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THE EFFECT OF SENSOR AND ACTUATOR ERRORS ON STATIC SHAPE CONTROL FOR LARGE SPACE STRUCTURES

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SUMMARY

This paper is concerned with quantifying the effect of sensor and actuator errors on the ability of thermal control actuators to correct static shape distortion of orbiting spacecraft such as large space antennas. Expressions for the statistical properties of the control effectiveness are derived based on the assumption of normally distributed errors.

An example of a 55m space-truss parabolic antenna distorted by orbital heating is used to demonstrate the effect of sensor and actuator error. It is found that in the case of even moderately large errors, increasing the number of actuators does not always enhance shape control.

LIST OF SYMBOLS

A	matrix defined by Eq. (5)
a_{ij}	elements of matrix A
B	normalizing matrix, Eq. (9)
C_{TT}	covariance matrix of $T_a - T_m$
C_{TT_a}	covariance matrix of $T_a - T_o$
C_{TT_m}	covariance matrix of $T_m - T_o$
C_{VV}	covariance matrix of V
$C_{\psi\psi}$	covariance matrix of ψ

E	expected value (average) operator
g	distortion ratio, Eq. (7)
g_o	distortion ratio in the absence of errors
G	matrix defined by Eq. (19)
k	number of structural degrees of freedom
L	the Cholesky factor of B $(B = LL^T)$
n	number of actuators
r	vector defined by Eq. (6)
r_j	jth component of r
r_o	r vector in the absence of sensor errors
r_m	r vector based on measured distortion
T	vector of temperature differentials
T_a	actuator temperature differential in the presence of errors
T_i	temperature differential of the ith actuator
T_m	actuator temperature differential based on measurement errors
T_{max}	maximum actuator temperature differential
T_o	actuator temperature differential in the absence of errors
U	matrix of u_i's
u_i	structural displacement due to unit temperature increase in ith actuator
v_o	reference volume
δ	corrected displacement field
δ_{rms}	root mean square of displacement field
σ	standard deviation

σ_T standard deviation of actuator error

σ_ψ standard deviation of error in measured distortion

ψ shape distortion vector

ψ_m measured shape distortion

ψ_{rms} $(\psi^T B\psi)^{1/2}$

ψ_{max} maximum component of ψ

Ω structural domain

INTRODUCTION

One of the most important requirements in the design of large space antennas is that of surface accuracy [1,2]. While studies have shown that under certain conditions high surface accuracies may be maintained by passive means [3], as a general rule active controls probably will be needed. The disturbances which deform the shape of space structures can be divided into two types. One type is transient and, hence, eventually leaves the structure unchanged. Transient disturbances can be countered by active or passive controls which enhance the damping of the structure. The second type of disturbance is typified by those due to manufacturing errors and aging [4] which may be considered at least quasi-static if not fixed. These latter disturbances may be offset by slowly applied, long-acting corrections. Most research to date has concentrated on controlling the transient disturbances by using damping actuators [5].

Interest in the problem of controlling quasi-static disturbances has recently increased. Much of the work reported on active control of quasi-static disturbances is related to active control of optical systems such as mirrors (see [6] for a survey of the state of the art as of 1978). Generally, force actuators are employed for static shape control (e.g. [7-11]). However, Bushnell [7] characterizes some of these (e.g. [12,13]) as displacement actuators because they are stiff enough to enforce prescribed displacements. Another variation of the force actuator in a truss structure is one which changes the length of a member by reeling a cable in or out or by using a screw mechanism. This approach is used on some antennas (e.g. [14]) to correct fabrication errors, albeit on the ground rather than in orbit. A recently proposed alternative is the use of applied temperatures on the structure. In [15] the basic concept of using heater actuators was described and evaluated on beam and antenna examples. In [16] the problem of finding near-optimum actuator locations was investigated and two methods based on heuristic integer programming were described and evaluated. To date no attempt has been made to study the effects of sensor and actuator errors on static shape control. The purpose of the present paper is to extend the work described in [15] and [16] to a study of the effect of such errors, and to obtain the statistical properties of the control effectiveness as a function of the magnitude of the errors. The analysis is limited to normally distributed errors and to configurations with a large number of sensors. An example of a 55m space-truss parabolic antenna is used to demonstrate the effects of sensor and actuator errors.

REVIEW OF STATIC SHAPE CONTROL METHOD BASED ON HEATER ACTUATORS

Although discussed in the context of heater actuators, the methods discussed in this paper are applicable to both linear force and temperature controls. The equations for temperature control from [15] are briefly summarized herein. The reader is referred to [15] for a similar derivation for force controls.

The structure is assumed to be in earth orbit and possess rigid body degrees of freedom. The structure is defined over some region Ω and it is assumed that its desired shape has been distorted by an amount $\psi(Q)$ where Q is a point in Ω and ψ is a vector containing displacement components in three orthogonal directions. The distortion is corrected by prescribing temperatures at n high-thermal-expansion inserts (actuators) placed in the structure. The distortion ψ is assumed to be slowly varying so that the actuator inputs may be calculated by a quasi-static analysis.

The residual displacement δ is the sum of the shape distortion and the correction

$$\delta(Q) = \psi(Q) + \sum_{i=1}^{n} u_i(Q)T_i \qquad (1)$$

where T_i is the temperature differential of the ith actuator relative to the temperature at which ψ is measured and u_i is the displacement field due to a unit value of T_i.

