A TECHNIQUE FOR DESIGNING ACTIVE CONTROL SYSTEMS FOR ASTRONOMICAL-TELESCOPE MIRRORS

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This paper considers the problem of designing a control system to achieve and maintain the required surface accuracy of the primary mirror of a large space telescope. Control over the mirror surface is obtained through the application of a corrective force distribution by actuators located on the rear surface of the mirror. The design procedure is an extension of a modal control technique developed for distributed parameter plants with known eigenfunctions to include plants whose eigenfunctions must be approximated by numerical techniques. Instructions are given for constructing the mathematical model of the system, and a design procedure is developed for use with typical numerical data in selecting the number and location of the actuators. Examples of actuator patterns and their effect on various errors are given.
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A TECHNIQUE FOR DESIGNING ACTIVE CONTROL SYSTEMS
FOR ASTRonomical-Telescope MIRRORS

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SUMMARY

This paper considers the problem of designing a control system to achieve and maintain the required surface accuracy of the primary mirror of a large space telescope. Control over the mirror surface is obtained through the application of a corrective force distribution by actuators located on the rear surface of the mirror. The design procedure is an extension of a modal control technique developed for distributed parameter plants with known eigenfunctions to include plants whose eigenfunctions must be approximated by numerical techniques. Instructions are given for constructing the mathematical model of the system, and a design procedure is developed for use with typical numerical data in selecting the number and location of the actuators.

Two techniques for treating disturbances to the plant are discussed. These two techniques, which treat the errors as deterministic and uncorrelated, respectively, are examined from the standpoints of sensitivity to various mirror errors, determining the number of actuators required, and means of finding the best locations. For the deterministic case it was found that the "best" actuator locations (those locations which will minimize the steady-state error) are very sensitive to the error distribution. In addition, these locations can presently be found only by exhaustive searches of all possible actuator locations, and the number of actuators required for a specific mirror and specific error can only be estimated after much computer time is used. In practice the error distribution over the mirror surface would be expected to change with the telescope attitude relative to the sun. Also, the exact nature of the mirror errors will be time varying and will not, in any case, be known very precisely. For these reasons it is not recommended that the errors be treated deterministically. In addition, when the errors at any particular time are treated as uncorrelated random variables, the actuator locations are much less sensitive to specific variations in error distribution, an estimate of the number of actuators required to produce a desired reduction in figure error can easily be made, and locations which will yield results near the estimated figure accuracy can be found in a reasonable manner. Thus, at present this technique is preferred even though it requires more actuators than the deterministic method for a specific assumed error.
Several numerical examples are presented for a 76-cm-diameter (30-inch), thin spherical mirror and the computer program to implement the design procedure is given in an appendix. The results include a comparison of the modal control law and an optimal (least-squares) control law. The results of this comparison indicate that not much performance is to be gained by the added complexity of this optimum control law.

INTRODUCTION

One of the most fundamental problems associated with orbiting a large, diffraction-limited telescope of the size and type discussed in reference 1 is that of manufacturing, figuring, and maintaining the figure of the large primary mirror. Many factors such as initial figuring errors, the change from 1g to 0g, and changing temperature gradients on the mirror while in orbit make conventional techniques of figuring and supporting telescope mirrors unsuitable. An alternate approach has been developed in which the mirror is actively controlled by first sensing figure errors on the primary mirror and then nulling them by properly deforming the mirror. This technique (ref. 2) has been successfully applied to a 76-cm-diameter (30-inch), 1.27-cm-thick (1/2-inch) mirror with an initial error of 1/2 wavelength rms ($\lambda = 0.6328$ $\mu$m). By using 56 actuators, the mirror was controlled to a figure accuracy of better than $\lambda/50$.

Since the time of the investigation reported in reference 2, consideration has been given to the application of a modal control technique to a class of mirrors. The modal control technique represents the plant to be controlled in terms of the eigenvalues and eigenfunctions of the linear differential operator which describes the behavior of the plant. In reference 3, this technique was applied to distributed parameter plants whose eigenvalues and eigenfunctions could be obtained in closed form. In many practical examples, however, the required eigenfunctions are not available. For the mirror, for example, the restrictions of practical mounts (boundary conditions) and the existence of holes in the center of the primary mirror used in Cassegrain telescopes preclude obtaining the required eigenfunctions in closed form. Estimates of these functions must be obtained via numerical approximation techniques. The purpose of this paper is to set forth for such a system a design procedure based on the use of the modal control law described in reference 3. First, the modal control concept is explained, the control system described, and the analysis procedure set forth. Certain specific details, such as accounting for the pad effects and the treatment of initial or expected error, are then covered. Numerical data for the 76-cm-diameter (30-inch) mirror are given and examples are presented. Appendix A contains a listing of the computer program; appendices B, C, and D, eigenvector listings and diagrams and eigenvalue listings for the mirror; appendices E and F, several examples of actuator placement and resultant mirror errors.
Symbols

Values in the body of the paper are given both in SI Units and U.S. Customary Units. The measurements and calculations were made in the U.S. Customary Units. The values in the appendixes are in U.S. Customary Units and are consistent with the program in appendix A.

A area of mirror

\(a_i\) \(i\)th modal coefficient which expands \(P\) in terms of the mode shapes (see eq. (35))

\(a^N\) \(N \times 1\) vector of coefficients of the force distribution in the modal domain which corresponds to the controlled modes

\(a^R\) \(R \times 1\) vector of coefficients of the force distribution on the mirror; these coefficients arise from the action of the \(N\) actuators

\(C\) \(M \times 1\) vector which is the sum of the control system displacements and the disturbances in the modal domain; \(C\) is partitioned into \(C^N\) and \(C^R\)

\(C^M\) figure sensor estimate of \(C\)

\(C^N\) \(N \times 1\) vector which contains the elements of \(C\) which are being controlled

\(\dot{C}^N\) figure sensor estimate of the \(N\) modal coefficients corresponding to the controlled modes

\(C^N_{ss}\) steady-state or final value of \(C^N\)

\(C^R\) \(R \times 1\) vector which contains the remaining elements of \(C\)

\(C^R_{ss}\) steady-state or final value of \(C^R\)

\(D^N\) \(N \times N\) diagonal matrix which contains the control system compensation (also referred to as the diagonal controller)

\(E\) performance index under the assumption of uncorrelated errors
\( E_N \) for a particular set of \( N \) actuators

\( f \) frequency

\( H \) \( M \times N \) matrix which converts the actuator forces to modal coefficients retaining the dimensions of force; \( H \) is partitioned into \( H^N \) and \( H^R \)

\( H^N \) \( N \times N \) matrix which contains the rows of the \( H \) matrix corresponding to the \( N \) modes being controlled

\( H^R \) \( R \times N \) matrix containing the remaining elements of the \( H \) matrix

\( h_{ij} \) \( ij \)th element of the \( H \) matrix

\( J, J^*, J_1 \) performance indices

\( K \) gain constant

\( M \) total number of modes (eigenvectors) used to model the mirror

\( m \) diagonal matrix of elemental masses \( \Delta m_i \)

\( m_t \) total mass of mirror

\( \Delta m_i \) mass of \( i \)th element of the structural model

\( N \) number of actuators or number of controlled modes

\( P \) total force distribution on the mirror from \( N \) actuators

\( q \) vector of disturbance coefficients in the modal domain

\( q_i \) modal error coefficient of the \( i \)th mode

\( q^M \) the \( M \times 1 \) vector \( q \)

\( q^N \) \( N \times 1 \) vector of disturbances in the modal domain which correspond to the controlled modes
\( q_R \) vector of disturbances which remain after \( q \) is partitioned into \( q^N \) and \( q^R \)

\( R \) remaining modes, \( R = M - N \)

\( s \) Laplace operator

\( U \) \( M \times M \) matrix of eigenvectors

\( W \) \( M \times 1 \) vector of mirror errors at the grid points

\( W_i \) figure error of the mirror at the ith grid point

\( x, y, t \) \( x, y \) coordinates on mirror at time \( t \)

\( Z \) coordinate axis directed (positive) along the optical axis

\( \alpha^N \) \( N \times 1 \) vector of forces applied to the mirror surface (\( \alpha = \alpha^N \))

\( \beta_j \) force distribution over the pad area of the jth actuator

\( \Gamma \) area over which the pads act

\( \varepsilon_i \) structural damping of the ith mode

\( \Lambda \) \( M \times 1 \) vector of eigenvalues

\( \lambda \) wavelength of light

\( \xi^M \) figure sensor error in determining \( C^M \)

\( \rho \) density of the mirror expressed in terms of its area

\( \sigma^2_{q_i} \) variance of the ith modal error

\( \tau, \tau', \tau'' \) time constants

\( \phi^2_i \) defined by equation (59); under the assumption of uncorrelated errors, this quantity gives the fraction of the ith modal error which appears in the final error
The Modal Control Concept

The modal control concept, as applied to mirrors for use in orbiting telescopes, is treated in detail in reference 3, and design examples for flat plates are presented. For purposes of analysis in the present study, the mirror is considered to be a structure tied to a set of supports or mounts that prevent rigid-body motions. The elasticity of the mounts themselves may or may not be considered, depending upon the degree of sophistication of the analysis. (The analysis used throughout this paper considers the mounts to be rigid.) The modes of vibration of the mirror, subject to the constraints of the supports, are the modes used in the analysis. The mode shapes are referred to as eigenvectors of the mirror and the frequencies are the eigenvalues.

Generally the mode shapes and frequencies must be obtained by numerical methods since the solution of the governing partial differential equation is not available. The eigenvectors and eigenvalues of the structure that are used in this paper were obtained from a
numerical program (SAMIS, ref. 4) and have been checked by NASTRAN (ref. 5). These results have been verified experimentally (ref. 6). The eigenvectors obtained from the numerical program are tabulated in the $U$ matrix (see appendix B), with column 1 denoting the first, or lowest frequency, eigenvector and each succeeding column denoting higher order mode shapes. The vector of eigenvalues $\Lambda$ (see appendix D) is ordered with the lowest frequency first.

The finite-element model that was used in SAMIS is given in reference 7. This model was used to extract the first 58 eigenvectors and eigenvalues of the mirror. (See appendix D.) This set of eigenvectors and eigenvalues has been used throughout the analysis.

One motivation for using the modal control law was to allow the designer to decouple the dynamic behavior of the control system; another and more important aspect of this control law is that the mode shapes provide a hierarchy of errors that are likely to occur in practice. That is, the modes may be ordered in such a way that mode 1, or the fundamental mode shape, is more likely to occur than mode 2. Also, a measure of the relative amplitude is available by examining the eigenvalues of the two modes. That is, if the eigenvalues of modes 1 and 2 differ by a factor of $n$, the second mode will require about $n$ times the input force disturbance to produce the same displacement error. This is just another way of saying that the mirror (plant) acts as a filter to high-order modes. The one exception to this is that careless initial polishing and figuring of the mirror could generate considerable error (as displacements) in the high-order modes. Conversely, this knowledge of the mirror should be used to avoid fabrication errors which will be particularly difficult to correct.

System Configuration

For the purposes of designing a control system for a mirror, the designer obtains a transformation from mirror surface deflections (or errors) to modal coefficients, which can be viewed as a coordinate transformation. That is,

$$q = [U]^{-1}W$$

(1)

represents a transformation from the error at a set of points $W$ over the surface of the mirror to a set of modal coordinates $q$. Figure 1 shows a block diagram of the mirror, figure error sensor, and actuators as they appear in a finite modal representation. The mirror itself is mathematically represented by the five blocks (matrices) labeled $H_N^N$ and $H_R^R$, $A_N^N$ and $A_R^R$, and $U^M$. The superscripts $N$ and $R$ have the relationship

$$N + R = M$$
Figure 1. Block diagram of mirror and control system.

- Figure sensor
- Coordinate transformation to modal domain
- Coordinate transformation to physical domain
- Mirror structural model
- Actuator forces
where

\[ M \] number of modes used to model the mirror (although there are an infinite number of mirror modes, practical limitations require a finite number, and 58 will be used later for numerical evaluation)

\[ N \] number of actuators used (numerically equal to the number of controlled modes)

\[ R \] remaining modes

In the physical world the actuator forces \( a^N \) are translated directly into mirror figure displacements \( W(x,y,t) \); in the mathematical model the \( N \) forces are transformed by the \( H^N \) and \( H^R \) matrices into a set of force coefficients \( a^N \) and \( a^R \), respectively, in the modal domain. These forces are then transformed by the \( A \) matrices into the modal coefficients of displacement. These coefficients, generated by the control system, are summed with the coefficients representing the error in the modal domain that previously existed on the mirror, and the result (denoted by \( C^N \) and \( C^R \)) is transformed by \( [U^M] \) into the final displacement \( W(x,y,t) \) according to the relationship

\[
[U^M]\begin{bmatrix}
C^N \\
C^R
\end{bmatrix} = W^M
\] (2)

To combine this model into a control system requires a sensor to measure \( W(x,y,t) \). The sensor output is then changed into the modal coordinate system by the proper transformation \( [U^M]^{-1} \). Since \( N \) actuators can control only \( N \) modes, the subset of the \( N \) selected modes to be controlled is usually all that is generated. One would normally control only the first, or lowest, \( N \) modes.

