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SELECTION OF ACTUATOR LOCATIONS FOR STATIC SHAPE CONTROL OF LARGE SPACE STRUCTURES BY HEURISTIC INTEGER PROGRAMING

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SELECTION OF ACTUATOR LOCATIONS FOR STATIC SHAPE CONTROL OF LARGE SPACE STRUCTURES BY HEURISTIC INTEGER PROGRAMING

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ABSTRACT

Orbiting spacecraft such as large space antennas have to maintain a highly accurate shape to operate satisfactorily. Such structures require active and passive controls to maintain an accurate shape under a variety of disturbances. This paper is concerned with methods for the optimum placement of control actuators for correcting static deformations. In particular, attention is focused on the case where control locations have to be selected from a large set of available sites, so that integer programming methods are called for. The paper compares the effectiveness of three heuristic techniques for obtaining a near-optimal site selection. In addition the paper presents efficient reanalysis techniques for the rapid assessment of control effectiveness. Two examples are used to demonstrate the methods: a simple beam structure, and a 55m space-truss-parabolic antenna.

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INTRODUCTION

In the design of large space antennas, one of the most stringent design requirements is that of surface accuracy [1,2]. While studies have shown that in some cases high-surface accuracies may be maintained with passive methods [3], it is expected that for many applications active controls may be needed. The disturbances which affect the shape of space structures are of two types. One type is transient which leaves the structure unchanged once damped out. Such disturbances usually call for active or passive controls which enhance the damping of the structure. The second type of disturbance is typified by fixed deformations such as those due to manufacturing errors [4] or those which are slowly varying and may be considered quasi-static. These latter disturbances may be offset by slowly-applied, long-acting corrections. Most research to date has concentrated on the first type of disturbance and the use of damping actuators [5]. There has been less research on controlling quasi-steady disturbances.

Much of the work reported on active control of quasi-steady disturbances is related to active control of optical systems such as mirrors (see [6] for a survey of the state of the art of 1978). Generally, the actuators employed are force actuators (e.g. [7-11]). Bushnell [7] characterizes some such actuators (e.g. [12,13]) as displacement actuators because they are stiff enough to enforce a prescribed displacement at a point. Another variation of the force actuator in a truss structure is one which effects a change in 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 [15] is the use of applied temperatures on the structure.

The present paper describes a follow-on effort from that of [15], namely the optimal placement of force or temperature control actuators in a flexible structure to correct static surface distortion. When the sites available for location placement are a continuum, the problem can be treated by standard continuous optimization techniques. For example, [16] contains a survey of techniques employed for actuator placement in vibration control, and [17] describes actuator placement for static shape control. In many practical problems, only discrete sites are available. The optimal selection of the locations becomes an integer programing problem which is usually much more difficult and costly to solve than a continuous optimization problem [18]. This discrete site problem has received relatively little attention.

Because of the high cost of solving integer programing problems rigorously, there is merit in considering heuristic site selection techniques which obtain near-optimal solutions at a relatively low computation cost. In [16] and [19] heuristic methods were developed in connection with actuator and sensor placement for vibraton control problems. An important adjunct to these technqiues is the rapid evaluation of the effect of adding or eliminating actuators. Reference [16] describes approximate methods for this type of evaluation in vibration control problems. The present paper describes two heuristic algorithms for actuator placement for static shape control. The paper also develops rigorous yet rapid analysis methods to evaluate the effects of adding or deleting actuators.

The methods discussed in the paper are applied to two problems: a free-free beam and a 55m space truss parabolic antenna reflector. Studies are made of the effect of starting points on the final design produced by the algorithms. Efficiency and effectiveness of the methods are evaluated and compared.

SYMBOLS

A	coefficient matrix in Eq. (4)
C	vector added to matrix A due to added actuator (Eq. 16)
d	diagonal term in matrix A corresponding to added actuator (Eq. 16)
e_i	unit vector with unity in ith position
g	ratio of corrected to original rms displacement (Eqs. (7) and (8))
m	number of available locations for actuators
n	number of actuators
r	right-hand-side vector in Eq. (4)
r_{mo}	rms value of distortion (Eq. (9))
T	vector of incremental temperatures
T_o	vector of incremental temperatures for nominal system
T_i	incremental temperature of ith actuator
u_i	displacement due to a unit temperature increment in ith actuator
u_{rms}	rms value of displacement
v_o	reference volume
ε_u	residual displacement (Eq. 1)
λ	Lagrange multiplier (Eq. 11)
ϕ	augmented function, Eq. (10)
ψ	disturbed shape
Ω	continuum occupied by structure

REVIEW OF STATIC SHAPE CONTROL METHOD

The methods discussed in this paper are applicable to both linear force and temperature controls. For completeness the equations for temperature control from [15] are summarized herein. The reader is directed 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. It is also assumed that the distortion can be accurately measured. The disturbance is corrected by prescribing temperatures at n high-thermal-expansion inserts (actuators) placed in the structure. The disturbance ψ is assumed to be slowly varying so that the actuator inputs may be calculated by a quasi-static analysis.

The residual displacement ε_u is the sum of the disturbed shape and the correction

$$\varepsilon_u = \psi + \sum_{i=1}^{n} u_i \, T_i \tag{1}$$

where T_i is the change in temperature of the ith actuator with respect to the temperature at which ψ is measured and u_i is the displacement due to a unit value of T_i.

The best values of T_i are those which most effectively nullify ψ and cause ε_u to be close to zero. A common measure of the smallness of ε_u is based on the rms value

$$u_{rms}^2 = \frac{1}{v_0} \int_{\Omega} \varepsilon_u \cdot \varepsilon_u d\Omega \tag{2}$$

where v_0 is a reference volume. The necessary condition for a minimum is

$$\frac{\partial u_{rms}^2}{\partial T_j} = (2/v_0) \int_{\Omega} (\psi + \sum_{i=1}^{n} u_i T_i) \cdot u_j d\Omega = 0 \qquad j = 1,\ldots,n \tag{3}$$

Equation (3) is a system of n linear algebraic equations for the control temperatures and may 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, g is given by

$$g^2 = \frac{\int_\Omega \varepsilon_u^2 d\Omega}{\int_\Omega \psi^2 d\Omega} \tag{7}$$

It follows from Eqs. (1), (4), (7) that

$$g^2 = \frac{r_{mo}^2 - 2r^T T + T^T A T}{r_{mo}^2} = 1 - \frac{r^T T}{r_{mo}^2} \tag{8}$$

where

$$r_{mo}^2 = \int_\Omega \psi^2 d\Omega \tag{9}$$

THE EFFECT OF REMOVING OR ADDING ONE ACTUATOR

The optimization algorithms used in this paper always compare a given configuration to another which is identical except that one actuator has either been removed or added. To reduce the computational cost of these algorithms, quick reanalysis procedures are derived below to assess performance for these special cases.

