EXPERIMENTS ON SHAPE MEMORY ALLOY ACTUATOR AND PRACTICAL APPLICABILITY CONSIDERATION

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Journal of Structural Mechanics,
Vol. 40, No. 1, 2007, pp. 57-64

SUMMARY

This paper describes the design and the experimental work on a force-generating Shape Memory Alloy (SMA) actuator concept. The objective of the work was to test the applicability of the actuator concept for semi-active vibration control. The actuator was designed for bolt-force adjustment in structural joints. The SMA material applied was standard commercial *NiTinol* alloy. Two different actuator designs were constructed and tested: a smaller air-heated design, and a larger water-heated design. The actuator's ability to generate a force as a function of the bolt pre-tension was studied in the experiments. The magnitude of the forces generated was from 1 kN to 70 kN. In terms of design and control, non-linear behaviour of the actuator was considered a challenge. For the industrial application point-of-view, the long-term behaviour and the price of the material were considered the greatest challenges. Ability to generate large forces relatively quickly was seen as a promising opportunity. Furthermore, both actuator constructions were relatively simple and consisted of small number of components.

INTRODUCTION

The objective of the presented work was to examine the applicability of standard commercial Shape Memory Alloy (SMA) for semi-active vibration control. The aim was to design a SMA actuator capable to adjust a bolt force in a range up to several thousands of Newton.

SMA material restores its shape when heated over a transition temperature. This behaviour is based on the phase change in the material. The original shape is taught during a thermal treatment. When heated, this shape is restored due to change to the austenitic phase. In the lower-temperature martensitic phase, the same material is more flexible, even super-elastic. Thus the actuator that is deformed in a lower temperature, aims to restore its shape when heated above the transition temperature. [1].

In semi-active vibration control, the characteristics of a structure are adjusted in such a way that vibration response is minimised (or maximised, if wanted). Compared to the purely active vibration control methods, the energy driven into the system is relatively low in semi-active vibration control solutions. For example, a component with controllable stiffness may be used to adjust the natural frequency of a structure. This provides an opportunity for resonance-avoidance control.

For further interest in active vibration control, see [2, 3]. Controllable friction joints have been utilised as the actuators in semi-active vibration control [4, 5]. In some applications, controllable friction joints have been used similarly to the viscous damping elements (shock absorbers).The controllable friction joints have some advantages over viscous dampers: 1) ability to generate a considerable damping force for small relative velocity between the joint members, and 2) ability to generate low damping force for high velocities. These features are advantageous for certain semi-active systems [6, 7].

The actuator concept examined in this paper is intended for normal force control between the structural members as shown in Fig. 1. Normal force control makes it possible to control the stiffness between the structural members by means of friction in the joint. The normal force is controlled by adjustable pre-tension in a joining bolt using the designed SMA actuator concept. This work concentrates the examination of the bolt force as a function of the bolt pre-tension force and the heat conducted in SMA material. The remaining components of the presented principle are not considered in the work.

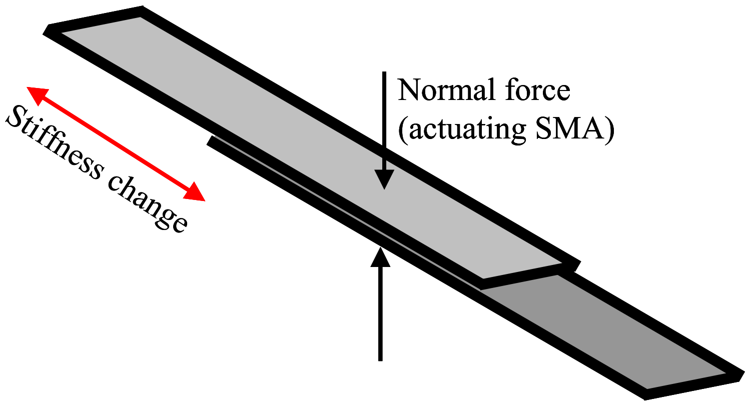

Figure 1. The principle of a controllable stiffness joint between two structural members.

