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Design, Development and Characterisation of a Bundled SMA Actuator

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Abstract: Due to small force developed by a single wire shape memory alloy (SMA) actuator, SMAs have found applications mostly in micro and miniature domains. However, to increase force output the bundles of SMA actuators are reported in literature. Existing bundle designs are merely parallel arrangement of individual wire actuators crimped at the ends using end plates. These designs are vulnerable to unequal strains and forces in the individual actuators. In this research, a novel bundle using a single 0.15 mm diameter wire actuator was designed and developed. The wire actuator was looped around Polytetrafluoroethylene (PTFE) coated pin supports to reduce frictional effects. The bundle was subjected to various actuation currents and corresponding strains were recorded. It was found that a 420 mA actuation current resulted in highest strain.

Keywords: Shape memory alloy, Shape memory effect, Bundled actuator, Actuation current.

1. INTRODUCTION

Shape memory alloys possess a property called Shape Memory Effect (SME) that enables them to return to its parent (original) shape when subjected to thermomechanical loading. The strength-to-weight ratio of SMAs is higher than 1000 (Mavroidis 2002). The use of SMA actuators results in many advantages: ease of actuation, choice of heating methods, small size, smooth and slow motion, cleanliness, direct drive, noiseless operation and biocompatibility (Gilbertson 2000). However, the force developed by a single wire actuator is low. For instance, a Flexinol® wire actuator of 0.15 mm diameter can only develop a force of 3.4 N (Dynalloy 2011). This force is not sufficient for macroscopic applications. Due to limited force produced by shape memory alloy actuators, most of the applications of SMAs have been confined to micro and miniature domains. In this paper, a novel bundle made from thin 0.15 mm diameter Flexinol® wire actuator is proposed to increase the force output of SMA actuator. Unlike existing designs, this bundle is not vulnerable to unequal forces in individual strings of the bundle. In section 2, need for the bundling of SMA actuators is explained. In section 3, design of proposed bundled actuator is presented. In section 4, selection of actuator for the bundle is explained. In section 5, results of tests conducted on the bundle are presented. In Section 6 the conclusions of the research are reported.

SMAs possess two phases: the high temperature phase is called Austenite and the low temperature phase is called Martensite. The low temperature phase has a lower Young's Modulus (28 GPa) than that of high temperature phase (75 GPa) (Gilbertson 2000). Due to lower yield point, SMAs in Martensite phase can easily be deformed. When alloy is heated above its transformation temperature, it transforms back to its parent high temperature phase known as Austenite. This phase transformation is accompanied by a contraction which can exert very large stresses as high as 600 MPa. The contraction can be as large as 8 % of the length but for cyclic applications, strain should be limited to 5 % (Dynalloy 2011). The cooling of Austenite results in twinned Martensite. A bias force is to be applied to change the microstructure to detwinned martensite before the alloy is heated again to its original Austenitic phase.

2. MATERIAL AND METHODS

SMA Bundling

Although SMAs possess very high strength-to-weight ratios as compared to the other actuators. However, the force developed by a single wire actuator is not sufficiently high to actuate macro systems. For instance the force produced by a 0.15 mm diameter Flexinol® wire actuator is only 3 N (Dynalloy 2011). This force magnitude is not sufficient for macroscopic applications. For example, the tip force produced by the index finger of human hand is about 45 N (An, Chao et al. 1985). Due to the small force produced by the shape memory alloy actuators, most of the applications of SMAs have been confined to the micro and miniature domains. However, given the outstanding properties like noiseless operation, muscle like motion and direct drive capabilities, some macroscopic applications of SMAs have also been reported (Kyberd, *et al.*, 2001; El Kady, *et al.*, 2010; Okamoto *et al.*, 2012). To increase force output, bundles made from SMA actuators have been reported in the literature. SMA actuator bundles proposed in literature are merely parallel arrangement of

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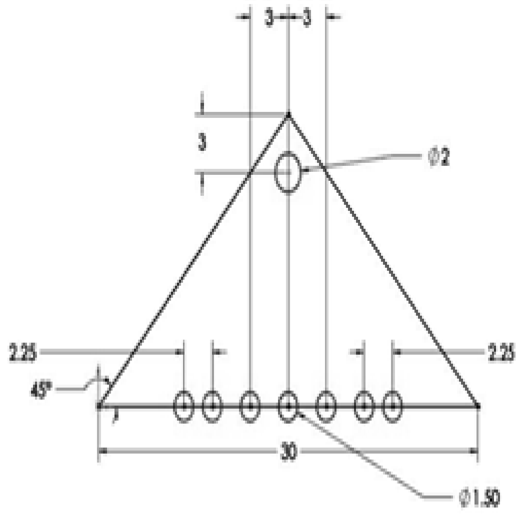
SMA wire actuators. Mosley and Mavroidis (Mosley and Mavroidis 2000) propose a bundle of 48 Nickel Titanium based wire actuators each having a diameter of 0.15 mm. Actuators are crimped to the top and bottom end plates. Each actuator is supplied with power separately. The problem with this arrangement is that each wire may not contract by the same amount. Therefore, this will result in unequal forces in each wire.

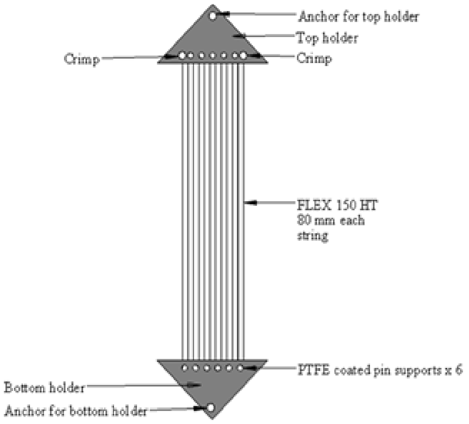
The bundle design proposed by Laurentis et al. (Laurentis and Mavroidis 2002) is composed of actuators of different cross sections. This arrangement can make problem of unequal actuation even worse as wires of different diameters may contract by different amounts. Similar issue of unequal force in individual actuators is also true for the designs proposed by O'Toole et al. (O'Toole, McGrath et al. 2009). The bundled actuator for the Lara Robot (2011) has also same design problem.