Removing an Actuator

Eq. (4) may be obtained by minimizing g^2 with respect to T. Removing the ith actuator can be simulated by performing the minimization under the constraint that $T_i = 0$. Employing Lagrange multipliers we look for stationary points of ϕ where

$$\phi = \frac{1}{2} r_{mo}^2 g^2 - \lambda T_i = \frac{1}{2} r_{mo}^2 g^2 - \lambda e_i^T T \tag{10}$$

where e_i is a vector with unity in the ith row and zeros elsewhere.

The conditions of stationarity of ϕ are

$$A\,T - r - \lambda e_i = 0 \tag{11}$$

$$e_i^T T = 0 \tag{12}$$

then from Eq. (11)

$$T = T_o + \lambda A^{-1} e_i \tag{13}$$

where T_o is the nominal vector of actuator temperatures ($T_o = A^{-1} r$).
From Equations (12) and (13) it follows that

$$\lambda = \frac{-e_i^T T_o}{e_i^T A^{-1} e_i} = \frac{-T_{oi}}{a_{ii}^{-1}} \tag{14}$$

where a_{ii}^{-1} is the ith diagonal of A^{-1}. Then from Eqs. (8), (13), and (14)

$$\Delta(g^2) = \frac{T_{oi}^2}{a_{ii}^{-1} r_{mo}^2} \tag{15}$$

Adding an Actuator

Adding an actuator requires increasing the order of A. Eq. (4) becomes

$$\begin{bmatrix} A & C \\ C^T & d \end{bmatrix} \begin{Bmatrix} T \\ T_{n+1} \end{Bmatrix} = \begin{Bmatrix} r \\ r_{n+1} \end{Bmatrix} \tag{16}$$

where C is the additional column and d the new diagonal element. From the expansion of Eq. (16) we obtain

$$T = A^{-1} r - A^{-1} C T_{n+1} = T_o - A^{-1} C T_{n+1} \tag{17}$$

$$T_{n+1} = \frac{r_{n+1} - C^T T_o}{d - C^T A^{-1} C} \tag{18}$$

and

$$\Delta(g^2) = \frac{-(r_{n+1} - C^T T_o)^2}{d - C^T A^{-1} C} \; \frac{1}{r_{mo}^2} \tag{19}$$

SELECTION OF OPTIMAL ACTUATOR LOCATIONS

The problem of selecting n actuator locations from a set of m available sites can be formulated and solved by standard integer programming techniques [18]. However, these tend to be extremely costly when the number of available sites is large compared to the number of actuators. This is due to the large number of possible combinations of placement configurations. For example, the number of possibilities for choosing 20 actuator locations from 100 sites is 5.4 x 10^{20}. This paper proposes two heuristic algorithms which improve a trial set of actuator locations at a moderate computational cost. Additionally, a study is made of another heuristic algorithm due to DeLorenzo and Skelton ([16] and [19]).

The two proposed algorithms start with a configuration I_0 which contains the desired number of actuators (n). The Worst-Out-Best-In (WOBI) algorithm first independently removes each of the n actuators to find the "worst" actuator i.e. the actuator which can be removed with the least detrimental effect on performance. Then the worst actuator is moved to each of the locations outside I_0 and tested by including it with the $n-1$ remaining actuators. The best location replaces the removed one. A total $n+(m-n)=m$ configurations are analyzed in each iteration. Iterations continue until no improvement is possible. The Exhaustive Single Point Substitution (ESPS) algorithm is more thorough than the WOBI algorithm. In an iteration, it moves each actuator in turn from I_0 to each of the $m-n$ unused locations and analyzes performance at each trial location. The best of these $n(m-n)$ configurations replaces I_0 and iterations continue until no improvement is possible. ESPS is more expensive per iteration than WOBI because $n(m-n) > m$.

The DeLorenzo algorithm starts with a configuration where all m locations are occupied by actuators. The least effective location is found by removing one actuator at a time. This least effective actuator is removed and the process is repeated with $m-1$ actuators. The process is repeated $m-n$ times until the number of actuators is reduced to n. The total number of configurations analyzed by DeLorenzo's algorithm is $(m+n)(m-n+1)/2$. Details of the three algorithms are given below.

Worst-Out-Best-In (WOBI) Algorithm

1. Select an initial configuration I_0 of n actuators, and calculate the rms reduction factor g_0.

2. Calculate the rms reduction factor, g, for each of the n configurations of $n-1$ actuators obtained by removing one actuator from I_0.

3. Select the actuator which when removed has the least effect on g as the "worst" actuator. Remove it to produce a configuration I_1 of $n-1$ actuators.

4. Calculate g for the $m-n$ configurations of n actuators obtained by placing an actuator at any of the available locations outside I_0.

5. Label the configuration with lowest g as I_1 and the corresponding g as g_1.

6. If $g_1 \geq g_0$ convergence is obtained and I_0 is the best configuraion.

7. If $g_1 < g_0$ set $I_0 = I_1$ and $g_0 = g_1$ and go to step 2.

Exhaustive Single Point Substitution (ESPS) Algorithm

1. Select an initial configuration I_0 of n actuators and calculate g_0.

2. Calculate g for each of the $(m-n)n$ configurations obtained by replacing one of the locations of I_0 by a location outside of I_0.

3. Label the configuration with lowest g as I_1 and the corresponding g as g_1.

4. If $g_1 \geq g_0$ convergence is obtained and I_0 is the best configuration.

5. If $g_1 < g_0$ set $I_0 = I_1$ and $g_0 = g_1$ and go to step 2.

DeLorenzo's Algorithm

1. Calculate g_0 for an initial configuration I_0 composed of m actuators (an actuator at every available location). Set $n_1 = m$.

2. Calculate g for all $n_1 - 1$ actuators obtained by removing one actuator from I_0.

3. Select the best configuration and label it I_0 and the corresponding g as g_0.

4. If $n_1 - 1 = n$ the process is completed.

5. If $n_1 - 1 \neq n$ go to step 2.

Sequential Application of WOBI and ESPS

To minimize the variation in WOBI and ESPS results due to the selection of the initial configuration the following strategy is useful. Each method is first applied for a small number of actuators and then the number of actuators is increased by one until the required number is reached. Each time, the best configuration obtained for n actuators is augmented by the first available site and used as the initial configuration for the selection of the n+1 locations.