We seek values of T_i which most effectively offset ψ, that is cause δ to be close to zero. A common measure of the smallness of δ is based on the rms value

$$\delta_{rms}^2 = \frac{1}{v_o} \int_\Omega \delta \cdot \delta d\Omega \tag{2}$$

where v_o is a reference volume and a dot represents a scalar product. The necessary condition for a minimum is

$$\frac{\partial \delta_{rms}^2}{\partial T_j} = (2/v_o) \int_\Omega (\psi + \sum_{i=1}^{n} u_i T_i) \cdot u_j d\Omega = 0 \qquad j = 1,2,\ldots,n \tag{3}$$

Equations (3), a system of n linear algebraic equations for the control temperatures, can be written as

$$AT = r \tag{4}$$

where the component a_{ij} of the matrix A is

$$a_{ij} = \int_\Omega u_i \cdot u_j d\Omega \tag{5}$$

and the jth component of the right-hand-side, r_j is

$$r_j = - \int_\Omega \psi \cdot u_j d\Omega \tag{6}$$

The ratio of controlled to uncontrolled rms distortion is called the distortion ratio g and is given by

$$g^2 = \frac{\int_\Omega \delta \cdot \delta \, d\Omega}{\int_\Omega \psi \cdot \psi \, d\Omega} \tag{7}$$

When the displacement vector is computed from a discretized model of the structure having k degrees of freedom, ψ, u and δ are finite-dimensional vectors of order k instead of vector functions. Equation (1) may then be written in a matrix form as

$$\delta = \psi + UT \tag{8}$$

where U is a matrix whose columns are u_i, i=1,2,...,n. Equation (2) becomes

$$\delta^2_{rms} = (\psi + UT)^T B (\psi + UT) \tag{9}$$

where B is a symmetric positive definite matrix. Similarly the expressions for A, r, and g^2 become

$$A = U^T BU \tag{10}$$

$$r = -U^T B\psi \tag{11}$$

$$g^2 = \frac{(\psi + UT)^T B (\psi + UT)}{\psi^T B\psi} = 1 + \frac{2\psi^T BUT + T^T U^T BUT}{\psi^T B\psi} \qquad (12)$$

where use has been made of the symmetry of B.

EFFECT OF SENSOR AND ACTUATOR ERRORS

General Equations

We define T_o as the vector of control temperatures which would be produced in the absence of both sensor and actuator errors. That is, T_o is calculated from Eq. (4) in terms of the actual distortion ψ by

$$AT_o = r_o = -U^T B\psi \qquad (13)$$

Because of sensor error we measure ψ_m instead of ψ and the control algorithm calculates a corresponding temperature vector T_m as

$$AT_m = r_m = -U^T B\psi_m \qquad (14)$$

Additionally, there are actuator errors (including, possibly computation errors) so that the control output is T_a. The distortion ratio g is then given from Eq. (12) as

$$g^2 = 1 + \frac{2\psi^T BUT_a + T_a^T U^T BUT_a}{\psi^T B\psi} \qquad (15)$$

Using Eqs. (10) and (13) and the identity $T_a = T_o + (T_a - T_o)$, Eq. 15 may be written as

$$g^2 = g_o^2 + \frac{(T_a - T_o)^T A (T_a - T_o)}{\psi^T B\psi} \qquad (16)$$

where g_o is the ideal distortion ratio (obtained when there are no errors)

$$g_o^2 = 1 + \frac{2\psi^T BUT_o + T_o^T U^T BUT_o}{\psi^T B\psi} = 1 - \frac{r_o^T T_o}{\psi^T B\psi} \qquad (17)$$

Statistical Properties of Distortion Correction

We assume that there are enough sensors to obtain an accurate reading of ψ in the absence of errors and that they have no bias. Then $\psi - \psi_m$ is a random vector with a zero mean. Similarly, we assume that there is no actuator bias so that $T_a - T_m$ is also a random vector with zero mean. Using Eqs. (13) and (14) we obtain

$$T_m - T_o = G(\psi_m - \psi) \qquad (18)$$

where

$$G = -A^{-1}U^{T}B \tag{19}$$

We further assume that $\psi_m - \psi$ and $T_a - T_m$ are independent, normally distributed, vectors with covariance matrices $C_{\psi\psi}$ and C_{TT}, respectively. Based on Eq. (18) $T_m - T_o$ is also a normally distributed random vector, and its covariance matrix C_{TT_m} is

$$C_{TT_m} = E[(T_m - T_o)(T_m - T_o)^T] = GC_{\psi\psi}G^T \tag{20}$$

Where E denotes the expected value operator. The total control error $T_a - T_o$ may be written as

$$T_a - T_o = (T_a - T_m) + (T_m - T_o) \tag{21}$$

and is, therefore, the sum of two independent normally distributed zero-mean vectors. Hence $T_a - T_o$ is also a normally distributed vector with zero mean. The covariance matrix of $T_a - T_o$ is defined as C_{TT_a}. From Eq. (21)

$$C_{TT_a} = C_{TT} + C_{TT_m} \tag{22}$$

Next we obtain the expected value and standard deviation of g^2. For this purpose we define the vector V

$$V = L^T U(T_a - T_o)/(\psi^T B\psi)^{1/2} \quad (23)$$

where L is the Cholesky factor of B (i.e., $B = LL^T$). Equation (16) may now be written in terms of V as

$$g^2 = g_o^2 + V^T V \quad (24)$$

The expected value of g^2, denoted $E(g^2)$, and the standard deviation $\sigma(g^2)$ may be given in terms of the covariance matrix C_{VV} of V (which from Eq. (23) is also a normally distributed vector with zero mean)

