Shape control of solar collectors using torsional shape memory alloy actuators

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ABSTRACT

Solar collectors that are focused on a central receiver are designed with a mechanism for defocusing the collector or disabling it by turning it out of the path of the sun's rays. This is required to avoid damaging the receiver during periods of inoperability. In either of these two cases a fail-safe operation is very desirable where during power outages the collector passively goes to its defocused or deactivated state. This paper will be principally concerned with focusing and defocusing the collector in a fail-safe manner using shape memory alloy actuators. Shape memory alloys are well suited to this application in that once calibrated the actuators can be operated in an on/off mode using a small amount of electric power. Also, in contrast to other smart materials that were investigated for this application, shape memory alloys are capable of providing enough stroke at the appropriate force levels to focus the collector. In order to accommodate the large, nonlinear deformations required in the solar collector plate to obtain desired focal lengths, a torsional shape memory alloy actuator was developed that produces a stroke of 0.5 inches. Design and analysis details presented, along with comparisons to test data taken from an actual prototype, demonstrate that the collector can be repeatedly focused and defocused within accuracies required by typical solar energy systems.

Keywords: adaptive structures, smart materials, shape control, shape memory alloy, torsional actuators, solar collectors

1. INTRODUCTION

Solar collectors that are focused on a central receiver are designed with a mechanism for defocusing the collector or deactivating it by turning it out of the path of the sun's rays. This is required to avoid damaging the receiver during periods of inoperability. In either of these two cases a fail-safe operation is very desirable where during power outages the collector passively goes to its defocused or deactivated state. This paper will be principally concerned with focusing and defocusing the collector in a fail-safe manner using smart materials. The use of smart materials as actuators to shape the collector provides a design that is solid state, i.e., a design that has no moving parts. The class of smart materials selected in the design of the actuators is that of shape memory alloys (SMAs)¹.

One collector design² currently in use consists of two silvered mylar membranes stretched over either side of an aluminum ring. The membranes are sealed to the ring so a vacuum can be pulled on the volume between them through a small tube inserted in one of the membranes. The vacuum deflects the membranes into the desired collector shape (parabolic) and the side without the tube is used for the reflecting surface. The vacuum system required in this design is somewhat cumbersome to implement and is subject to maintenance problems. In addition the silvering on the mylar material has a limited lifetime (approximately 10 years) which leads to undesirable maintenance costs over the lifetime of the plant (30 years). As a result of these issues, a more cost effective (in terms of cost of energy) collector design is being sought.

In addition to SMAs, piezoelectric smart materials were considered in the actuator design. To investigate the use of piezoelectric actuator materials, a collector/actuator configuration consisting of a circular composite plate with the piezoelectric material comprising the outer layers was selected. In this configuration the electric field is applied through the thickness of the piezoelectric material causing a transverse strain. A positive voltage polarity is applied to the upper piezoelectric material producing transverse extension, and a negative one to the lower material producing transverse contraction. This action produces a uniform bending moment in the plate, resulting in a uniform curvature and a spherically shaped surface. Although a parabolic shape is the shape of choice,

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for focal lengths of interest here (greater than three times the plate diameter), a spherical shape is adequate. If the middle structural layer of the composite plate is eliminated and the piezoelectric material, PZT5H, is used at thicknesses large enough to support its weight for a plate diameter of three feet, a radius of curvature of approximately 400 inches is obtained. This value of R is sufficient for the current application, but requires high voltage and large sheets of PZT5H which may be difficult and/or costly to manufacture.

Actuator designs utilizing SMA materials offer several advantages. The actuator designs are simple, inexpensive and use a minimal amount of SMA material. They are well suited to this application in that once calibrated the actuators can be operated in an on/off mode using a minimal amount of electric power. SMAs are capable of providing enough stroke at the appropriate force levels to focus the collector.

A previous design by the current authors³ consisted of approximating a uniform moment around the edge of a circular plate using uniformly spaced discrete couples. From linear plate theory, the uniform moment loading deforms the plate into a spherical shape. The actuators designed for this configuration consisted of simple SMA wires that contracted when heated, pulling the plate down against stops placed a short distance outboard of the actuators. For this collector/actuator design, collector shapes for shorter focal lengths are compromised by nonlinearities associated with the required large plate deformations.

