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Design and Simulation of a One Degree of Freedom SMA Bundle Actuated Finger

J. DAUDPOTO, Z. ALI, D. M. PATHAN

Department of Mechanical Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan

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Abstract –In this paper a bundled shape memory alloy (SMA) actuator is proposed. A 0.15 mm diameter Nickel Titanium based commercially available actuator known as Flexinol® is used to develop a 12-string bundled actuator. Strain characteristics of the bundled actuator are investigated by using a custom-built test rig equipped with load cell and laser displacement sensor. A set of three bundled actuators in a special configuration is proposed for actuation of a one degree of freedom finger. The proposed finger is made from three phalanges, links and pin supports. This configuration results in six distinct positions of the finger. The simulation of the finger is carried out by using a software package known as Working Model®. The joint angles in various positions of the finger are calculated by using strain data of the bundle.

Keywords: Shape memory Alloy, Bundled actuator, strain, one degree of freedom finger, joint angles.

1. INTRODUCTION

Shape memory alloys undergo change in the microstructure with change of temperature and stress (Otsuka and Wayman 1999). This transformation is accompanied by release of energy. The Nickel-Titanium (Ni-Ti) based SMAs are widely used as actuators because of their better actuation properties and biocompatibility (Van Humbeeck 2001; El Feninat, Laroche *et al.* 2002; Mavroidis 2002). SMA actuators possess two phases, one is a high temperature parent phase (called Austenite) and the other is low temperature phase (called Martensite). The Martensite has a lower Young's Modulus (28 GPa) than that of Austenite (75 GPa) (Gilbertson 2000). Due to this, Martensite can easily be deformed. When alloy is heated above its transformation temperature, the alloy transforms back to its parent high temperature phase (Austenite). This transformation is accompanied by a contraction which can exert very large stresses as high as 600 MPa. The contraction can also be as large as 8 % of the length of the actuator. However, for cyclic applications stress and strain should be confined to 190 MPa and 3-5 % respectively (Dynalloy 2011).

Despite of the fact that SMAs possess very large strength-to-weight ratios, the force developed by a single actuator is limited. For instance, a 0.15 mm diameter actuator can develop only a force of 3.2 N which is based on the safe cyclic stress level of 172 MPa (Gilbertson 2000). To increase the force output of the SMA actuators, the larger diameter actuators can be used. However, this increases the cycle time as large diameter wires take longer to cool off (Dynalloy 2011). For instance, cooling time for a 0.15 mm diameter wire actuator is 2 s, that of 0.3 mm diameter wire actuator is 8 s and for 0.5 mm wire actuator it is 16 s (Gilbertson 2000). To increase force produced by a single wire SMA actuator, bundled actuators have been reported in the literature (Mosley and Mavroidis 2000; DeLaurentis, Fisch *et al.* 2002; Laurentis and Mavroidis 2002; Mavroidis 2002; Ibuki, Maruyama *et al.* 2008). However, the bundles reported in the literature are formed by arranging individual actuators in parallel and crimping or screwing them into two end plates. This arrangement results in the unequal strains of the strings of actuators. In this research a single long actuator is looped around pin supports to overcome this problem.

2. MATERIALS AND METHODS

2.1.1 Actuators

The Nickel-Titanium based SMA actuator manufactured by Dynalloy® Inc., USA under the commercial name of Flexinol® was used to develop the bundled actuator. The diameter of the actuator was 0.15 mm and its transformation temperature was 90 ^{0}C.

2.1.2 Test Rig

An instrumented test rig was designed and developed to investigate the actuation characteristics of the bundled actuator. Test rig was equipped with load cell and laser displacement sensor to set initial tension and measure the length of stroke of the actuator.

++ Corresponding author, Z. ALI, E-mail: engsam68@yahoo.com Ph: +92 (0) 22 277 1382

National Instruments ® data acquisition card was used to record the measurements. **(Fig. 1(a)** shows the instrumented test rig and Fig. 1(b) shows the bundled actuator mounted on the rig.

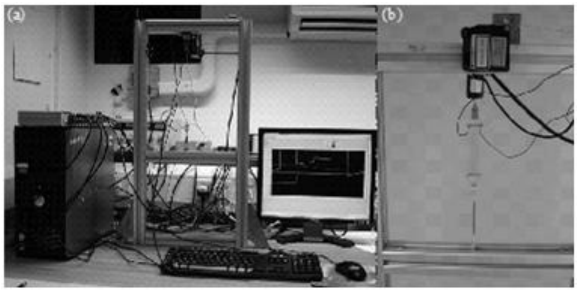

Fig. 1. (a) Instrumented test rig; (b) Bundled actuator mounted on the test rig.

2.2 Bundled actuator

The bundle holder was made from Perspex® sheet 2 mm thick **(see Fig. 2).** A single actuator 960 mm long was passed over pin supports inside the holder. This resulted in a bundled actuator with twelve parallel strings of the actuator. The PTFE coated pin supports were used to provide gliding surface for the actuator.

