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Mono- and bi-stable planar actuators for stiffness control driven by shape memory alloys

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ABSTRACT

This contribution compares two novel smart, planar actuators driven by shape memory alloys (SMAs) with regard to their potentials and limitations. The principle set-ups, mathematical models and experimental results are described. Both actuators are supposed to control the flexural stiffness in multi-layered beams with variable stiffness. One uses trained SMA wires and buckling springs and possesses one stable active state. The other one uses spiral SMA springs and a bi-stable mechanism to generate two stable, active states.

1. Introduction

For several decades, there have been great efforts to develop smart, self-sensing and -controlling materials which can adapt their material properties upon changing environmental conditions, e.g. [1–4]. In modern light-weight constructions, components, such as aircraft wings and wind turbine blades, are exposed to bending loads, which result in static or dynamic deformation. Common materials, possessing constant mechanical properties, sustain constant resulting deformations and eigenfrequencies. Therefore, such materials cannot adapt their mechanical behavior in changing environmental conditions. An advantageous approach would be to develop composite materials which can change their bending stiffness and, therefore, also their bending-eigenfrequencies within a wide range.

The range of application of such structures with adjustable bending stiffness is wide. Especially, in compliant and soft robotics an application is possible, to enable contemporaneously large deformations while simultaneously allowing rigid interaction with the environment. Also tunable machine mounts or smart structures for seismic control for suppressing oscillation transmitting could be an application [5]. Furthermore, bio-medical engineering could be one of the largest fields of application [6]. Basically the application of structures with adjustable inter-layer slip is very general and, hence, a field worth studying deeply.

There are already several studies which deal with changing properties of mechanical structures. In principle, there are two possible ways to influence the bending stiffness of a flexural beam-structure. One possibility is to directly change the Young's modulus Y by warming and cooling of polymer materials (e.g. [7–11]). The other one is to control the internal structure of composite materials and, therefore, their area moment of inertia I, (e.g. [12]). Adjusting the area moment of inertia can change the flexural stiffness of composite beams by more then one order of magnitude using multi-layered composite beams [13]. To switch between several stiffness states it is necessary to adjust the sliding behavior between the independent layers. This can be achieved either by friction [13] or by form closure [14,15]. Form-closure is more reliable and can take higher amounts of bending moments, but needs so-called form-closure actuators to switch. The main design purpose of the actuators was a maximum elongation to reliably control the bending stiffness of a multi-layered structure. Due to the fact demonstrators were designed with large diameter SMA wires which results in a very low maximum switching frequency of $f_{max} \approx 0.05$ Hz.

2. Buckling mechanisms to enhance actuator performance

To enhance the actuation performance of active materials in composite structures it is advantageous to use elastic columns in their post-buckled compression state. Those actuators were

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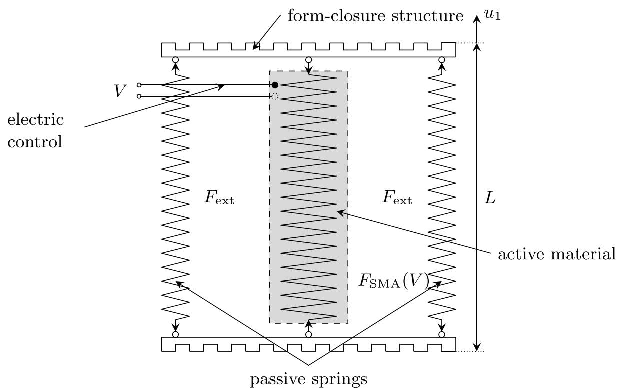

Fig. 1. Schematic set-up of a SMA-driven form-closure actuator, u_1 – elongation, L – actuator length, V – electric control (voltage), F_{ext} – external spring force, $F_{\mathrm{SMA}}(V)$ – force of SMA unit.

described by Vos et al. [16], to enhance the actuation capabilities of piezoelectric bending actuators for flight control. An actuator stroke of 300% was shown. The application of piezoelectric actuators can cause problems with tensile failure on convex phases. Therefore, the application of SMA actuators in Post-Buckled Precompressed (PBP) plates were suggested by Sinn et al. [17]. As well as treating tensile failure, the energy consumption of the SMA will also be reduced [18].

SMA actuators have one disadvantage to other actuators: they are very energy consuming, because a steady electrical current is needed to actuate them. To reduce the energy consumption the use of bi-stable mechanisms with snap through effect was suggested and described by Schultz [19]. All those actuators are designed to control an airfoil structure and, hence, are optimized for exact control. However, the application of the actuators presented here is mechanical switching in a multi-layer structure. Therefore, the design aim is maximum reliable actuation between two positions and stroke control between these positions is not necessary. That reduces the effort of external control to a minimum of only constant current supply.