This paper presents a new collector and SMA actuator system designed using nonlinear finite element analysis that can achieve the shorter focal lengths. The actuator consists of an SMA rod that twists when heated providing a stroke of up to 0.5 inches through a lever arm attached to the end of the rod. Design and analysis details of this collector/actuator system are presented below, along with test data taken from a prototype developed to demonstrate the concept.

2. COLLECTOR/ACTUATOR SYSTEM DESIGN

The new collector/actuator design is shown in Figure 1. The view in Figure 1 is from the backside of the collector looking through the support system. The support system consists of sixteen radial spokes connected at a large central hub. On the end of each spoke a pad is attached at which the edge of the plate is supported through the use of a support post (denoted by the "o's"). The posts are attached to the plate in such a manner that the plate rotations are not inhibited. The eight actuators (denoted by the "x's") are attached to the hub at a radius (5.75 inches), a location that produces a deformed shape that is closest to the optimal one in a least squares sense. When activated the actuators pull the plate down against the posts.

Figure 1. Schematic of the collector system with discrete support.

In order to investigate the degree to which the surface produced by activating the eight discrete actuators conforms to the optimal shape, a finite element model of the collector was created, the details of which will be described later. First however, with the results of the finite element analysis in hand, the system used for comparing these results to specifications will be reviewed. The most efficient shape for a dish style solar collector is that of a paraboloid cap (which is equivalent to a spherical one for this application) as shown in Figure 2. The equation for this paraboloid cap is given by:

$$w = a(x^2 + y^2 - r_p^2) \quad (1)$$

The coefficient, a , is related to the focal length, f_l , by the expression

$$f_l = \frac{1}{4a} \quad (2)$$

The value of a can be determined such that the best paraboloid fit (in a least squares sense) of a set of discrete data is obtained. As the specifications for a solar collector require accuracy in slope, the set of discrete data is chosen to be the slope values, $\left(\frac{\partial w}{\partial x}\right)_i$ and $\left(\frac{\partial w}{\partial y}\right)_i$ (determined from finite element analysis), at the locations specified by (x_i, y_i) . With the exact slopes given by $2ax_i$ and $2ay_i$, the least square error value for a is given by:

$$a = \frac{\sum \left[\left(\frac{\partial w}{\partial x}\right)_i x_i + \left(\frac{\partial w}{\partial y}\right)_i y_i \right]}{2 \times \sum (x_i^2 + y_i^2)} \quad (3)$$

Using this value for a , the cosine of the angle, θ_i , between the desired surface normal and the actual one is given by:

$$\cos \theta_i = (n_d)_i \cdot (n_a)_i \quad (4)$$

where,

$$(n_d)_i = \frac{2ax_i i + 2ay_i j - k}{\sqrt{2ax_i i + 2ay_i j - k}^2} \quad (n_a)_i = \frac{\left(\frac{\partial w}{\partial x}\right)_i i + \left(\frac{\partial w}{\partial y}\right)_i j - k}{\left[\left(\frac{\partial w}{\partial x}\right)_i i + \left(\frac{\partial w}{\partial y}\right)_i j - k\right]^2} \quad (5)$$

For a discrete sample of n angular errors, θ_i , the root mean square error, θ_{rmse} , is given by:

$$\theta_{rmse} = \left[\frac{\sum \theta_i^2}{n-1} \right]^{1/2} \quad (6)$$

An additional metric can be developed for displacement errors. Using the value for a computed in Equation 3 and the exact displacements given by Equation 1, the root mean square error for the displacement, Δz_{rmse} , is given by:

$$\Delta z_{rmse} = \left[\frac{\sum [a(x_i^2 + y_i^2 - r_p^2) - w_i]^2}{n-1} \right]^{1/2} \quad (7)$$

Here w_i is the actual value of the displacement (determined from finite element analysis) at the locations specified by (x_i, y_i) .

Figure 2. Schematic of the paraboloid cap.

Figure 3. Distribution of sample points.

The values of θ_{rmse} and Δz_{rmse} as computed in Equation 6 and Equation 7 can be adjusted to reflect the desired focal length through multiplication by a factor determined using Equation 2. If the desired focal length, $(f_l)_d$ is α times the computed one (i.e. $(f_l)_d = \alpha f_l$) then the factor for adjusting θ_{rmse} and Δz_{rmse} is $1/\alpha$.