The \( N \) selected modes are then fed through the dynamic compensation \( D^N(s) \) in which the proper gains and compensation are applied to each mode independently. If a type 1 system is used, as will be specified in the section entitled "Evaluation of Steady-State Errors," then each diagonal element of \( D^N \) corresponding to one channel of the decoupled controller will contain an integration. The output of \( D^N \), denoted \( a^N \), is still in the modal domain. In fact, this output is a set of modal coefficients which describe the desired force patterns to be distributed on the mirror. To change these to discrete forces, which is the way they must be applied to the mirror, the values of \( a^N \) must be transformed by multiplying by \( [H^N]^{-1} \). This matrix \( [H^N]^{-1} \) also accounts for the effect
of the physical mechanism through which the actuator applies a load to the plant. This completes the description of the control system which will be analyzed in later sections. For a more complete and rigorous discussion, see reference 3.

Modal Representation of Figure Error

The modal control technique has been developed for mirrors whose modes, denoted by \( U_i(x,y) \), are assumed to be members of a complete orthonormal set. Since this set of modes is complete, a modal expansion of any shape the mirror can take can be obtained by using the correct coefficient for each mode:

\[
W(x,y,t) = \sum_{i=1}^{\infty} C_i(t) U_i(x,y)
\] (3)

Therefore, for any \( N \) points on the mirror, the following equation may be written symbolically in matrix format:

\[
\begin{bmatrix}
W_1'(x_1,y_1) & \cdots & W_N'(x_N,y_N)
\end{bmatrix}
= \begin{bmatrix}
U_1(x_1,y_1) & \cdots & U_N(x_N,y_N)
\end{bmatrix}
\begin{bmatrix}
C_1(t) \\
C_2(t) \\
\vdots \\
C_N(t)
\end{bmatrix}
\begin{bmatrix}
\sum_{i=1}^{\infty} C_i(t) U_1(x_1,y_1) \\
\sum_{i=1}^{\infty} C_i(t) U_2(x_2,y_2) \\
\vdots \\
\sum_{i=1}^{\infty} C_i(t) U_N(x_N,y_N)
\end{bmatrix}
\] (4)

or

\[
W_N = U^{\text{CN}} N + U^{\text{CR}} R
\] (5)

where

\[
U^{\text{CR}} R = \begin{bmatrix}
U_{N+1}(x_1,y_1) & \cdots & U_M(x_1,y_1) & \cdots \\
\vdots & \ddots & \ddots & \ddots \\
U_{N+1}(x_N,y_N) & \cdots & U_M(x_N,y_N) & \cdots \\
\vdots & \ddots & \cdots & \cdots
\end{bmatrix}
\begin{bmatrix}
C_{N+1}(t) \\
\vdots \\
C_M(t)
\end{bmatrix}
\] (6)

and \( U^R \) is an \( N \times \infty \) matrix and \( C^R \) is an \( \infty \times 1 \) vector.
The second term in equation (5) causes an error when the mode amplitudes are determined since they are not available, and the amplitudes $C^N$ are estimates denoted $\hat{C}^N$.

$$\hat{C}^N = [U^N]^{-1}W^N = C^N + [U^N]^{-1}URCR$$

(7)

The term $[U^N]^{-1}URCR$ represents the error in the estimate of $C$. It is possible to take more measurements than the number of actuators used. If for example the number of measurements is selected to be $M$ $(M > N)$, then

$$\hat{C}^M = [U^M]^{-1}W^M = C^M + \xi^M$$

(8)

where

$$\xi^M = \begin{bmatrix} U_{M+1}(x_1, y_1) & \cdots & \cdots & C_{M+1}(t) \\ \vdots & \ddots & \vdots & \vdots \\ U_{M+1}(x_N, y_N) & \cdots & \cdots & \cdots \end{bmatrix}$$

(9)

If $M$ is sufficiently large, then $\xi^M$ will be negligible. Therefore, it will be assumed that

$$\xi^M = 0$$

From figure 1, the following equation may be written (with the $x, y, t$ notation dropped):

$$C^N = q^N + \Lambda^N H^N \alpha^N$$

(10)

Since

$$\alpha^N = [H^N]^{-1}D^N \hat{C}^N$$

(11)

and it is assumed that

$$C^N = \hat{C}^N$$

(12)
substituting equations (11) and (12) into equation (10) gives

$$C^N = q^N - \Lambda^N H^N [H^N]^{-1} D N C^N$$

or

$$C^N = [I + \Lambda^N D N]^{-1} q^N$$

From the other path in the system model in figure 1,

$$C^R = \Lambda^R H^R \alpha^N + q^R$$

Substituting equations (11) and (12) into equation (15) yields

$$C^R = -\Lambda^R H^R [H^N]^{-1} D N C^N + q^R$$

Substituting equation (14) into equation (16) to eliminate $C^N$ gives

$$C^R = -\Lambda^R H^R [H^N]^{-1} D N [I + \Lambda^N D N]^{-1} q^N + q^R$$

By inserting $[\Lambda^N]^{-1} \Lambda^N$ into equation (17), the following expression for $C^R$ is obtained:

$$C^R = -\Lambda^R H^R [H^N]^{-1} [\Lambda^N]^{-1} \Lambda^N D N [I + \Lambda^N D N]^{-1} q^N + q^R$$

Equations (14) and (18) give the dynamic values of the modal coefficients of the error in the mirror surface. In the present application it is anticipated that the primary errors will be the initial figuring errors and thermal gradients that vary relatively slowly with time. Therefore it is reasonable to expect that the system will be generally at or near its steady state. The steady-state performance of the system is discussed in the following section.

Evaluation of Steady-State Errors

In determining the steady-state performance of the entire system, first equation (14) will be used to assess the resulting error in the controlled modes and then equation (18)
will be used to determine the error in the remaining modes. Taking the Laplace transform of equation (14) and considering the disturbance vector $q$ as a step input allows application of final-value theorem to determine the steady-state condition:

$$C^N_{ss} = \lim_{t \to \infty} C^N(t) = \lim_{s \to 0} sC^N(s) = \lim_{s \to 0} s \left[ I + \Lambda^N D^N \right]^{-1} \text{col} \left( \frac{q_i}{s} \right) \quad (i = 1, \ldots, N) \quad (19)$$

The matrices $\Lambda^N$ and $D^N$ are both diagonal with

$$\Lambda^N = \text{diag} \left[ \frac{1}{s^2 + \epsilon_i s + \omega_i^2} \right] \quad (i = 1, \ldots, N; \quad \epsilon > 0) \quad (20)$$

where equation (20) assumes some structural damping.

The diagonal matrix $D^N$ can be formulated at the discretion of the designer; however, a type 1 system is assumed, so that the combination of $\Lambda^N$ and $D^N$ is of the form

$$\Lambda^N D^N = \text{diag} \left[ \frac{K (\tau_1 s + 1) \ldots (\tau_n s + 1)}{s (\tau_1 s + 1) \ldots (\tau_n s + 1)} \right] \quad (21)$$

and

$$\left[ I + \Lambda^N D^N \right] = \text{diag} \left[ \frac{n \prod_{i=1}^{n} (\tau_i s + 1) + K \prod_{i=1}^{n} (\tau_i s + 1)}{s \prod_{i=1}^{n} (\tau_i s + 1)} \right] \quad (22)$$

which can be simplified to the form

$$\left[ I + \Lambda^N D^N \right] = \text{diag} \left[ \frac{\prod_{i=1}^{\ell+1} (\tau_i s + 1)}{s \prod_{i=1}^{n} (\tau_i s + 1)} \right] \quad (23)$$
by properly combining the numerator of equation (22) and factoring. Putting equation (23) into equation (19) and taking account of the inverse yields

\[
C_{ss}^N = \lim_{s \to 0} \left\{ s \text{ diag} \left[ \frac{1}{s} \sum_{i=1}^{n+1} \left( \tau_i s + 1 \right) \right] \right\} = 0 \quad (i = 1, \ldots, N)
\]

This is the expected result that a type 1 system will drive the error in the controlled modes to zero.

In anticipation of evaluating the steady state of equation (18), equation (21) and the inverse of equation (23) are combined to get

\[
\lim_{s \to 0} \Lambda N_DN \left[ I + \Lambda N_DN \right]^{-1} = \lim_{s \to 0} \text{ diag} \left[ \frac{n}{s} \sum_{i=1}^{n+1} \alpha_i \left( \gamma_i s + 1 \right) \right] = I
\]

Furthermore, since

\[
\lim_{s \to 0} \Lambda R = \lim_{s \to 0} \text{ diag} \left[ \frac{1}{s^2 + \epsilon_1 s + \omega_1^2} \right] = \text{ diag} \left[ \frac{1}{\omega_1^2} \right]
\]

and

\[
\lim_{s \to 0} \left[ \Lambda N \right]^{-1} = \lim_{s \to 0} \text{ diag} \left[ \frac{1}{s^2 + \epsilon_1 s + \omega_1^2} \right]^{-1} = \text{ diag} \left[ \omega_1^2 \right]
\]

equation (25) can be used to determine the steady-state value of equation (18):

\[
C_{ss}^R = \lim_{s \to 0} sC_{ss}^R(s) = -\Lambda R R \left[ \Lambda N \right]^{-1} \left[ \Lambda N \right]^{-1} q^N + q^R
\]

or

\[
C_{ss}^R = q^R - \Lambda R R \left[ \Lambda N_H N \right]^{-1} q^N
\]
where equations (26) and (27) indicate the nature of $\Lambda^R$ and $[\Lambda^N]^{-1}$. The nature of the $H$ matrix and how to evaluate it is given in the next section. Equation (29) states that the final steady-state error consists of two parts. The first part ($q^R$) is that due to the original error in the $R = M - N$ modes which were not controlled. The second part of the error is that generated by the control system itself as it corrects the error in the first $N$ modes.

A few notes on the dimensionality of the matrices in equation (29) are in order. The error vector $q^N$ is the initial error in the $N$ modes (not necessarily the first $N$) selected to be controlled and is $N \times 1$; $q^R$ is the set of errors in the remaining modes and is $R \times 1$. Therefore,

$$
\begin{bmatrix}
q^N \\
q^R
\end{bmatrix} =
\begin{bmatrix}
\Lambda^N \\
\Lambda^R
\end{bmatrix}
$$

The $\Lambda^N$ matrix is an $N \times N$ diagonal matrix which consists of the natural frequencies of the modes being controlled; $\Lambda^R$ is an $(M - N) \times (M - N)$ diagonal matrix of the frequencies of the remaining modes. The $H^N$ and $H^R$ matrices are $N \times N$ and $(M - N) \times N$, respectively. How these are obtained is given in the next section.

**Determination of Pad Effects**

The function of the $H$ matrices ($H^N$ and $H^R$) is to take the point loads of the actuators and transform them into modal coordinates. To determine the elements of the two $H$ matrices, consider first the continuous case. Let the force distribution on the mirror $P(x,y,t)$ be denoted by $P$

$$
P = \sum_{j=1}^{N} \alpha_j(t) \beta_j(x,y)
$$

where $\alpha_j(t)$ is the time-varying coefficient of the $j$th actuator and $\beta_j(x,y)$ is the distribution of the force on the mirror because of the pad. A "pad" is the physical device that connects the actuator to the mirror. This force distribution may be expanded by using the complete orthonormal set of modes:

$$
\beta_j = \sum_{i=1}^{\infty} h_{ij} U_i
$$

15
where the $(x,y,t)$ notation is understood. Because of the properties of this set, the coefficients may be determined immediately:

$$h_{ij} = \int_\Gamma U_i \beta_j \, d\Gamma$$  \hspace{1cm} (33)

where $\Gamma$ is the area over which the pad acts.