3. Proposed Bundle Design

The bundle holder was made from 2 mm thick Perspex® sheet **(see Fig.1 (a)).** The bundled actuator is **(shown in Fig. 1(b)).** Top end and bottom end holders were made of two of these triangular plates to accommodate actuators. A single actuator 960 mm long passed over five pin supports inside the top holder and six pin supports inside the bottom holder. Stainless steel pin 1 mm outside diameter was coated with PTFE tube 2 mm outside diameter. This pin was then cut into 5 mm long pieces which were then inserted between the corresponding holes made in the bundle holders. The pins provided a low friction surface for the actuator to glide over during actuation and relaxation.



(a)



(b)

Fig. 1. (a) Holder of the proposed bundle; (b) SolidWorks® model of the bundle

4. Selection of actuator

The actuators were obtained from Dynalloy® Inc, USA which is one of the leading manufacturers of the conditioned SMA actuators. It was decided to use actuator having diameter of 0.15 mm on the basis of following guidelines provided in the datasheet (Dynalloy 2011).

For actuators having diameters of 0.15 mm or smaller, the actuation current causing actuation in 1 s may be left on the actuator indefinitely without causing overheating. The cooling time for 0.15 mm diameter actuator is 1.7 s as compared to 2.7 s for that of actuator of 0.2 mm diameter.

The actuator is available under the commercial name of Flexinol®. Flexinol® actuators come in two types depending on their transformation temperature. The High Temperature (HT) version has the transformation temperature of 90 ^{0}C whereas the transformation temperature of Low Temperature (LT) version is 70 ^{0}C. The HT version of the actuator was selected because of its smaller cooling time as compared to LT version.

The variation in the diameter of the actuator was found taking 20 measurements of the diameter of a 5 m long actuator at randomly different locations by using a digital micrometer. The results of these measurements are recorded in **(Table 1)**.

5. RESULTS AND DISCUSSION

Tests Conducted on Bundles

A purpose-built test rig was designed and developed to characterise the behaviour of bundled actuators. The test rig was equipped with load cell, laser displacement sensor and thermocouple to set initial tension, measure strain and temperature of the of the actuator respectively. Fig. 2(a) shows the purpose-built test rig and Fig. 2(b) shows the bundled actuator mounted on the test rig.

Table 1. Diameter statistics

Mean, mm	0.1495
Standard Deviation	0.000638
Range, mm	0.002
Minimum, mm	0.148
Maximum, mm	0.15

Fig. 2. (a) Purpose built test rig to characterize SMA bundle; (b) SMA bundle mounted on rig

The test parameters are recorded in **(Table 2)**

Table. 2. Test parameters for the bundle

Actuator	Act. time, s	Act. current, mA	Rate of Bias Spring, N/mm	Initial Tension, N
Flex 150 HT	5	100 - 420	0.2	7.42

Actuation time of 5 s is allowed to fully investigate the behaviour of actuator. The recommended current by the manufacturer is 400 mA [3]. In this set of tests the maximum current supplied to the actuator is limited to 420 mA. An extension spring having a spring rate of 0.2 N/mm was used to provide bias force to actuator.

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

Using the stress-force relationship,

$\sigma = F / A$

Here:

σ = Stress, MPa,

F = Force, N and

A = Area of cross section, mm^2

Inserting, σ = 35 MPa, and A = $\left(\frac{\pi}{4}\right).d^2$, d = 0.15 mm in this equation, for 12 loops of actuator, the bias force shall be:

F = 0.618 * 12 = 7.42 N

Repeated tests using different levels of actuation currents were carried out. Results of this set of tests are presented in Fig. 3. As expected, currents of 200 mA and below did not produce much strain. This It is noted that currents of 400 to 420 mA produced strains of nearly the same order i.e. 3 %.

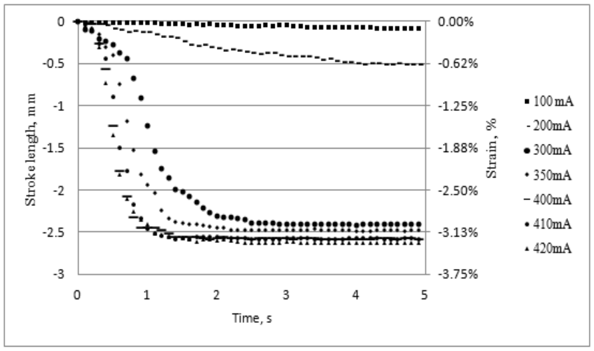


Fig. 3. Results of tests carried out to determine the correct heating current

6. CONCLUSION

SMA actuated bundled actuators reported in the literature are merely a set of individual SMA actuators arranged in parallel which are either crimped or screwed at both terminals. These designs may result in unequal strain and force in each actuator of the bundle using end plates. To eliminate this potential problem, the proposed design is composed of a single SMA wire actuator 960 mm long which loops over PTFE coated pins inside the top and bottom holders. The use of PTFE tubes for the pins was made because of the excellent heat resistant and low friction properties of PTFE.

Tests were conducted on the bundle to determine the right level of current. It is found that actuation current of 420 mA gives the highest strain without overheating of the actuators as overheating would have caused yielding in the actuators. This level of actuation current is very close to the activation current of 410 mA as recommended by the manufacturer.

7. ACKNOWLEDGEMENTS

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