Two scaled down bundles having actuator lengths of 60 % and 40 % of the full scale bundle were proposed to form a set of three bundles for the actuation of the finger **(see Fig. 3(a) and (b)).**

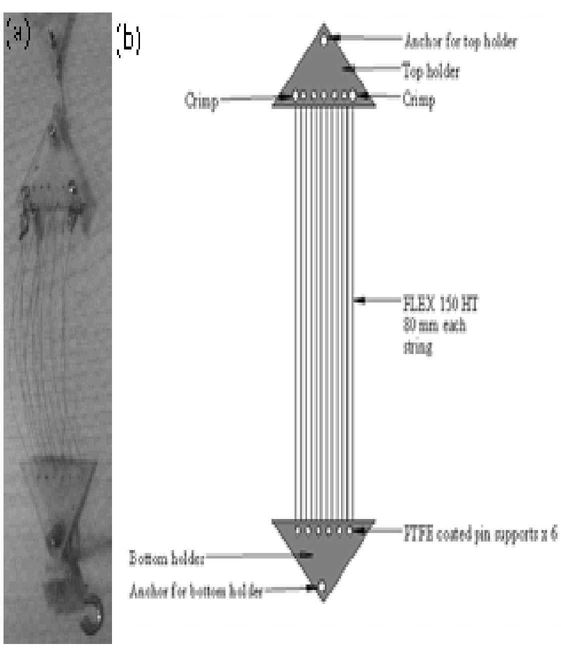

Fig. 2. (a) Full-scale bundled actuator; (b) It's dimensions

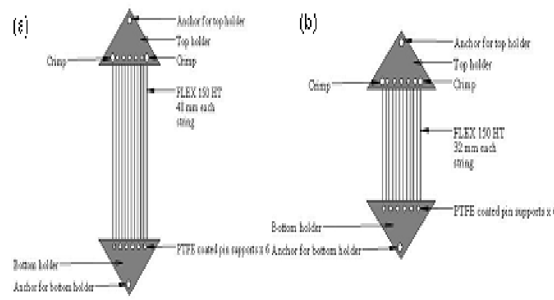

Fig. 3. (a) Bundle with actuator length of 576 mm; (b) Bundle with actuator length of 384 mm

2.4 Test parameters

To determine appropriate level for initial tension, guidelines provided in the datasheet (Dynalloy 2011) were followed. For cyclic applications, a bias stress of 35 MPa is recommended therein.

Using the stress-force relationship,

$$\sigma = F / A \qquad (1)$$

Here:

σ = Stress, MPa,

F = Force, N and

A = Area of cross section, mm^2

Using recommended bias stress as 35 MPa, diameter of actuator as 0.15 mm, the recommended bias force for 12-string bundled actuator can be determined by using Eq. (1).

$$F = 0.618 * 12 = 7.42 \text{ N}$$

The recommended actuation time and actuation current are used for the bundle. A bias spring having spring rate of 0.2 N/mm is used to exert bias force on the bundle. The test parameters are recorded d in **(Table 1).**

Table 1 Test parameters for the bundle

Actuator	Actuatio n time, s	Actuation current, mA	Rate of Bias Spring, N/mm	Initial Tension, N
Flex 150 HT	1	410	0.2	7.42

2.5 Design of Finger

A one degree of freedom finger composed of triangular elements, links and pin joints is proposed **(see Fig.4).** The dimensions of the proposed finger are comparable with the dimensions of author's index finger as recorded in **(Table 2).**

Table 2 Dimensions of index finger

Dimension, mm	Proximal Phalange (PP)	Middle Phalange (MP)	Distal Phalange (DP)
Length	53	25	27
Width	20	16	12
Height	15	15	15

The finger was made of plastic which is a built-in material in the library of the Working Model® software. Design was made in SolidWorks® and then files were exported to Working Model® using dxf import/export function (**Fig.4).**

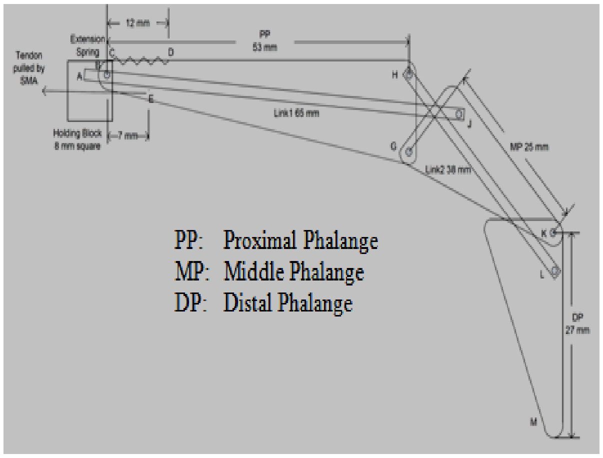

Fig. 4. Proposed one degree of freedom finger in unactuated state

2.6 Bundle arrangement

A set of three bundled actuators is proposed for the actuation of a one degree of freedom finger. The bundles were proposed to be arranged as shown in **(Fig.5).** Bundle 3 is the full scale bundle which is designed, developed and tested using the test rig described in section. Bundles 1 and 2 are the scaled down version of the full scale bundle. The actuation strains of the scaled down bundles are calculated from the strain data of bundle 3. This arrangement resulted in the total strain for the actuation system to be equal to the sum of the strains of the three bundles.

