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Sergey Y. Yurish

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Geometrical Amplification of SMA Actuator Displacement Using Externally Actuated Beam

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Abstract: A major deficiency of shape memory alloy (SMA) actuators is that their displacement is limited. This paper discusses the utilization of deflected flexible beams to amplify the displacement of a SMA actuator. The actuator is composed of a SMA wire fixed eccentrically along a flexible beam dividing it into equally spaced segments. A geometrical model based on the assumption that the geometry of the beam when subjected to bending can be approximated by an arc (part of a circle). The model is built to compute the beam end displacement and deflection upon heating the SMA wire for different number of segments and different eccentricities. The model has been experimentally verified and the results showed that the model is useful to predict the geometrical behavior of the actuator.
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Keywords: Shape memory alloy, Beam, Amplification.

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1. Introduction

Shape memory alloy (SMA) materials have received increasing attention in the development of innovative engineering systems for their dual functionality of sensing and actuating [1]. SMA actuators can attain a high strength to weight ratio, which makes them ideal for miniature application compared with conventional actuators such electrical, hydraulic and pneumatic which have difficulties in generating significant forces when their size and weight are scaled down. Many linear SMA actuators have been developed by researchers [2-11]. However; there are some limitations that need to be overcome while using such actuators.

The main physical limitation that needs to be overcome is the absolute percent strain that SMA's can achieve. The workable strain is usually around 5 percent. Many designs of actuators using SMA depend on mechanically amplifying the displacement either through the use of long straight fibers or through the use of coils [12].

Generally, two types of SMA beam actuators were proposed; internal (or embedded) actuators [13] and external actuators [14] to control the beam characteristics or behaviour upon loading. External actuators have much more control authority because with them differential movement between the actuator and the beam is possible. This differential movement between the actuator results in an additional moment as the beam deflects. External actuators can also be placed at different offset distances from the beam. The moment, caused by the actuation force from the externally line actuator, is much greater than that in a composite beam with an embedded line actuator along the beam and with the same magnitude of the actuation force. Such a configuration also allows the introduction of fast convection cooling [15].

The objective of this research is to amplify the SMA actuator strain (displacement) using externally actuated flexible beams.

2. Materials and Methods

The actuator used in this research is an external actuator for the advantages mentioned before. It was fabricated from a beam (150mm x 15mm x 1mm). The beam was divided into six segments by drilling seven holes throughout its length, 25mm apart. Seven screws drilled laterally were used for fixing the wire eccentrically along the beam (Fig. 1). The wire was electrically insulated from the beam by inserting the screws through nylon insulating spacers (M3 x3).

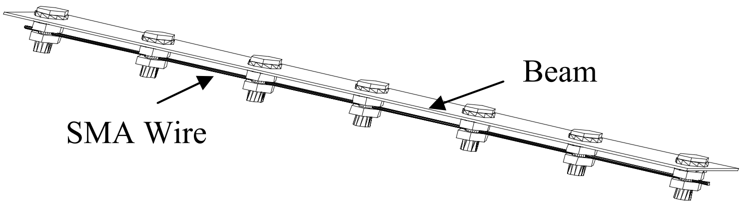
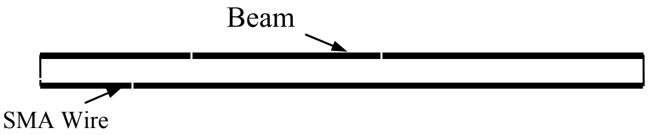
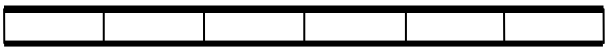


Fig. 1. Shape memory alloy beam actuator.

The experiments were conducted to test the beam deflection and hence the axial displacement. The beam was tested for one, two, three and six segments (Fig. 2). Fig. 3 shows examples of one and two segments configurations upon heating the SMA wire. The hypothesis is that for a higher number of segments a higher deflection and end displacement is obtained upon heating the SMA wire.



(a) one segment



(b) six segments

Fig. 2. SMA beam different configurations.

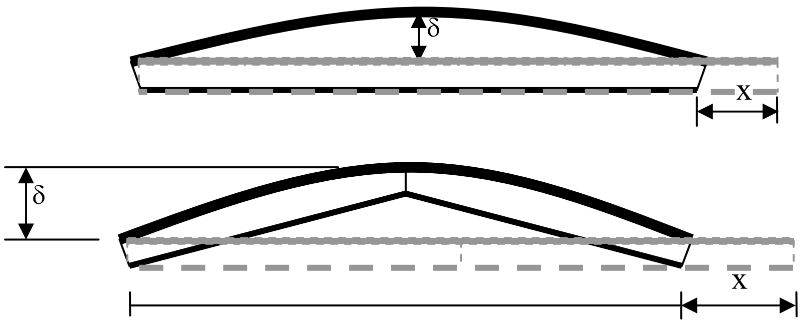


Fig. 3. Performance of externally actuated beam for one and two segments.