Substituting equation (32) into equation (31) gives

$$P = \sum_{j=1}^{N} \alpha_j \sum_{i=1}^{\infty} h_{ij}U_i = \sum_{i=1}^{\infty} \left( \sum_{j=1}^{N} h_{ij} \alpha_j \right) U_i$$  \hspace{1cm} (34)

Another way of writing equation (31) is

$$P = \sum_{i=1}^{\infty} a_i U_i$$  \hspace{1cm} (35)

which expresses $P$ directly in terms of the eigenvectors. The implication of equations (35) and (34) is that

$$a_i = \sum_{j=1}^{N} h_{ij} \alpha_j$$  \hspace{1cm} (36)

or

$$\left\{ a \right\} = \begin{bmatrix} \frac{a_N}{a^R} \\ \frac{H_N}{H^R} \end{bmatrix} \left\{ \alpha^N \right\}$$

The elements of the $H$ matrix are defined by equation (33). If small pads are assumed and it is further assumed that the load distribution is uniform, then

$$\beta_j = \frac{1}{\int_\Gamma dA}$$  \hspace{1cm} (37)
The assumption of small pads leads to the conclusion that the mode shape is relatively constant over the area of one pad, and equation (33) becomes

\[ h_{ij} = \int_{\Gamma} U_i \beta_j \, d\Gamma = \beta_j \int_{\Gamma} U_i \, d\Gamma = \frac{\int_{\Gamma} U_i(x_j, y_j) \int_{\Gamma} r \, d\Gamma}{\int_{\Gamma} \, d\Gamma} \]  

(38)

and

\[ \lim_{\Gamma \to 0} \begin{bmatrix} U_1(x_1, y_1) & U_1(x_2, y_2) & \cdots & U_1(x_N, y_N) \\ U_2(x_1, y_1) & U_2(x_2, y_2) & \cdots & U_2(x_N, y_N) \\ \vdots & \vdots & \ddots & \vdots \\ U_M(x_1, y_1) & U_M(x_2, y_2) & \cdots & U_M(x_N, y_N) \end{bmatrix} \]

(39)

When selecting the terms \( U_i(x_j, y_j) \) in equation (39), the coordinates \((x_j, y_j)\) are determined by the actuator locations since \( \beta_j \) is assumed zero everywhere except at the actuator location. Note that the \( H \) matrix is not square. There will be \( N \) columns corresponding to the \( N \) actuator locations used; however, all \( M \) rows will be present since each and every actuator will, in general, excite all \( M \) modes. For analysis purposes it is convenient to partition the \( H \) matrix into two parts:

\[ H = \begin{bmatrix} H^N \\ H^R \end{bmatrix} \]

(40)

The first matrix \( H^N \) consists of the \( N \) rows which correspond to the modes which have been selected to be controlled by the \( N \) actuators; \( H^N \) is therefore square. It is not necessary that the first \( N \) rows (\( N \) modes) be selected; however, this is usually desired. The reason for this will become clear in the examples. This arrangement will be assumed in future notation for the \( H^N \) matrix.

Since \( H^N, H^R, A^N, A^R, q^N, \) and \( q^R \) have now been obtained, the steady-state error from equation (29) may be calculated for a given choice of actuator locations and modes to be controlled. The only remaining consideration is the performance index.
PERFORMANCE EVALUATION

Calculation of the Performance Index

To obtain the best performance from an optical system, it is necessary to minimize the \( r.p.s. \) surface error of the elements (ref. 8). This error is defined as

\[
J^* = \sqrt{\frac{1}{A} \int_A W^2(A) \, dA}
\]  

(41)

For analysis purposes it is usually easier to work with a slightly different quantity which provides an equally valid measure of relative performance:

\[
J = J^*^2
\]  

(42)

Using \( J \) as the performance index and changing to discrete notation because of the numerical nature of the mirror problem gives

\[
J = \frac{1}{A} \sum_{i=1}^{M} W_i^2 \Delta A_i
\]  

(43)

or, in matrix notation,

\[
J = \frac{1}{A} W^T [\Delta A] W
\]  

(44)

where

\[
[\Delta A] = \text{diag} [\Delta A_i]
\]

\( W \) \( M \times 1 \) vector of mirror displacements or errors

\( A \) total area

The first \( N \) modes will contribute no steady-state error to a step response in a type 1 system since it was assumed that \( \hat{C}^N = C^N \). The final value of \( W \) is therefore given by
\[ W = \begin{bmatrix} U & 0_R \\ C_{ss} & 0 \\ \end{bmatrix} \]  

where \( C_{ss}^R \) is the \((M - N) \times 1\) or \( R \times 1 \) vector of the final error in the uncontrolled mode and is obtained from equation (29). If \( U \), the matrix of eigenvectors, is obtained from a finite-element program — as was done herein — then the eigenvector matrix is orthogonal with respect to the mass matrix \( m \) (refs. 4 and 5):

\[ U^T m U = I \]

For a homogeneous mirror of uniform thickness, \( m \) may be specified as an area associated with each grid point in the analysis times an area density constant \( \rho \). Then \( m \) may be written as

\[ m = \rho \text{diag}(\Delta A_i) = \rho [\Delta A] \]  

or

\[ \frac{1}{\rho} [m] = [\Delta A] \]  

Using equations (47) and (45) in equation (44) gives

\[ J = \frac{1}{A} C_{ss}^R \begin{bmatrix} C_{ss}^R \\ \end{bmatrix}^T U^T \frac{1}{\rho} [m] U [C_{ss}^R] \]  

\[ J = \frac{1}{\rho A} C_{ss}^R \begin{bmatrix} C_{ss}^R \\ \end{bmatrix}^T U^T [m] U [C_{ss}^R] \]  

\[ J = \frac{1}{\rho A} C_{ss}^R \begin{bmatrix} C_{ss}^R \\ \end{bmatrix}^T \]  

\[ J = \frac{1}{m_t} C_{ss}^R C_{ss}^R = \frac{1}{A} W^T [\Delta A] W \]
where the total mass is

\[ m_t = \sum_{i=1}^{M} \Delta m_i \]  

The contribution to the mean-square error of any mode is seen from equation (51) to be given by \( C_i^2 / m_t \).

In any approach where the controller is designed by use of an alternate representation of the mirror, it is important to express the desired system performance within the framework of the alternate reference frame. The significance of equation (51) is that it expresses the figure of merit of the system performance — rms error — as a very simple function of the amplitudes of the higher order modes. Thus, minimum rms surface error on the mirror is obtained by minimizing the sum of the squares of the amplitudes of the higher order modes. If only a relative measure of one actuator arrangement over another is of interest, the term \( 1 / m_t \) may also be dropped since it is constant for any given mirror. This gives

\[ J_1 = \begin{bmatrix} C_{Rt}^S \end{bmatrix}^T \begin{bmatrix} C_{Rt}^S \end{bmatrix} \]  

Treatment of Initial Errors or Disturbances

The vector obtained from equation (1) assumes that the error at each grid point on the mirror surface is known. When this is used in equation (29), the resulting design represents a deterministic treatment of the errors. While such a treatment of the errors will lead to minimum final error, the result can also lead to overoptimism on the part of the designer. Consider the following case.

Given a set of initial errors, the designer determines that a specific actuator arrangement will reduce the final error to an acceptable value. When the mirror is placed in orbit, it is highly likely that the errors will be different from those anticipated. As a result, the second term in equation (29) — the error generated by the control system — will change, possibly significantly. Consequently, the total error as given by equation (29) may now be unacceptable. It is concluded, therefore, that the "best" actuator location, based on deterministic errors, is sensitive to initial error. The question is, of course, how sensitive? Usually very sensitive, because the actuator positions have been chosen to generate specific amounts of error in the uncontrolled modes (generally opposite and equal to what was originally there) when specific amounts of error are removed in the controlled modes. A slight change in the error in the controlled modes, therefore, could make a great deal of difference in the final error.
An alternate way to treat an error is in an uncorrelated fashion, as suggested in reference 3. In this approach the values of $C_{ii}^R$ are still given by equation (29); however, the performance index is now the expected value of the mean-square error

$$E(J) = \frac{1}{A} E[w^T \Delta A w]$$

(54)

where $E$ is the expectation operator. If the errors are uncorrelated, then

$$E(q_i q_j) = 0 \quad (i \neq j)$$

(55)

and the performance index becomes

$$E(J) = E\left(q_i^T R^{-1} q_i + q_i^T \psi \psi N q_i\right)$$

(56)

For the assumed type 1 system, where

$$\psi = \Lambda R H R \Lambda H^{-1}$$

(57)

equation (56) may be rewritten as

$$E(J) = \sum_{i=N+1}^{M} \sigma_{q_i}^2 + \sum_{i=1}^{M-N} \left( \sum_{j=1}^{N} \psi_{j,i} \sigma_{q_i}^2 \right)$$

(58)

where the variance of the error, which is assumed to have zero mean, is given by $\sigma_{q_i}^2$.

By reversing the order of summation in the second term of equation (58) and making the additional substitution

$$\phi_i^2 = \sum_{j=1}^{M-N} \psi_{j,i}^2$$

(59)

equation (58) can be rewritten

$$E(J) = \sum_{i=N+1}^{M} \sigma_{q_i}^2 + \sum_{i=1}^{N} \phi_i^2 \sigma_{q_i}^2$$

(60)
One notation addition is needed in equation (60), that is, to add the subscript \( N \) to \( E \) and to \( \phi_1^2 \) to indicate the number of actuators being used. This will prevent confusion later. Equation (60) is then written

\[ E_N = \sum_{i=N+1}^{M} \phi_i^2 q_i^2 + \sum_{i=1}^{N} \phi_{iN}^2 q_i^2 \]  

(61)

It should be pointed out that equation (61) represents an expected error. Depending upon the inclination of a particular individual, he may choose \( J^*, J, \) or \( J_1 \), given by the previous equations, as a measure of the performance. The only problem with these equations for the performance is that they require exact knowledge of the error vector and may be quite sensitive to changes in the error vector, while equation (61) requires only a knowledge of the variance of the error. It is more realistic to make an engineering estimate of this latter quantity than of the actual errors.

In equation (61) both parts of the error are seen to be positive. This means that the two error components will add directly. To influence the expected error, the designer may do two things. First, he should encourage the opticians to keep the error in the higher order modes as small as possible because he cannot do anything to reduce this error except possibly increase the value of \( N \). Second, he should select actuator locations which would minimize the value of \( \phi_{iN}^2 \). In fact, if \( \phi_{iN}^2 \) could be made zero for \( i = 1, \ldots, N \), then the expected error would be independent of the initial error in the controlled modes. Since most of the error will likely occur in the first \( N \) modes, choosing actuator locations to minimize \( \phi_{iN}^2 \) will lead to locations which tend to produce performance indices virtually independent of changes in error.

In the following sections and the appendices, various design examples will be given which are based upon the theory developed up to this point. Effects of initial errors, actuator placement, error treatment, and the number of actuators necessary for a particular case will be discussed.

**DESIGN PROCEDURE**

**Numerical and Physical Data**

The mirror which will be used in the analysis is shown in figure 2. It is a 1.27-cm-thick (1/2-inch), 76-cm-diameter (30-inch), \( F/3 \) spherical mirror which is supported on a kinematic (non-overconstrained) mount.

As mentioned in the Introduction, it is generally not possible to obtain closed-form expressions of the eigenfunctions of a practical mirror configuration such as that con-
Figure 2.- Photograph of 76-cm-diameter (30-inch) deformable mirror which was modeled for this report.
considered here. Therefore, estimates of the eigenfunctions are sought through numerical techniques. An analysis of the mirror was made with the SAMIS structural analysis program (ref. 4) and the grid breakup shown in figure 3(a). This grid breakup was adopted to comply with the SAMIS recommendation for use of equilateral triangles for maximum accuracy. This pattern also insured the location of a grid point (where forces may be applied and displacements sensed) at each actuator and sensor location of the existing mirror shown in figure 2. The actuator and sensor locations are shown in figure 3(b), where the numbers refer to grid points. As reported in reference 7, this procedure provides a satisfactory discrete model of the mirror behavior.

In the preceding sections, M has represented the finite number of modes used in lieu of the infinite number which would be required for an exact representation of the mirror. In performing a specific design it is desirable to select a value for M which is high enough to limit the error in the analysis and yet is not so high that it would require an excessive amount of calculation. Because of the inability to place a bound on the error incurred through the choice of a specific value of M, the choice is not subject to precise evaluation. In the present study the mirror shown in figure 2 was available for verification of theoretical results. This mirror has 58 displacement sensors, which similarly limit the maximum number of mode amplitudes that can be estimated. For this reason M = 58 was selected for the present study. It is believed that this number is more than adequate for the present application; however, an exhaustive study on this point was not performed and it is possible that a smaller value of M might also be satisfactory.

