A Preliminary Investigation of Temperature Dependency of a Shape Memory Actuator with Time-Based Control in Aircraft Interiors

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Abstract. Shape memory alloys (SMA) possess an array of unique functional properties which are influenced by a complex interaction of different factors. Due to thermal sensitivity, slight changes in the environmental temperature may cause the properties to change significantly. This poses a huge challenge especially for the use of SMAs as actuators. The most common and elementary activation strategy of SMA actuators is based on the duration of activation and cooling with constant activation parameters. However, changing environmental influences cause the necessity to modify these parameters. This circumstance needs to be especially considered in the design process of actuator controls. This paper focuses on investigating the influence of environmental temperature changes on time-based activated SMA actuators. The results of the described experiments form the base for designing reactive control strategies for SMA actuators used in alternating environments. An example for application fields with changing environments and particularly changing temperatures are aircraft related implementations. This area also stands to benefit from the actuators’ advantages in ecological efficiency.

1. Introduction
Actuators which are based on functional materials might lead to significant progress in fields with mainly conservative technologies. These fields benefit highly from the advantages offered by unconventional actuators. Examples for these innovative technologies are actuators based on shape memory alloys (SMA). These SMA actuators provide some major benefits because of their high energy density and the resulting possibilities in lightweight construction and miniaturization. An application field which can strongly profit from these benefits is aviation. Especially in civil aviation, aircraft weight and ecological efficiency are becoming more and more important [1]. The area of aircraft interiors offers many possible applications suitable for SMA actuators. There are many conventional systems used in comfort and safety applications that can be substituted and improved by innovative SMA actuators because of their unique properties. Beyond that, there are numerous possibilities of implementing SMA actuators in new applications which are only feasible because of this functional material’s advantages such as compact design, silent actuation or energy efficiency. However, there are only few established applications of SMA actuators in aircraft industry. In order to use this untapped potential, the research project FLAAI (“Shape Memory Lightweight Actuators for Applications in Aircraft Interiors”) of the Ruhr-University of Bochum is investigating the applicability of SMA actuators in the interiors of civil aircrafts. Systems in this application field require, amongst others, different ranges of environmental temperatures and temperature alterations which may not have any influence on the functionality of the actuators. As SMAs are a thermally sensitive material, their properties have an especially high interdependence on temperature variations. For this reason, the
authors have investigated the properties of SMA actuators regarding the environmental temperature requirements in cabins of civil aircrafts using the example of an antagonistic actuator with a time-based control.

2. Shape Memory Alloys and Actuators

2.1. Shape Memory Alloys (SMA)
SMAs are functional materials which can remember a previously defined shape by thermal activation and also show high elastic properties. These effects are based on a reversible, diffusionless transition between the low temperature phase (martensite) and the high temperature phase (austenite). The thermal effect can be described as the one-way effect that shows shape recovery during heating as well as the two-way effect that is characterized by an additional shape modification during cooling. The shape recovery can be triggered by the intrinsic effect or external loads. These effects make SMAs suitable for a variety of actuator applications [2].

Generally, SMA actuators are based on the extrinsic two-way effect due to its higher amount of technical parameters as force and displacement [3]. When these actuators are activated electrically, the change in temperature is caused by joule heating [4, 5]. The most important electrical parameters for SMA performance concerning force, displacement and fatigue are the current, voltage and activation time [6].

The resetting of the actuator position can be realized by different technical principles (illustrated in fig. 1). The three common ones are a constant mass, a return spring or an antagonistic SMA element, which is subject to an opposed activation strategy [7, 2].

![Figure 1. Three principles for resetting an SMA element, a) weight force, b) return spring, c) another SMA wire (agonist-antagonist-principle), based on Kohl [7].](image)

2.2. SMA Actuators in Aircraft Interior Systems

The Fraunhofer institute for machine tools and forming technology developed an unlocking mechanism based on SMAs for small oxygen masks (see fig. 2) [8]. Nowadays, these masks are electrically released by a solenoid. For functionality or safety checks, a manual release mechanism is designated [9]. Replacing the solenoid by an SMA actuator, it has been possible to reduce the weight of the system by half [9]. Further constructive measures have lowered the weight down to 66% compared to the conventional actuator. In addition, the power consumption has been reduced to 34% and the number of system parts has fallen from 27 to 18, which is a reduction of 67% [10].

