DINAME 2019 - Proceedings of the XVIII International Symposium on Dynamic Problems of Mechanics,
M.A. Savi, T.G. Ritto and W.M. Bessa (Editors), ABCM, Buzios, RJ, Brazil, March 10th to 15th, 2019

Biomimetic thermomechanical cycling of a multi-utility shape memory alloy device

Pedro C. Leal[1], Marcela Cabral-Seanez[1], Jolan Theriault[2], Douglas Altshuler[2], and Darren J. Hartl[1]

[1] Department of Aerospace Engineering, Texas A&M University, College Station, Texas, 77840, darren.hartl@tamu.edu

[2] Department of Zoology, University of British Columbia, Columbia, Canada V6T 1Z4

Abstract: An aircraft wing is a multifarious system composed of numerous specialized subsystems (e.g., ribs, spars, and flaps). An avian musculoskeletal system is similarly multi-utility, performing the tasks of an actuator, a brake, and a spring with variable compliance. Biomimicking these natural systems could yield effective solutions for complex engineering problems. This work proposes the use of shape memory alloy wires subject to electro-thermomechanical stimuli to reproduce the work-loops performed by a humerotriceps of a pigeon. The biomimicked actuation cycles are achieved for temperature-driven (temperature regulated via a thermal chamber) or voltage-driven (Joule heating and natural convection cooling) experiments, leading to responses that are compatible with a range of brake and actuator applications. Consequently, net positive volume-specific work-loops utilizing SMA wire components are demonstrated for the first time using this approach. Furthermore, a numerical model accurately representing the experiment is calibrated and used for further exploring the design domain enabled by the thermomechanically stimulated smart actuators.

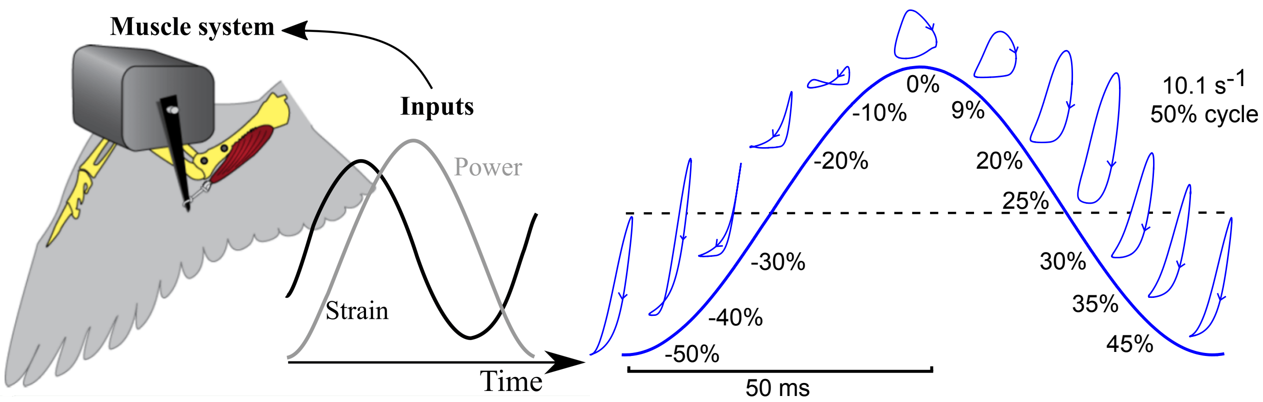
Keywords: Shape Memory Alloys, Thermomechanical Cycling, Pigeon humerotriceps, Avian-inspired, Biomimicry

INTRODUCTION

Since before powered flight was achieved, inventors have explored avian-inspired concepts for motivation and inspiration. Unorthodox designs ranging from flapping wings to the Wright Brother's warping controls were tested (Hagler, 2013). As technology advanced, these concepts were deemed infeasible because of: undesired structural vibrations, adoption of metallic materials such as aluminum as the key structural material instead of wood, and advances in engine technology that allowed higher flight velocities. However, with recent advances in the study of avian physiology (Chin et al., 2017) coupled with the maturity of smart materials analysis and design tools (Lagoudas, 2008), bio-inspired concepts are once again an enticing and relevant option for designers. Herein, a smart actuator is used to mimic the behavior of a pigeon's triceps muscle functioning in the roles of a spring, brake, and actuator based on the timing of the thermal (or electrical) and mechanical stimuli.