The matrix of eigenvectors determined from this model is given in appendix D, and appendix C contains plots of mode lines for a selected set of modes. The numbers on these plots are the value of the eigenvectors at the grid points. Therefore, each figure represents one eigenvector. The orientation of the figures in appendix C is the same as that in figure 3(b) to allow grid point numbers and eigenvalues to be correlated. The eigenvalues of the mirror are given in appendix B and are plotted in figure 4. For completeness appendix D also contains a listing of the diagonal mass matrix.

For design and analysis purposes three error vectors were assumed. The first error vector was obtained from reference 2 and is the error in figuring the mirror. The second and third were arbitrarily generated. The second was generated by assuming a set of four forces of 4,448 newtons (1 pound) located at grid points 16, 26, 21, and 40. The third example error was a parabolic error. The modal coefficients $q_i$ for these three error examples are listed in table I.

Control System Design Evaluation

The basic design procedure consists of setting up a trial design, evaluating $C_{ss}^{R}$ from equation (29), calculating $J_1$ from equation (53), and comparing this value of $J_1$
b, Grid arrangement and numbering used for control system analysis.

c, and (b) curved and grid arrangement for the analytical solution.
Figure ... eigenvalues of thin mirror as determined by SAMIS. Lowest frequency is associated with mode 1. SAMIS eigenvalues are inversely proportional to frequency.
with previous or desired results. If the results are not satisfactory, then a new design is tried. Since many trials will be necessary, the only practical approach is to perform the design with the aid of a computer. A program to build the various matrices and to evaluate $C_{ss}$ and the performance index $J_1$ has been written in FORTRAN IV and is given in appendix A. The flow diagram for the program is given in figure 5, where the steps of the design procedure are set out in a straightforward manner.

As shown in figure 5, the program will first read in values of the eigenvector matrix, the eigenvalues, and the initial error, or disturbance, vector. The program must then be supplied with the number of actuators $N$ to be used and the placement of these actuators. Actuator placement is specified by grid numbers. The selection of actuator location and number is the major degree of freedom that the control system designer has, and this selection more than any other will influence the value of $J_1$. The program must then be supplied with the number of modes to be controlled (the number of controlled modes must equal the number of actuators) and these modes identified. Identification of modes is by mode number corresponding to the column numbers of the $U$ matrix. With minor exceptions, these should always be the first $N$ modes. From this point, the program will sort the $\Lambda$, $q$, and $H$ matrices and carry out the calculation of $C_{ss}$ and $J_1$. The program will also do one other task; namely, it will calculate the actuator forces and final error on the basis of making a least-squares fit of the errors to the desired shape. This allows a comparison of the modal control law to an optimal control law for the same actuator locations. One restriction on the program, and ultimately the designer's freedom, is that the choice of actuator placement must be restricted to grid points of the structural analysis model. This restriction has not been found to be serious in the present model, which has 58 grid points.

One particular word of caution is in order about this, or any other program, which is used to calculate the final error. For a given pad shape and size and a given set of modes to be controlled, selecting the actuator placement pattern fixes the $H^N$ matrix. Since the inverse of $H^N$ is part of the controller, the actuator locations must be chosen to ensure that $H^N$ is nonsingular. A singular (or ill-conditioned) $H^N$ matrix indicates that the designer has placed actuators in such a manner that the amplitude of at least one controlled mode at these actuator locations is (or is nearly) a linear combination of the amplitudes of the other controlled modes. If $H^N$ is singular, the actuators cannot independently control the given modes. If $H^N$ is ill conditioned, the modes can be controlled but only at the expense of large applied control forces, which generate considerable error in the higher order modes. The designer obviously must avoid these cases; however, spotting a potentially singular matrix mainly on the basis of an actuator-placement pattern is almost impossible. The computer especially has trouble spotting this condition, since for reasons of numerical roundoff and the particular inversion procedure used, it will obtain "inverses" for very ill-conditioned or even singular matrices. The program given in
Figure 5.- Flow diagram of computer program in appendix A. This program evaluates the performance index for a given mirror and a given, or selected, set of actuator locations.
Appendix A treats this problem by calculating and printing out the normalized determinant of $H^N$. If the normalized determinant is very small relative to 1.0, then $H^N$ is said to be ill conditioned. (See ref. 9.) Usually an ill-conditioned $H^N$ matrix will result in a large value of $J_1$, which automatically excludes that actuator arrangement. This, however, is not always the case. (See, e.g., fig. E10 and associated discussion.)

Results for Deterministic Errors

From the first set of errors a series of design trials were run with various numbers of actuators. For the 58-node mirror model, all possible combinations of one, two, three, four, and five actuators were surveyed. Beyond five actuators, the number of possible combinations becomes too large to make exhaustive searches. Several design "rules of thumb" were tried to choose actuator locations; however, none of these provided values of $J_1$ that were considered to be near the minimum in light of the results from the exhaustive searches carried out for fewer actuators.

The technique that produced the best results was a gradient-type search which used the computer interactively. In this technique an initial actuator placement is chosen and the output of the computer is presented on a CRT. A perspective view of the mirror is also generated which shows the deformed state after control. A series of these perspective plots for five actuators is given in figure 6. On the basis of the tabulated data and the perspective plot, one actuator is moved one grid point and the program rerun to see whether a gradient can be set up on $J_1$ to improve the mirror performance. At most, six trials are required to exhaust the possible moves for one actuator. The most important single piece of information turned out to be the perspective plot—especially early in the search procedure. This plot allowed the grid point with the largest error to be easily spotted, and the actuator nearest this error was moved. The series in figure 6 took approximately 2 hours and improved the performance index $J_1$ from an initial value of 1136.6 to a value of 100, a factor of 10. Further effort beyond this point failed to provide improvement.

The results obtained from these gradient runs can be compared with the known minimum value $J_1 = 72$, obtained from an exhaustive search. The total number of runs that were required in the gradient-search process was 63. If the program were implemented so that the computer made all the choices of actuator placement, the gradient search would require about 30 seconds of computer time. The use of the computer in the interactive mode, however, allowed considerably more insight to be gained into what factors were affecting performance and what factors were not.

The results of the exhaustive searches for up to five actuators are given in appendix E. In each case the best 10 locations are shown. The initial performance index in all cases was $J_1 = 1136.6$ and two final errors are given. The first is the final error
Figure 6.- Perspective views of the mirror at various stages during the gradient search for best actuator location - five-actuator case. The final diagram D is a local minimum, i.e., moving any one actuator one grid point will not improve the figure. (Vertical scaling is variable for visibility purposes.)
obtained with the modal control law and the second is the result obtained when the actuator force is selected to minimize the rms error on the mirror. This is referred to herein as the optimal control law. A summary of these results is given in figure 7 for the modal control law. This figure shows the minimum error obtained plotted against the number of actuators used. The top curve is for the first error example and the lower curve is for the parabolic-error condition. Note that the vertical scale is logarithmic.

The plot in figure 7 suggests an empirical method of estimating the minimum number of actuators that a particular disturbance vector might require for a given mirror and performance index. That is, an exhaustive search over the model is made for a limited number of actuators and the results extrapolated to the desired performance. This would, of course, be equivalent to assuming an exponential decay of error with increasing number of actuators. The class of errors and plants for which such an assumption would hold is not known. Clearly, the error generated by the four loads of 4.448 newtons (1 pound) at the discrete grid points is not in this class since the final error is zero for four or more properly located actuators.

The problem with the deterministic approach is that first, there is presently no way to determine readily the best actuator placement, and second, the placement is very sensitive to initial error.

Results for Uncorrelated Errors

When the designer assumes uncorrelated errors, considerably more can be said about where actuators should be placed and how many actuators will be needed.

First, equation (51) is minimized instead of equation (29). Since the first term in equation (51) is constant for a particular number of actuators, the goal is to minimize the second term, which is the error generated in the uncontrolled modes by the control system. Instead of writing a program to do this, an alternative procedure which enabled the existing computer program to be used was adopted. This procedure yielded results that closely approximated those which would be obtained from equation (61). The alternate procedure consisted of a deterministic minimization of the second term in equation (29). This corresponds to the intent of the uncorrelated case in eliminating the possibility of a control-system-generated error canceling an existing error. If the values of $\sigma^2_{IN}$ are sufficiently small, there will only be a trivial difference in performance between the two procedures. Since the second term of equation (61) is to be assumed small, the final value of the expected error is the first term of equation (61). A plot of this portion of the equation is given in figure 8.

Since the actuator locations are less sensitive to initial error for this criterion, exhaustive searches were run for only the first error example. The results of these searches are given in appendix F for one, two, three, and four actuators. The values of
Figure 7: Error decay as a function of number of actuators for deterministic errors.
Figure 5. - Mean-square error $\sum_{i=N+1}^{\infty} q_i^2$ after $N$ controlled modes. This plot indicates expected performance with $N$ actuators, assuming uncorrelated errors. (Mode errors were taken from mirror of ref. 2.)
for the best run of each number of actuators are given in table II. Since the values of \( \phi_{IN}^2 \) are relatively small, the expected error falls right on the predicted values of figure 8.

The choice of possible actuator locations can be considerably reduced when it is desired to minimize the generated error. A look at the actuator location for four actuators shows that each set lies very close to the node lines of mode 5 and several higher modes. As pointed out in reference 3, this means that these modes will not be excited to any great extent. The first mode that is excited to any great extent by this arrangement of four actuators is mode 11. The ratio of eigenvalues for mode 11 to mode 4 is

\[
\frac{\lambda_{11}}{\lambda_4} = \frac{4.89 \times 10^{-4}}{2.95 \times 10^{-3}} = 0.166
\]

This means that the filtering action by the mirror is about 6 times as much for mode 11 as for mode 4, the last controlled mode.

To test the concept of placing actuators at, or near, nodes of higher order modes to minimize the generated error, the case for seven actuators was tried. The seven-actuator case was chosen because of two factors. First the eigenvalue plot of figure 4 shows a distinct jump between modes 7 and 8. This implies good filtering action by the mirror at this point. Second, the expected-error plot of figure 8 shows a jump between six and seven actuators. This implies that a considerable increase in performance can be obtained with seven actuators over six actuators. In selecting the actual grid locations the node lines for modes 8, 9, and 10 were overlaid and a set of grid points near the junction of these modes was selected. (See the last diagram of fig. F5 in appendix F.) This reduced set of grid points was searched for those locations which yielded minimum generated error. The results of this search are given in table II \( (\phi_{17}^2) \) and in the last set of figures of appendix F (actuator locations). The expected performance index with the best arrangement of seven actuators, obtained by using the minimum generated-error criterion, was \( J_1 = 274.9 \). Had all the values of \( \phi_{17}^2 \) been exactly zero, the performance index would have been \( J_1 = 250.6 \). The results, therefore, are very close to the predicted values of figure 8.

It should be noted that this result was obtained by searching only a relative few of the possible actuator locations, therefore, it cannot be said that the result represents the actual minimum. The important point is that a relatively short computer run was able to establish a set of actuator locations having a final error very close to the absolute minimum.
Comparison of Modal Control and Optimal Control Laws

As was stated earlier the computer program which was used to calculate the final errors also calculated the error that would have been obtained if an optimal control law (least-squares fit to best sphere) had been used. In the modal domain the error is given by merging equations (10) and (15) to get

\[
C = \begin{bmatrix} C^N \\ C^R \end{bmatrix} = \begin{bmatrix} q^N \\ q^R \end{bmatrix} + \left[ \frac{A^N H^N}{A^R H^R} \right] \alpha^N
\]

\[
C = q + \Delta H \alpha
\]  \hspace{1cm} (63)

It is desired to find the value of \( \alpha \) which minimizes

\[
J_1 = C^T C
\]  \hspace{1cm} (64)

Therefore,

\[
\frac{\partial J_1}{\partial \alpha} = 2[\Delta H]^T \Delta H \alpha + 2[\Delta H]^T q
\]  \hspace{1cm} (65)

This yields

\[
\alpha = -\left[ (\Delta H)^T \Delta H \right]^{-1} [\Delta H]^T q
\]  \hspace{1cm} (66)

From equation (66) the value of the forces needed to minimize the value of \( J_1 \) is calculated. The vector \( C \) is then calculated from equation (63), and \( J_1 \) is determined from equation (64). The computer program outputs the \( \alpha \) vector and the value of \( J_1 \). This can then be compared with the similar value of \( J_1 \) under the modal control law.