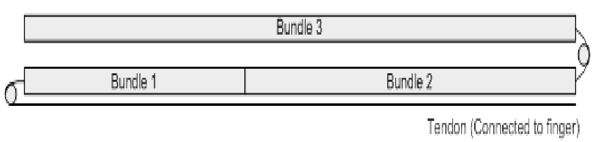

Fig. 5. The arrangement of the proposed three bundles

There were six different possible actuation states of the system depending on which bundled actuators were actuated. The resulting positions are given in **(Table 3)**.

Table 3 Various positions of finger under different actuation states of bundles

Bundled Actuator 1	Bundled Actuator 2	Bundled Actuator 3	Position
Off	Off	Off	0
On	Off	Off	1
Off	On	Off	2
Off	Off	On	3
On	Off	On	4
Off	On	On	5
On	On	On	6

2. RESULTS

3.1 Bundled actuator

The bundled actuator was tested using the test parameters recorded in Table 1. The test rig mentioned above was used to conduct tests. The bundled actuator was loaded for 100 cycles. A cooling time 8 s was allowed in between the actuation cycles so that actuator was completely restored to its austenitic phase. The results of the tests are presented graphically in **(Fig.6)** which shows the heating and cooling pattern for the bundled actuator in the 100th cycle. It can be seen that 1 s actuation time resulted in a strain of approximately 3.45 %. This level of strain fell within the prescribed range of strains (3-5 %) for the Flexinol® actuators (Dynalloy 2011). As soon as power is cut off, the actuator began to relax. This is evidenced by the decrease of strain (see Fig.5). It took 3 s for the actuator to fully restore to its initial position under the action of bias force.

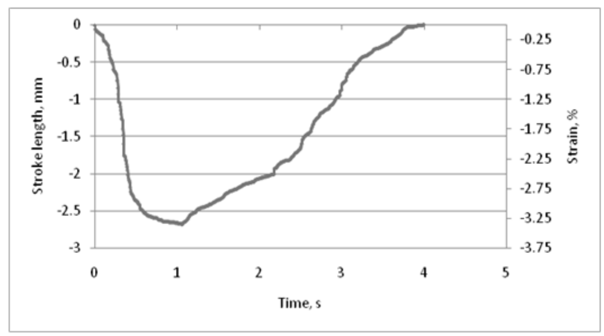

Fig. 6. Heating and cooling pattern of the bundled actuator

3.2 Finger simulations

As noted above, the strain data for the full-scale bundle with 960 mm long actuator was obtained by subjecting the bundle to an actuation current of 410 mA for 1 s. The other two bundles were the scaled down versions of the first bundle. Strain characteristics of three bundles are given in **(Table 4)**.

Table 4. Strain characteristics of bundled actuators

Attribute	Bundled Actuator 1	Bundled Actuator 2	Bundled Actuator 3
No. of strings	12	12	12
Strain, %	3.31	3.31	3.31
Length of stroke, mm	1.06	1.59	2.65

The total length of stroke of the set bundled actuators is determined by using Table 3. These lengths of stroke for various positions are given in **(Table 5).**

Table 5 Lengths of stroke of bundled actuators

Position	Length of stroke, mm
0	0
1	1.06
2	1.59
3	2.65
4	3.71
5	4.24
6	5.3

The orientation of the three phalanges in various positions is recorded in Table 6. The orientation of unactuated phalanges (Position 0) was selected so that it approximately mimicked the human finger at rest. The largest rotation of the phalanges were recorded in position 6, when all three bundled actuators were actuated. In this position the rotations of proximal, middle and distal phalanges were found to be 64^0, 90^0 and 112^0 respectively. These rotations are comparable to phalange rotations of the human finger (An, Chao *et al.* 1979; An, Chao *et al.* 1985).

Table 6. Orientation of phalanges

Position	Orientation of phalanges, Degree		
	Proximal	Middle	Distal
0	0	45	90
1	19.8	67.2	115.8
2	27.4	76.8	127.8
3	40	93	149
4	50.2	109.3	169.9
5	55.2	117.7	180.8
6	64	135	202

3. CONCLUSION

A one degree of freedom anthropomorphic robotic finger comparable in dimensions to that of author's index finger was proposed. Simulations were carried out using a software package known as Working Model® 2D. The finger was actuated by three bundled actuators. The strain data for the full scale bundle were obtained by subjecting the bundle to current and bias force as recommended by the manufacturer. The finger could have six possible positions. These positions were determined by the actuation states of the three bundles. Bias force was applied in the form of extension spring. Rotation of all of the three phalanges was sufficient to carry out most of the functions performed by the human finger.

5. ACKNOWLEDGEMENTS

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