RESULTS AND DISCUSSION

Free-Free Beam

The first example is a free-free beam (fig. 1) initially straight but distorted into a shape described by a cubic polynomial. Results of using actuator locations obtained with the WOBI and ESPS algorithms were compared with each other and with the performance of a set of equispaced actuators. The number of actuators (n) was either six or eight. The number of available sites (m) was 20, 40, and 80. For each combination (n,m), ten arbitrary initial configurations (I_0) were used to assess the variations due to the initial configuration (see Table 1 and figure 1(b)).

The results summarized in Table 2 reveal the following characteristics of the WOBI and ESPS algorithms. The WOBI algorithm is much more sensitive to the initial configuration. In fact for some initial configurations it did not do as well as the equispaced configuration. The scatter in the ESPS algorithm is much milder, and the improvement in its performance over the equispaced solution ranged up to 38 percent. The number of iterations for convergence of both algorithms was small (typically three) and as a result, the number of configurations

tions which had to be analyzed is small. For example, in selecting 8 sites from 80 available (equivalent to 4 out of 40 because of symmetry) there are 91,390 possible combinations. Three iterations of the WOBI technique check 120 of these combinations while three iterations of the ESPS technique check 432 combinations. The best and worst locations obtained by WOBI and ESPS are shown in Figure 2. The disturbed shape and typical corrected shapes are shown in Figure 3.

Antenna Reflector

The second example is a 55m space-truss parabolic antenna reflector shown in Figure 4. The antenna is assumed to be 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 surfaes of the antenna is shown in Figure 5. Although in practice, disturbances corresponding to several points in the mission must be considered, for this example only the design point corresponding to the maximum temperature gradient through the reflector was considered in selecting the actuator locations.

The antenna reflector finite element model contains 420 elements which are potential sites for actuators. However, it was determined that adequate control can be achieved with actuator locations chosen from the 120 sites available on the lower surface elements in the reflector. A configuration with an actuator at all 120 sites results in value of $g = 0.0016$.

First, we tried to find the best locations for 12 actuators. In an earlier study [15], where intuitive actuator placement was employed, 12 actuators on the lower surface gave $g = 0.412$. The ESPS algorithm yielded $g = 0.275$, and the

WOBI algorithm $g = 0.329$, an improvement of 33 percent and 20 percent respectively. The scatter of the ESPS method due to choice of initial configuration was less than 5 percent while the WOBI method produced about 70 percent scatter. Convergence typically required fewer than 10 iterations so that fewer than 13,000 of the 1.05×10^{16} possible configurations were checked. The DeLorenzo algorithm [16] when applied to this problem did not perform well, producing $g = 0.459$, which is worse than the configuration chosen intuitively in [15]. This is likely due to the generally poor performance of this algorithm when the number of actuators is much less than the number of possible sites. To check whether the result from the DeLorenzo method corresponded to a local minimum it was used as an initial configuration for the ESPS algorithm. The ESPS algorithm moved from the DeLorenzo design and converged to one having $g = 0.282$ which is quite close to the best design obtained previously by ESPS.

The actuator locations from the ESPS, WOBI, and DeLorenzo algorithms are shown in Figure 6 along with the locations used in [15]. Figure 7 depicts the uncorrected and corrected shapes for the antenna based on the various actuator locations. Shown are cross-sections of the shapes corresponding to a section through a diagonal of the reflector (the line $y = 0$). These shapes are intended to convey the nature of the shape correction associated with the various actuator placement algorithms. However, the figure does not include all of the points in the structure, and therefore it is not as suitable as the values of g for comparing the overall effectiveness of the various algorithms.

A study was performed to test the behavior of the ESPS, WOBI, and DeLorenzo algorithms as the number of actuator locations was increased. The number of locations was varied from 12 to 120 out of the 120 available sites. To minimize the effect of scatter, the sequential strategy described in the previous section was used with the ESPS and WOBI algorithms. This strategy was not needed for the DeLorenzo algorithm.

The results of the comparison of the three algorithms are summarized in Table 3. The table shows that the ESPS and WOBI algorithms produced designs superior to those obtained by the DeLorenzo algorithm, for all numbers of actuators. However, as the number of actuators is increased the DeLorenzo algorithm requires analyzing a smaller number of configurations than ESPS and WOBI. Consequently, when the number of actuators is a large fraction of the number of available sites, the DeLorenzo technique would be a reasonably good choice. Table 3 suggests that for antenna structures it may be difficult to satisfy high surface accuracy requirements with a small number of actuators even if these are optimally placed. For example, 60 sites are needed to reduce the distortion by an order of magnitude ($g = .112$ for $n_c = 60$).

Finally to give a graphical indication of the effect of increasing the number of actuators, the corrected shapes for 12 and 40 actuators located by the ESPS technique are shown in Figure 8. Use of 40 actuators not only results in an increased reduction in overall distortion ($g = 0.157$ compared to 0.275) but also yields a relatively smooth shape compared to the highly oscillatory shape produced by 12 actuators.

CONCLUDING REMARKS

Two heuristic algorithms were described for the optimal selection of actuator locations to correct surface distortion of orbiting spacecraft. These algorithms are denoted Worst-Out-Best-In (WOBI) and Exhaustive-Single Point Substitution (ESPS). The algorithms produce results which depend somewhat on the intial guess - however, they determine improved locations while evaluating only a small fraction of the possible choices. The computational efficiency of the algorithms was enhanced by the derivation of fast re-analysis techniques for estimating the effect of changing the location of an actuator.

The algorithms were demonstrated for a free-free beam and a space antenna reflector and the performance of the algorithms was compared to those previously obtained with a set of intuitively-located actuators. It was shown that the WOBI and ESPS algorithms were able to significantly improve shape corrections by relocating actuators. For example, in the beam with 8 actuators the WOBI and ESPS corrections were up to 38 percent better than corrections obtained by equally-spaced actuators. For the reflector with 12 actuators, WOBI was 20 percent better than the intuitively-placed actuators and ESPS was 33 percent better. As part of the present work, a previously-developed location selection technique due to DeLorenzo was also evaluated for the antenna example. While the DeLorenzo technique is often computationally cheaper than the WOBI and ESPS algorithms, it did not perform as well as either when a relatively small number of the available sites had to be selected. When a large fraction of the available sites were used, the DeLorenzo technique was a reasonable choice.