Numerical comparisons are given in appendixes E and F. Generally, given a set of actuator locations that were "good," there was little difference in the final result. The counterbalancing features of these two control laws are that the modal control law enables the dynamic behavior of the mirror to be considered while the optimal control law would never make the mirror worse than it was originally. To create more error than the original error would require a rather gross misplacement of actuators on the part of the control-system designer; however, it is possible.

For example, when the errors of example 4 in table I are treated deterministically, the conclusion is that the best actuator location is in the center of the mirror. If now the
error distribution changes so that the mode 1 error and the mode 3 error are inter-changed, the final error will be much worse than the original.

The reason for this is that the actuator was placed on a node of mode 1 while instructed to control mode 1. This produces considerable force, which generates considerable error. In the original distribution it was desirable to generate a lot of extraneous mode 3 error, but in the modified error distribution it is not desirable to generate much mode 3 error. The optimal control law, faced with the same situation, would do almost nothing in the second case, resulting in almost no change of figure error. For either control law the actuator placement was bad.

It should be recognized that any closed-loop control law, except one that has a decision-making capability as to relative performance, could result in a mirror figure that is worse than the original figure if the actuators are placed in a poor location. The ability of the modal control law to "order," or to establish a hierarchy of, likely mirror deformations through the eigenvectors and to provide a measure of relative likelihood through the ratio of eigenvalues means that the control-system designer will not place actuators in a bad location when using this control law.

Design Examples

To be specific, consider the case for four actuators and error example 1. Trial actuator locations are grid points 2, 30, 42, and 45; and the controlled modes are to be modes 1 to 4 inclusive. The \( H^N \) matrix is therefore given by

\[
H^N = \begin{bmatrix}
-1.092 \times 10^{-2} & 9.997 \times 10^{-3} & -1.307 \times 10^{-3} & 3.009 \times 10^{-2} \\
5.199 \times 10^{-3} & 7.297 \times 10^{-3} & 3.454 \times 10^{-2} & -1.016 \times 10^{-2} \\
-2.278 \times 10^{-2} & -4.529 \times 10^{-2} & -3.302 \times 10^{-2} & -3.347 \times 10^{-2} \\
-1.453 \times 10^{-2} & -5.481 \times 10^{-2} & -1.235 \times 10^{-2} & -1.229 \times 10^{-2}
\end{bmatrix}
\]

(67)

The following information is then obtained from the computer program for this case:

(1) The normalized determinant of \( H^N \) is 0.23, which is considered satisfactory.

(2) The force vector \( \mathbf{a} \) is \( \text{col}[-2.108, 5.916, -3.256, 3.781] \) newtons

(\( \text{col}[-0.471, 1.33, -0.732, 0.850] \)) \( \mathbf{b} \), given in the same order as the actuator grid locations.

The remaining important results are tabulated below in both their relative values (\( J_1 \)), as determined by the program in appendix A, and their absolute values (\( J^* \)) as given by equation (41).
The results correspond to the best possible location for four actuators for the deterministic error criterion and error example 1.

For the case just given, all factors worked together to produce an acceptable design; however, it is instructive to consider briefly a case that does not produce good results.

For example, it was stated earlier that the first (lowest) N modes were usually controlled. Now consider a case in which this is not true. In error example 1, table 1, it can be seen that the four modes which contain most of the error are modes 1, 2, 7, and 10. Suppose that the above actuator locations (2, 30, 42, and 45) are used and the control system is designed to drive these four modes to zero instead of the first four. The \( H^N \) matrix would now be different. For reference, the first column would now be

\[
\begin{bmatrix}
-1.092 \times 10^{-2} \\
0.519 \times 10^{-2} \\
-3.007 \times 10^{-2} \\
5.809 \times 10^{-9}
\end{bmatrix}
\]

This, in itself, presents no problems; however, in equation (62) the ratio of the eigenvalue of the first mode which would be excited \( \lambda_{11} \) to the eigenvalue of the highest controlled mode \( \Lambda_4 \) was

\[
\frac{\lambda_{11}}{\Lambda_4} = 0.166 < 1
\]

which results in an attenuation of the control-system-generated error. For the case in which the four modes containing the most error are controlled, the ratio

\[
\frac{\Lambda_3}{\Lambda_{10}} = \frac{3.06 \times 10^{-2}}{5.67 \times 10^{-4}} = 54
\]
results in an amplification of the control-system-generated error. One might therefore expect that the final error for controlling modes 1, 2, 7 and 10 could be worse than the error for controlling modes 1, 2, 3, and 4. The actual calculated final error for controlling modes 1, 2, 7, and 10 was found to be

\[ J_1 = 1.83 \times 10^5 \]

which is worse than the original error. It might be argued that a different actuator placement would improve this answer. Although this is probably true to some extent, a new set of actuator locations can only change the \( H^N \) matrix but not the ratio in equation (68), which is the underlying cause of the problem.

CONCLUDING REMARKS

A design procedure for selecting actuator locations on thin mirrors which are to be controlled by a modal control law has been worked out for use with typical numerical data. Instructions are given for constructing mathematical models of the system. Two ways of treating disturbances are discussed. These two techniques, deterministic and uncorrelated, are examined from the standpoint of sensitivity to various mirror errors, determining the number of actuators required, and means of finding the best locations. For the deterministic case it was found that the "best" actuator locations (those locations which will minimize the error) are very sensitive to the error distribution; these locations can presently be found only by exhaustive searches of all possible actuator locations, and the number of actuators required for a specific mirror and specific error can only be estimated after much computer time is used. For these reasons it is not recommended that errors be treated deterministically because the exact nature of the final figure-error distribution on the mirror surface will change with telescope attitude.

When the errors are treated as if they are uncorrelated, the locations are much less sensitive to variations in error distribution, an estimate of the number of actuators required to produce a desired reduction in figure error can easily be made, and locations which will yield results near these estimates can be found in a reasonable manner. At present, this technique is much preferred even though it requires more actuators than the deterministic method for a specific assumed error.

For example, the deterministic case for five actuators and 58 possible locations requires \( 4.6 \times 10^6 \) trials. When the errors are treated as uncorrelated variables, however, it is possible to select a subset of the 58 grid points which will yield results close to the theoretical limit. This subset is chosen by selecting potential locations near the common node lines of the next few higher modes and making an exhaustive search of these
locations. Also, for the uncorrelated treatment it is possible to estimate the number of actuators a given mirror and mount configuration will require by using an estimate of only the variance of the expected errors.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., November 11, 1972.
APPENDIX A

COMPUTER PROGRAM DESCRIPTION, LISTING, AND PRINTOUT

This appendix contains a listing of the program to calculate figure error of the mirror on the basis of a type 1 modal controller which controls N modes. The program contains a great deal of comment statements to aid the user, but a few additional comments are in order.

First, one must obtain a set of eigenvalues and the eigenvectors for the particular mirror to be analyzed. This is a major undertaking and should be done with a standard structural analysis program. The size of the eigenvector matrix is a critical item. Since actuators can be placed only at grid points of the structural analysis model, a sufficient number of these grid points must be used to allow reasonable flexibility in actuator placement. Too many grid points will result in a matrix that is too large to handle and requires excessive storage. The 58 grid points and the $58 \times 58$ matrix used in this analysis have proved to be reasonable. This results in a storage requirement of 110 000 bytes, which may be too large for some systems.

The next requirement is to obtain an error vector. This may be obtained from experimental data by estimating or determining the mirror error at each grid point and multiplying by $[\mathbf{U}]^{-1}$, or it may be artificially generated, as were examples 2 and 3. In any case the program assumes that the error vector is already in modal coordinates. An option of multiplying by a constant (to change units) is provided also.

The next option selects the output. The short option is recommended for all runs except debugging and examining final runs. An example of the complete output is given after the program listing. The short option is the last page of output.

The final option allows the designer to change a few of the actuators and control modes without completely rewriting the data cards. By setting $\text{NEW} = 1$, a single actuator location (or several locations) can be shifted by one number. For example, if a set of seven actuators is being run and it is desired to vary the location of one or two actuators to several selected points on the mirror, it can be done by using this option. Assume that the original data cards contain modes 1, 2, 3, 4, 5, 6, and 7 as controlled modes and actuator locations of 6, 16, 20, 24, 38, 55, and 50, and it is desired to change an actuator location from grid point 50 to grid point 49. In this case the $\text{MOCHNGE}$ would be zero and $\text{LOCHNGE}$ would be 1, and the next card would contain the number 49 in proper format. The controlled modes would then be the same, but the actuator locations would be 6, 16, 20, 24, 38, 55, and 49. Note that it is necessary to place the actuator(s) to be moved at the end of the list in the original data card.
APPENDIX A – Continued

The remainder of the program sorts matrices, calculates the various quantities needed to evaluate the performance, and formats the output. One point near the end of the program might cause confusion if data on a different mirror are used, that is, the conversion of the force vectors to pounds. The value of $1.25 \times 10^{-9}$ assumed that the original errors on the mirror surface were in fringes ($\lambda = 0.6328 \text{ m}$). If not, the error can be scaled in the first part of the program. Another potential trouble source is in the use of the eigenvalues. SAMIS eigenvalues are inversely proportional to frequency squared, and other programs (NASTRAN) output eigenvalues in frequency directly. This can be corrected at line 000467 by changing $\text{OMEGASQ}(J) = 10000./\text{LAMBDA}(I)$ to $\text{OMEGASQ}(J) = 10000. \times (\text{frequency squared})$. 
PROGRAM ALTUATE (INPUT, OUTPUT, TAPE1)
REAL LAMBDA(58)
INTEGER UMDG(58), ULGCAT(58)
DIMENSION UJ(58,58), MUDC(58), LDCAT(58), OMGA(S0(38), UNMDC(58),
1 HN(58,58), R(58,58), WN(58), U(58), MODJ(38,28)
DIMENSION DUMMY(58,1), IPUMU(58), INDEX(58,2)
DIMENSION PHID(58,58), PROD2(58), CRSS(58)
DIMENSION HCLUD(58,58)
DIMENSION ANIGUDE(58)
DIMENSION ARRAY(58,58), VECOR(58)
DIMENSION ALPHAX(58), ALPSKX(58)
DIMENSION PHI(30), LDAEL(8)
DIMENSION UNVFLX(58)
!
M = 0
N5E = 58
!
READ IN THE \( U \) (EIGENVECTOR) MATRIX. THE EIGENVECTORS ARE COLUMNS
OF THE MATRIX.
!
DO 5 J=1,58
READ (10) U(I,J), J=1,58
5 CONTINUE

READ IN THE CORRESPONDING EIGENVALUES.
!
READ 203, LAMBDA
PRINT 204, LAMBDA

READ IN A DESCRIPTIVE HEADING FOR THE ERROR VECTOR.
!
READ 207, LABEL
PRINT 260, LABEL

READ IN ERROR VECTOR AND THE SCALER MULTIPLIER.
!
READ 203, UNVUE
PRINT 205, UNVUE
READ 261, FACTOR

SCALE THE DEFLECTION VECTOR.
!
DO 403 I=1, 58
000100  UINVCE(I) = UINVCE(I) * FACTOR
000102  CONTINUE
000104  PRINT 262, FACTOR, UINV

C
C    READ IN IPRINT. IF IPRINT = 0 PRINTOUT WILL BE ABBREVIATED TO ONE PAGE
C    PER RUN. OTHERWISE PRINTOUT WILL INCLUDE SEVERAL INTERMEDIATE MATRICES.
C
000113  READ 205, IPRINT
C
C    NUMRUN IS THE NUMBER OF RUNS TO BE MADE. EACH ONE INVOLVES A
C    DISTINCT SET OF NODES CONTROLLED AND ACTUATOR LOCATIONS.

000121  READ 206, NUMRUNS

C
C    BEGINNING OF DO-LOOP WHICH PROCESSES EACH RUN.

000127  DO 350 IRUNS=1,NUMRUNS

C
C    READ IN NEW. IF NEW = 1, A NEW SET OF NODES AND ACT. LOCATIONS IS READ IN.

000131  READ 260, NEW
000136  IF (NEW .EQ. 1) GO TO 415

C
C    IF NEW .NE. 1, READ IN THE FOLLOWING TWO VALUES WHICH INDICATE THE NUMBER
C    OF NODES AND ACT. LOCATIONS TO BE CHANGED.

