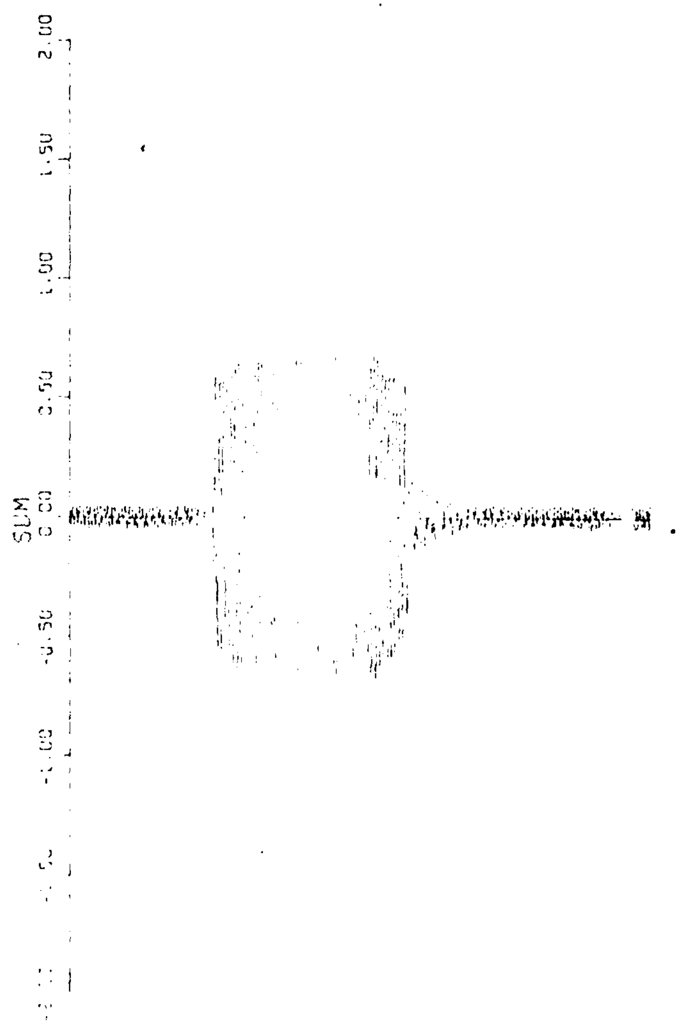

Fig. 7. Transient response of the adaptive array for K_1=.05, K_2=1.25x10-5.

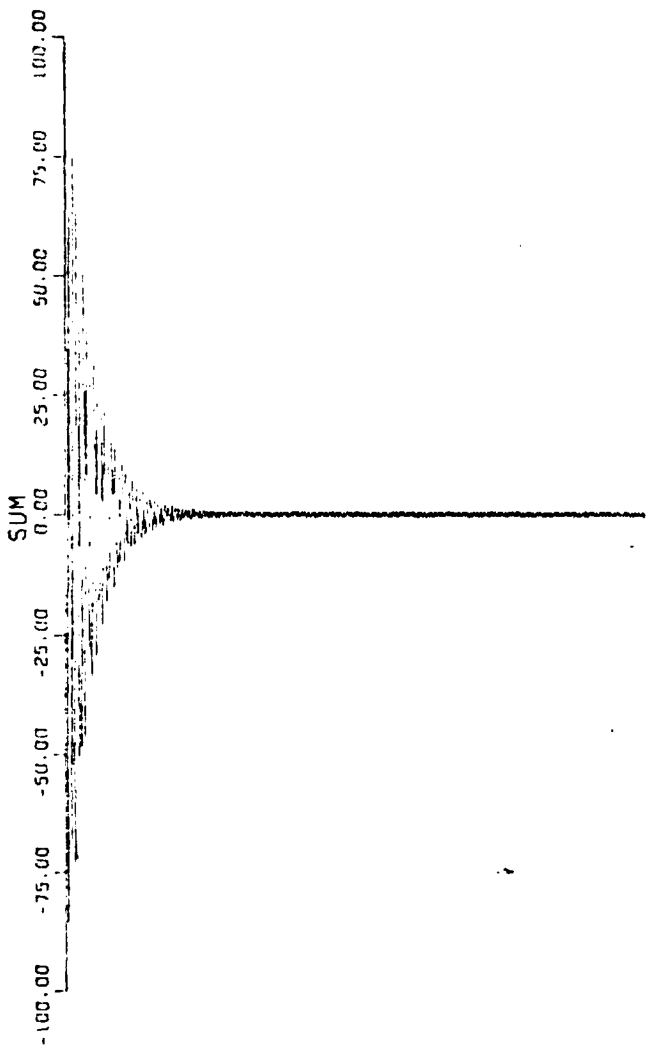

Fig. 8. Transient response of the adaptive array for K_1=.005, K_2=1.25x10^{-6}.