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TABLE 1.- INITIAL DESIGNS USED TO ASSESS EFFECT OF STARTING POINT ON FINAL DESIGN FOR BEAM (n = NUMBER OF ACTUATORS, m = NUMBER OF AVAILABLE SITES).

n \ m	20	40	80
6	1,2,3,18,19,20 2,4,6,15,17,19 3,6,9,12,15,18 2,3,4,17,18,19 3,5,7,14,16,18 3,4,5,16,17,18 4,5,6,15,16,17 5,6,7,14,15,16 6,7,8,13,14,15 7,8,9,12,13,14	1,2,3,38,39,40 2,4,6,35,37,39 3,6,9,32,35,38 4,8,12,29,33,37 5,10,15,26,31,36 6,12,18,23,29,35 2,3,4,37,38,39 3,4,5,36,37,38 4,5,6,35,36,37 5,6,7,34,35,36	1,2,3,78,79,80 2,4,6,75,77,79 3,6,9,72,75,78 4,8,12,69,73,77 5,10,15,66,71,76 6,12,18,63,69,75 7,14,21,60,67,74 8,16,24,54,65,73 9,18,27,54,63,72 10,20,30,51,61,71
8	1,2,3,4,17,18,19,20 2,4,6,8,13,15,17,19 2,3,4,5,16,17,18,19 3,4,5,6,15,16,17,18 4,5,6,7,14,15,16,17 5,6,7,8,13,14,15,16 6,7,8,9,12,13,14,15 7,8,9,10,11,12,13,14 3,5,7,9,12,14,16,18 4,6,8,10,11,13,15,17	1,2,3,4,37,38,39,40 2,4,6,8,33,35,37,39 3,6,9,12,29,32,35,38 4,8,12,16,25,29,33,37 5,10,15,20,21,26,31,36 2,3,4,5,36,37,38,39 3,4,5,6,35,36,37,38 4,5,6,7,34,35,36,37 5,6,7,8,33,34,35,36 6,7,8,9,32,33,34,35	1,2,3,4,77,78,79,80 2,4,6,8,73,75,77,79 3,6,9,12,69,72,75,78 4,8,12,16,65,69,73,77 5,10,15,20,61,66,71,76 6,12,18,24,57,63,69,75 7,14,21,28,53,60,67,74 8,16,24,32,49,57,65,73 9,18,27,36,45,53,61,69 10,20,30,40,41,51,61,71

(SEE FIGURE 1 FOR SITE LOCATIONS)

TABLE 2.- SCATTER IN RMS REDUCTION FACTORS g DUE TO STARTING POINT FOR VARIOUS NUMBERS OF SITES (m) AND ACTUATORS (n) FOR BEAM PROBLEM.

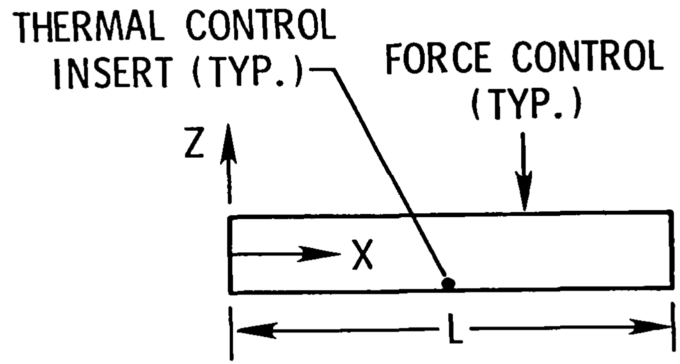
	n	m	ALGORITHM	
$g_{equispaced}$			WOBI	ESPS
0.0711	6	20 40 80	0.0508 - 0.0709 0.0542 - 0.0843 0.0497 - 0.0892	0.0508 - 0.0709 0.0499 - 0.0550 0.0476 - 0.0544
0.0542	8	20 40 80	0.0358 - 0.0528 0.0364 - 0.0601 0.0350 - 0.0551	0.0358 - 0.0419 0.0341 - 0.0443 0.0332 - 0.0383

TABLE 3.- COMPARISON OF RMS REDUCTION FACTORS (g) AND NUMBER OF CONFIGURATIONS EVALUATED (n_c) BY THREE HEURISTIC OPTIMIZATION ALGORITHMS FOR ANTENNA REFLECTOR.

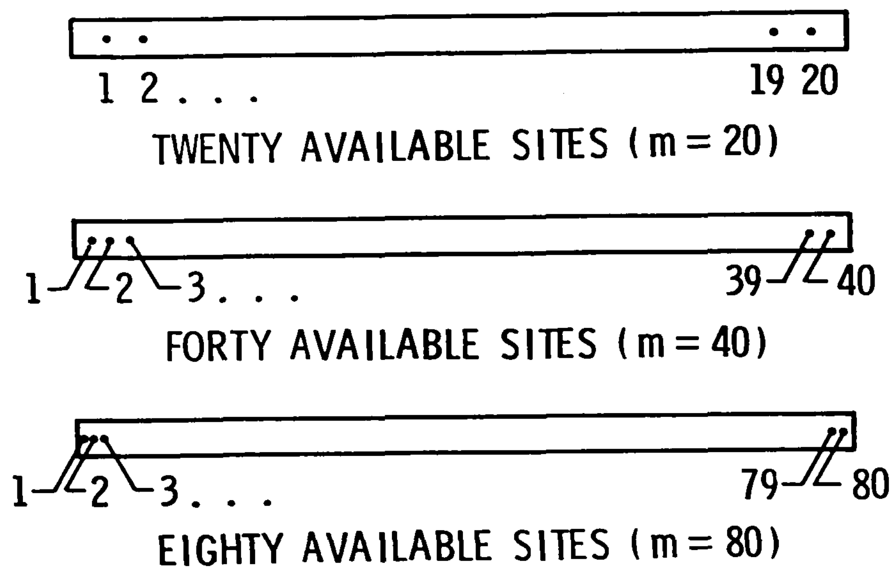
NUMBER OF ACTUATORS	12	15	20	30	40	60	80	120
ESPS	0.275 (27741)	0.228 (42208)	0.198 (67978)	0.179 (129054)	0.157 (248449)	0.112 (561876)	0.081 (824708)	0.0016 (1)
WOBI	0.329 (1687)	0.280 (2410)	0.240 (3615)	0.192 (6266)	0.170 (10238)	0.134 (22047)	0.083 (22047)	0.0016 (1)
DeLorenzo (Ref. 16)	0.459 (7182)	0.390 (7140)	0.304 (7050)	0.249 (6795)	0.225 (6440)	0.168 (5430)	0.111 (4020)	0.0016 (1)
(Ref. 15)	0.412							