TEST SET UP

The first actuator design planned was a tubular design; a SMA tube surrounding a bolt. Heating or cooling the actuator would have been performed by a fluid inside the tube. The design was discarded due to poor availability of SMA tubes with sufficiently large dimensions. Only tubes with a diameter of few millimetres were commercially available. Welding a tube from a SMA plate was also considered, but discarded due to relatively thin plates available (mainly sub-millimetre scale). SMA sheets up to about 1-mm thickness had the best availability. This encouraged to use several smaller pieces of SMA material and to magnify the force available.

The working principle of the actuators was to pre-tension the SMA sheets by a bolt and then adjust the bolt force by adjusting the temperature of SMA. The standard commercial *NiTinol* alloy was chosen for the purpose. Its austenite finish temperature declared by the manufacturer was 65 °C [8]. Both actuator designs consisted of two end plates and vertically positioned 1.25-mm-thick SMA sheets between the end plates. A bolt, whose force was to be controlled, located in the middle of the end plates pressing the plates and the SMA sheets in between together. The pre-stress in the SMA sheets and in the bolt were adjusted by tightening the bolt. The bolt force was then controlled by controlling the temperature of the SMA sheets. The two designs were different from each other in temperature control and in size. The first design was air-heated and smaller whereas the second design was water-heated and larger. The air-heated actuator was heated by an air blower and cooled by ambient room-temperature air. The water-heated actuator was heated and cooled by hot and cold tap water (10°C to 90°C).

AIR-HEATED ACTUATOR DESIGN

The air-heated test actuator had eight pieces of 1.25-mm-thick-SMA plates (Fig. 2, Fig. 3). The length of one SMA plate was 50 mm and its height 12 mm. The total active surface area of SMA material was 500 mm^2. The plates were placed in between the aluminium blocks pushed together by an 8-mm-thick bolt (standard M8 bolt). The bolt was situated in the actuator centre having four SMA plates in its both sides. The tension force of the bolt, equal to the compression force exerted on the SMA sheets, was measured with a washer-type strain-gage bolt force sensor. Temperatures were measured on-line at three spots together with the bolt force. The actuator temperature was measured from a SMA sheet, the sensor located in the middle of the actuator close to the bolt. This temperature measurement was used to analyse the force-production of the actuator. Another temperature measurement was in the air nozzle; it was to monitor the temperature of the incoming air. Third temperature sensor was attached to the force sensor in order to compensate its temperature dependency.

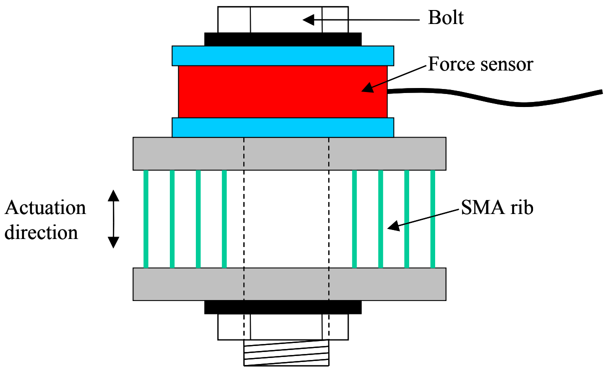

Figure 2. The air-heated rib actuator design. The actuation direction is parallel with the 12-mm-long edges of the SMA plates.

Figure 3. The SMA rib actuator. The bolt force sensor on the top.

WATER-HEATED ACTUATOR DESIGN

The other design based on heating (and cooling) the actuator with a liquid (ordinary tap water was used in the experiments). The working principle was similar to the air-heated actuator: thin SMA sheets were located in between two plates that conduct the force to the bolt at the centre of the actuator (Fig. 4). In order to generate larger forces, the total area of the SMA material was doubled being 1000 mm^2. The force increase and the requirement on water tightness required a more solid construction than in the air-heated actuator. A watertight chamber was constructed of two end plates (top and bottom) and two cylinders (inner and outer), all of them made of stainless steel. The outer and the inner cylinders were fixed to the bottom plate. The joint, sealed by the *O*-rings, between the top plate and the cylinders allowed a movement between the plates. Water was conducted in and out through two connectors in the outer cylinder.