Other products, for which SMA actuators can be used, are the backrest adjustment and the extension of seating areas in aircrafts (see fig. 3). In order to use less powerful SMA actuators instead of electric motors, the passenger weight is used to reduce the required actuator force.

For extending the seating or lying area, a pivotal expansion element (2) can be folded out. This is done by a tubular SMA actuator (3) and a surface element (4) which is loaded by the passenger’s weight (1) and thus supports the SMA actuator. Furthermore, there is a locking mechanism (5) to hold the
expansion element in the desired position. It consists of a catch which is unlocked by an SMA wire actuator.
When a passenger is sitting on the seat, the backrest is pre-tensioned in vertical direction by a flexible joint (7) and an element (7) within the backrest. The flexible joint (7) has the possibility to store energy. If an angular adjustment of the backrest is desired, the backrest is pressed into a flat position by the weight of the passenger (1). This further increases the preload on the flexible, elastic joint (7). Only a small force is required to bring the back into the upright position. This movement is realized by an SMA wire [11].

Figure 2. SMA based unlocking actuator for oxygen masks, developed by Fraunhofer IWU, based on Eppler [10].

Figure 3. Schematic illustration of the SMA based seat adjustment systems, based on Lawall et al. [12].

3. Temperature requirements for electronic devices in aircraft interiors
To enhance the operation field of an actuator, it is necessary to consider the temperature requirements of category D1 of the RTCA (Radio Technical Commission for Aeronautics) directive DO-160D. The temperature range in operation is between -20°C to +55°C and the temperature maxima between -55°C to +70°C (see table 1). If an actuator fulfills these requirements, it can be used in an air-conditioned but not pressure-controlled system in the aircraft at a flight altitude of up to 15,200 m. In this case, actuators can be easily used in commercial aircrafts since the maximum flight altitude is 13,100 m according to this directive.
Furthermore, the temperature change is limited to 2°C per minute, since the actuator is located in the temperature-regulated aircraft interior. Therefore, only category C of the RTCA DO-160D has to be fulfilled instead of category A with 10°C per min [13, 14].
4. Material and methods

4.1. Experimental Procedure

The experimental procedure contains the following steps: First, it is necessary to experimentally determine the parameters for the time-based control for the current supply at room temperature. Preliminary studies as described below are needed to provide a basis for the main experiment. The main experiment investigates temperature influences on the activation behavior and thus on the reliable functionality of a time-based controlled SMA actuator.

4.2. Preliminary Studies

Thanks to its availability and simple programming language, the programmable logic control type LOGO! by Siemens AG is used as control unit. The first step is to determine the activation and cooling times. Due to their dependency on parameters like wire length, wire diameter, applied electrical voltage and load on the wire, the activation and cooling times have to be identified on an experimental setup as is illustrated on figure 4.

Figure 4. Schematic experimental setup for the determining of the activation and cooling time parameters.

For this experiment, a wire specimen of 100 mm in length and 0.3 mm in diameter is clamped and loaded with a constant mass of 1,080 g which corresponds to a wire tension of 150 N/mm². As specimen material, SmartFlex 90 wires by SAES Getters are used for all tests that are described in this paper. The mounted wire specimen is activated by means of a current source type EA-PS 3016-20 B, by Elektro-Automatik. The displacement of the SMA wire is detected by the ultrasonic position sensor, type CH-8501 DADM by Baumer Holding AG. The data of the displacement sensor as well as the applied voltage and current are transmitted via a MGC Plus measuring amplifier, by Hottinger Baldwin Messtechnik GmbH (HBM), to a measuring computer. The measurement software Catman Easy AP by HBM processes the data for the visualization and output. Five wire specimens with different activation and cooling times are tested in parallel. One activation cycle contains a heating and a cooling phase. The heating times are equidistant from 0.8 to 1.4 s. A voltage value of 2.4 V is set according to the SMA characteristic current course [15, 16]. Figure 5 shows the intervals at which current is applied to a specimen as well as the displacement curves of each specimen.
According to the applied voltage and the resistance change due to the phase transformation from martensite to austenite, the current value is within the range of 1,600 to 2,000 mA as can be seen in figure 5. Ideally, the current course should end at the zenith to avoid overheating of the SMA wire. Figure 5 shows also the displacement courses of the specimens, while the specimens 3 and 4 provide the best results regarding a displacement of 3.5 %, which complies with the manufacturer specifications [17]. For the control program, 1.3 s as the activation time and 7.5 s as the minimum cooling time are determined, which corresponds approximately to the values of specimen number 4. Table 2 shows the determined parameters for the time-based control.