upper entry - g

lower entry - n_c

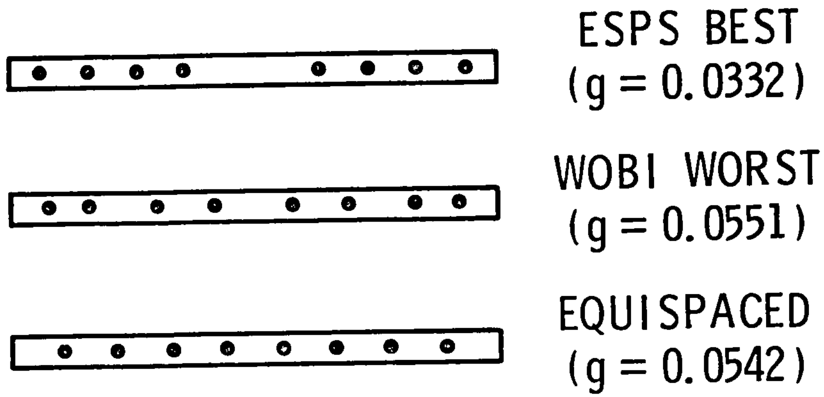


(a) Beam geometry and nomenclature.

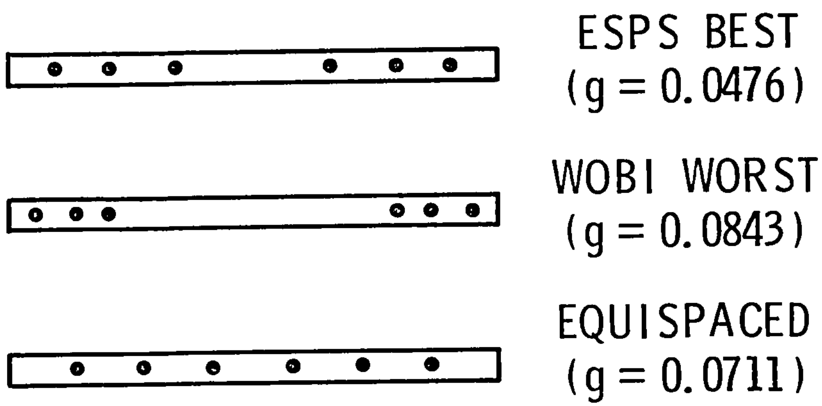


(b) Available sites for 20, 40, and 80 actuators.

Figure 1.- Geometry and locations of available actuator sites for beam problem.



(a) 8 locations chosen from 80 sites.



(b) 6 locations chosen from 80 sites.

Figure 2.- Worst and best actuator locations obtained by WOBI and ESPS for beam.

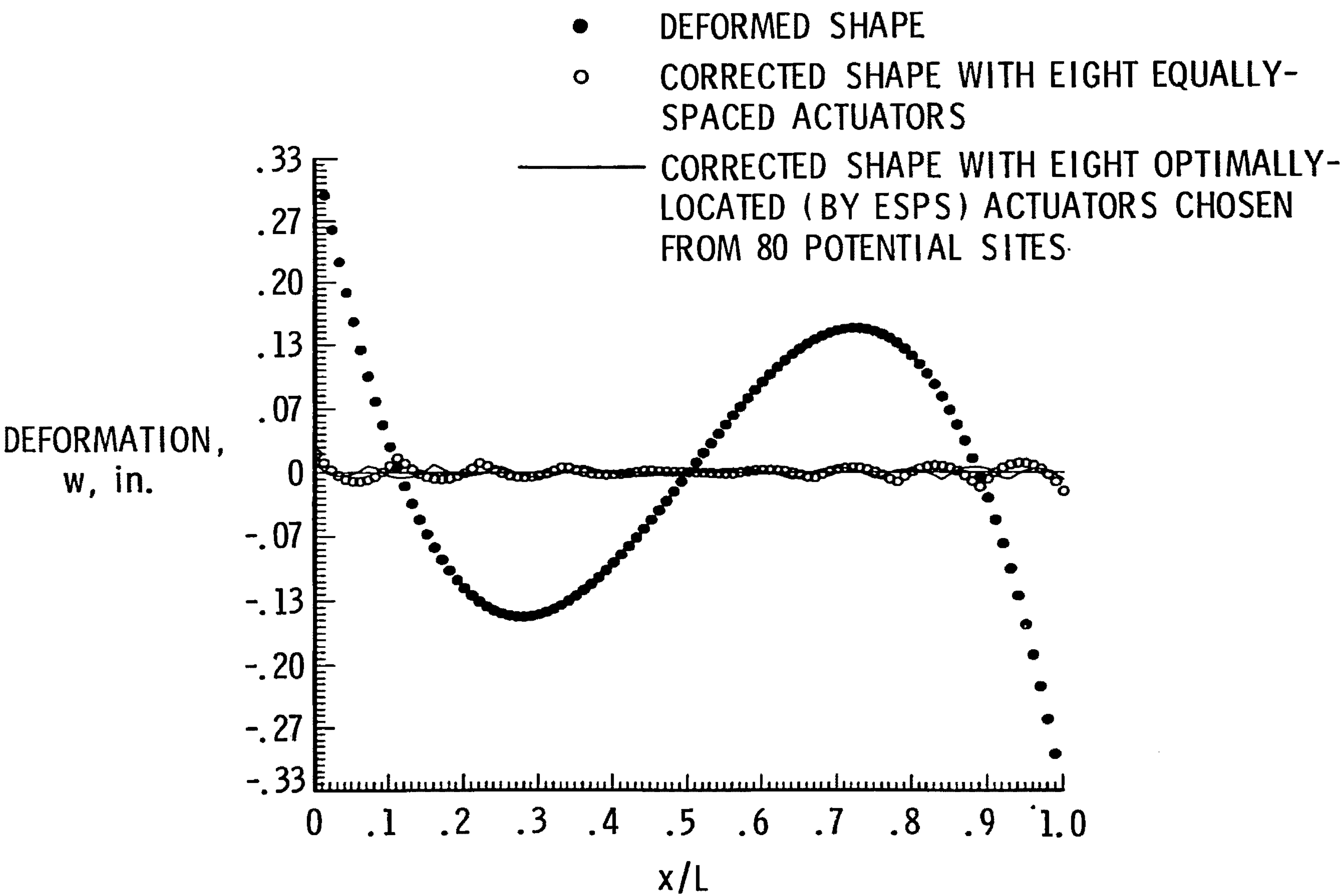


Figure 3.- Deformed and corrected shapes for beam.