Insight into bird wing adaptations for changing flight conditions could lead to aircraft performance improvements. The muscle anatomy of a bird allows active wing shape morphing to tailor performance to atmospheric conditions, e.g., high winds (Swartz, Breuer, and Willis, 2007) and multiple maneuvers, e.g., capturing prey and gliding (Ghose et al, 2006). An important mechanism believed to be responsible for shape change in the wing is the elbow motion driven by two triceps muscles, the humerotriceps and scapulotriceps (Theriault, 2017). Theriault and Altshuler endeavored to study the effects of relative electrical and mechanical cyclical stimuli timings on produced mechanical power in a pigeon humerotriceps as depicted in Fig. 1a. Varying the phase shift between the mechanical and electrical cyclic stimuli altered the net work produced, as shown in Fig. 1b. A positive work cycle, counterclockwise in the stress-strain space, corresponds to the muscle functioning as an actuator. Negative work, clockwise in stress-strain space, equates to a brake. Although not considered explicitly herein, the muscle can also result in zero net work cycles similar to a spring if its stress-strain response is non-hysteretic. Therefore, the humerotriceps can function as a brake, spring, or a spring with variable compliance depending on activation properties.

In a traditional mechanism, actuators, brakes, and structures are distinct subsystems, but for a flying vertebrate, all functions are performed by the musculoskeletal system (Chin et al., 2017). This design gap between natural and engineering systems can be bridged by the use of a smart material known as shape memory alloy (SMA). SMA components, usually formed from nickel and titanium alloys (nitinol), generate and recover large strains and dissipate energy when undergoing phase transformation between austenite and martensite (Lagoudas, 2008). Depending on the initial state and thermomechanical loading, different phenomena can be observed. When not transforming, SMA components are generally linearly elastic. However, if sufficiently mechanically loaded, an initially austenitic nitinol wire will transform toward a microstructural configuration of oriented martensite variants in a macroscopically non-linear, dissipative fashion. This is known as the pseudoelastic effect. A wire in an oriented martensite state can also be heated until it transforms into austenite and recovers large strains under high loads in a non-linear, dissipative manner known as the shape memory effect. SMA actuators generate positive mechanical work given supplied thermal energy (Leal and Savi, 2018), but after cooling the net work-loop is negative because of hysteretic behavior. To the authors' knowledge, this study demonstrates



(a) Experimental setup. (b) Resultant work-loops as a function of phase between inputs.

Figure 1: Influence of strain and power cycles over net work-loops for a pigeon humerotriceps (Theriault, 2017).

positive net work-loops (i.e., in stress-strain space) via a combination of thermal and mechanical cyclic stimuli for the first time. In this way, nitinol wires lead to responses that mimic all the functions of a pigeon's triceps muscle.

EXPERIMENTAL PROCEDURE

To demonstrate that net positive work-loops are achievable, a 0.4 mm diameter nitinol wire obtained from SAES Getters was subject to thermomechanical cycling on an MTS Insight tensile testing machine utilizing the setup depicted in Fig. 2. The experiments performed are here classified as either temperature-driven or voltage-driven. The temperature-driven tests utilized a temperature chamber with the capability of heating and cooling at a specific rate to control the temperature with a desired time history. For the voltage-driven tests, a voltage was directly applied to the wire to increase temperature via Joule heating; cooling is provided via natural convection, which accurately represents application conditions and overcomes speed limitations from the temperature chamber. Two ABS 3D-printed connectors were used to electrically insulate the load frame from current applied to the nitinol wire.