In order for these metrics to be meaningful, the plate locations or sample points where the data is taken must be distributed in a reasonably uniform fashion so that all areas of the plate will be equally represented. Such a distribution is shown in Figure 3. In addition the number of locations selected must be large enough to be statistically meaningful. According to Brownlee⁴, the mean square error, s^2 , of a sample of size n from a normal distribution is distributed as $\sigma^2 \chi^2(n-1)/(n-1)$ where σ is the standard deviation and χ^2 signifies the chi squared probability distribution. As n approaches infinity $\chi^2(n-1)/(n-1)$ approaches 1 and therefore s^2 approaches σ^2 . It follows that the quantity $(n-1)s^2/\sigma^2$ is distributed as $\chi^2(n-1)$ and confidence limits can be obtained for σ^2 as shown below. Beginning with

$$Pr\{\chi^2_{p_1}(n-1) < \chi^2(n-1) < \chi^2_{p_2}(n-1)\} = (P_2 - P_1) \quad (8)$$

inserting $(n-1)s^2/\sigma^2$ for $\chi^2(n-1)$, and performing the necessary algebra, the expression below is obtained:

$$Pr\left\{\frac{s^2(n-1)}{\chi^2_{p_2}(n-1)} < \sigma^2 < \frac{s^2(n-1)}{\chi^2_{p_1}(n-1)}\right\} = P_2 - P_1 \quad (9)$$

Here, P_1 and P_2 are the desired lower and upper probability points in the distribution. If n is selected to be 56 (the number of points in Figure 3), $P_2 = 0.999$, and $P_1 = 0.10$, Equation 9 becomes

$$Pr\{0.591s^2 < \sigma^2 < 1.305s^2\} = 0.90 \quad (10)$$

Equation 10 states that for a computed value of the mean square error, s^2 , from a sample size of 56, there is a 90% probability that the true value of s^2 (that would be obtained if the sample size were infinite) lies between $0.591s^2$ and $1.305s^2$. The corresponding root mean square error, s , lies between $0.769s$ and $1.142s$. Thus for a computed value of θ_{rmse} , there is a 90% probability that the true value lies between 0.769 and 1.142 times the computed value. For this work this level of confidence on θ_{rmse} is adequate.

Figure 4. Finite element mesh.

Having discussed measures of performance, the details of the finite element⁵ analysis will now be addressed. For this analysis only a quarter of the plate was modeled due to its symmetry. Within that quarter there are four support posts denoted by the "o's" in the finite element mesh plot of Figure 4. These posts are modeled with displacement boundary conditions at points around the perimeter of the plate. The actuators, denoted by the "x's" in Figure 4, are modeled as concentrated forces. The radial location of the actuators was determined computationally in an iterative fashion, minimizing the slope error, θ_{mse} , of Equation 6. The finite element mesh was developed using 992 8-node plate elements. The plate material is aluminum with a thickness of 0.080 inches and a diameter of 36 inches. Because of the relatively large displacements sought (greater than the thickness of the plate) and because the deformation surface is doubly curved, significant stretching of the midplane of the plate is anticipated. Consequently the finite element analysis included geometric nonlinearities.

A contour plot of the transverse displacement of the actuated plate is shown in Figure 5. Although there are some departures from axial symmetry locally in the vicinity of the support posts and at the actuator locations, the displacement pattern for the majority of the plate possesses a high degree of axial symmetry. The plate exhibits buckling behavior in the hoop direction along its circumference wherein the plate bows down between each set of adjacent support posts. In Figure 6 the displacement along a diameter of the plate is plotted as a function of radial position. The pluses on this curve denote a subset of the points used in the slope error computation. The center displacement of the plate is 0.4421 inches. The other curve in this figure represents the parabola that best minimizes the slope error in an rms sense between it and the computed shape. The departure of the computed shape from the parabolic one is due to nonlinear behavior. In Figure 6 this slope error is denoted by the variable, θ_{mse} , of Equation 6, and is substantially lower (0.00112 radians) than the typical value (0.003 radians) used by the solar community in specifying surface accuracy requirements. The focal length for the parabola is 15.49 feet as indicated in the figure. Load and stroke requirements for each actuator are 19.12 lbs. and 0.412 inches, respectively.

An additional finite element computation was completed to investigate an alternate hoop buckling pattern at the plate circumference. Rather than bowing down between each set of adjacent support posts, the plate alternately bows down and then up between consecutive support posts. This pattern was induced by applying small upward transverse loads between support posts where

Figure 5. Contour plot of the transverse displacement.