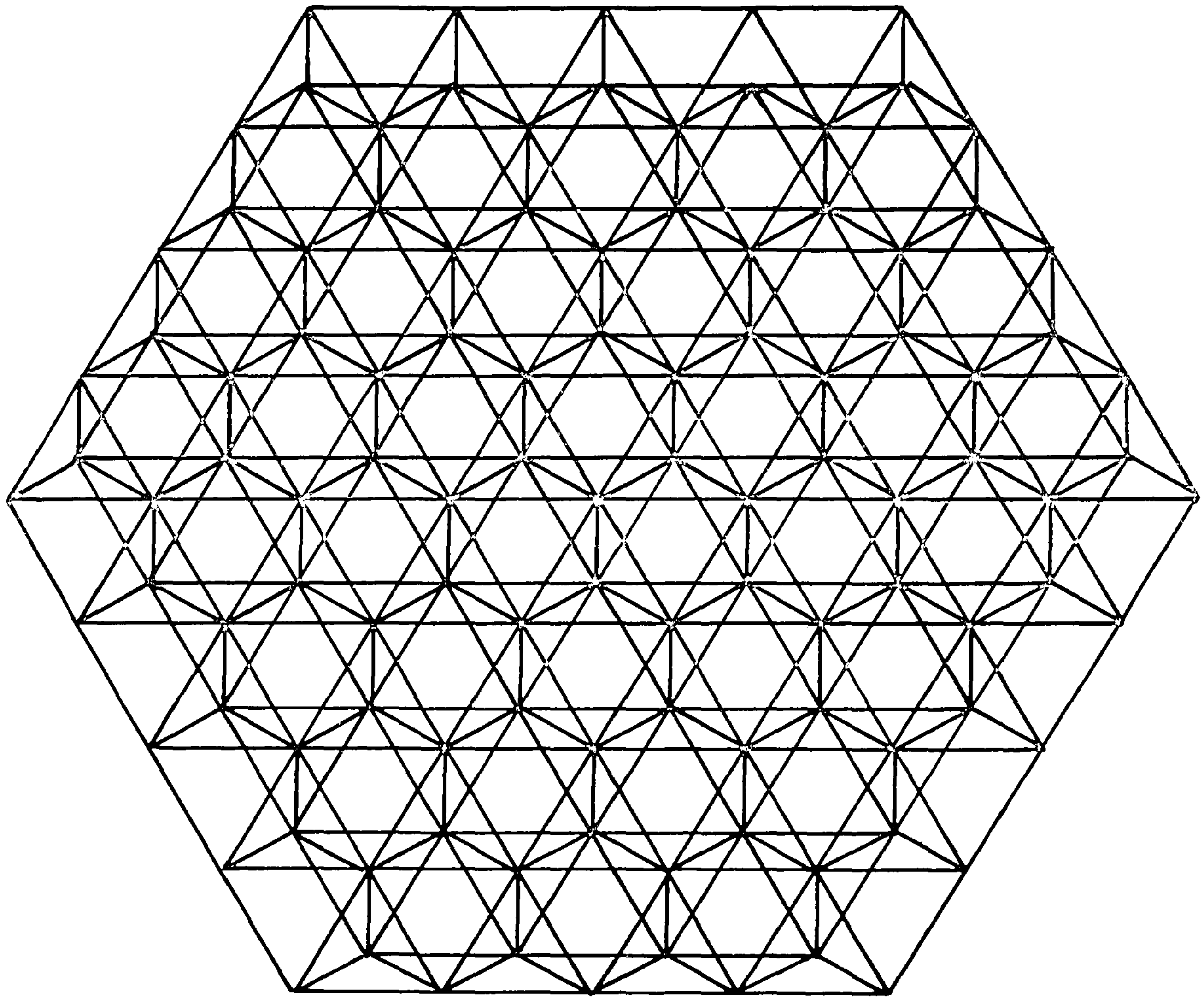


Figure 4.- Tetrahedral truss antenna reflector.

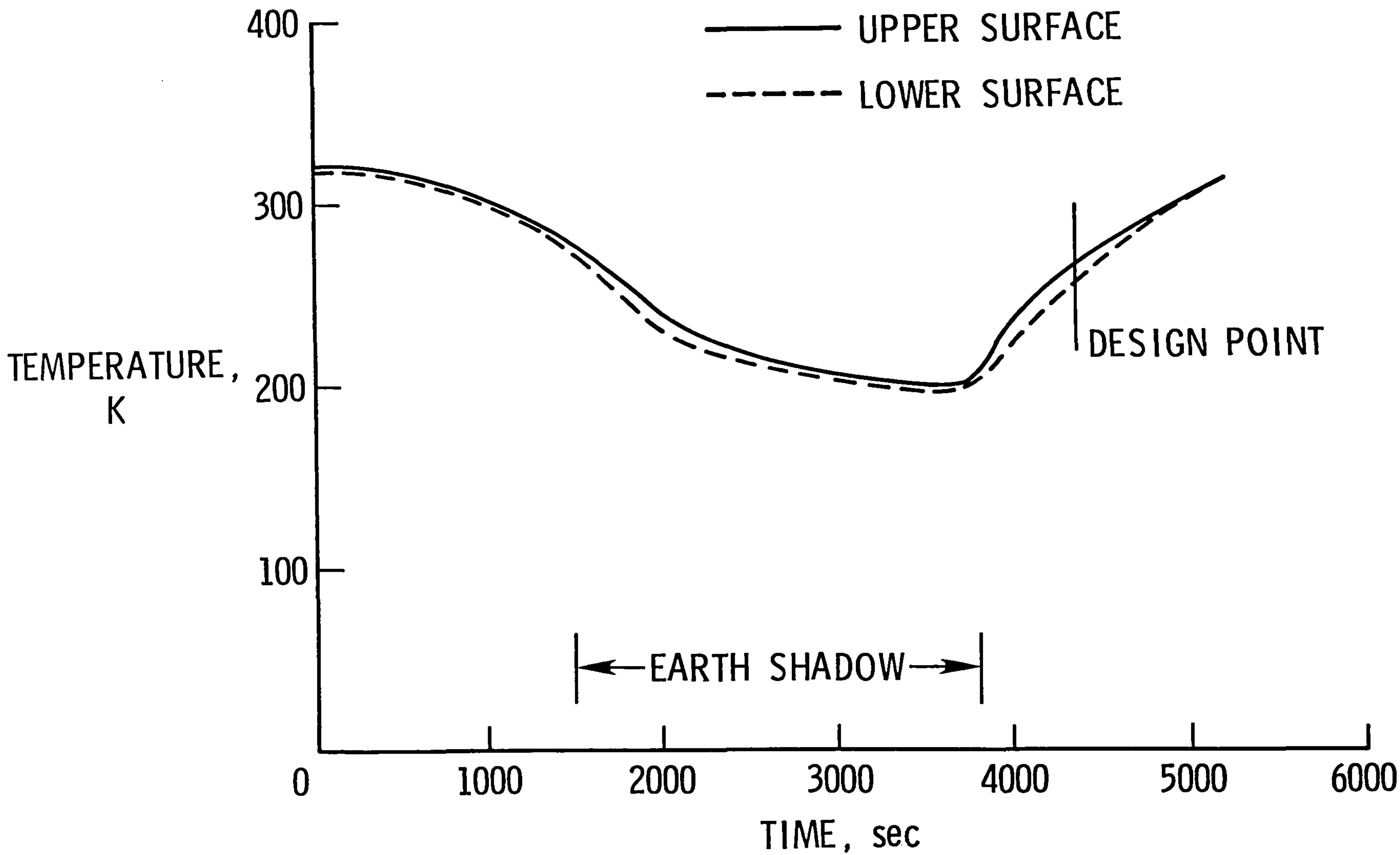
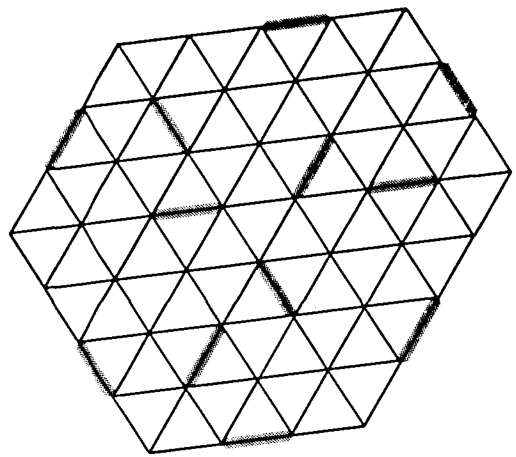
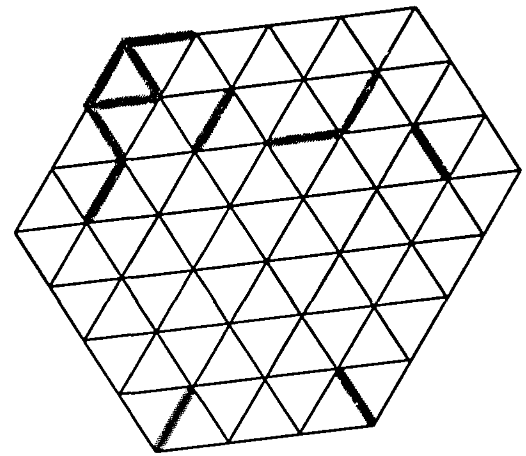


