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Using instability to reconfigure smart structures in a spring-mass model

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ABSTRACT

Multistable phenomenon have long been used in mechanism design. In this paper a subset of unstable configurations of a smart structure model will be used to develop energy-efficient schemes to reconfigure the structure. This new concept for reconfiguration uses heteroclinic connections to transition the structure between different unstable equal-energy states. In an ideal structure model zero net energy input is required for the reconfiguration, compared to transitions between stable equilibria across a potential barrier. A simple smart structure model is firstly used to identify sets of equal-energy unstable configurations using dynamical systems theory. Dissipation is then added to be more representative of a practical structure. A range of strategies are then used to reconfigure the smart structure using heteroclinic connections with different approaches to handle dissipation.

1. Introduction

Many structures are designed to be multi-stable equilibrium systems, so-called compliant mechanisms such as bi-stable mechanism and tri-stable mechanisms. These mechanisms store energy in some initial position and then release the stored energy through motion to another stable position [1]. For example, a discrete truss model, which consists of two bars connected by pin joints, has been investigated as a pseudo-bistable structure for morphing [2]. Others have investigated a thin-walled bi-stable geometry from natural systems and origami design principles. Finite element analysis and experimental results show the bi-stability of a reinforced silicone elastomer [3]. However, unstable equilibria could be considered to connect different configurations, as presented by Guenther et al. [4]. Some special anisotropic patterning of structures can help deal with instability [5]. Moreover, active control can be used to maintain the structure in an unstable state using an agent-based approach, which controls the structure to suppress instability [6]. Such active control can in principle allow the use of heteroclinic connections to transition a smart structure between unstable states.

A large number of engineering application have been investigated using multi-stable devices, for example an advanced helicopter rotor blade has used them for morphing to generate additional lift-load [7]. An adaptive antennae has been designed by synthesising compliant mechanisms to enable a morphing approach from a given curve into a target curve [8]. In addition, some simple models have analysed the stability of a buckled elastic beam, using an applied a load as an actuator for snap-through phenomenon [9], while experiment results show the detailed dynamics of the buckled beam as

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compared to numerical results [10]. Meanwhile, the properties of lightweight components in mechatronic devices can produce quick and precise movement or forces. A range of such components are designed and manufactured using smart materials, whose properties are controlled by external stimuli such as moisture, temperature, electric or magnetic fields [11,12]. There are a number of types of smart materials with various characteristics, such as shape memory alloys (SMAs), temperature-responsive polymers (TMPs) and piezoelectric materials. Currently, a wide range of SMA actuators have been successfully applied in low frequency vibration and actuation applications [13]. Furthermore, recent research shows that structures made of shape-memory polymers can provide large deformation under active control [14,15]. Broad applications of such smart materials can be found in the Aerospace, Energy and Marine sectors, particularly for energy harvesting, vibration control and structural health monitoring [16]. In addition, several unconventional applications have arisen, for example a self-folding origami structure was presented, constructed using shape memory composites that could be activated with uniform heating [17]. Moreover, a crawling robot has also been investigated which can fold itself from a flat sheet with embedded electronics, such as shape-memory composites, and can transform itself into a functional machine [18]. A single sheet can be reconfigured to desired shapes through multiple controllers by an optimised design [19].

In previous work, a simple model of a smart structure was presented by McInnes and Waters [20]. The model comprised a two mass chain with three springs which were approximated to provide simple cubic nonlinearity. Then, dynamical system theory was used to investigate the characteristics of this simplified system to identify both stable and unstable equilibrium configurations, some of which were connected using heteroclinic connections. This cubic nonlinear model has also been used to investigate vibrational energy harvesting through the use of stochastic resonance [21]. The cubic model is considered as a simple mechanical system which can change its kinematic configuration between a finite set of stable or unstable equilibria. The equal energy unstable equilibria are connected through heteroclinic paths in the phase space of the problem. Therefore, in principle zero net energy is required to achieve transitions between these configurations in the absence of dissipation. Numerical results illustrated that reconfiguration between unstable equilibria can in principle be energetically efficient compared to transitions between stable configurations, which need to cross a potential barrier. In addition, a reconfiguration method based on a reference trajectory and an inverse control method has been applied to this cubic model and then extended to a more complex model for which it is difficult to generate heteroclinic connections numerically. It is envisaged that being computationally efficient, the strategy could form the basis of real-time reconfiguration of smart structures. [22].

In this paper a more complex and realistic spring-mass model is developed to consider the differences between the cubic approximation used in previous work and a real spring model with dissipation, which illustrates the possibility of using heteroclinic connections to reconfigure real smart structures, expanding on Ref. [23]. Again, a set of equilibria can be found and can in principle be connected through heteroclinic paths. Then, strategies are considered to deal with the dissipation term. Two control methods are investigated, using an end-point control and an optimal control strategy. In addition, a bifurcation control strategy is investigated which allows the stability properties of the equilibria to be controlled, enabling stable equilibria to become temporarily unstable and so connected by heteroclinic paths. Numerical results are presented to illustrate the control strategies developed.

2. Smart structure model

Consider a simply clamped smart structure model, which consists of a two mass chain connected by three linear springs of stiffness (k_1, k_2, k_3) and natural lengths (L_1, L_2, L_3), as illustrated in Fig. 1. It is assumed that the masses can only move in the vertical direction. If the displacement of a mass is defined by $\boldsymbol{x}(x_1, x_2)$, while the spring clamps are separated by $3d$, it can be shown that the spring lengths after deformation are described by

$$l_1 = \sqrt{(x_1^2 + d^2)} \tag{1}$$

$$l_2 = \sqrt{((x_1 - x_2)^2 + d^2)} \tag{2}$$

$$l_3 = \sqrt{(x_2^2 + d^2)} \tag{3}$$

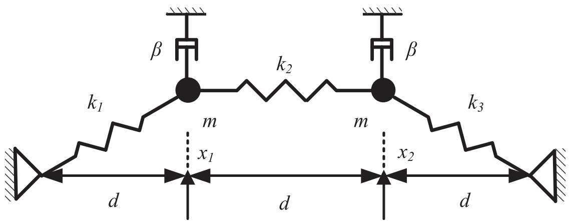

Fig. 1. 2 degree-of-freedom bucking beam model with damping coefficient β.