The measurement of the force was carried out similarly to the air-heated case. Only the bolt to be tensioned was changed thicker; a 12-mm bolt was used (M12). The temperature measurements were changed, although the same semi-conductor sensor elements were used. Water temperatures were measured at two spots: 1) incoming water temperature before the inlet connector, and 2) outgoing water temperature after the outlet connector. Hence, the temperature of the SMA sheets was not measured directly. The third temperature measurement was used to compensate the temperature dependency of the actuator, as with the air-heated actuator.

The hot water source was a water boiler heating water up to 95°C. The cold water was taken directly from the tap, the temperature being about 5°C. The temperature of the SMA sheets was controlled manually by mixing cold and hot water. Different temperature ramps were used in the experiments. Exact information on ramp rates, nor the amount of heat transferred, were not available, since the flow rates were not monitored during the tests.

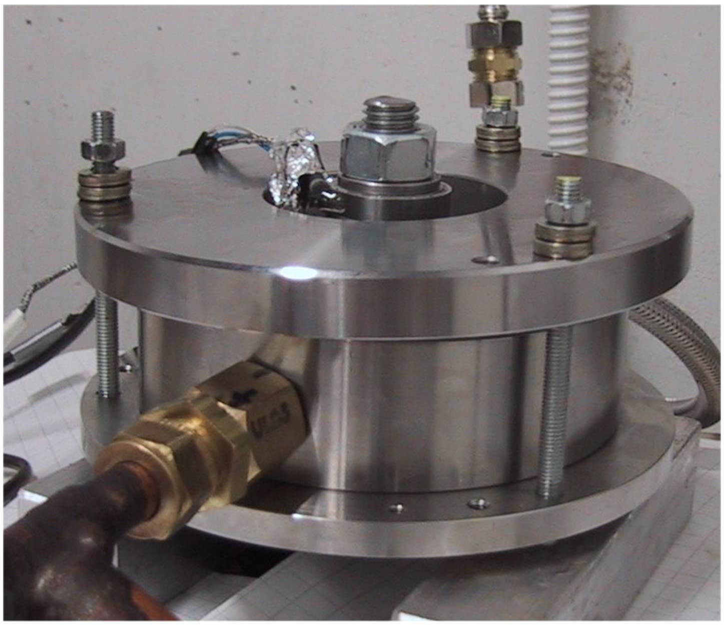

Figure 4. The water-heated actuator.

RESULTS

In the experiments, the actuator worked as expected in the rough mathematical study according to [9]. The air-heated actuator exhibited relatively good repeatability and worked smoothly in tests. The water-heated actuator exhibited larger deviation in the produced in consecutive experiments. This was probably caused by more aggressive temperature ramps and variations in the ramps from a measurement to another. The dynamic ranges of the actuators were defined by measuring the force at low temperature below the SMA transition temperature and at high temperature above the transition (Fig. 5). The temperatures were 35°C and 70°C for both actuators (note that temperatures are not exactly commensurable due to different measurement arrangements in the air-heated and in the water-heated actuator design). The air-heated actuator was operated in the bolt force range from 0 kN to 8 kN whereas the water-heated actuator was operated up to 60 kN in the dynamic range measurement. The largest force observed was 70 kN for the water-heated actuator. For the air-heated actuator, the relative dynamic range was larger than the bolt pre-tension (*i.e.* the bolt force was more than doubled during transition to high temperature. For the water-heated actuator, the relative dynamic range was somewhat smaller being mainly less than the pre-tension.