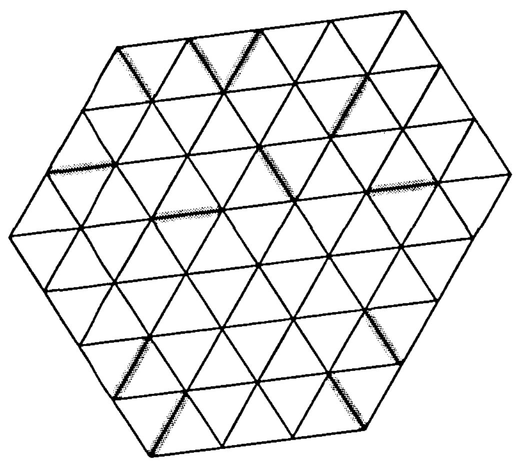
Figure 5.- Temperature history for antenna reflector.



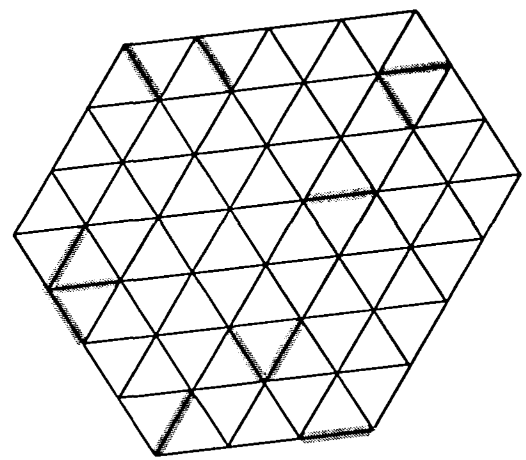
(a) Locations used in
in reference 15, G = 0.412.



(c) Locations from WOBI
method, G = 0.329.



(b) Locations from ESPS
method, G = 0.275.



(d) Locations from DeLorenzo
algorithm, G = 0.459.

Figure 6.- Actuator locations for control of antenna surface distortion.