Figure 6. Plate displacement along a diameter.

upward bowing was sought. A contour plot of the displacements corresponding to this alternate buckling pattern are shown in Figure 7. The new buckling pattern is readily apparent along with a significant degradation of axial symmetry. The center displacement of the plate is 0.4463 inches. In Figure 8 the displacements along a diameter for the alternate buckling pattern are shown. The curves and legends in this figure correspond precisely to those of Figure 6. Note the factor of seven increase in the slope error, θ_{mse} (0.00750 radians), over that for the original buckling pattern. Actuator load and stroke requirements for the alternate buckling pattern are 16.38 lbs. and 0.415 inches respectively.

Figure 7. Contour plot of the transverse displacement, alternate buckle pattern.

Figure 8. Plate displacement along a diameter alternate buckle pattern.

Figure 9. Arrangement of SMA actuators on support system hub and a single actuator close-up.

3. ACTUATOR DESIGN

Two photographs of the SMA torsional actuators are shown in Figure 9, one showing the arrangement of the eight actuators on the hub of the support system and the other, a close-up of one of the actuators. In the former photograph the spokes of the support system are evident with the collector support posts attached near their ends. Each actuator consists of an SMA rod which is clamped at one end and free to rotate in a nylon bushing at the other end. The rod extends past the nylon bushing far enough for a torque arm to be clamped to it. The working region of the SMA rod, which is 4.00 inches long and 0.3 inches in diameter, is wrapped with electrically insulated nichrome heating wire to elevate its temperature for actuation. The working length of the torque arm is 4.05 inches and a screw stop has been incorporated to limit the actuator stroke. The SMA rod material is nitinol with an austenitic start temperature, A_s , of 80 degrees C and a martensitic finish temperature, M_f , of 51 degrees C. Thus A_s is high enough so that normal daily high temperatures will not activate the actuators, and M_f is high enough normal convection heat transfer processes will adequately cool the actuators to their deactivated state.

Figure 10. Measured torque versus temperature and rotation versus temperature for the laboratory constrained recovery test.

Figure 11. Experimental setup for testing the collector/actuator system.

A constrained recovery test was implemented in the laboratory to measure the performance of the actuators. In the test the actuator was set up to drive a torque wrench having a rotational stiffness of 7 in-lbs/degree, which approximates the environment the actuator will see in the solar collector application (e.g., for a 3 inch torque arm with a 7.6 degree rotation, the actuator stroke is 0.4 inches with a corresponding load of 17.2 lbs.). The measured torque versus temperature and rotation versus temperature are shown in Figure 10. As the curves for the torque and rotation represent data taken from separate tests they are not consistent. Note that although the rotation goes to a repeatable value upon activation, it drops to an increasingly negative value with each successive deactivation cycle. This behavior was also observed during the testing of the solar collector wherein the collector plate would tend to bow up after an activation/deactivation cycle. This produced an even greater defocusing effect.

Repeatability test were also conducted on the actuators. Results indicate that there is a rapid degradation in the torque recovery for the first 100 cycles (25%), after which it slows to an asymptotic value of 50% total degradation at 600 cycles. However, even with 50% degradation, the actuators are still capable of supplying the stroke and force required in the solar collector application. Additional details on the actuator design, fabrication and testing can be found in Reference 6.

4. COLLECTOR/ACTUATOR SYSTEM TESTING

The experimental setup used to measure the accuracy of the deflected shape resulting from the activation of the actuators is shown in Figure 11. This test⁷ is based on the fact that for a spherical mirror (or a shallow parabolic one), light rays that emanate from a point at twice the focal length, f , from the mirror on the mirror's axis are reflected back to the same point. Thus the target in the left photograph of Figure 11 is placed at approximately twice the focal length of the collector (shown in the right photograph of Figure 11) and centered on its axis. It is mounted on a track so that measurements can be taken over a small range of distances from the collector. At the center of the target, which is composed of concentric bands of color, is a small circular hole through which light rays pass into a video camera mounted behind the target. The image from the video cam is cropped so that the field of view is restricted to the mirrored surface of the collector.