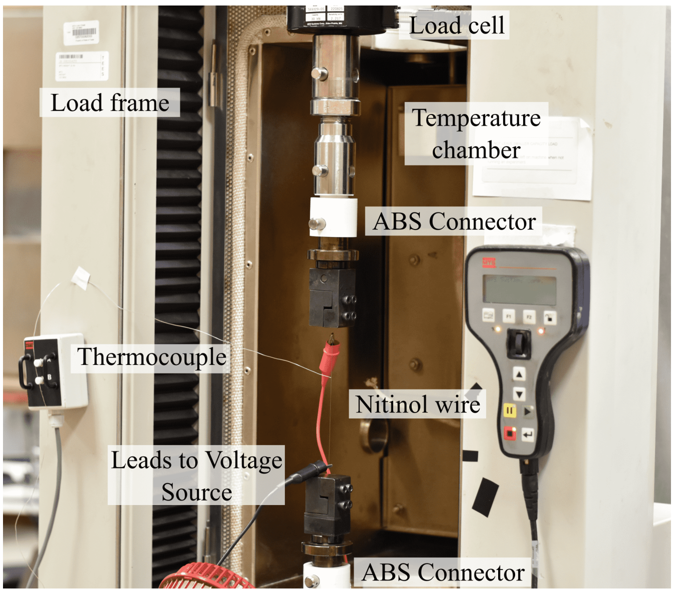


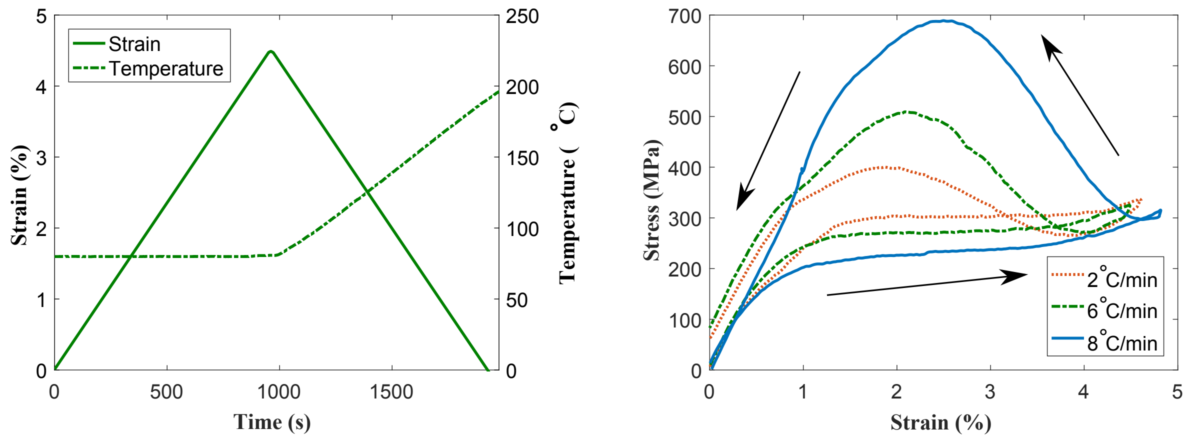
Figure 2: Experimental setup.

As a means to determine the nitinol properties, a characterization process following ASTM E3097 (ASTM, 2017) was carried out. Transformation temperatures, austenite and martensite Young's modulus, and other material characteristics were obtained. Based on these results, thermomechanical cycling tests were performed by initially pre-heating the wire to ensure an initial austenite state. The thermal stimulus for both experiments were 90° out of phase in regards to the mechanical stimulus.

EXPERIMENTAL RESULTS

TEMPERATURE-DRIVEN WORK-LOOPS

Utilizing a thermal chamber, work-loops were evaluated for three different temperature rates (2°C/min, 6°C/min, and 8°C/min) as shown in Fig 5b. Various strain rates were also considered. The first and second tests, 2°C/min and 6°C/min respectively, were strained 0.135 (mm/mm)/min, while the last test, 8°C/min, was strained twice as fast at 0.27 (mm/mm)/min. The results for the temperature-driven work-loops were depicted in Fig. 5. As temperature rate increased the peak stress and the work generated also increased. In increasing order of temperature rate, the generated volume-specific work for each loop was: 197.5 J/m^3, 512.2 J/m^3, and 1138.9 J/m^3. At the highest temperature rate, there are no subloops and all of the work-loop were counterclockwise just as observed in the triceps muscle of a pigeon (Theriault, 2017). These results demonstrate that it is possible to biomimic a pigeon humerotriceps with SMA actuators via the correct combination of mechanical and thermal stimuli, albeit at lower frequencies.