3. Mathematical Modeling

A geometrical analysis was first carried out to investigate the deformed shape of a flexible beam caused by an externally-attached SMA wire. The proposed bending actuator configuration originates from that the geometry of the flexible beam when subjected to bending can be approximated by an arc (part of a circle).

The SMA wire provides actuating force to produce bending of the flexible beam. When the wire is heated above austenitic start temperature, the wire will start to contract to its original length, thereby applying an actuation force on the beam. As the actuator is cooled below the martensitic finish temperature, the wire will elongate back approximately to its prestrained length by the virtue of the flexural rigidity of the beam. Heating and cooling the wire results in cyclic contraction and expansion of the actuator.

The first configuration considered is that in which the SMA wire is attached to the ends of the beam. Since the interest is in bending, the wire was attached eccentrically at an offset distance (*a*) (Fig. 4). Before heating the wire:

$$L = m$$

where L and m are the beam length and the SMA wire length, respectively.

After heating the wire:

$$m = L(1 - \varepsilon) \tag{1}$$

where ε is the SMA wire strain.

Since the curved beam was assumed to be part of a circle:

$$L = R\theta \tag{2}$$

where R and θ: are the circle radius and the central angle, respectively.

$$m = 2(R - a)\sin\left[\frac{\theta}{2}\right] \tag{3}$$

Hence the end displacement, *x*, is given by:

$$x = L - m \tag{4}$$

or

$$x = L - 2(R - a)\sin\left[\frac{\theta}{2}\right] \tag{5}$$

Therefore, Solving Eq. 2 and Eq. 3 for a given *L* and *ε*, the end displacement can be found. The beam deflection can be given by:

$$\delta = R\left(1 - \cos\left[\frac{\theta}{2}\right]\right) \tag{6}$$

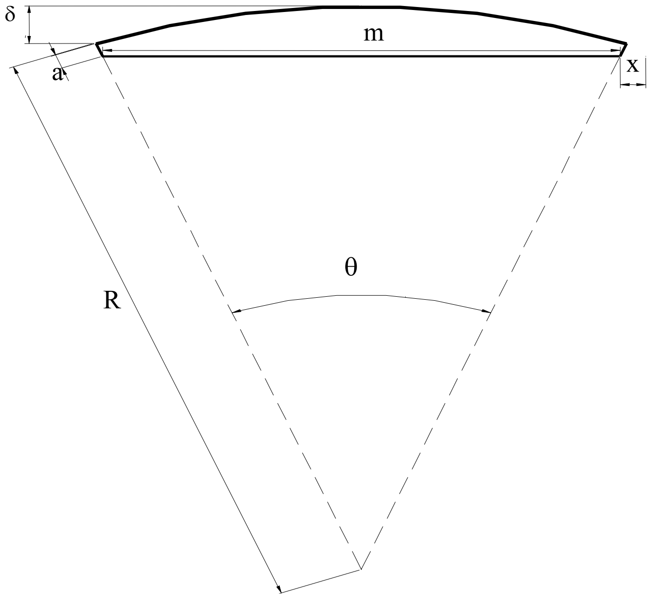


Fig. 4. Deformation of one segment beam.

For two segments (Fig. 5), as observed a new term is included, which is k. Following the same previous procedure (for one segment), the end displacement and the deflection can be found as follows:

After heating the wire

$$m = L(1 - \varepsilon)$$

$$L = R\theta \tag{7}$$

$$m = 4(R - a)\sin\left[\frac{\theta}{4}\right] \tag{8}$$

$$k = 2(R-a)\sin\left[\frac{\theta}{2}\right] \tag{9}$$

$$x = L - k\ , \tag{10}$$

where k is the distance between the beam ends

$$x = L - 2(R-a)\sin\left[\frac{\theta}{2}\right] \tag{11}$$

$$\delta = R\left(1-\cos\left[\frac{\theta}{2}\right]\right) \tag{12}$$

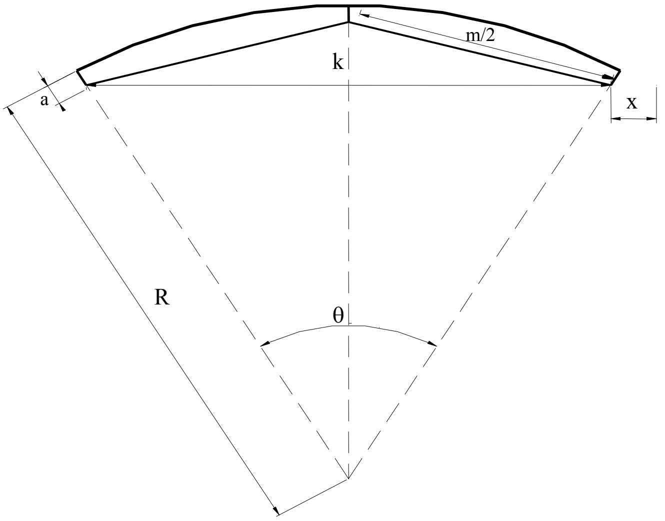


Fig. 5. Deformation of two segments beam.

Generally and for n number of segments the following equations are derived:

$$m = 2n(R-a)\sin\left[\frac{\theta}{2n}\right] \tag{13}$$

$$k = 2(R-a)\sin\left[\frac{\theta}{2}\right] \tag{14}$$

$$x = L - 2(R-a)\sin\left[\frac{\theta}{2}\right] \tag{15}$$

$$\delta = R\left(1-\cos\left[\frac{\theta}{2}\right]\right) \tag{16}$$

3. Result and Discussion

3.1. Simulation

The SMA wire used is of 0.7 mm diameter, and prestrained to a residual strain of 4.8 % (actual displacement is 6.95 mm) so that the wire length is 150 mm. The eccentricity was 5 mm. Due to the nonlinearity of the end displacement and the deflection equations; the simulation was performed using a FORTRAN language. The constant parameters in the simulation were the beam length, the eccentricity and the SMA wire strain. The program was run for different number of segments to obtain the end displacement and the deflection for each segment.

Fig. 6 represents the results obtained using Eq. 15 for the end displacement versus the number of segments. The figure shows that the end displacement increases as the number of segments increase. However, for number of segments higher than 6 the increment is not significant. Fig. 7 represents the results obtained using equation Eq. 16 for the beam deflection versus the number of segments. The figure shows the beam deflection increases as the number of segments increase. However, again for number of segments higher than 6 the increment is not significant. This indicates that the beam of six number of segment is more suitable for the SMA actuator design.

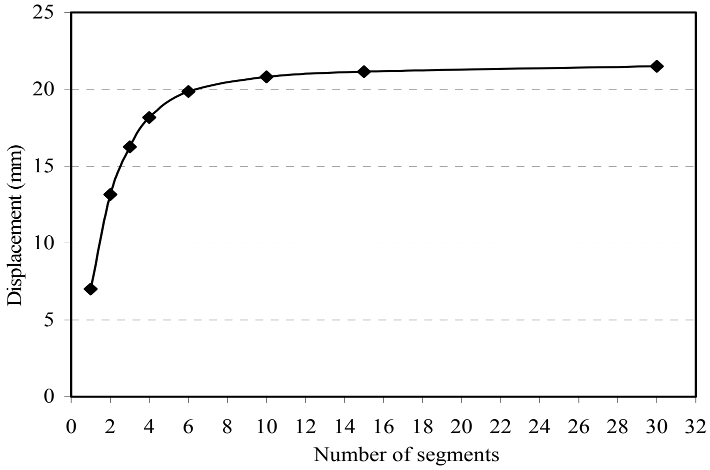


Fig. 6. Analytical results for end displacement at different number of segments.

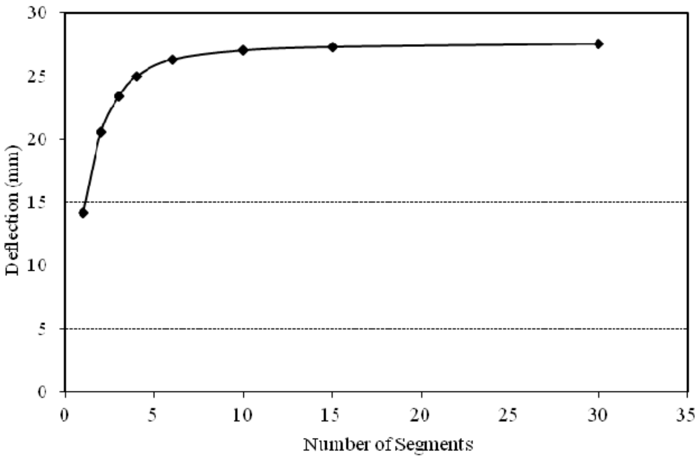


Fig. 7. Analytical results for beam deflection at different number of segments.