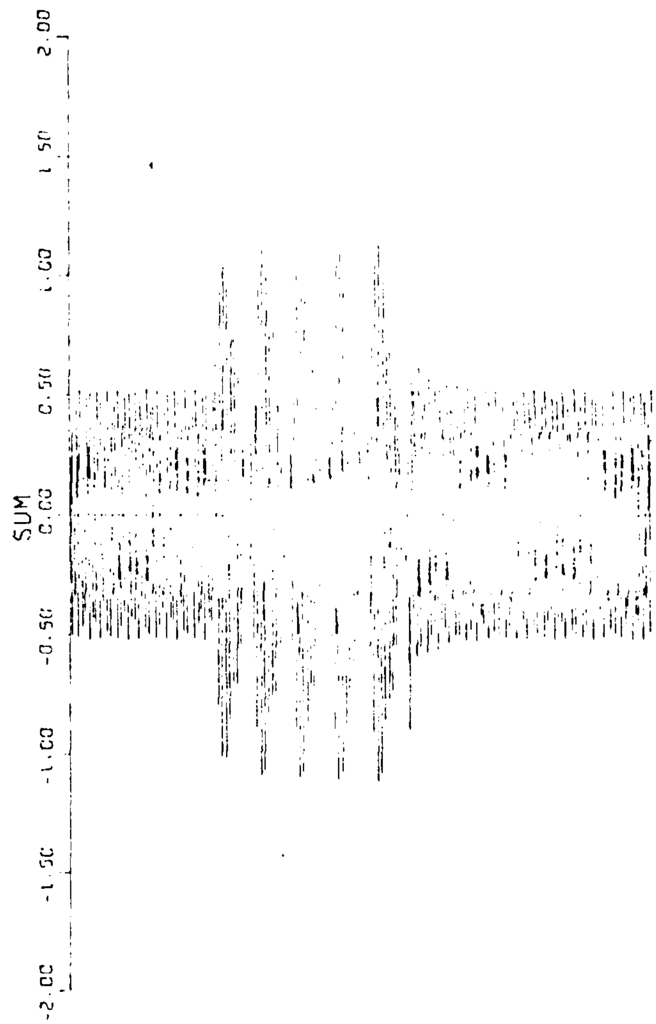

Fig. 9. Transient response of the adaptive array for K_1=.005, K_2=1.25x10^{-6}.