### Table 2. applied parameters for the time-based control.

| specimen no. | voltage [V] | activation time [s] | cooling time [s] |
|--------------|-------------|---------------------|-----------------|
| 4            | 2.4         | 1.3                 | 7.5             |

4.3. **Experimental Setup and Material**

The SMA actuator (see fig. 6) is based on an antagonistic principle with two SMA wires that can be activated alternatingly to switch between two actuator positions. Each of these end positions, retracted or extended, are held by a mechanical locking device. The actuating displacement is approx. 7 mm at room temperature.

The temperature influences on the functionality of the SMA actuator with time-based control are investigated on an experimental setup as shown schematically in figure 7. The SMA actuator is mounted inside a climate chamber, type SU-221, by ESPEC CORP. Two current sources, type TOE 8805, by TOELLNER Electronic Instrumente GmbH, are used to activate each of the SMA wires of the actuator. To measure the actuator position, a laser displacement sensor, type OADM 12U6460/S35A by Baumer Holding AG is used. An anchor plate, which reflects the laser beam, is attached to a linear guidance shaft. This shaft is mounted in an air-bearing to minimize the friction loss that would influence the measurement results. A ball joint connects the actuator with the shaft in order to avoid torsional moments on the linear shift. Measured values are the actual temperature inside the climate chamber and the displacement position of the SMA actuator. All these values are sent to the measuring computer for data processing via the measuring amplifier, type MX840A by HBM. The temperature of the climate chamber is controlled by the PChamber software.
5. Results

5.1. Temperature Influence

This experiment investigates the temperature dependence of the functionality of an antagonistic SMA actuator which is activated by a time-based control. The applied temperature range from -20°C up to +70°C complies with the maximum operating temperatures for aircraft interior actuators further tests can be made if a reliable functionality of the actuator in an operating temperature range from -20°C to +55°C is fulfilled. The detailed test procedure is conducted according to the directive RTCA DO-160 (see above).

The two diagrams (see fig. 8 and fig. 9) show the displacement of the antagonistic SMA actuator exposed to defined environmental temperature variations as a function of time. Due to the time-based control, the time intervals between each activation cycle are the same.

The left diagram illustrates the influence of a decreasing temperature profile on the reliable functionality of the SMA actuator. At a temperature of about 3.5°C, the first malfunction can be detected. The actuator fails to switch to the displacement from about +7 mm to -1 mm. After one complete switching cycle of the actuator, it fails completely in the further course of the test at environmental temperatures of about 2.5°C.

The right diagram shows the influence of an increasing temperature profile up to 70°C on the functionality of the actuator. It can be seen that the absolute displacement is reduced from approx. 7 mm at room temperature to less than 4 mm at 70°C. Generally, the actuator is still switching its
position, which leads to the conclusion that the functional reliability is provided at a maximum temperature limit.

![Graph showing displacement vs. time for decreasing temperature profile](image)

**Figure 8.** Displacement of the antagonistic SMA actuator influenced by a decreasing temperature profile (low temperature dependency).

![Graph showing displacement vs. time for increasing temperature profile](image)

**Figure 9.** Displacement of the antagonistic SMA actuator influenced by an increasing temperature profile (high temperature dependency).

### 5.2. Discussion

There is a temperature dependency regarding the reliable functionality of the time-based controlled SMA actuator. Especially temperatures below 3.5°C can be considered as critical. According to the RTCA DO-160 directive, the actuator would not meet the requirements and may not be applied. The actuator fails to switch the displacement position which indicates that the SMA wire is not activated completely due to the low environmental temperature. The most probable reason for this is that the agonistic wire does not receive enough energy to be heated up to the austenite finish temperature and thus to transform completely into the austenite phase. For a phase transformation at lower temperatures, it is possible to either raise the current time of the control system or to raise the current value. Therefore it is necessary for the actuator control to tap the environmental temperature and adjust activation parameters.