3.1. Experimental Results

An experiment was conducted to verify the increase of end displacement and beam deflection when increasing the number of segments. The tests were conducted for 1, 2, 3 and 6 number of segments. The wire was heated above the austenite finish temperature until the whole applied strain is recovered. Table 1 shows the results obtained for 1, 2, 3 and 6 number of segments. The end displacement increases by 100 %, 220 %, 280 % for 2, 3 and 6 number of segments when compared with the displacement obtained by 1 segment. As a result this type of actuators was successfully used as presented by Elwaleed et al. [16,17].

Table 1. Experimental Results for End Displacement and Beam Deflection.

No. of segments	Deflection (δ)	End points distance (k)	End displacement (x)	Increment (%)
1	15	145	5	0
2	21	140	10	100
3	23	134	16	220
6	25	131	19	280

Fig. 8 and 9 represent analytical and experimental results obtained for the end displacement and beam deflection, respectively, versus the number of segments. The experimental results show that there is an increase in both end displacement and deflection with the increase of number of segments. The closeness of the analytical results and experimental results show that the analytical approach in this research provides a useful tool to quantitatively predict the behaviour of the actuator. The discrepancies could be attributed to the geometrical approximations. The accuracy can be improved by using smaller screws to reduce the part of the wire gripped by the nuts and hence increasing the activated wire length.

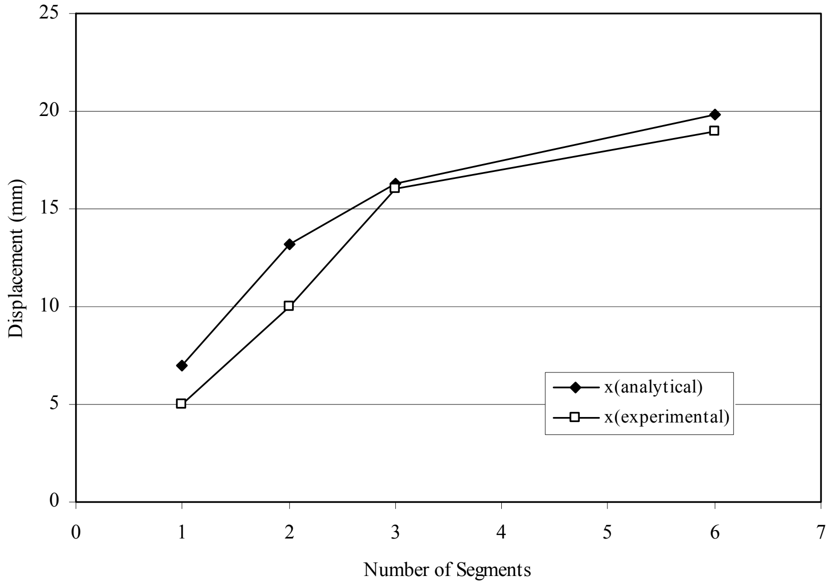


Fig. 8. Analytical and experimental results for end displacement at different number of segments.

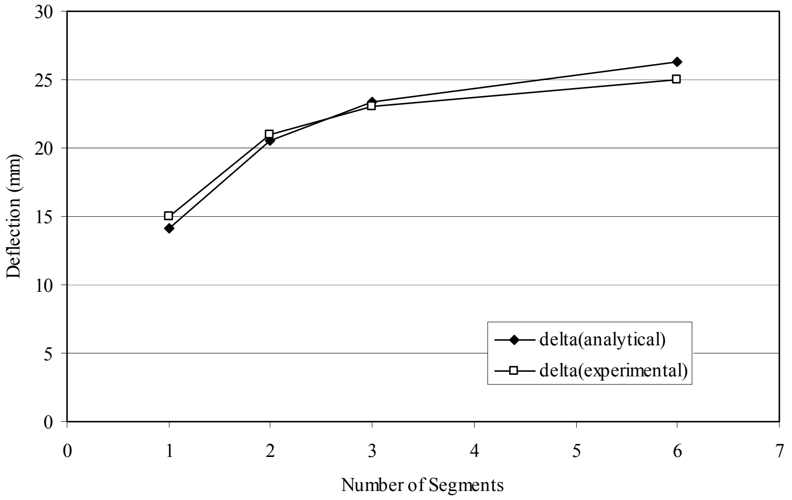


Fig. 9. Analytical and experimental results for beam deflection at different number of segments.