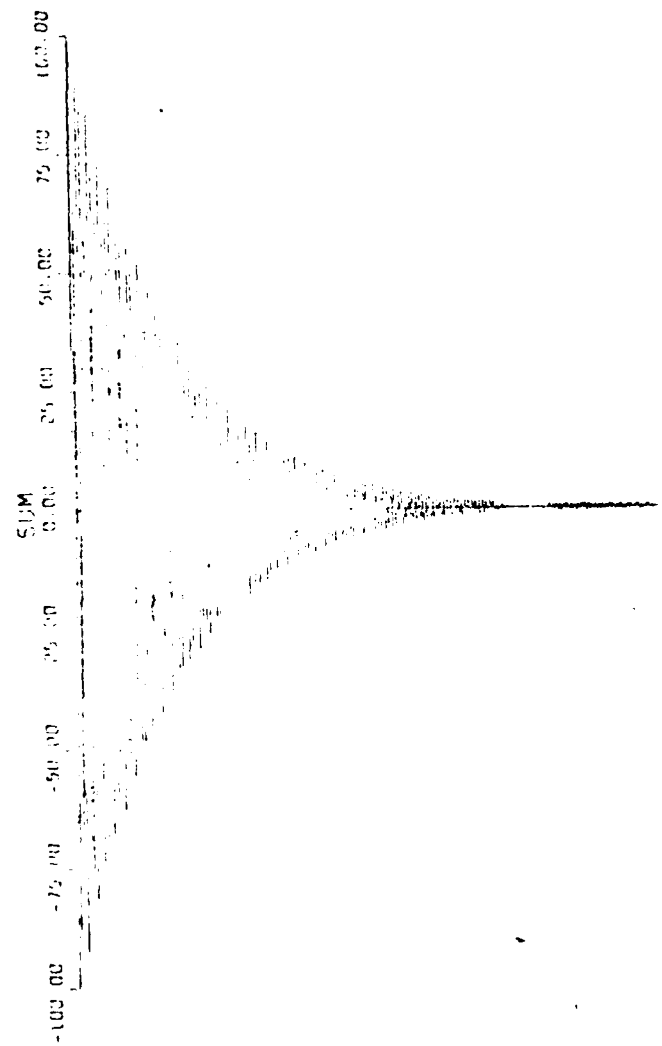

Fig. 10. Transient response of the adaptive array for $K_1=.5$, $K_2=5x10^{-4}$.

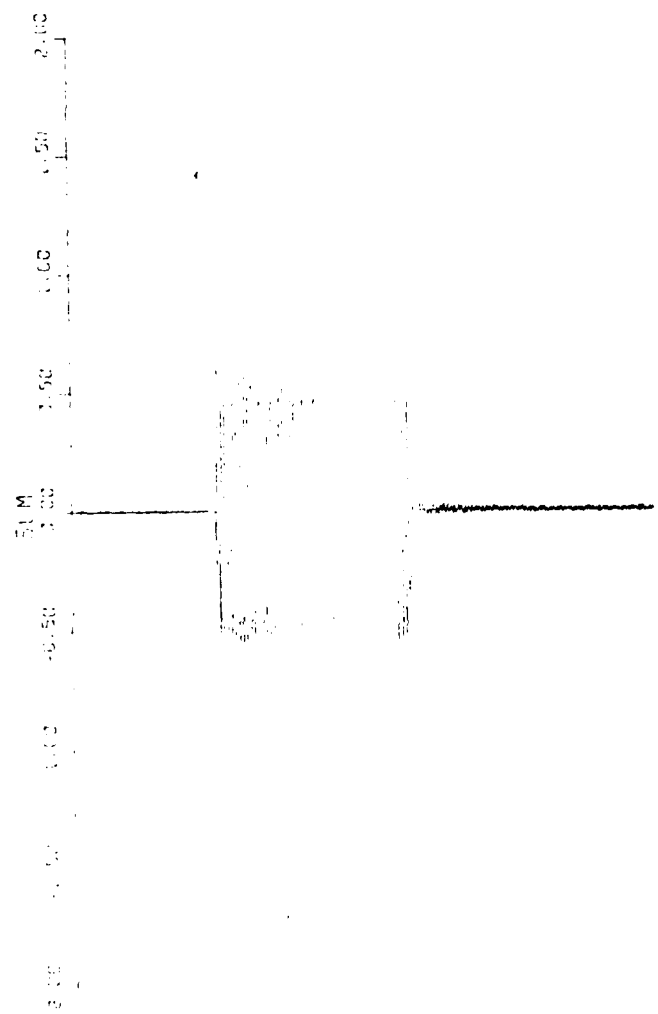

Fig. 11. Transient response of the adaptive array for $K_1=.5$, $K_2=5x10^{-4}$.