000140  READ 260, MOCHNGE, LCCHNGE
000150  IF (LCCHNGE .EQ. 0) GO TO 405
000150  MOCHNGE = MODE + 1 - MOCHNGE

C
C    REPLACE THE LAST MOCHNGE NODE NUMBERS WITH THE FOLLOWING--

000160  READ 206, (CMODE(I),I=MOCHNGE,MODE)
000166  +05 IF (LCCHNGE .EQ. 0) GO TO 420
000167  LCCHNGE = NACT + 1 - LCCHNGE

C
C    REPLACE THE LAST LCCHNGE ACT. LOCATIONS WITH THE FOLLOWING--

000171  READ 206, (ULOCAT(I),I=LCCHNGE,NACT )
000204  GC TO 420

C
C    READ IN AN ENTIRE NEW SET OF NODES AND ACT. LOCATIONS.
000205      415 READ 200, MODE, (OMDC(I)), I=1,MODE
000222      READ 200, (ULOCAT(I), I=1, MODE)
000235      NACT = MODE
000237      420 GO 422 I=1, MODE
000241      MDC(I) = OMC(I)
000243      LOCAT(I) = OLOCAT(1)
000244      422 CATIALE
000246      IF (MDC.EQ. I) GO TO 9

C
C THE FOLLOWING LOOPS SORT THE MOLES AND ACTUATOR LOCATIONS IN ASCENDING
C ORDER.

000250      LIMIT = MODE - 1
000251      DO 8 I=1, LIMIT
000252      IBEGIN = I + 1
000254      DO 6 JJ=IBEGIN, MODE
000256      IF (MDC(I) .LT. MDC(JJ)) GO TO 6
000258      IMUL = MDC(I)
000260      MDC(I) = MDC(JJ)
000262      MDC(JJ) = IMUL
000265      6 CONTINUE
000266      8 CONTINUE

C
C CONSTRUCT THE MN AND MR PARTITIONS OF THE EIGENVECTOR MATRIX.

000271      JJ = IBEGIN, NACT
000273      IF (ULOCAT(I) .LT. ULLOCAT(JJ)) GO TO 7
000276      HMUL = LLOCAT(I)
000279      LLOCAT(I) = MLOCAT(JJ)
000282      7 CONTINUE
000285      8 CONTINUE
000290      9 IF (PRINT.EQ.0) GO TO 15
000291      PRINT 207, MODE, (MDC(I), J=1, MODE)
000294      20 PRINT 208, (ULOCAT(I), I=1, NACT)
000300      15 MMIALSA = 58 - NACT

C
C
000310      II = 1
000344      NNN = 1
000345      ANN = 1
000346      DO 40 I=1,5d
000350      IF (I .EQ. MDC(I)) 20, 30
000354      20 II = II + 1
000356      IF (II .GT. MODE) MDC(I) = 0
000361      GO 25 J=1, NACT
C Continue
C STORE MATRIX IN AGO AND THEN INVERT IT.
C 65 CONTINUE
C 60 I = 1
C 50 II = 1
C 40 J = 1
C 30 NR = 1
C 20 PRINT 210, NR, NACT, N, M, K, K
C 10 IPRINT = EQO 0
C 5 CONTINUE
C 4 CONTINUE
C 3 CONTINUE
C 2 CONTINUE
C 1 CONTINUE
C

APPENDIX A - continued
IF (ISCALE .EQ. 0) GO TO 66
PRINT 231
GO TO 350

C PRINTS UUT MN INVERSE.

66 IF ((PRINT .EQ. 0) GO TO 675
PRINT 218
DO 67 I=1,NACT
PRINT 211, (HN(I,J),J = 1, NMODE)
CONTINUE

C Normalize the determinant of HN.

675 GIV = 1.
DO 70 I=1,NMODE
AODIVE(I) = 0.
DO 66 J=1,NACT
AODIVE(I) = AODIVE(I) + HCNO(I,J)**2
CONTINUE

DO 70 I=1,NMODE
DIV = DIV / AODIVE(I)
CONTINUE

C Normalize = DETERM / DIV

30 CONTINUE

C Check the inversion routine by re-multiplying

GO 72 J=1,NMODE
DO 72 I=1,NACT
PROD(I,J) = 0.0
DO 72 K=1,NMODE
PROD(I,J) = PROD(I,J) + HCNO(I,K) * HN(K,J)
CONTINUE

72 CONTINUE

IF (PRINT .EQ. 0) GO TO 735
PRINT 219
DO 73 I=1,NACT
PRINT 211, (PROD(I,J),J=1, NMODE)
CONTINUE

73 CONTINUE

C Calculate the alpha vector under the modal control law.

735 DO 140 I=1,NACT
ALPHA(I) = 0.0
GO TO 74, MODE
GO 74, J=1, MODE
GO 71, ALPHA(I) = ALPF(I,I) + R(I,J) * OMEGASQ(J) + QA(J)
GO 72, CONTINUE
GO 73, 74 ALPS(I,J) = ALPHA(I)
GO 74, CONTINUE
GO 75, ATAM = 0.
GO 76, CONTINUE
GO 77, DO 140 L=1,NACI
GO 78, CONTINUE
GO 79, ATAM = ATAM + ALPHA(I)**2
GO 80, CONTINUE
GO 81, CONTINUE
GO 82, CONTINUE
GO 83, C
GO 84, C CALCULATE THE ALPHA VECTOR UNDER THE OPTIMAL CONTROL LAW.
GO 85, C COMPLETE (LAM**T)*K + (LAM**H)*J-I + (LAM**H)**2 + Q
GO 86, C
GO 87, C
GO 88, OC 150 I=1, MMINUSH
GO 89, CO 150 J=1, NACT
GO 90, CO 155 M = I + MODE
GO 91, CONTINUE
GO 92, CONTINUE
GO 93, HGLD(KLJ) = KRI(I,J)
GO 94, CONTINUE
GO 95, 150 CONTINUE
GO 96, CONTINUE
GO 97, DO 156 I=1,58
GO 98, CONTINUE
GO 99, CO 155 J=1, NACT
GO 100, CONTINUE
GO 101, CO 155 J = I, NACT
GO 102, CONTINUE
GO 103, K = I, J = I, NACT
GO 104, CONTINUE
GO 105, CONTINUE
GO 106, IF 1 PRINT *EC* 0 \ GO TO 157
GO 107, 150 CONTINUE
GO 108, 156 CONTINUE
GO 109, PRINT 257
GO 110, CONTINUE
GO 111, PRINT 202, (HOLD(I,J), J=1, NACT)
GO 112, C
GO 113, C INVERSE THE MATRIX, AND NORMALIZE ITS DETERMINANT IN THE CALCULATION
GO 114, C
GO 115, CF = PHA.
GO 116, CONTINUE
GO 117, 157 DIV = 1.
GO 118, CO 169 I=1, NACT
GO 119, CONTINUE
GO 120, ACIV(I,E) = 0.0
GO 121, CONTINUE
GO 122, CO 167 J=1, NACT
GO 123, CONTINUE
GO 124, ARRAY(I,J) = 0.0
GO 125, CONTINUE
GO 126, CO 165 K = 1, 58
GO 127, CONTINUE
GO 128, ARRAY(I,J) = ARRAY(I,J) + HGLD(K,I)*HGLD(K,J)
GO 129, CONTINUE
GO 130, 165 CONTINUE
GO 131, CONTINUE
GO 132, ADIV(I,E) + ADIV(I,E) + ARRAY(I,J)**2
GO 133, CONTINUE
GO 134, CONTINUE
GO 135, CONTINUE
GO 136, ADIVCE(I,E) = SQRT(ADIVI(E)**
GO 137, CONTINUE
GO 138, CONTINUE
GO 139, DIV = CV + ADIV(E)
GO 140, CONTINUE
GO 141, CONTINUE
GO 142, CONTINUE
GO 143, CONTINUE
CALL PATINV (ARRAY, NACT, GUMMY, H, DETERM, IPIVJT, INDEX, N58, ISCALE)

DETERM = DETERM / DIV

IF (IPRINT <= 0) GO TO 175
PRINT 247, DETERM, ISCALE, DETERM

PRINT CUT THE INVERSE OF (
LAMH)T * (LAMH)

PRINT 258
CU 171 1=1, NACT
PRINT 202, (ARRAY(I,J), J=1,NACT)
171 CONTINUE

DO 180 J = 1, NACT
VECTORK(J) = CMPLX(J)
180 CONTINUE

FMUD = 1 + NGUE
DO 169 J = MGUD, 58
VECTOR(J) = CMPLX(J-MGUD)
169 CONTINUE

DO 153 I = 1, NACT
ALPHA(I) = 0.0
153 CONTINUE

DO 143 J = 1, 58
PROC(I,J) = 0.0
143 CONTINUE

DO 139 K = 1, NACT
PRCC(I,J) = PRCC(I,J) + ARRAY(I,K) * MOLC(J,K)
139 CONTINUE

ALPHA(I) = ALPHA(I) + PRCC(I,J) * V ECTOR(J)

ALPHSL = 0.0
DO 124 I = 1, NACT
ALPHSL = ALPHSL + ALPHSUM + ALPHA(I)**2
124 CONTINUE

ALPHSL = SQRT(ALPHSUM)

NOW CALCLATE E TRANSPOSE E

DO 153 I = 1, 58
VECTOR(I) = 0.0
153 CONTINUE

DO 175 J = 1, NACT
VECTOR(i) = VECTOR(i) + HCl(i,j) * ALPHA(j)
DO 195 CONTINUE
   DO 156 I=1,MODE
   VECTOR(i) = VECTOR(i) - CM(i)
   CONTINUE
DO 196 I=1,MMINUSN
   J = MODE + I
   VECTOR(J) = VECTOR(J) - QM(J)
   CONTINUE
   SUM = 0.0
   DO 198 I=1,59
      SUM = SUM + VECTOR(I)**2
   CONTINUE
   CTE = SQRT(SUM)
C C CALCULATE P'CO, THE MATRIX PRODUCT--
C LAMBDA(I)*H(I)*H(INVERSE)*LAMBDA(INVERSE) INVERSE. THE MULTIPLICATION
C IS SIMPLIFIED BECAUSE THE LAMBDA MATRICES ARE DIAGONAL.
   DO 200 J=1,MODE
      DO 200 I=1,MMINUSN
   PROD(I,J) = Q0
   CONTINUE
   DO 255 I=1,MODE
      PROD(I,J) = PROD(I,J) + HRI(I,K)*HRK(J,I)
   CONTINUE
   75 CONTINUE
   PROD(I,J) = PROD(I,J) * CMGASQ(J) / UMegasq(MODE + J)
   CONTINUE
C C----CALCULATE AND PRINT INTERMEDIATE DATA FOR PSI MATRIX.
C IF (IPRINT .eq. 0) GC TO 83
   IF (IPRINT .eq. 0) GC TO 83
   PRINT 794
   PRINT 299, I, (PROD(I,J), I=1,MMINUSN)
   CONTINUE
DO 82 I=1,MODE
   PHII(I) = 0.
   DO 84 I=1,MMINUSN
      PHII(I) = PHII(I) + PROD(I,J)**2
   CONTINUE
   84 CONTINUE
   IF (IPRINT .eq. 0) GC TO 94
   PRINT 298, (PHII(I), I=1,MODE)
MULTIPLY PROD BY THE ERROR VECTOR IN THE CONTROLLED MODES.

DO 95 I = 1, MMINUS
PRCD(I) = 0.0
DC 95 K = 1, MODE
PRCD(I) = PROD2(I) + PROD(K, I) * CNK(I)
95 CONTINUE

IF (PRINT .EQ. 0) GO TO 98
PRINT 230, (PRD2(I), I = 1, MMINUS)

CALCULATE THE ERROR OF CONTROL.

