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Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Piezoelectric vibration-driven locomotion systems – Exploiting resonance and bistable dynamics

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ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form
7 September 2016
Accepted 5 December 2016
Handling Editior: A.V. Metrikine

Keywords:
Micro robot
Snap-through
Inter-well oscillation
Basin of attraction
Basin stability

ABSTRACT

While a piezoelectric-based vibration-driven system is an excellent candidate for actuating small-size crawling-type locomotion robots, it has the major drawback of limited stroke output that would severely constraint the system's locomotion performance. In this paper, to advance the state of the art, we propose two novel designs of piezoelectric vibration-driven locomotion systems. The first utilizes the resonant amplification concept, and the second explores the design of a bistable device. While these two ideas have been explored for piezoelectric actuation amplification in general, they have never been exploited for crawling-type robotic locomotion. Numerical analyses on both systems reveal that resonance and bistability can substantially increase the systems' average locomotion speed. Moreover, this research shows that with bistability, the system is able to output high average locomotion speed in a wider frequency band, possess multiple locomotion modes, and achieve fast switches among them. Through proof-of-concept prototypes, the predicted locomotion performance improvements brought by resonance and bistability are verified. Finally, the basin stability is evaluated to systematically describe the occurring probability of certain locomotion behavior of the bistable system, which would provide useful guideline to the design and control of bistable vibration-driven locomotion systems.

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1. Introduction

In recent years, the growing demands for industrial and civilian applications such as mini-fabrication, mini-manipulation, accurate positioning, and minimally invasive surgery necessitate wide research in the field of micro locomotion robots. Due to the limited space and sensitive working environment in these applications, the conventional wheeled and legged designs for large-scale robots encounter many challenges due to their mechanical complexity, controllability, and component size. On the other hand, inspired by limbless animals like snakes and earthworms, crawling robots are able to perform effective locomotion in various media by either changing their own configuration or driving internal masses [1–6]. Among various approaches, it has been recognized that the "*Vibration-Driven System*" provides a promising propulsion mechanism for crawling-type locomotion. Generally, a vibration-driven locomotion system is composed of an inertial body M and a movable internal mass m (Fig. 1(a)); the system as a whole can move forward in various environment owing to the periodic motion of the internal mass and the anisotropic resistance between the system and the working environment [7,8]. Since

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http://dx.doi.org/10.1016/j.jsv.2016.12.009
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Please cite this article as: H. Fang, & K.W. Wang, Piezoelectric vibration-driven locomotion systems – Exploiting resonance and bistable dynamics, *Journal of Sound and Vibration* (2016), http://dx.doi.org/10.1016/j.jsv.2016.12.009

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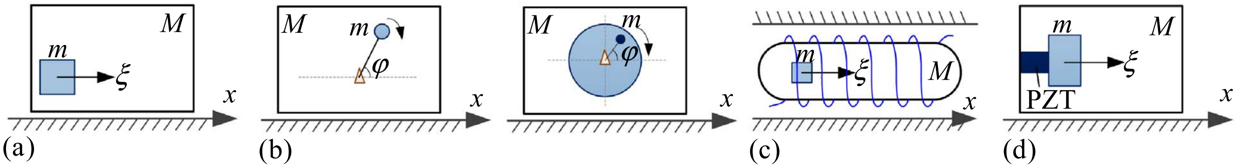

Fig. 1. (a) General model of the vibration-driven locomotion system. (b)–(d) Mechanical models of previous designed/prototyped vibration-driven locomotion systems: (b) systems actuated by internal motors or rotors; (c) system with electromagnetic actuation; (d) system with internal PZT actuator.

the locomotion is achieved without protruded components (like legs, wheels, or jets, etc.), the system can be made hermetic and smooth, and possesses great miniaturization potential. Such advantages are exactly what micro locomotion robots needs, and as a result arouse researchers' enthusiasm to develop vibration-driven locomotion systems.