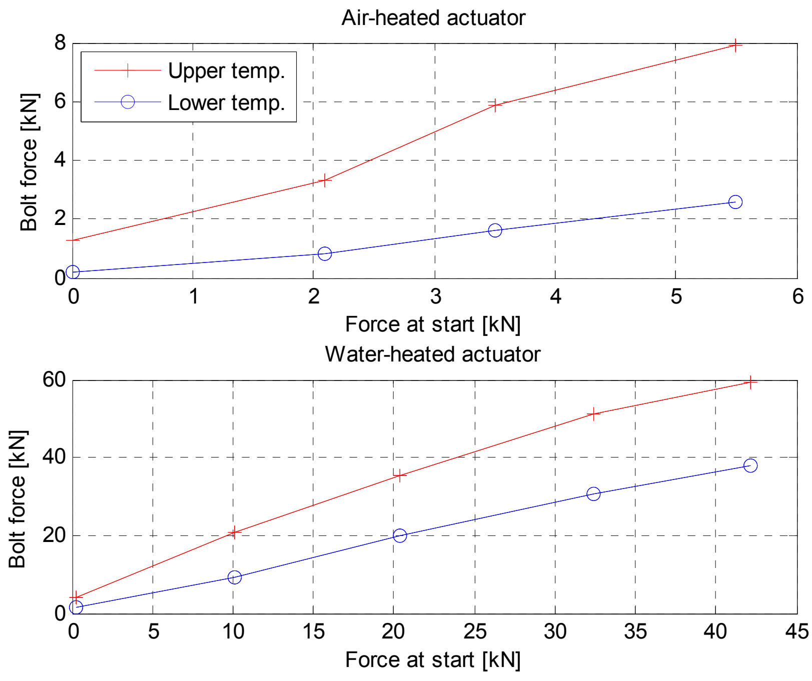

Figure 5. The dynamic ranges of the actuators.

The use of hot water instead of air blower made the heat transfer faster and caused the actuator to react faster. The maximum slopes for the water-heated actuator were from 0.1 kN/s to 0.5 kN/s depending on the bolt pre-tension; higher pre-tension produced higher slopes. Larger instantaneous slopes were observed up to about 3 kN/s near the transition. The corresponding figures for the air-heated actuator were about ten times lower.

A typical force-temperature curve is shown in (Fig. 6). First, the bolt was pre-tensioned to about 10 kN. Second, hot water was conducted trough the actuator until the average water temperature was about 90°C. Third, cold water was conducted trough the actuator in order to return at the low-force state. In this case, the heating-cooling procedure was repeated three times. The phase transition of SMA occurred when the average water temperature was about 60°C. The same test result is shown as a function of time in Fig. 7.

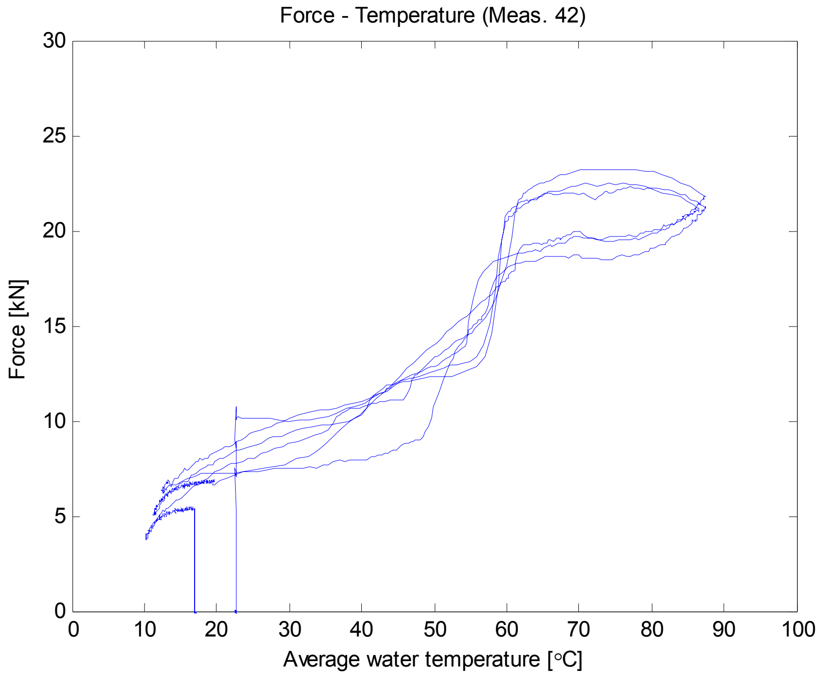

Figure 6. The bolt force in the water heated actuator as a function of average water temperature (the curve advances anti-clockwise with increasing time).