The previous analysis was performed for constant eccentricity (5 mm). However, if the eccentricity is varied this will result in variation of the end displacement and beam deflection. Fig. 10 shows the variation of end displacement with wire contraction for different eccentricities. It is obvious that the increase of eccentricity lead to increase in displacement. The eccentricity is governed by conditions, such as space occupied by the actuator, required moment and beam stiffness. This means the eccentricity also play an effective role in the design.

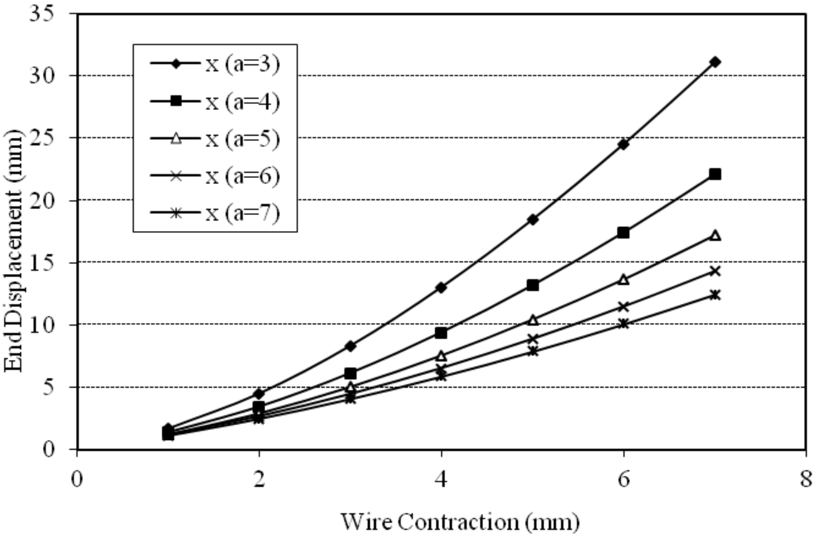


Fig. 10. Variation of displacement with deformation for different eccentricities.

5. Conclusions

The results showed that the geometrical model is useful to predict the geometrical behavior of the externally actuated beam in terms of end displacement and deflection. Both displacement and deflection are increased when increasing the number of segments. An increment of 280 % in end displacement can be obtained six segments. However, it is not beneficial to use actuators with more than six segments due to the insignificant increment of deflection and end displacement.

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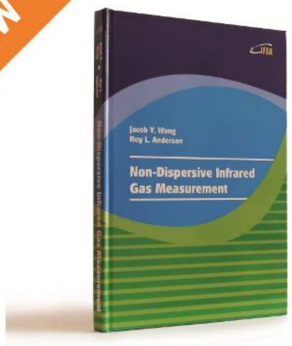

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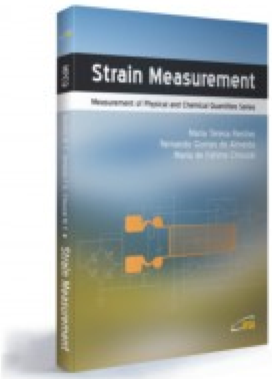

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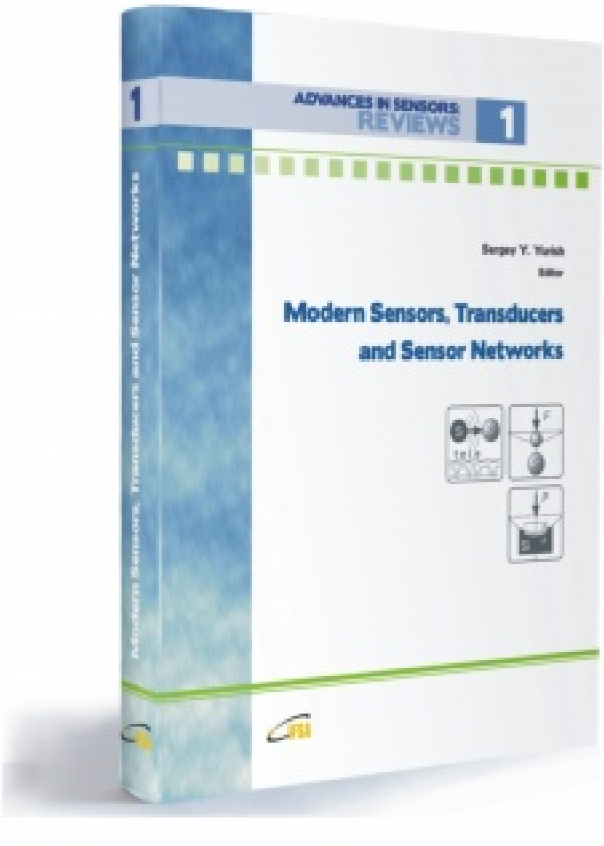

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