$$C_{VV} = L^T U C_{TT_a} U^T L/\psi^T B\psi \quad (25)$$

From Eq. (24) denoting the components of V as v_i

$$E(g^2) = g_o^2 + \sum_{i=1}^{k} \sigma^2(v_i) \quad (26)$$

where $\sigma^2(v_i)$ i.e., the variances of the components of V are the diagonal terms of C_{VV}

$$\sigma^2(v_i) = (C_{VV})_{ii} \quad (27)$$

The variance of g^2 is

$$\sigma^2(g^2) = E[g^2 - E(g^2)]^2 = E[V^TV - \sum_{i=1}^{k} \sigma^2(v_i)]^2$$

$$= E[(V^TV)^2] - [\sum_{i=1}^{k} \sigma^2(v_i)]^2$$

$$= \sum_{i=1}^{k} \sum_{j=1}^{k} E(v_i^2 v_j^2) - [\sum_{i=1}^{k} \sigma^2(v_i)]^2 \qquad (28)$$

It is shown in [17] that

$$E(v_i^2 v_j^2) = (C_{VV})_{ii}(C_{VV})_{jj} + 2(C_{VV})_{ij}^2 \qquad (29)$$

using equations (27) and (29) in equation (28)

$$\sigma^2(g^2) = 2\sum_{i=1}^{k} \sum_{j=1}^{k} (C_{VV})_{ij}^2 \qquad (30)$$

While exact expressions are available for the average and standard deviation of g^2, only approximate expressions are obtained for the corresponding properties of g. Following the method used in [18] the first three terms of a Taylor series are used. Specifically for the square root function

$$x^{1/2} \cong x_o^{1/2} + \frac{1}{2} x_o^{-1/2}(x - x_o) - \frac{1}{8} x_o^{-3/2}(x - x_o)^2 \qquad (31)$$

substituting g^2 for x and $E(g^2)$ for x_o we obtain

$$g \cong E^{1/2}(g^2) + \frac{1}{2} [g^2 - E(g^2)]/E^{1/2}(g^2) - \frac{1}{8} [g^2 - E(g^2)]^2/E^{3/2}(g^2) \qquad (32)$$

Equation (32) is a good approximation if $|g^2 - E(g^2)|$ is small compared to $E(g^2)$. Taking the expected value of both sides of Eq. (32) gives

$$E(g) \cong E^{1/2}(g^2) - \frac{\sigma^2(g^2)}{8E^{3/2}(g^2)} \qquad (33)$$

and

$$\sigma^2(g) = E[g - E(g)]^2 = E(g^2) - E^2(g)$$

$$\cong \frac{\sigma^2(g^2)}{4(E(g^2)} - \frac{\sigma^4(g^2)}{64E^3(g^2)} \qquad (34)$$

ANTENNA REFLECTOR EXAMPLE

An example of a 55m space-truss parabolic antenna reflector from [19] shown in Figure 1 is used to demonstrate the effects of actuator and sensor errors on the distortion ratio. The antenna is constructed of graphite epoxy while the control elements are aluminum. The reflector is distorted from its ideal shape by thermal deformation due to orbital heating. The temperature history of the lower and upper surfaces of the antenna calculated as in [15] is shown in Figure 2. A previous study [16] obtained near optimal actuator locations for controlling the thermal distortion with varying number of actuators, and these actuator locations were used in the present study. In the present study it was assumed that a sensor is located at each of the joints of the truss so that in the absence of sensor errors all the displacement components at the joints are known. The matrix B of Eq. (9) was taken to be a diagonal matrix with unit entries corresponding to the displacement components normal to the reflector surface. This means that the mission of the control system was to minimize the rms value of the normal displacements at the joints. It was assumed that sensor errors are uncorrelated and all have the same standard deviation σ_{ψ}. Similarly, it was assumed that acturator errors were uncorrelated and have the same standard deviation σ_T.

First, the effects of sensor and actuator errors were studied for a 12 actuator configuration from [16] (which had $g_o = 0.275$). The effect of actuator errors on the expected value and standard deviation of the distortion ratio is shown in Figure 3. In Figure 3, the actuator temperature error is normalized to the maximum component of the temperature vector T_o. The distortion ratio is normalized to g_o. As may be predicted on the basis of equations (25) and (28), E(g) and σ(g) vary quadratically with σ_T. This is due to the actuator temperatures being the solution of a minimization problem so that small errors in the temperatures do not have any first order effect. However, it is seen from Figure 3 that errors with σ_T greater than about ten percent of the maximum actuator temperature differential substantially degrade the effectiveness of the control procedure. The bands of width $\sigma(g)/g_o$ indicate the scatter of the distortion ratio, but since g is not a normal random variable, care must be exercised in the interpretation of σ(g). Figure 4 shows the effect of sensor error on the expected values and standard deviation of the distortion ratio. In Figure 4, the sensor error is normalized to the maximum component of the distortion vector ψ. Here, substantial degradation in performance occurs for errors which are above ten percent of the maximum component of the distortion vector.

Next the effect of the number of actuators was studied. An error combination which has a moderate effect on the 12-actuator configuration was selected. The value of σ_ψ was selected to be 10^{-5} in. (corresponding to 0.25 percent of maximum component of ψ and the value of σ_T was selected to be 0.01 degrees (corresponding to 6.5 percent of the 12-actuator maximum temperature differential). This combination corresponds to $E(g)/g_o$ of 1.11 for the 12-actuator configuration. The number of actuators was varied from 12 to 60 with the same values of σ_T and σ_ψ. The results are summarized in Table 1 (a) and also in Fig. 5 which shows the one-σ scatter band about

E(g). Figure 5 shows that as the number of actuators increases, the effect of the error becomes more severe, to the point that the benefit of increasing the number of actuators beyond twenty is questionable.