DO 99 I = 1, MMINUS
CRSS(I) = QR(I) - PRD2(I)
99 CONTINUE


ECM = 0
DC 100 I = 1, MODE
ECM = ECM + CNI**2
100 CONTINUE

SGTCRM = SQRT(ECM)
ECRM = 0
DC 105 I = 1, MMINUS
SRLM = ECRM + QRII**2
105 CONTINUE

SGRTELM = SQRT(EULM)
GD = ECM + EULM
SGRTOD = SQRT(EOD)
CRC = 0
DC 110 I = 1, MMINUS
CRC = CRC + PROD2(I)**2
110 CONTINUE

SGRTAC = SQRT(CRC)
CRS = 0
DC 115 I = 1, MMINUS
CRS = CRS + CRSS(I)**2
115 CONTINUE

SGRTNRM = SQRT(CRS)
C EXPAND THE ERROR OF CONTROL VECTOR TO 50 ELEMENTS WITH ZEROS
C CORRESPONDING TO THE CONTROLLED MODES. THEN MULTIPLY BY THE U MATRIX,
C TO CALCULATE THE FINAL DEFLECTION VECTOR.
C
DO 120 I=1, NMAXUSH
   120 CONTINUE
II = 1
N = 1
GO TO 133
123 CRSS(I) = 0.0
II = II + 1
GO TO 133
128 CRSS(I) = MOLGEN(I)
N = N + 1
GO TO 133
133 CONTINUE
GO 136 J=1,50
136 PRINT 255, (PDC(I,I),I=1,50)
C CONVERT FORCE VALUES TO PRINTOUT FOR PRINTOUT.
C
ATAM = ATAM + 1.25E-09
ALPHSLM = ALPHSLM + 1.25E-09
CG 138 I=1, NACT
ALPSTG(I) = ALPSTG(I) + 1.25E-09
ALPHA(I) = ALPHA(I) + 1.25E-09
GO TO 138
138 CONTINUE
PRINT 232, OTRAC(I,J), I=1, J=1
PRINT 233, OTRAC(I,J), I=1, J=1
PRINT 137, (ALPSTG(I),I=1, NACT)
IF (NACT .LE. 8 ) PRINT 270
ATAM = ATAM + 1.25E-09
PRINT 254, ATAM
PRINT 137, (ALPSTM(I), I=1, NACT)
IF (NACT .LE. 8 ) PRINT 270
PRINT 251, LTE
PRINT 251, LTE
PRINT 279, CO, SUTDUC, ECM, SURTECH, EMN, SUTEDM, ENS, SUTEDC.

1 CHS, SUTEC.

CJ1775
350 CONTINUE

CJ2040
DICE

CJ2002
242 FORMAT (1, 1E15.5) !

CJ2002
203 FORMAT (6E13.5) !

CJ2002
204 FORMAT (1-1, * THE EIGENVALUES CORRESPONDING TO THE EIGENVECTOR

MATRIZ U.///, / (7E13.5/) !

CJ2002
205 FORMAT (1H, // (7E13.5/) !

CJ2002
206 FORMAT (1D14.16) !

CJ2002
207: IMAT (11N1), * NUMBER OF CONTROLLED MODES = *, // * THEY ARE

3 MODES = 1215, // (19x, 1215) !

CJ2002
208 FORMAT (1H, // ACTUAL LOCATION:, 1215, // (19x, 1215) !

CJ2002
209 FORMAT (1H, // NMA PARTITION OF THE EIGENVECTOR MATRIX *//

CJ2002
210 FORMAT (1H, // // NMA PARTITION OF THE Q VECTOR IS *, //

1 (1E15.4) !

CJ2002
211 FORMAT (1H, // // NMA INVERSE LISTED BY RNS, //

CJ2002
212 FORMAT (1H, // // MATRIX TO CHECK MN INVERSION - SHOULD BE IDENTI

CJ2002
213 FORMAT (1H, // // MATRIX LISTED BY RNS, //

CJ2002
225 FORMAT (1H, // 37X, * MEAN SQUARE RMS LAKR, * 37X, !

1 *ERROR*, // 0X, *ORIGINAL DISTURBANCE*, 4X, 2E13.4, // 0X, !

2 *ORIGINAL ERROR IN , 7A, 2E10.4, // 0X, // THE CONTROLLED MODES //

3 0X, *ORIGINAL ERROR IN THE*, 3A, 2E10.4, // 0X, *UNCONTROLLED

40 MODES // 0X, *ERROR GENERATED IN THE*, 2E10.4, // 0X, !

5 *UNCONTROLLED MODES UT , / 0X, *CONTROL SYSTEM*, // 0X, *ERROR O

6 OF CONTROL , 4X, 2E14.4 !

CJ2002
230 FORMAT (1H, // 63X PSI MATRIZ * ERROR VECTOR (EMCR VECTOR IS IS IN THE MODAL DOWAIN) // * THIS COLUMN * CTR GIVES THE ERA

CJ2002
233 FORMAT (1H, // 2X GENEATED IN EACH MODE, // // (7E15.4) !

CJ2002
231 FORMAT (1H, // * THE DETERMINANT APPEARS EXCESSIVELY LARGE OR

CJ2002
232 FORMAT (1H, // (12X) // IS THE VALUE OF THE NORMALIZED DETERMIN

CJ2002
14X IF 0. IF THIS VALUE IS SMALL // 15X. // COMPARE TO 1, THE

CJ2002
234 FORMAT (1H, // * FORCE VECTOR UNDER THE MODAL CONTROL LAW (POUND

CJ2002
240 FORMAT (1H, // 1051, // (12X) // 7E13.4) !

CJ2002
246 FORMAT (1H, // (12X) // IS THE VALUE

CJ2002
247 FORMAT (1H, // (12X) // IF THE DETERMINANT OF THE MATRIX (ELAMAP* // (LMFM) I USED IN

CJ2002
250 FORMAT (1H, // * THE FORCE VECTOR UNDEP THE OPTIMAL CONTROL LAW

ANNEX B - Continued
1 (POUNDS) *, // (512.4, 7E15.4) 
032002 251 FORMAT (1H*, // * THE FINAL ERROR UNDER THE OPTIMAL CONTROL LAW 
1 IS * , 1E15.4 *) 
002002 253 FORMAT (1H*, // * THE RSS VALUE OF THE FORCE VECTOR UNDER THE OPTIMAL CONTROL LAW IS* , 1E15.4 , * POUNDS* *) 
002002 254 FORMAT (1H*, // * THE RSS VALUE OF THE FORCE VECTOR UNDER THE MEDIAN CONTROL LAW IS* , 1E15.4 , * POUNDS* *) 
002002 255 FORMAT (1H*, // * THIS COLUMN VECTOR GIVES THE DEFORMATION OF THE E6 MIRROR AT EACH GRID POINT* , // * UNITS ARE THE SAME AS THE ORIGINIAL VECTOR* , // (8E15.4) *) 
002002 257 FORMAT (1H*, // 31H LAMBDA * H LISTED BY ROWS* , ) 
002002 258 FORMAT (1H*, // 60H THE INVERSE OF ([LAMBDA]*T * [LAMBDA]* ) * LISTED 
10 BY ROWS* , // ) 
002002 260 FORMAT (1H*, 8A10 ) 
002002 261 FORMAT (1H*, F10.4 ) 
002002 262 FORMAT (1H*, /// * ERROR VECTOR, EACH TERM MULTIPLIED BY *, 
1, F10.4 , // (8E15.4) *) 
002002 270 FORMAT (1H* ) 
002002 294 FORMAT (1H* , /// * Y99 THE MATRIX PRODUCT -- LAMBDA(A)* H(R) * 
L(A)* INVERSE * LAMBDA(A)* INVERSE -- LISTED BY COLUMNS* , * THIS 
2 MATRIX IS CALLED THE PSI MATRIX* , * ) 
002002 296 FORMAT (1H*, // 60H THE DIAGONAL ELEMENTS OF TH: PSI TRANSPOSE 
1* PSI MATRIX* , // * THESE ARE THE PHI SQUARED TERMS* , // 
2 (8E15.4) ) 
002002 299 FORMAT (1H*, // * COLUMN NO. *, 14 , // (8E15.4) *) 
002002 ENC
### THE EIGENVALUES CORRESPONDING TO THE EIGENVECTOR MATRIX U

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**The error vector is:** UINV * ERROR EXAMPLE NO. 1

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**Error vector, each term multiplied by:** 1.0000

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NUMBER OF CONTROLLED MODES = 5
THEY ARE MODES 1 2 3 4 5
ACTUATOR LOCATIONS 2 30 31 44 45

Hx PARTITION OF THE EIGENVECTOR MATRIX

-1.0374E-02 9.9971E-03 1.3953E-03 7.6825E-04 3.0995E-02
5.1990E-03 7.2879E-03 3.0486E-02 -1.1727E-02 -1.0167E-02
-2.2785E-02 -4.5298E-02 -4.2840E-02 -2.2867E-02 -3.3475E-02
-1.4533E-02 -5.4817E-02 -3.4064E-02 -1.4801E-02 -1.2299E-02
-5.5135E-02 1.8150E-02 2.2451E-02 2.7355E-02 1.7254E-02

THE Hx PARTITION OF THE Q VECTOR IS

-1.7184E+01 -1.1100E+01 7.4458E+00 -1.1009E+01 -3.0741E+00

Hx INVERSE LISTED BY FCWS.

-1.1002E+01 -5.7141E+00 -1.5412E+01 6.0853E+00 -1.1731E+01
1.0608E+01 -6.3121E+00 2.5464E+01 -3.9150E+01 -2.9006E+00
-3.1487E+00 2.4583E+01 -1.9352E+01 2.0553E+01 5.5376E+00
-4.3643E+00 -2.7237E+01 -2.4137E+01 1.2582E+01 1.2737E+01
2.6971E+01 -4.2413E+01 -1.2536E+01 1.3938E+01 -3.8769E+00
MATRIX TO CHECK INVERSION - SHOULD BE IDENTITY MATRIX, LISTED BY ROWS:

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</tbody>
</table>

LAMBDA = LISTED BY ROWS.

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<th>4.3664e-11</th>
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</table>

2.1982e-73  * 10**1  = 0.0231 is the value of the determinant of the matrix (lamphit * (lamph)) used in finding alpha.

1.8146e+05 is the normalized determinant. If this value is small compared to 1, the matrix is ill-conditioned.

THE INVERSE OF (lamphit * (lamph)) is listed by rows:

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<td>-4.8507e+14</td>
<td>8.9162e+14</td>
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</tbody>
</table>

THE MATRIX PRODUCT -- (lamda(+1) * M) * MINI INVERSE * (lamda(-1)) INVERSE -- LISTED BY COLUMNS.

This matrix is called the psi matrix.

COLUMN NO.  1
The diagonal elements of the Psi transpose X Psi matrix. These are the PHI squared terms:

<p>| | | | | |</p>
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</table>

**Psi Matrix X Error Vector** (Error Vector is in the Modal Domain.)

This column vector gives the error generated in each mode:

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<tr>
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<th></th>
<th></th>
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This column vector gives the deflection of the mirror at each grid point. Units are the same as the original w vector:

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</tr>
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</table>
NUMBER OF CONTROLLED MODES = 5

THEY ARE MODES  1  2  3  4  5

ACTUATOR LOCATIONS  2  30  31  44  45

1.5386E-01 is the value of the normalized determinant of HN. If this value is small compared to 1, the matrix is ill-conditioned.

FORCE VECTOR UNDER THE MODAL CONTROL LAW (POUNDS).
-2.4256E-02  1.5213E+00  -1.0707E+00  -5.0983E-01  -7.8129E-01

THE RSS VALUE OF THE FORCE VECTOR UNDER THE MODAL CONTROL LAW IS 2.4534E+00 POUNDS.

FORCE VECTOR UNDER THE OPTIMAL CONTROL LAW (POUNDS).
-6.5699E-02  1.6305E+00  -1.1431E+00  -4.3576E-01  -7.6832E-01

THE RSS VALUE OF THE FORCE VECTOR UNDER THE OPTIMAL CONTROL LAW IS 2.3365E+00 POUNDS.

THE FINAL ERROR UNDER THE OPTIMAL CONTROL LAW IS 1.1330E+01

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<td>ORIGINAL ERROR IN THE CONTROLLED MODES</td>
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<tr>
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<tr>
<td>ERROR GENERATED IN THE UNCONTROLLED MODES BY CONTROL SYSTEM</td>
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<tr>
<td>ERROR OF CCF TCL</td>
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</table>
APPENDIX B

EIGENVECTORS OF THE MIRROR

This appendix contains a listing of the $U$ matrix (matrix of eigenvectors) for the 76-cm-diameter (30-inch) thin mirror. This matrix was obtained from the SAMIS program in reference 4. A more graphic display of the first 10 eigenvectors is contained in appendix C. The eigenvalues associated with each eigenvector are given in appendix D. Lambda(1) is associated with column (1), and so forth. The diagonal mass matrix $m$ is also given in appendix D. The $U$ matrix is orthogonal with respect to the mass matrix (refs. 4 and 5):

$$U^T m U = 1$$
<table>
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<th>Column No. 25</th>
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</table>

APPENDIX B - Continued
APPENDIX C

EIGENVECTOR DIAGRAMS

This appendix contains schematic representations of the first 10 modes of the thin mirror (figs. C1 to C10). For each of these modes the mirror deflection along the Z-axis at each grid point is written beside that grid point. The contour lines indicate the nodes of each mode. Note that mode 3 is a bowl-shaped mode and therefore has no node line. The numbers at the grid points are taken directly from appendix B, columns 1 to 10 inclusive, and are displayed in this manner to provide more insight into actual shapes than can be obtained from looking at columns of numbers. Each number has been multiplied by 100 for scaling purposes.
Figure C1. - Mode 1 of the thin mirror.