(a) Strain and temperature inputs ($\dot{T}$ = 6 °C/min).

(b) Stress-strain output for three temperature rates.

Figure 3: Experimental temperature-driven work-loop for varying temperature rates.

VOLTAGE-DRIVEN WORK-LOOPS

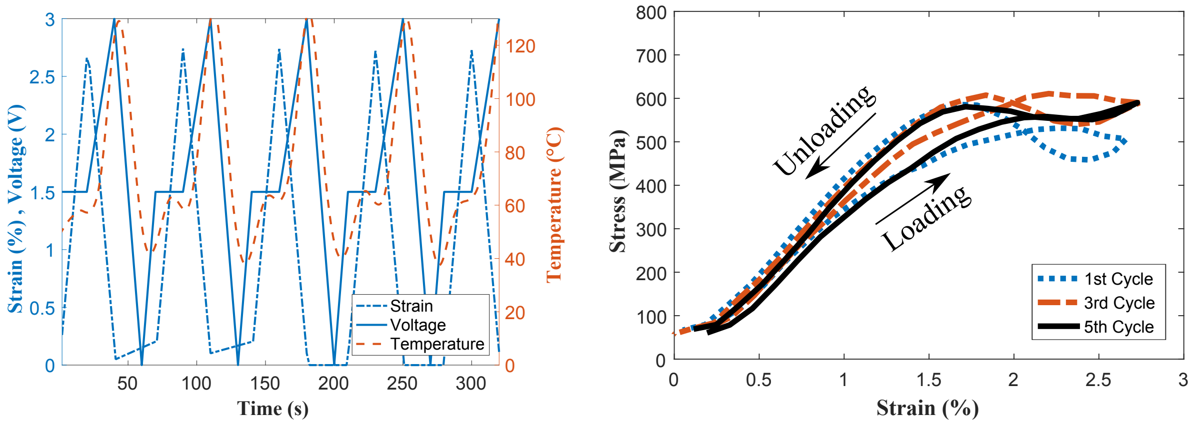
Using the chamber for heating for the temperature-driven tests took on average an hour for each loop (0.00028 Hz); for bird muscles, work-loops are completed in fractions of seconds. Thus, voltage-driven tests were performed, decreasing the run time of each cycle to 70 s with 30 s intervals to naturally cool the specimen (a frequency of 0.011 Hz). The strain and temperature rates were set to 8 (mm/mm)/min and 200°C/min, respectively. The test was performed for a total of five cycles as depicted in Fig. 4. As a consequence of utilizing voltage as an input instead of temperature, there was a delay between the applied voltage cycle and the resultant temperature cycle, and the wire did not return to room temperature during cycling (c.f., Fig. 4a). Positive net work, shown as counterclockwise loops in stress-strain space, was attained at higher actuation frequencies. After each cycle, the loops tended to a solution with equivalent stress as the initial cycle and no subloops (c.f., Fig. 4b). The generated volume-specific work for each cyclic loop as the test continued were: 109.3 J/m^3, 26.8 J/m^3, 40.2 J/m^3, -13.1 J/m^3, and 102.0 J/m^3. These additional preliminary results again indicate that it is possible to reproduce bird muscle behavior at even higher frequencies using SMA actuators.

NUMERICAL RESULTS

A temperature-driven model of an SMA wire (Lagoudas et al., 2012) is utilized to further explore the design domain enabled by the proposed biomimetic concept without the experimental constraints limiting previous results. The material properties used for the model correspond to an SMA wire calibrated in previous work (Leal and Savi, 2018) and the model is taken from (Lagoudas et al., 2012). Thermomechanical stimuli similar to the experiments (c.f., Fig. 5a) are used with a maximum strain of 4.6 % and initial temperature equal to 28 °C. Increasing temperature rate to strain rate ratio r leads to varying work-loops comparable to those of a humerotriceps muscle. Analogous to experimental results, temperature rate increase leads to work-loops with more generated work, eventually resulting in fully counterclockwise (i.e., fully positive) work-loops.

