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Research paper

A vibrating mechanism for large amplitude, non-reciprocal motion, exploiting multiple buckling modes

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ABSTRACT

A bi-stable mechanism capable of generating non-reciprocal motion is presented. This mechanism can efficiently generate a wave-like non-reciprocal trajectory with large amplitudes, using a single actuator, without feedback control. By optimizing the mechanisms topology, and thus the potential energy surface, a natural support for non-reciprocal motion is obtained. The task of generating a non-reciprocal motion in an efficient manner, often involves several actuators, sensors, and closed loop control. In this work, the non-reciprocal motion is obtained by making the mechanism to continuously alternate between stable and unstable buckling modes. The desired motion path is designed by optimizing the mechanism's total potential energy map. By tailoring the dynamic motion of a single actuator to the obtained potential map, two degrees of freedom and a non-reciprocal trajectory can be formed. A theoretical model describing the dynamical behavior was developed and investigated and it shows good agreement with an experimental system. It is demonstrated by simulation and experiment that by shaping the potential map and stable configurations, non-reciprocal as well as other types of complex motions can be generated. This mechanism can potentially serve as a multi-stable actuator or as a robotic limb where non-reciprocal motions are preferred.

1. Introduction

This work deals with a mechanism capable of generating non-reciprocal motions that approximate a traveling wave. Traveling waves are formed by producing non-reciprocal deformed states and they find use in propulsion in several applications. Ultrasonic motors [1], acoustic levitation motors [2–4] in which traveling waves generate pressure acoustic waves that propel the levitated object by a propagating wave. Miniature creatures and robotic swimmers immersed in fluids reside in a low Reynolds environment, for which inertial forces are negligible and viscous forces are dominant. In the absence of inertia forces, traveling waves are required for propulsion. Indeed, it has been demonstrated that robotic swimmers at low-Reynolds-number have to use traveling waves as the source of propulsion [5–8].

Mechanisms that move rapidly are required to exploit dynamics so that they produce sufficiently high propulsion forces and therefore large amplitudes of vibrations. However, it can be rather difficult to obtain large amplitudes when exciting a traveling wave in a flexible or compliant structure [9]. Rather than relying on structural elasticity solely, a mechanism based on three rigid links [10,11] exploiting inertia and buckling states is proposed. Such a mechanism, having two stable geometric configurations, often referred as a bi-stable or multi-stable system [12,13]. A bi-stable element has two stable

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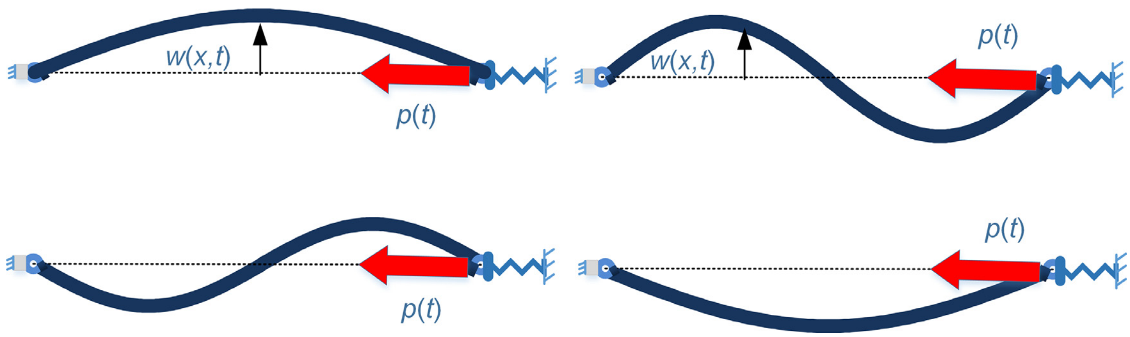

Fig. 1. Illustration of the two initial buckling modes of an axially excited beam. A pseudo traveling wave is obtained by switching between the modes clockwise or counter-clockwise.

configurations related to wells or minima in its potential map. These wells are separated by unstable states related to a potential barrier or local maximum. Large deformations, depending on the spacing between deformed states at which these wells reside, can be obtained by switching between stable configurations of the mechanism in a sequence. By exploiting the natural dynamics of the mechanism, minimal excitation levels can make the mechanism alternate between these wells periodically, thus large amplitude motions are obtained. The energy required for the switching depends on the potential topography and it can be minimized by carefully optimizing the potential map and the required excitation.

Bi-stable structures were extensively studied, especially in Micro Electro Mechanical Systems (MEMS) [14–16]. MEMS devices often use bi-stable elements when several stable states are required such as microvalves, micro-relays and micro-switches [17–19]. A mechanism utilizing bi-stable elements for vibrations suppression is described in [20]. Another use of bi-stable elements is for energy harvesting [21,22]. In this work, the design of the mechanism relies on the shaping of the potential map, which determines the mechanism's motion.

It is shown for the proposed mechanism, that while being excited by a single actuator, it experiences, in effect, a parametric-like excitation [23]. Along the desired trajectory, the alternating geometry changes the system's effective stiffness and mass periodically [24,25]. This type of excitation is uncommon in oscillating mechanisms since the excitation is not synchronized with the deformation frequency. Exciting the system at either the fundamental or principal parametric resonance frequencies of the system [25–27], the proposed mechanism is capable of generating different types of motion, efficiently.

Initially, the principle of generating a traveling wave by the proposed mechanism having a tailored potential map is presented. Then, a dynamic model for the mechanism is developed. The model is characterized and analyzed through its total potential energy map. Later, described is an experimental mechanism that was built for this work and through several experiments, it is compared to the analytical model. These comparisons demonstrate the capability to generate the desired traveling wave motion and the conditions to achieve them.

2. Kinematic principle of the traveling waves mechanism

Consider a bending beam-like structure, hinged at its edges and actuated axially as depicted in Fig. 1. The axial force can cause the beam to buckle into one of its buckling modes.

Since there are several such buckling modes, the beam can assume several configurations [28], which can be described as:

$$\phi_n(x) = \sin\left(n\pi\frac{x}{L}\right) \quad n = 1, 2, 3, ..., \tag{1}$$

where L is the beam's length. Spatially sampling $\phi_1(x)$, $\phi_2(x)$ at uniform time intervals, the sequence of deformed states is obtained. As shown in Fig. 2(a) and (b), each mode deformation is a standing wave. However, combining them together as:

$$\begin{aligned} w(x,t) &= W_1\phi_1(x)\cos(\omega t) + W_2\phi_2(x)\sin(\omega t) = \\ &= W_1\sin\left(\pi\tfrac{x}{L}\right)\cos(\omega t) + W_2\sin\left(2\pi\tfrac{x}{L}\right)\sin(\omega t)\text{'} \end{aligned} \tag{2}$$

and observing the sequence of deformed states generated, one obtains the sequence of deformed states shown in Fig. 2(c). Showing that $w(x, t)$ has some region of propagation of the phase along the structure, where the envelope of $w(x, t)$ is nearly constant.

Fig. 1 presents a time-sampled sequence of transition between buckling modes that create a traveling wave-like motion by repeating the sequence either clockwise or counter clockwise. This description refers to a quasi-static switching between the buckling modes.

When the mode switching becomes faster, the beam's motion can be considered as a combination of the two modes of vibrations of the beam. Exciting a beam in the vibration pattern that was described does not provide significant amplitudes