DISCUSSION

The actuator exhibited relatively good repeatability and worked smoothly in experiments. The behaviour of the air-heated actuator was more repeatable than the behaviour of water-heated actuator. This was probably due less aggressive and more constant heating process when using air. The actuation capability (dynamic actuation range) of the both actuators was large. Very approximately, we can conclude that the average actuation scales were half of the bolt pre-tension when heating was slow. This concerns particularly the air-heated case. The largest dynamic ranges were achieved with low bolt pre-tensions. Faster heating reduced the dynamic ranges. The largest bolt forces observed were about 70 kN for a pre-tension of 50 kN. The change from the air-heated actuator to the water-heated actuator made the force-generation substantially faster. The maximum slopes for the bolt-force change were 0.5 kN/s for the water-heated actuator whereas the air-heated was by a decade slower.

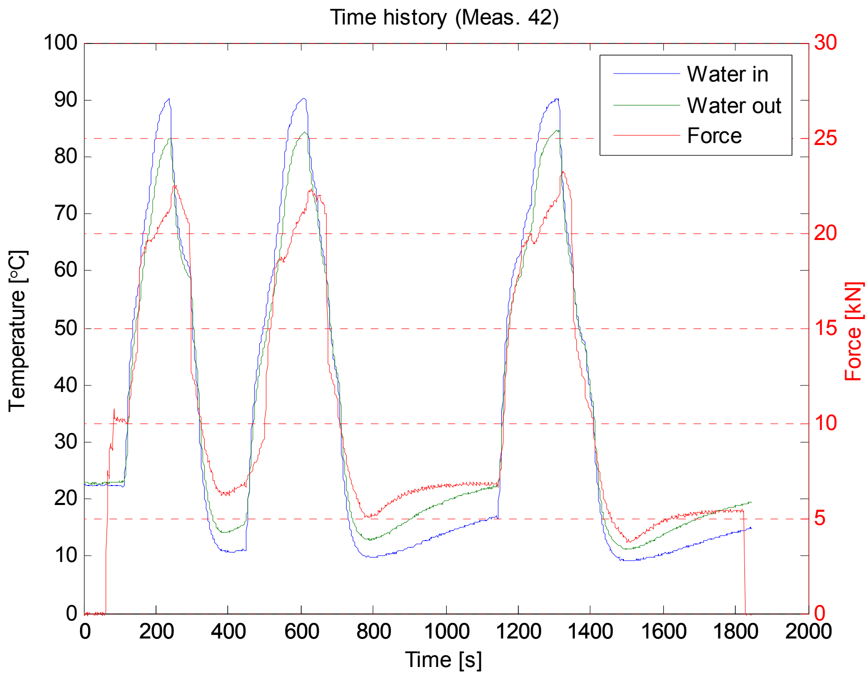

Figure 7. The incoming and outgoing water temperatures with the bolt force in the water-heated actuator as a function of time.

The actuators always exhibited certain relaxation in the bolt force after first the heating-cooling loop following the bolt tightening. After the first loop, the bolt force returned to a lower tension than it was tightened.

In terms of applicability, the non-linear behaviour of the SMA actuator poses challenges in design and control. The estimation of the forces generated cannot be very accurate without a force feedback. Observation of the force is also necessary, because, of unknown long-term behaviour of SMA. These questions should be studied carefully before implementing the actuator in practice. Other questions to be solved are related to the availability and to the price. When designing the test system, the SMA material was not available in large dimensions or in large quantities and the price was relatively high (the SMA sheets for the air-heated actuator cost about 200 €). Nevertheless, improvements in manufacturing technologies have been estimated to improve the availability of SMAs and to reduce their price.

The actuator lacks a returning function. Some tension always remained in the bolt. However, the experiments with water indicated better return than the experiments with air. This was due to the availability of cold water. The actuator was always tightened in a higher temperature than the actuator was at its coldest.

Provided that the mentioned challenges can be controlled, the SMA material is a potential solution for quasi-static control with relatively high force.

ACKNOWLEDGEMENT

The same article is being published in VTT Symposium series. The work was carried out within *I.P. Hercules* TIP3-CT-2003-506676 funded by the European Union. The author wants to thank Mr. Kari Wichmann and Mr. Petri Kaarmila for their contribution during the experimental work.

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