Some efforts have been devoted to the fundamental mechanics [7–12] and optimal control [13–16] of vibration-driven locomotion systems, where the internal mass can perform harmonic oscillation, velocity-controlled motion, and acceleration-controlled motion. Then the research was extended to systems with multiple internal masses [16–18], vibro-impact systems [19–21], and multi-module systems [22–24]. Based on the vibration-driven mechanism, several single-module vibration-driven locomotion robots have been designed and prototyped [11,19–26] (see their mechanical models in Fig. 1(b)–(d)). The "internal motions" of these prototypes were driven through different methods, including conventional motor or rotor actuations [17,25–27] (Fig. 1(b)), electromagnetic actuation [21,28–30] (Fig. 1(c)), and piezoelectric actuation [31,32] (Fig. 1(d)).

While the previous designs and prototypes have shown the feasibility of vibration-driven mechanism in locomotion robots, there are still some important limitations. The motors and electromagnetic devices are able to provide the systems with sufficient actuation forces, but severely restrict the systems' miniaturization ability due to their own size constraints. The piezoelectric actuator, on the other hand, is currently one of the best solutions that endow the vibration-driven locomotion systems with high miniaturization potential, but have serious limitations on the systems' locomotion speeds due to the limited stroke output [32]. In other words, there are still significant tradeoffs between miniaturization and actuation performance in these investigations. In addition, prior studies paid little attention to improve the systems' other locomotion properties or to further explore their potential. That is, with various application prospects, properties other than locomotion speed are also essential. For example, the working frequency band is an important index to evaluate the system's adaptability with respect to perturbations, and the potential to have multiple locomotion modes is beneficial for the system to handle multiple tasks. A careful study of these properties will be essential to fully understand and exploit the systems' locomotion performance.

2. Research goals and approach overview

Based on the above discussions, the goal of this research is to advance the state of the art by addressing the aforementioned issues and exploring new designs of vibration-driven locomotion systems. More specifically, we focus on achieving higher locomotion speed with piezoelectric actuation (strong potential for miniaturization) via output amplification, as well as improving the other locomotion properties via incorporating nonlinearities into the system.

A typical approach to amplify low actuation output is making use of the resonant effect. By coupling the internal mass with the external frame through stiffness/spring elements, and driving the internal mass near one of the system natural frequencies, small actuation output can be significantly amplified. Such an amplification mechanism has been adopted in micro in-pipe vibration-driven locomotion robots [21,30,33], where the internal electromagnet-actuated mass becomes a mechanical resonator. In terms of piezoelectric applications, resonance has also been utilized to amplify the displacement output to improve energy harvesting performance [34,35]. However, the integration of piezoelectric actuation and resonant effect has not been achieved in vibration-driven locomotion systems. Hence, this research will explore feasible architecture to amplify the weak piezoelectric output via resonance and examine its effects on the system's locomotion speed.

On the other hand, exploiting nonlinearities, especially bistability, has become in recently years an effective performance-enhancement option in many fields that utilize vibration-driven devices/systems, including actuators [36,37], energy harvesters [38–42], dampers [43], and vibration isolators [44,45]. Despite these promising applications, the potential of integrating bistability into locomotion systems has never been explored. In this study, we will advance the current knowledge by investigating the dynamic behavior of vibration-driven locomotion systems incorporating bistability, and discuss how bistable dynamics would contribute to the locomotion performance. Attention will not only be focused on the locomotion speed but also on other locomotion properties induced by bistability.

Overall, this research introduces new vibration-driven locomotion system concepts by adopting a structural composition inspired by the resonant and bistable dynamics effects. Two novel designs based on internal piezoelectric cantilevers are devised, with one making use of mechanical resonance, and the other utilizing bistability. Equivalent lumped-mass models are established; their characteristic dynamics as well as the corresponding average locomotion speeds are numerically investigated. Moreover, based on these models, the working frequency band and the possible multiple locomotion modes

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