Regarding the increasing temperature profile up to +70°C, it has been possible to prove the functional reliability of the actuator with time-based control. Although the absolute displacement of the actuator is reduced to less than 4 mm, the actuator position is still switching. The reduced displacement can be explained by a slight pre-activation of both SMA wires. In high environmental temperatures, the material is not able to transform completely into the low temperature phase. As a result of this, there are two main dissipation factors according to the antagonistic principle. On the one hand, there is a higher opposing force for the activated agonistic SMA wire to overcome because the opposed wire is slightly activated by the environmental temperature. On the other hand, the agonistic wire is also slightly pre-activated for the same reason and has thus already contracted before the controlled activation.
6. Conclusion and Outlook

Generally, a time-based control can be applied on SMA actuators under the following considerations: There may not be any extreme environmental temperature variations or – as most application fields, e.g. aircraft interior systems, involve such requirements – the control system has to be temperature dependent. In the latter case, it is necessary to apply an additional temperature sensor. It enables defined temperature ranges with related control parameters. For example, the activation time could be longer or the electrical current needs to be increased at low temperatures. The exact parameters are to be determined for each particular SMA actuator. In order to reduce the high effort needed to investigate this huge number of parameters, another approach is a resistance-based control system. The martensitic and austenitic phase have different values of electrical resistance. A change of the resistance value can be detected, which provides conclusions on the current material phase and thus on the actuator condition. In case of an incomplete phase transformation, the control keeps the SMA element activated or vice versa and it stops the activation in case of an earlier phase transformation. Furthermore, the resistance-based control can be considered as a condition monitoring device, which predicts a possible failure of the SMA actuator. Although there are still a few systematical limits, this investigation has served to prove that a time-based control can be applied as a rather simple activation solution for aircraft interiors.

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7. References

[1] M. Hinsch, J. Olthoff, Pulse Generator aviation. Industrial leadership through aviation specific setup and process concepts, Springer, Berlin Heidelberg, 2013.
[2] A. Czechowicz, S. Langbein, Design technology shape memory technology, Springer, Wiesbaden, 2013.
[3] P. Guempel; S. Glaeser, N. Jost, Shape memory alloys. Opportunities in mechanical engineering, medical technology and actuators with 119 pictures and 9 tables, expert verlag, 2004.
[4] A. Musolff, Shape memory alloys, experimental studies and development of adaptive structures, Technical University of Berlin, Berlin, 2005.
[5] B. Fleczok, M. Lubisch, B. Kuhlenkoetter, Development of a pre-evaluation method to design an electrically activated NiTi-based shape-memory wire actuator. Higher Education Forum, Hong Kong International Conference on Engineering and Applied Sciences, Hong Kong, VR China, 2015, pp. 1-8.
[6] H. Janocha, Adaptronics and smart structures: Basics, materials, design, and applications, Springer, Berlin, New York, 2007.
[7] M. Kohl, Development of micro-actuators based on shape memory alloys, Dissertation, Institution for micro-structure technology, University Kalsruhe (TH), Kalsruhe, 2002.
[8] Fraunhofer IWU. Information on https://www.iwu.fraunhofer.de/de/forschung/leistungsangebot/kompetenzen-von-a-bis-z/mechatronik-adaptронik/smart-materials/entriegelung-sauerstoffmasken.html
[9] Fraunhofer IWU: Smart-FLUOX: Unlocking donning masks with shape memory alloys, Fraunhofer IWU, Chemnitz, 2016.
[10] C. Eppler, Unlocking donning masks with shape memory alloys, Fraunhofer IWU, Chemnitz, 2013.
[11] J.P. Lawall, N.D. Mankame, R.J. Skurkus, Using resting load to augment active material actuator demand in power seats, DE Patent 102013211923 B4, Germany, 2013.
[12] J.P. Lawall, N.D. Mankame, R.J. Skurkis, Using resting load to augment active material actuator demand in power seats, US Patent 20120267928 A1, USA, 2012.

[13] Radio Technical Commission for Aeronautics Inc., RTCA DO 160D Environmental Conditions and Test Procedures for Airborne Equipment, Washington D.C., 1997.

[14] A. Joern, Aircraft development through the example of Airbus A380. From the idea to the admission, Bachelor and Master publication, Hamburg, 2015.

[15] D.C. Lagoudas, Shape memory alloys. Modeling and engineering applications, Springer, Boston Massachusetts, 2008.

[16] M. Kristen, Investigation of the electrical control of shape memory drives in handling technology, Mechanics centre of the technical university of Braunschweig, 1994.

[17] M. Mertmann, H. Borgmann (ed.), Fatigue in Nitinol actuators, Proceedings of the actuator, Bremen, Germany, 2006.