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Increasing stroke and output force of linear shape memory actuators by elastic compensation

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ABSTRACT

Shape memory actuators are a class of very interesting actuators due to the high power to weight ratio, plus the fact that they can work in harsh environments and can be easily constructed. The main defects of this technology are the short strokes and the non-uniformity of the useful force over the stroke. This paper aims to limit these two problems by introducing a passive system of elastic compensation. We first develop a functional design procedure of the active elements and of the compensation system in order to obtain the force and stroke desired. We also show two compensation mechanisms that are able to execute the laws required, and we provide expressions for the kinematic design. A numerical example for an actuator with a single shape memory element shows that, all other conditions being equal, the elastic compensation produces increases in stroke (for equal useful force) or useful force (for the same stroke) that are more than 2.5 times greater. A proof-of-concept actuator including a rocker-arm compensating mechanism is also built and tested to confirm the theoretical predictions.

1. Introduction

Shape memory alloys (SMAs) are metal alloys (e.g. nickel–titanium) with many interesting functional characteristics such as pseudo-plasticity, pseudo-elasticity and shape memory effect. The shape memory effect, which allows the deformed material to recover a memorized shape when heated above the transformation temperature, can be exploited effectively to build smart robots [1,2] or solid-state actuators [3] with very high specific power. The key features of SMA modeling for engineering purposes are described in [4]. Comprehensive reviews of design rules and applications of SMAs in the field of mechanical actuation are found in [5,6].

An actuator based on these materials is made up of an SMA element that works against a contrasting element (a weight or other constant force, a conventional spring, or a second SMA element). When the actuator is off (low temperature), the contrasting element overcomes the resistance of the easily deformable SMA element. The actuator is activated by heating the SMA element above the transformation temperature. The resulting increase in stiffness enables the SMA element to overcome the resistance of the contrast, thus generating useful displacements and producing mechanical work.

Typically, the force delivered by shape memory actuators varies linearly with the displacement, achieving the maximum and minimum values at the ends of the stroke. By contrast, the loads that need to be overcome are usually constant. The design of an SMA actuator is thus performed so that the minimum force output is higher than the external load [7]. This implies a reduction in the useful stroke with respect to the limit value dictated by the maximum deformation that the shape memory elements can withstand.

The idea behind this study is to introduce a compensation system that can take power from the SMA element in positions where the force is high, and then return this power in positions where the force is limited [8]. As in the field of manipulators [9] and constant force support devices [10], we capitalize on bistable mechanisms associated with an elastic spring element. The compensation system thus created has a negative elastic characteristic, which means that it generates a force that decreases as the deformation of the mechanism increases. The same principle has already been successfully applied in the field of electroactive polymer (EAP) actuators by introducing compliant mechanisms [11].

This paper is mainly devoted to developing the theory behind the compensation concept and illustrating the synthesis of specific mechanisms used to achieve compensation of whatever SMA actuator. A numerical example and a proof-of-concept prototype are also presented to illustrate the advantages of compensated actuators over their classical (uncompensated) counterparts.

2. Functional design of the compensated actuator

2.1. Typical force–displacement curve of shape memory actuators

To highlight in principle the advantages of the compensation system, Fig. 1 shows the force–displacement diagrams of a

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