The same study was repeated for a smaller error combination and the results are summarized in Table 1 (b) and Fig. 6. While it is clear that the effect of the error becomes more severe as the number of actuators increase, the error is small, and the performance still improves with increasing numbers of actuators.

CONCLUDING REMARKS

An analytical study was performed to predict and assess the effect of actuator and sensor errors on the performance of a shape control procedure for flexible space structures using applied temperatures. Approximate formulas were derived for the expected value and variance of the rms distortion ratio (ratio of rms distortions with and without corrections) based on the assumption of zero-mean normally distributed random errors in measured distortions and actuator output temperatures.

Studies were carried out for a 55-meter radiometer antenna reflector distorted from its ideal parabolic shape by non-uniform orbital heating. The first study consisted of varying the sensor and actuator errors for the case of 12 actuators and computing the distortion ratio. It was found that substantial inaccuracies occurred when the actuator error exceeded about ten percent of the maximum actuator temperature differential, or when the sensor error exceeded about ten percent of the maximum component of distortion. In a second study, sensor and actuator errors were held constant and the number of actuators was varied. Results of this study indicated that for sufficiently large errors, the error magnification, due to increasing the number of actuators, can offset the benefits of having more actuators, leading to the anomalous result that increasing the number of actuators can eventually degrade the performance of the control system.

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TABLE 1. EFFECT OF SENSOR AND ACTUATOR ERRORS ON DISTORTION REDUCTION. g_o = DISTORTION RATIO NEGLECTING BOTH ERRORS. σ = ONE STANDARD DEVIATION

(a) $\sigma_\psi = 10^{-5}$, $\sigma_T = .01$

Number of Actuators	g_o	E(g)	σ(g)	E(g) + σ(g)	E(g) - σ(g)
10	.3124	.3358	.015	.3508	.3208
20	.1980	.2645	.035	.2995	.2295
30	.1793	.2683	.043	.3113	.2253
40	.1533	.2722	.051	.3232	.2212
50	.1335	.2790	.061	.3400	.2180
60	.1120	.2799	.069	.3489	.2109

(b) $\sigma_\psi = 10^{-5}$, $\sigma_T = .005$

Number of Actuators	g_o	E(g)	σ(g)	E(g) + σ(g)	E(g) - σ(g)
10	.3124	.3185	.0039	.3224	.3146
20	.1980	.2171	.011	.2281	.2061
30	.1793	.2061	.014	.2201	.1921
40	.1533	.1913	.018	.2093	.1733
50	.1335	.1826	.024	.2066	.1586
60	.1120	.1720	.029	.2010	.1430