Figure C2. - Mode 2 of the thin mirror.
Figure C3. - Mode 3 of the thin mirror.

Figure C4. - Mode 4 of the thin mirror.
Figure C5. - Mode 5 of the thin mirror.

Figure C6. - Mode 6 of the thin mirror.
Figure C7. - Mode 7 of the thin mirror.

Figure C8. - Mode 8 of the thin mirror.
Figure C9.- Mode 9 of the thin mirror.

Figure C10.- Mode 10 of the thin mirror.
APPENDIX D

EIGENVALUES AND MASS MATRIX FOR THE MIRROR

This appendix contains a listing of the eigenvalues and the diagonal mass matrix \( m \). The SAMIS program eigenvalues are inversely proportional to frequency squared and may be converted to frequency (in hertz) by the following relationship:

\[
f_i = \frac{1}{2\pi} \sqrt{\frac{0.97 \times 10^{-4}}{\Lambda_i}} \quad (i = 1, \ldots, M)
\]

The elements of the mass matrix have the units of lb-sec\(^2\)/in.

The eigenvalues of the \( U \) matrix are:

\[
\begin{align*}
\text{LAMBD(1)} &= 3.911E-02 \\
\text{LAMBD(2)} &= 1.941E-02 \\
\text{LAMBD(3)} &= 2.030E-02 \\
\text{LAMBD(4)} &= 2.294E-03 \\
\text{LAMBD(5)} &= 2.851E-03 \\
\text{LAMBD(6)} &= 2.973E-03 \\
\text{LAMBD(7)} &= 3.249E-03 \\
\text{LAMBD(8)} &= 3.384E-03 \\
\text{LAMBD(9)} &= 3.591E-03 \\
\text{LAMBD(10)} &= 3.615E-03 \\
\text{LAMBD(11)} &= 3.615E-03 \\
\text{LAMBD(12)} &= 3.615E-03 \\
\text{LAMBD(13)} &= 3.615E-03 \\
\text{LAMBD(14)} &= 3.615E-03 \\
\text{LAMBD(15)} &= 3.615E-03 \\
\text{LAMBD(16)} &= 3.615E-03 \\
\text{LAMBD(17)} &= 3.615E-03 \\
\text{LAMBD(18)} &= 3.615E-03 \\
\text{LAMBD(19)} &= 3.615E-03 \\
\text{LAMBD(20)} &= 3.615E-03 \\
\text{LAMBD(21)} &= 3.615E-03 \\
\text{LAMBD(22)} &= 3.615E-03 \\
\text{LAMBD(23)} &= 3.615E-03 \\
\text{LAMBD(24)} &= 3.615E-03 \\
\text{LAMBD(25)} &= 3.615E-03 \\
\text{LAMBD(26)} &= 3.615E-03 \\
\text{LAMBD(27)} &= 3.615E-03 \\
\text{LAMBD(28)} &= 3.615E-03 \\
\text{LAMBD(29)} &= 3.615E-03 \\
\text{LAMBD(30)} &= 5.29E-05 \\
\end{align*}
\]
APPENDIX D — Concluded

The elements of the diagonal mass matrix are

| MASS (1, 1) | 1.19E-03 | MASS (30, 30) | 1.25E-02 |
| MASS (2, 2) | 1.25E-03 | MASS (31, 31) | 1.25E-03 |
| MASS (3, 3) | 1.19E-03 | MASS (32, 32) | 1.25E-03 |
| MASS (4, 4) | 1.43E-C3 | MASS (33, 33) | 1.19E-C3 |
| MASS (5, 5) | 1.25E-C3 | MASS (34, 34) | 1.43E-C3 |
| MASS (6, 6) | 1.25E-03 | MASS (35, 35) | 1.25E-C3 |
| MASS (7, 7) | 1.25E-C3 | MASS (36, 36) | 1.25E-C3 |
| MASS (8, 8) | 1.19E-03 | MASS (37, 37) | 1.25E-C3 |
| MASS (9, 9) | 1.19E-03 | MASS (38, 38) | 1.43E-C3 |
| MASS (10, 10) | 1.25E-C3 | MASS (39, 39) | 1.25E-C3 |
| MASS (11, 11) | 1.25E-C3 | MASS (40, 40) | 1.25E-C3 |
| MASS (12, 12) | 1.25E-C3 | MASS (41, 41) | 1.25E-C3 |
| MASS (13, 13) | 1.25E-C3 | MASS (42, 42) | 1.25E-C3 |
| MASS (14, 14) | 1.25E-C3 | MASS (43, 43) | 1.19E-C3 |
| MASS (15, 15) | 1.19E-C3 | MASS (44, 44) | 1.25E-C3 |
| MASS (16, 16) | 1.50E-C4 | MASS (45, 45) | 1.25E-C3 |
| MASS (17, 17) | 1.19E-C3 | MASS (46, 46) | 1.25E-C3 |
| MASS (18, 18) | 1.19E-C3 | MASS (47, 47) | 1.25E-C3 |
| MASS (19, 19) | 1.19E-C3 | MASS (48, 48) | 1.25E-C3 |
| MASS (20, 20) | 1.25E-C3 | MASS (49, 49) | 1.25E-C3 |
| MASS (21, 21) | 1.25E-C3 | MASS (50, 50) | 1.25E-C3 |
| MASS (22, 22) | 1.19E-C3 | MASS (51, 51) | 1.19E-C3 |
| MASS (23, 23) | 1.25E-C3 | MASS (52, 52) | 1.19E-C3 |
| MASS (24, 24) | 1.19E-C3 | MASS (53, 53) | 1.43E-C3 |
| MASS (25, 25) | 1.19E-C3 | MASS (54, 54) | 1.19E-C3 |
| MASS (26, 26) | 1.25E-C3 | MASS (55, 55) | 5.30E-C4 |
| MASS (27, 27) | 1.25E-C3 | MASS (56, 56) | 1.19E-C3 |
| MASS (28, 28) | 1.25E-C3 | MASS (57, 57) | 1.43E-C3 |
| MASS (29, 29) | 1.25E-C3 | MASS (58, 58) | 1.19E-C3 |
APPENDIX E

BEST ACTUATOR LOCATIONS – DETERMINISTIC CASE

This appendix contains an enumeration of actuator locations which were found to produce minimum error when the errors were considered to be completely known (deterministic) and nonvarying (figs. E1 to E12). Each figure contains 10 diagrams which show the best 10 actuator locations for one of the three error examples and a specific number of actuators. Grid numbers for the actuator locations can be found by comparison with the numbered pattern in the lower right-hand portion of each figure. The values of the final error for the modal control law and the optimal control law are given beside each figure in the form

\[ \frac{A}{B} \]

where \( A \) is the error under the modal control law and \( B \) is the error under the optimal control law. These final errors are those given by the square root of equation (53), which requires that these values be multiplied by 0.40 to obtain rms error in microinches or by 0.019 to obtain rms error in wavelengths.

A particular point of interest occurred in figure E10 (two actuators, error example 3). In this figure the \( H^N \) matrix was decidedly ill conditioned for most of the examples. The normalized determinant was as low as \( 6 \times 10^{-5} \) and the best value was \( 3.5 \times 10^{-2} \). If this case arose in practice, it would be best to look at three actuators or more. In figure E11 (three actuators) the normalized determinant was of the order of 0.3, which is very good.
Figure 11.- Actuator locations which minimize the rms error of the mirror for one actuator and error example 1.
Figure 30.1 - Various patterns which minimize the rms error of the mirror for two actuators and error example 1.
Figure 14. Actuator locations which minimize the run errors of the mirror for three actuators and error example 1.
Figure E.1 - Actuator locations which minimize the rms error of the mirror for four actuators and error example 1.
Figure E.1 - Location of the superconducting wires in the vacuum chamber and sample setup.
Figure 17: Actuator locations which minimize the rms error of the mirror for two actuators and error example 2.
Figure E8. - Actuator location which minimize the rms error of the mirror for three actuators and error example 2.
Figure 19. Actuator locations which minimize the rms error of the mirror for one actuator and error example 3.
Figure 110.- Actuator locations which minimize the rms error of the mirror for two actuators and error example 3.
Figure III. - Actuator locations which minimize the rms error of the mirror for three actuators and error example 3.
Figure E12. - Actuator locations which minimize the rms error of the mirror for four actuators and error example 4.
APPENDIX F

BEST ACTUATOR LOCATIONS—UNCORRELATED ERRORS

This appendix contains an enumeration of actuator locations which were found to generate minimum error under the modal control law (figs. F1 to F5). These were obtained by using the errors of example 1. The answers are given beside each diagram in the figures in the following form:

\[
\begin{align*}
A & \quad \text{error predicted by equation (61) assuming all values of } \phi_{1N}^2 \text{ are 0} \\
B & \quad \text{error obtained from equations (53) and (29)} \\
C & \quad \text{error under the optimal control law}
\end{align*}
\]

where

A the error predicted by equation (61) assuming all values of \( \phi_{1N}^2 \) are 0
B the error obtained from equations (53) and (29)
C the error under the optimal control law

The performance index is that obtained from the square root of equation (53) and must be multiplied by 0.49 to obtain rms error in microinches or by 0.019 to obtain rms error in wavelengths.

Selecting other error examples would, of course, result in the selection of different actuator locations; however, it can be seen from the values of \( \phi_{1N}^2 \) in table II that the effect of a different actuator location could not make the final answer much better because the values of \( \phi_{1N}^2 \) are already very small. For this reason the searches for actuator locations were restricted to the one example. The searches for one to four actuators inclusive considered all possible combinations, whereas those for seven actuators considered only a small subset of all possible combinations. This subset was chosen from those locations near the nodes of the next three higher order modes. This reduced the number of runs required to a reasonable value and resulted in a selection of actuator locations which were reasonably close to the theoretical limit.
Figure F. - Actuator locations which minimize the error generated by the control system in driving the first mode to zero with one actuator. Error distribution is taken from error example 1.
Figure 1: Location locations which minimize the error generated by the control system in driving the first two poles to specific test frequencies. Error distribution is taken from case example 1.
Figure F.3: Actuator locations which minimize the error generated by the control system in driving the first three modes to zero using three actuators. Error distribution is taken from error example 1.
Figure 1. Actuator locations which minimize the error generated by the control system in driving the first few modes to zero with four actuators. Error distribution is taken from error example 1.
Figure F. - Actuator locations which resulted in the minimum generated error for error example 1. The following 16 grid points were used in the search procedure: 6, 10, 14, 17, 20, 23, 26, 27, 31, 34, 40, 47, 58, 53, 56, and 57.
REFERENCES


<table>
<thead>
<tr>
<th>Mode number</th>
<th>Error example 1</th>
<th>Error example 2</th>
<th>Error example 3</th>
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<td>Mode 9</td>
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</table>
TABLE II.- VALUES OF $\phi_{1N}^2$ FOR $N = 1, 2, 3, 4, \text{AND} 7$

Determined for error example 1; actuator grid locations corresponding to these values are tabulated below the values of $\phi_{1N}^2$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\phi_{11}^2$</th>
<th>$\phi_{12}^2$</th>
<th>$\phi_{13}^2$</th>
<th>$\phi_{14}^2$</th>
<th>$\phi_{17}^2$</th>
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<td>1</td>
<td>0.29</td>
<td>2.011</td>
<td>$1.46 \times 10^{-2}$</td>
<td>$1.35 \times 10^{-3}$</td>
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<tr>
<td>2</td>
<td>3.336</td>
<td>$7.58 \times 10^{-4}$</td>
<td>$1.35 \times 10^{-3}$</td>
<td>$8.6 \times 10^{-3}$</td>
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<td>$9.8 \times 10^{-4}$</td>
<td>$9.7 \times 10^{-4}$</td>
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<td></td>
</tr>
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<td>$4.4 \times 10^{-3}$</td>
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<td></td>
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<td>Actuator grid locations</td>
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<td>16, 23, 47</td>
<td>16, 20, 24, 55</td>
<td>6, 23, 26, 31, 53, 56, 57</td>
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