3. Set up of form-closure actuators

Form-closure actuators can suppress the sliding between independent beam layers. Therefore, it is necessary to generate large elongations to transfer shear stresses between the beam layers, when the beam-structure is bent. Furthermore, the actuators have to be as flat as possible, because they are ordered between the layers. To fit both requirements the actuators have to be driven by materials with high energy density and large elongations, such as electroactive polymers (EAPs) [20] and shape memory alloys (SMAs) [21], respectively. Because SMAs possess higher energy density and sufficient elongation, SMA-driven actuators were chosen to control the bending stiffness.

SMAs are able to generate actuation by switching between two different crystalline configurations which depend on the temperature. Due to its electric conductivity, it is possible to control the elongation by electrical current and voltage. Fig. 1 depicts the fundamental set-up of SMA form-closure actuators. The actuator consists of rigid form-closure structures, active material and passive springs. The springs pre-strain the SMA by applying an external force F_{ext} which is in equilibrium with the SMA's force $F_{\mathrm{SMA}}(V)$. By applying electrical voltage V this equilibrium can be changed and the actuator will elongate or shorten, respectively. Therefore, the elongation u_1 can be controlled by the applied voltage.

4. Mono-stable planar SMA actuators

A first actuator design possesses one passive and one stable activated elongation state. It is driven by 0.2 mm diameter SmatFlex SMA wires (SAES getters). SmartFlex wires consist of a nickel titanium alloy (54.8% Ni, 45.3% Ti) and are trained to shorten their length L by 3–5% when their temperature exceeds ca. 95 °C [22]. Fig. 2 depicts the set-up of such an actuator. It comprises two independent rigid actuator frame parts, which are manufactured by selective laser sintering (material: EOS PA 3200 GF). Three SMA wires are mounted in the actuator frames. They are electrically connected in series and mechanically in parallel. Electrical connection between the wires is enabled by silver conductive paint, which was manually painted by a brush. The external force is generated by four buckling springs, which act according to the fourth EULER-case. The actuator has a total thickness of t = 2.5mm. In Fig. 2a the actuator is in its passive state, where no electric voltage is applied to the wires. Therefore, the SMA wires are fully elongated and have their initial length l_0. The buckling springs are not buckled and hold both frame parts in this initial, stable position. Fig. 2b shows the same actuator, when electrical voltage is applied to the SMA wires and the activation temperature T_{act} is reached. The SMA wires shorten and exceed the critical force F_{crit}, which is necessary to buckle the buckling beams. The number of pre-straining buckling springs and SMA wires is chosen in such a way, that the force F_{SMA} generated by the SMA wires is high enough to reliable buckle the springs.

4.1. Actuator model

To enable a sufficient actuation, the total force generated by the SMA-wires has to overcome the total critical force F_{spr} of the four buckling springs:

$$3F_{\mathrm{SMA}} > 4F_{\mathrm{spr}}. \tag{1}$$

Therefore, the critical force of one buckling spring has to be:

$$F_{\mathrm{spr}}(u) < \frac{3}{4}F_{\mathrm{SMA}}. \tag{2}$$

The maximum force generated by one SMA-wire is given by the manufacturer as $F_{\mathrm{SMA}}^{\mathrm{max}} = 19\,\mathrm{N}$. The suggested operation force is given as $F_{\mathrm{SMA}}^{\mathrm{opr}} = 5\,\mathrm{N}$, to ensure long-time stability and life time. Applying to large external forces can lead to a reduction of lifetime down to only several thousand cycles [23] and affect the activation temperature [24]. Whereas a suitable stress levels enable long lifetime up to several million cycles [25]. All four buckling springs are clamped, i.e. they are in the fourth EULER-case. The critical force yields [26]:

$$F_{\mathrm{crit}} = \frac{\pi^2 YI}{(0.5l)^2}, \tag{3}$$

with the YOUNG's modulus Y, the area moment of inertia I and the length of the buckling spring l. Starting from the term for the critical force, it is possible to determine force deformation characteristics,

$$k(u_1) = \frac{F}{l - x_1(s = l)} = \frac{F}{u_1}, \quad \forall F > F_{\mathrm{crit}}. \tag{4}$$

The spring stiffness $k(u_1)$ in Eq. (4) depends on the deflection u_1 along the initial spring axis and will be derived in the next steps. Due to the fixed ends of the buckling springs, deflections are only allowed along the spring axis with the overcritical force $F > F_{\mathrm{crit}}$, the initial length l of the buckling spring, the x_1-position $x_1(s = l)$ of the force application point and s the coordinate along the buckled spring. Fig. 3 depicts the mathematical model of such a buckled beam. An introduction to the calculations needed to solve Eq. (4) is given in [27,28]. Using a moment equilibrium at the buckled beam a