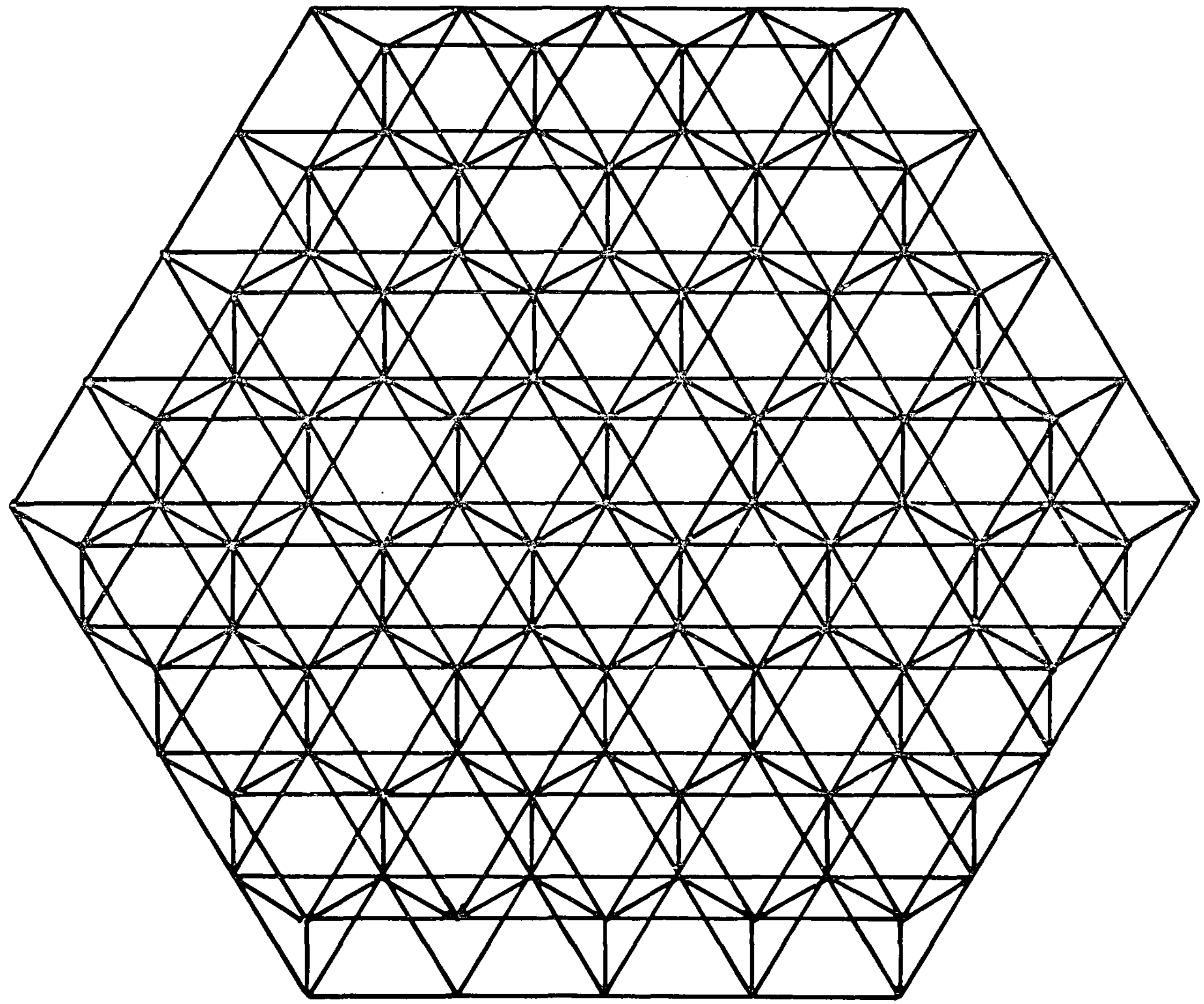

Figure 1.- Tetrahedral truss antenna reflector

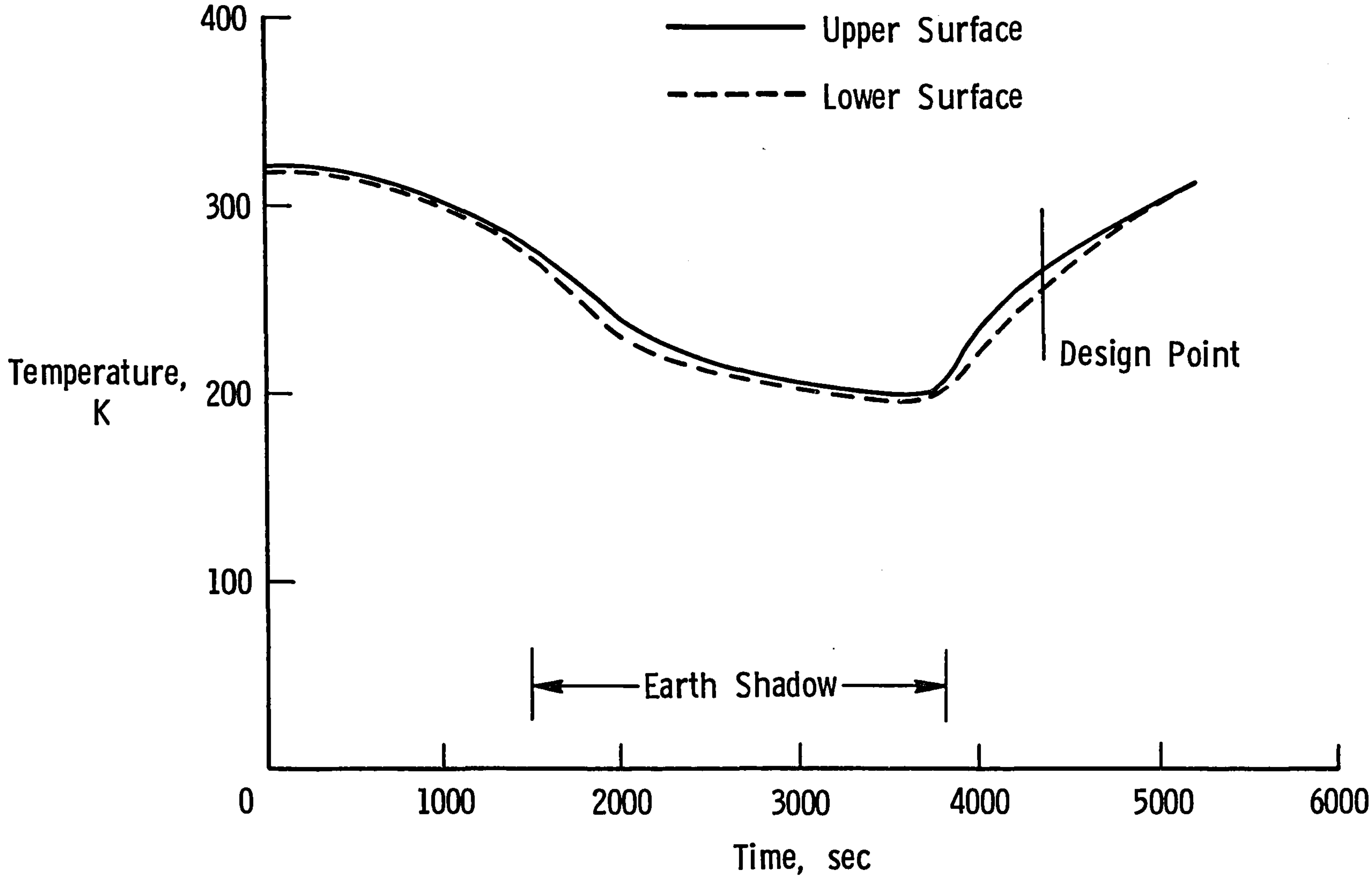

Figure 2.- Temperature history for antenna reflector

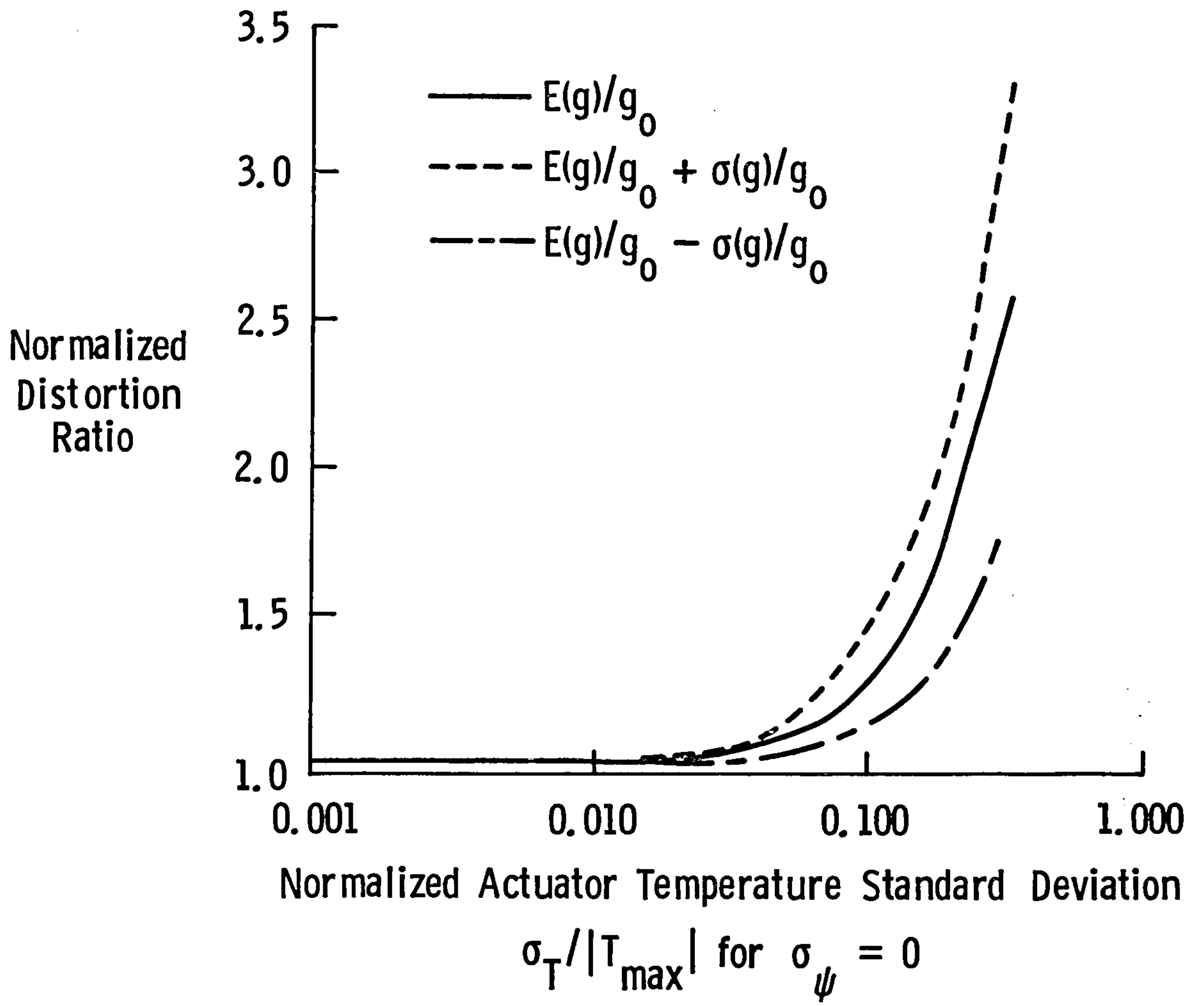