For an imperfect collector, the image picked up by the video cam will contain various colors from the target. This occurs because small errors in the slope of the mirror will cause a ray emanating from a particular point on the colored surface of the target to be reflected into the hole at the center of the target. The magnitude of this slope error, θ_{err} , is equal to one half the radius, r_{cb} , of the

Figure 12. Experimental results for the collector/actuator system.

color band on the target divided by the distance, d_t ($\sim 2f_l$), the target is from the collector, i.e.,

$$\theta_{err} = \frac{r_{cb}}{2d_t} \quad (11)$$

Thus, the root mean square error, θ_{rmse} , for the slope of the collector can be obtained by taking an area weighted average of the colors in the video cam image, associating a slope error from Equation 11 with each color band in the target. In this area weighted average, areas with colors that are not recognized as target colors are not included in the average. Nonrecognizable colors occur for large slope errors where a ray emanating from the region outside of the target is reflected into the central hole. These large slope errors can be the result of blemishes in the mirrored surface as well as shape irregularities. In addition to θ_{rmse} , the percentage of the image made up of colors from the target is a figure of merit for the collector. The computations associated with these figures of merit are done with software installed in an on-site computer which also receives input from the video cam.

Results from the test are shown in Figure 12. The photograph to the left in this figure is a black and white representation of the color image recorded by the video cam. It is clear from this image that the "alternate buckling" pattern has occurred. During the test efforts were made to force the collector into the more accurate "original buckling pattern" without success. The black indentations near the edge of the image are the result of rays emanating from outside the target that are reflected to the central hole. The curves to the right in Figure 12 show the slope error, θ_{rmse} , and the percent of the target colors in the image as a function of target distance. From Figure 12 the smallest value of the slope error is approximately 3.25 milliradians (at a target distance of 32.2 ft.) which is considered very reasonable for a design prototype. It would probably be more consistent with the predicted value of 7.50 milliradians if the black indentations (areas with large slope errors) were included in the computation. At the same target distance the percent of the target in the image is approximately 75.7% (from Figure 12).

5. CONCLUSIONS AND RECOMMENDATIONS

In this paper the design, analysis and testing of a solar collector which is deformed into its desired shape by torsional SMA actuators is presented. The actuators met and exceeded stringent design specifications of 0.5 inches of stroke at a 20 lb. load. Repeatability testing indicated that although a degradation in performance did occur, after 600 cycles the actuator stabilized with sufficient performance to meet the above specifications. The collector/actuator system prototype, when activated, demonstrated acceptable performance at a focal length of 15 feet for a design prototype. Experimental results were in reasonable agreement with analytical predictions for the "alternate" (longer wavelength, greater slope error) buckling pattern that was observed. The deviations of the actual shape of the collector from the desired parabolic one were slightly greater than typical requirements of the solar energy community.

On the basis of finite element computations described herein the slope error can be reduced by a factor of seven by constraining the collector so that it remains in the "original" (shorter wavelength) buckling pattern. This can be achieved with minor hardware modifications. New ways of reducing parasitic energy losses resulting from heating the actuators must be pursued. This can be accomplished by using SMA materials with lower austenitic start temperatures and/or devising ways of heating the actuator in a more efficient fashion.

The feasibility of using SMA actuators to shape solar collectors to short focal lengths has been demonstrated. As this design evolves there are a number of potential benefits over current practices in the areas of simplicity, economics and maintenance.

6. REFERENCES

1. H. Funakubo, *Shape Memory Alloys*, Gordon and Breach Science Publisher, New York, 1987.
2. J. W. Grossman, R. M. Houser and W. W. Erdman, "Testing of Prototype Facets for the Stretched-Membrane Faceted Dish," *Sandia National Laboratories Report SAND91-2202*, December, 1991.
3. D. W. Lobitz, J. W. Grossman, J. J. Allen, T. M. Rice, C. Liang, and F. M. Davidson, "Shape Control of Solar Collectors Using Shape Memory Alloy Actuators," *Proceedings of the AIAA/ASME Adaptive Structures Forum*, Part 5, pp. 3357-3367, New Orleans, April 1995.
4. K. A. Brownlee, *Statistical Theory and Methodology in Science and Engineering*, Second Edition, pp282-283, John Wiley & Sons, New York, 1965.
5. ABAQUS User Manuals (Version 5.3), Hibbitt, Karlsson & Sorensen Inc., Pawtucket, RI.
6. C. Liang, F. M. Davidson and D. W. Lobitz, "Investigation of Torsional Shape Memory Alloy Actuators," *Proceedings of the SPIE 1996 Symposium on Smart Structures and Materials*, San Diego, February 1996.
7. J. W. Grossman, R. M. Houser and W. W. Erdman, "Testing of the Single Element Stretched-Membrane Dish," *Sandia National Laboratories Report SAND91-2203*, December, 1991.