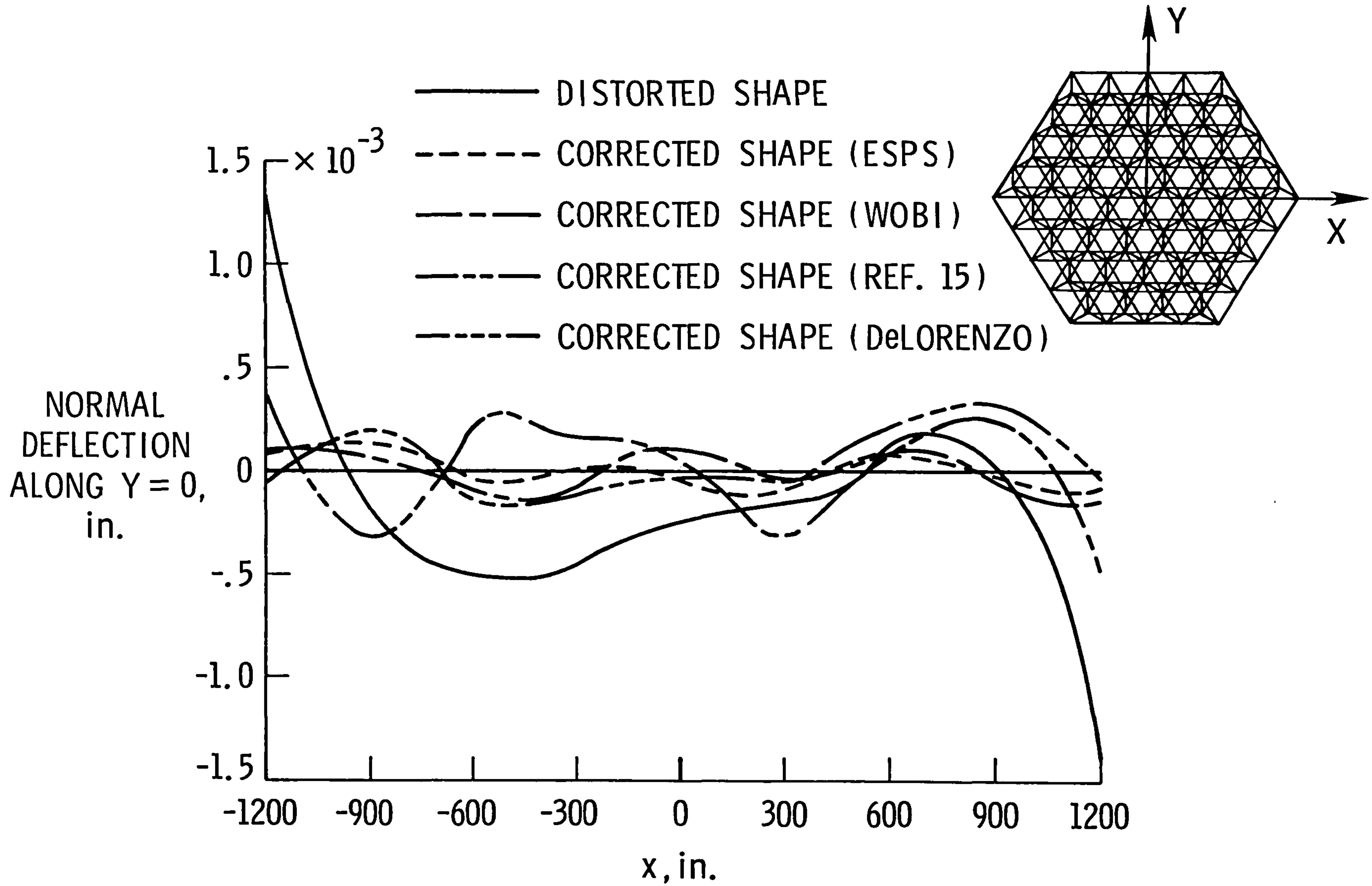


Figure 7.- Control of antenna surface distortion by applied temperatures (12 actuators).

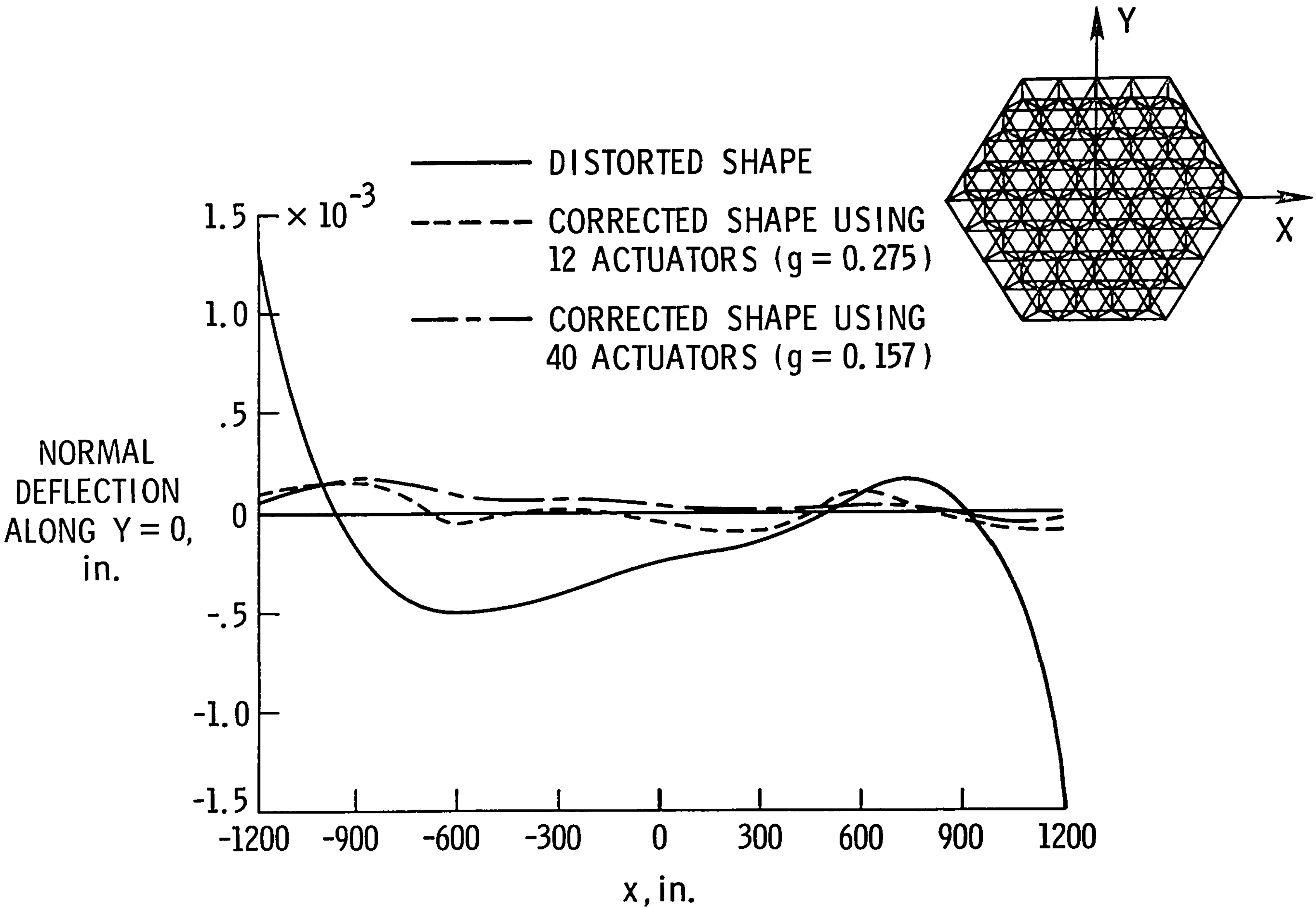


Figure 8.- Corrected shapes with 12 and 40 actuators (locations determined by ESPS).

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16. Abstract

Orbiting spacecraft such as large space antennas have to maintain a highly accurate shape to operate satisfactorily. Such structures require active and passive controls to maintain an accurate shape under a variety of disturbances. This paper is concerned with methods for the optimum placement of control actuators for correcting static deformations. In particular, attention is focused on the case where control locations have to be selected from a large set of available sites, so that integer programing methods are called for. The paper compares the effectiveness of three heuristic techniques for obtaining a near-optimal site selection. In addition, the paper presents efficient reanalysis techniques for the rapid assessment of control effectiveness. Two examples are used to demonstrate the methods: a simple beam structure and a 55m space-truss-parabolic antenna.

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