Figure 3.- Effect of actuator error on distortion ratio

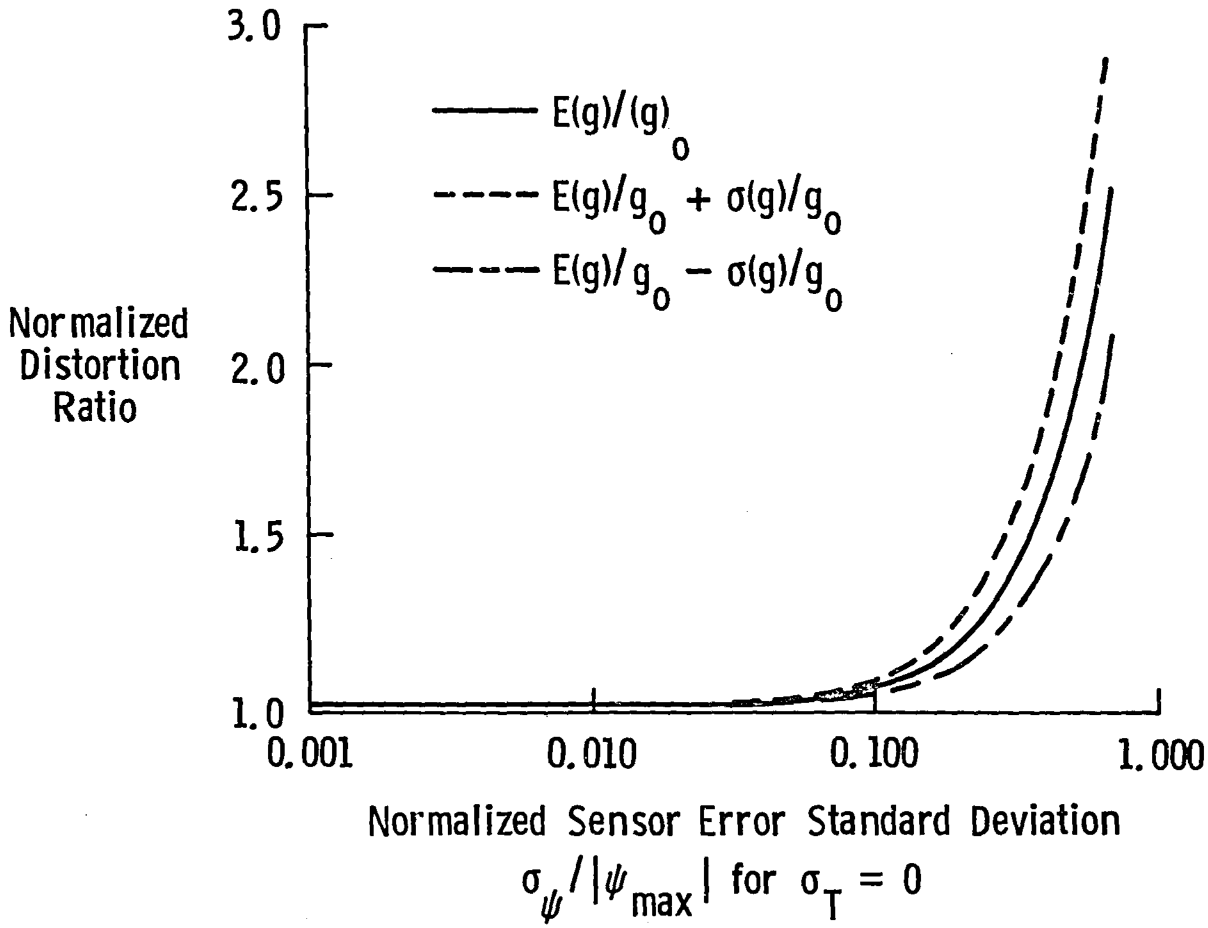

Figure 4.- Effect of sensor error on distortion ratio

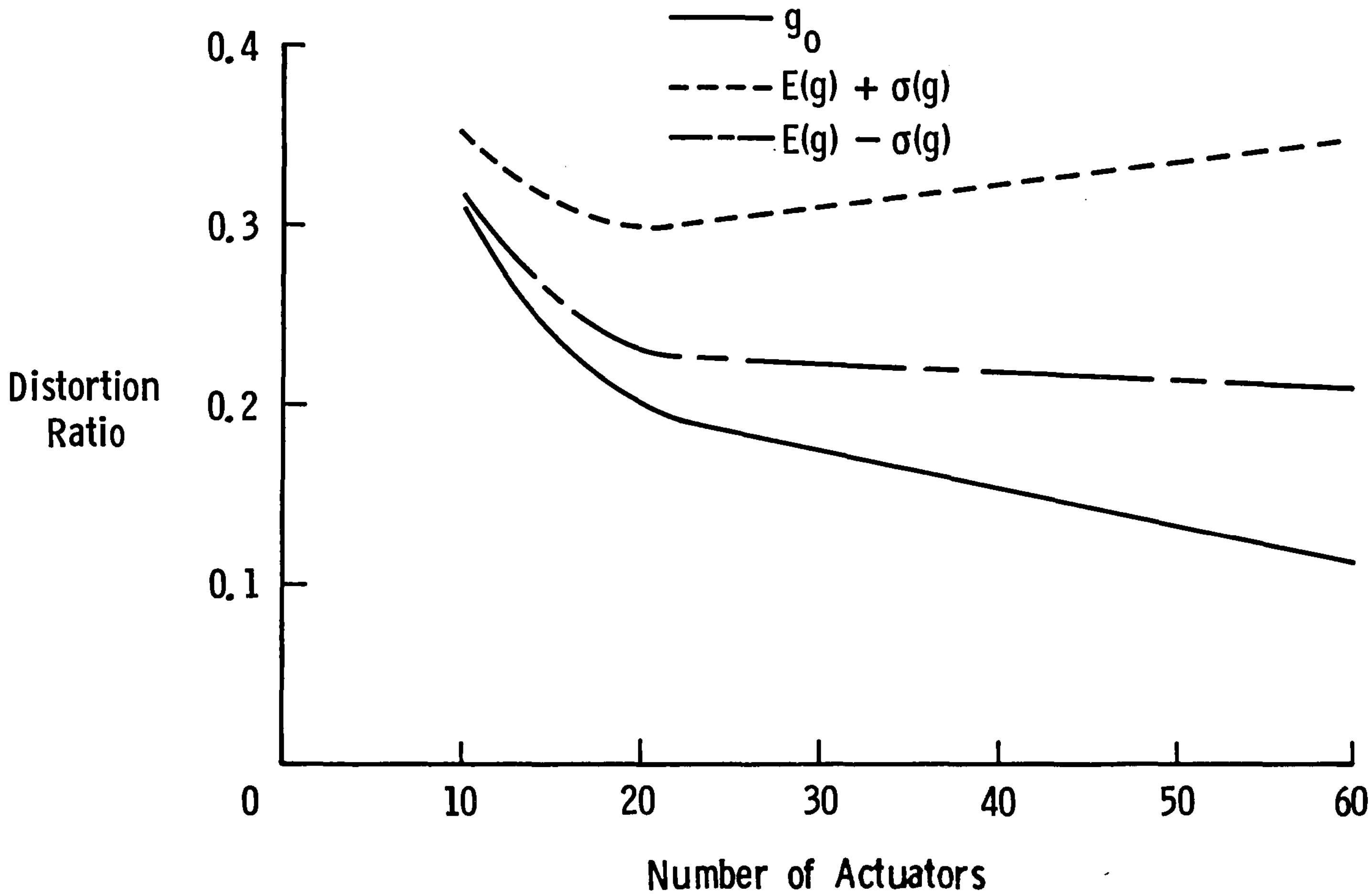

Figure 5.- Effect of sensor and actuator errors on distortion ratio
g_o = distortion ratio without error ($\sigma_\psi = \sigma_T = 0$)
σ = one standard deviation based on $\sigma_\psi = 10^{-5}$, $\sigma_T = 1\times10^{-2}$