CONCLUSIONS

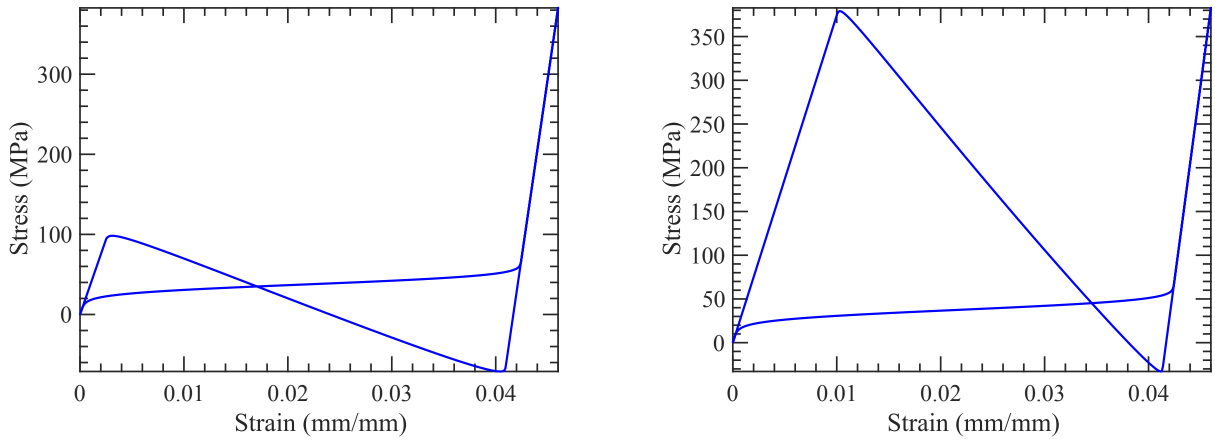
A new biomimetic concept utilizing SMA wires has been explored and verified. Through the combination of different thermal and mechanical stimuli, diverse work-loops have been obtained which represent the following functionalities during cyclic loading: a spring (zero net work), a brake (negative net work), and, for the first time, an actuator (positive



(a) Input stimuli and measured temperature.

(b) Stress-strain output (work-loops).

Figure 4: Voltage-driven work-loops done at a strain rate of 8 (mm/mm)/min and temperature rate of 200 °C/min.



(a) r = 1453 °C/(mm)/(mm).

(b) r = 2758 °C/(mm)/(mm).

Figure 5: Numerical temperature-driven work-loop for varying temperature rates.

net work). Current efforts are directed towards demonstrating a calibrated numerical model to further explore the design domain empowered by this novel idea and how to explore this phenomenon for aerospace and biological studies.

REFERENCES

Hagler, G., 2013, “Modeling ships and space craft: the science and art of mastering the oceans and sky”, Ed. Springer.

Chin, D.D., Matloff, L.Y., Stowers, A.K. and Tucci, E.R. and Lentink, D., 2017, “Inspiration for wing design: how forelimb specialization enables active flight in modern vertebrates”, Journal of The Royal Society Interface, Vol.14, No. 131, pp. 20170240.

Lagoudas, D., 2008, “Shape memory alloys: modeling and engineering applications”, Ed. Springer.

Swartz, S.M., Breuer, K.S., and Willis, D.J., 2007, “Aeromechanics in aeroecology: flight biology in the aerosphere”, Integrative and Comparative Biology, Vol.48, No.1, pp.85-98.

Ghose, K., Horiuchi, T.K., Krishnaprasad, P.S., and Moss, C.F., 2006, “Echolocating Bats Use a Nearly Time-Optimal Strategy to Intercept Prey”, Vol.4, No.5, pp. e108.

Theriault, J., ‘Work loop dynamics of the pigeon (Columba livia) humerotriceps and its potential role for active wing morphing”, Master’s thesis, University of British Columbia.

Leal, P.B.C., and Savi, M.A., 2018, “Shape memory alloy-based mechanism for aeronautical application: Theory, optimization and experiment”, Aerospace Science and Technology, vol.76, No. 5, pp. 155-163.

ASTM, “Standard Test Method for Mechanical Uniaxial Constant Force Thermal Cycling of Shape Memory Alloys (E3097)”, 2017.

RESPONSIBILITY NOTICE

The authors are the only responsible for the material included in this paper.