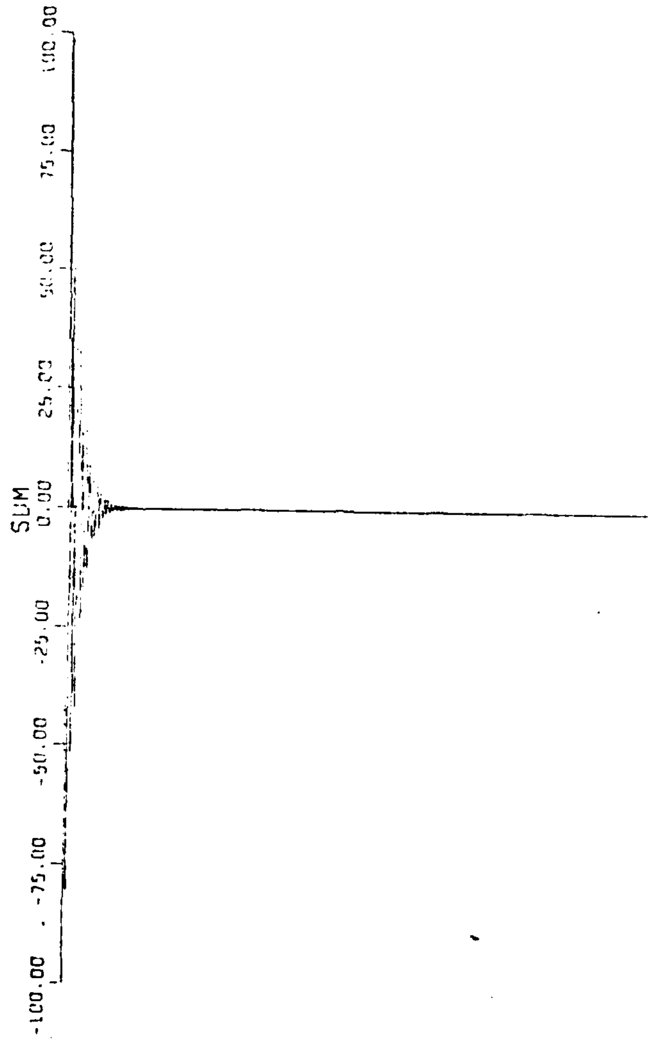

Fig. 12. Transient response of the adaptive array for $K_1=.5$, $K_2=.5\times10^{-4}$.

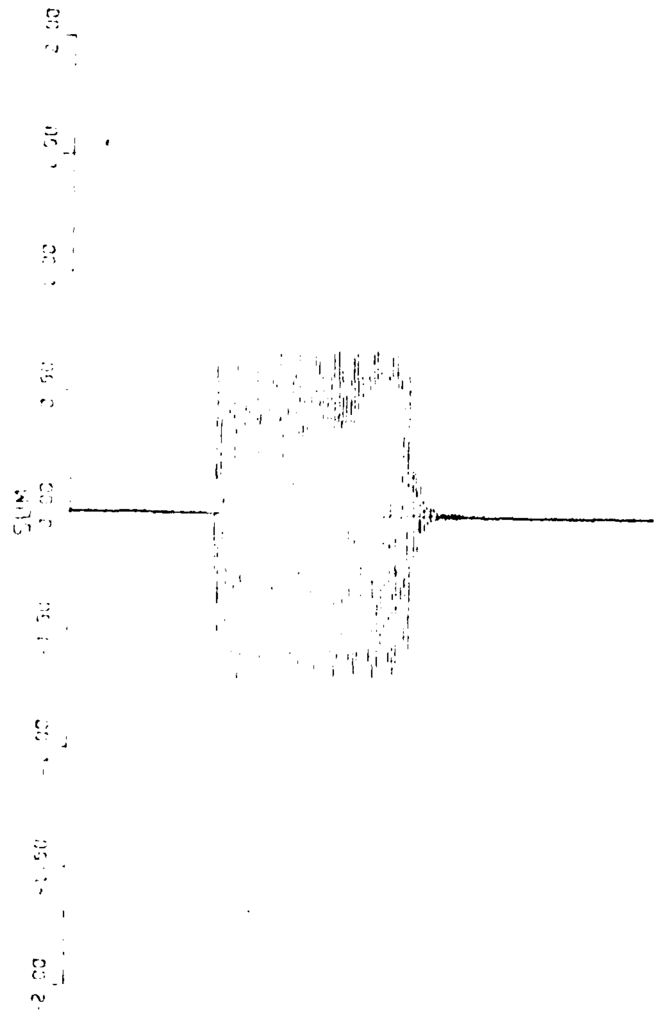

Fig. 13. Transient response of the adaptive array for $K_1=.5$, $K_2=.5\times10^{-4}$.