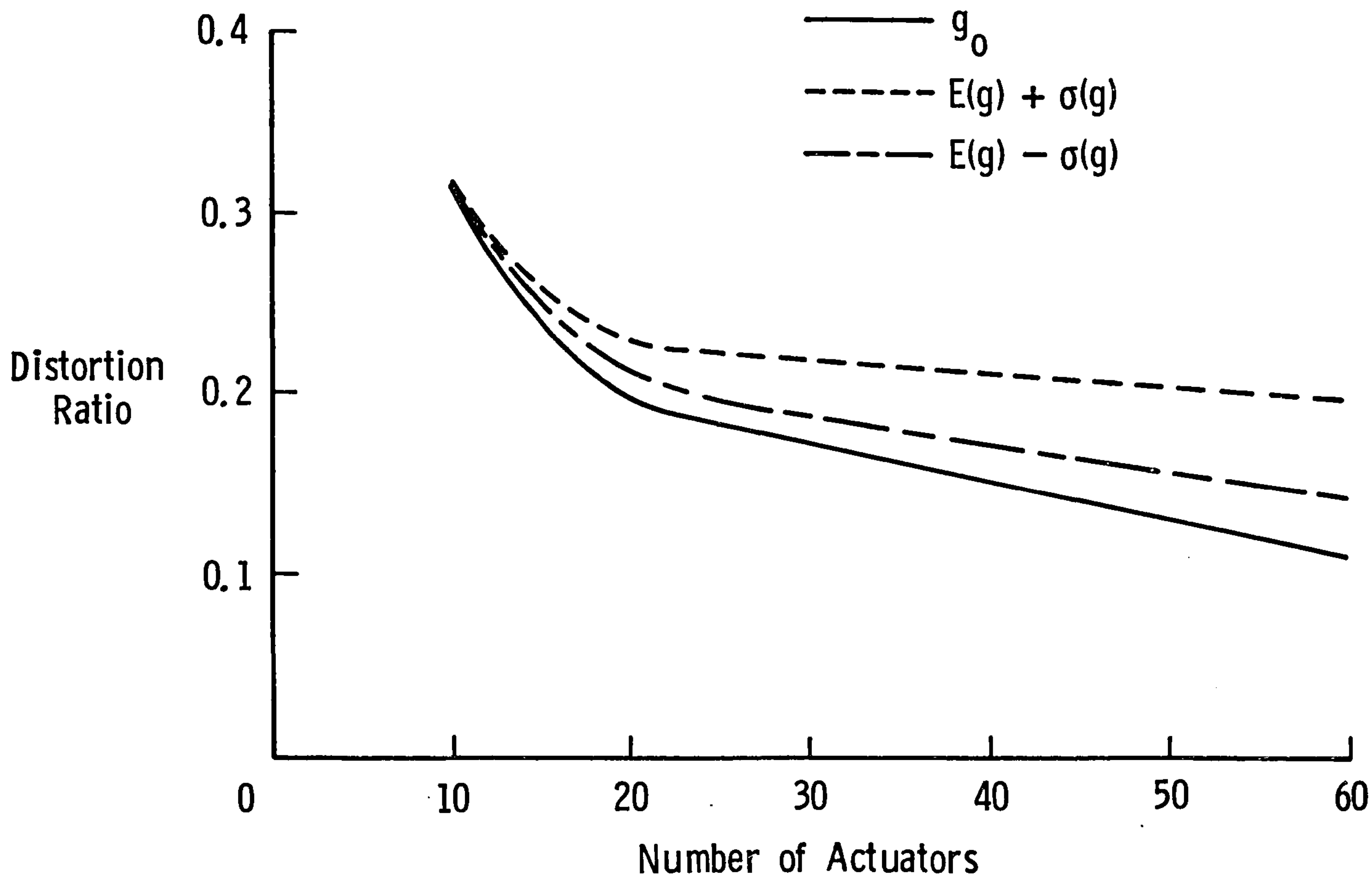

Figure 6.- Effect of sensor and actuator errors on distortion ratio
g_o = distortion ratio without error ($\sigma_\psi = \sigma_T = 0$)
σ = one standard deviation based on σ_ψ 10^{-5}, $\sigma_T = 5x10^{-3}$

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16. Abstract

An analytical study was performed to predict and assess the effect of actuator and sensor errors on the performance of a shape control procedure for flexible space structures using applied temperatures. Approximate formulas were derived for the expected value and variance of the rms distortion ratio (ratio of rms distortions with and without corrections) based on the assumption of zero-mean normally distributed random errors in measured distortions and actuator output temperatures. Studies were carried out for a 55-meter radiometer antenna reflector distorted from its ideal parabolic shape by non-uniform orbital heating. The first study consisted of varying the sensor and actuator errors for the case of 12 actuators and computing the distortion ratio. In the second study, sensor and actuator errors were prescribed and the effect of increasing the number of actuators was evaluated.

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