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APPENDIX
COMPUTER PROGRAM

```
      DIMENSION IBUF(100),TIME(601),Y(6),W(6),WO(6),
     $SUMA(601),SUMB(601)
C     INITIAL SETTINGS FOR WEIGHTS
      W(1)=1.
      WO(1)=1.
      DO 1 I=2,6
      W(I)=0.
      WO(I)=0.
 1    CONTINUE
      PI=3.14159265359
      TWOPI=6.28318530718
C     FREQUENCY OF DESIRED AND INTERFERENCE SIGNALS
      FRED=1.E 09
      FREI=1.1E 09
C     PHASE DELAY
      ALPHA=PI*SIN(PI*30./180.)
      BETA=PI*SIN(PI*60./180.)
C     UPPER LIMIT FOR RESETTING TIME INCREMENT
      UP=3.5/(4.*FRED)
C     LOOP GAIN CONSTANT
      CI=.005
      CO=.005E 06
C     INITIAL OUTPUTS FOR ELEMENTS 2,3,5 AND 6
      Y(2)=0.
      Y(3)=0.
      Y(5)=0.
      Y(6)=0.
C
      T=0.
      TD=0.
      DO 2 J=1,1951
      IF(J.LE.1500) GO TO 11
      IF(J.GT.1500 .AND. J.LE.1720) GO TO 422
 11   DESIG=0.
      DESIGD=0.
      GO TO 17
 422  DESIG=SIN(TWOPI*FRED*TD)
      DESIGD=SIN(TWOPI*FRED*TD-ALPHA)
 17   OMET=TWOPI*FREI*T
      IF(OMET.GT.TWOPI) GO TO 111
      GO TO 101
 111  OMET=OMET-TWOPI
      IF(OMET.GT.TWOPI) GO TO 111
 101  Y(1)=DESIG+100.*SIN(OMET)
      Y(4)=DESIGD+100.*SIN(OMET-BETA)
      SUM=0.
      DO 3 K=1,6
      SUM=W(K)*Y(K)+SUM
 3    CONTINUE
      IF(J.LE.601) GO TO 502
      IF(J.GT.1350) GO TO 503
      GO TO 543
 502  SUMA(J)=SUM
      TIME(J)=T*FRED
      GO TO 543
 503  M=J-1350
      SUMB(M)=SUM
 543  DO 4 L=1,6
      W(L)=(1.-1./CO)*W(L)+WO(L)/CO-2.*(CI/CO)*Y(L)*SUM
 4    CONTINUE
      T=T+1./(4.*FRED)
      TD=TD+1./(4.*FRED)
      IF(TD.GT.UP) TD=0.
      Y(3)=Y(2)
```

```
      Y(2)=Y(1)
      Y(6)=Y(5)
      Y(5)=Y(4)
 2    CONTINUE
      CALL PLSUA(SUMA,TIME)
      CALL PLSU(SUMB,TIME)
      CALL EXIT
      END
C
      SUBROUTINE PLSUA(SUM,T)
      DIMENSION T(6Ø1),SUM(6Ø1),IBUF(1ØØ)
      CALL PLOTS (IBUF,1ØØ,3)
      CALL PLOT (1.,5.5,-3)
      CALL AXIS (Ø.,Ø.,1HT,Ø,5.,Ø.,Ø.,3Ø.Ø5,1.,2)
      CALL AXIS (Ø.,-4.,3HSUM,3,8.,5Ø.,-1ØØ.,25.,1.,2)
      X=T(1)/3Ø.Ø5
      Y=SUM(1)/25.
      CALL PLOT (X,Y,3)
      DO 7 M=2,6Ø1
      X=T(M)/3Ø.Ø5
      Y=SUM(M)/25.
      CALL PLOT (X,Y,2)
 7    CONTINUE
      CALL PLOT (5.,-5.5,999)
      RETURN
      END
C
      SUBROUINTE PLSU(SUM,T)
      DIMENSION T(6Ø1),SUM(6Ø1),IBUF(1ØØ)
      CALL PLOTS (IBUF,1ØØ,3)
      CALL PLOT (1.,5.5,-3)
      CALL AXIS (Ø.,Ø.,1HT,Ø,5.,Ø.,Ø.,3Ø.Ø5,1.,2)
      CALL AXIS (Ø.,-4.,3HSUM,3,8.,5Ø.,-2.,.5,1.,2)
      X=T(1)/3Ø.Ø5
      Y=SUM(1)/.5
      CALL PLOT (X,Y,3)
      DO 88 M=2,6Ø1
      X=T(M)/3Ø.Ø5
      Y=SUM(M)/.5
      CALL PLOT (X,Y,2)
 88   CONTINUE
      CALL PLOT (5.,-5.5,999)
      RETURN
      END
*
```

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