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Experiments on vibration-driven stick-slip locomotion: A sliding bifurcation perspective

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ABSTRACT

Dry friction appears at the contact interface between two surfaces and is the source of stick-slip vibrations. Instead of being a negative factor, dry friction is essential for vibration-driven locomotion system to take effect. However, the dry-friction-induced stick-slip locomotion has not been fully understood in previous research, especially in terms of experiments. In this paper, we experimentally study the stick-slip dynamics of a vibration-driven locomotion system from a *sliding bifurcation* perspective. To this end, we first design and build a vibration-driven locomotion prototype based on an internal piezoelectric cantilever. By utilizing the mechanical resonance, the small piezoelectric deformation is significantly amplified to drive the prototype to achieve effective locomotion. Through identifying the stick-slip characteristics in velocity histories, we could categorize the system's locomotion into four types and obtain a stick-slip categorization diagram. In each zone of the diagram the locomotion exhibits qualitatively different stick-slip dynamics. Such categorization diagram is actually a sliding bifurcation diagram; crossing from one stick-slip zone to another corresponds to the triggering of a sliding bifurcation. In addition, a simplified single degree-of-freedom model is established, with the rationality of simplification been explained theoretically and numerically. Based on the equivalent model, a numerical stick-slip categorization is also obtained, which shows good agreement with the experiments both qualitatively and quantitatively. To the best of our knowledge, this is the first work that experimentally generates a sliding bifurcation diagram. The obtained stick-slip categorizations deepen our understanding of stick-slip dynamics in vibration-driven systems and could serve as a base for system design and optimization.

1. Introduction

Dry friction is a source of *stick-slip* dynamics that receives vast attentions for decades [1–13]. Although mostly been regarded as the origin of dynamic instability, noise, and reduction of performance [14–17], dry friction and stick-slip effects can also serve as essential factors in certain nature and engineering systems, such as snakes' and earthworms' locomotion [18,19], multi-legged robots [20], and high-precision positioning [21,22].

The vibration-driven locomotion system is another example that relies on resistance forces (e.g., dry friction) to take effect. Actuated by the oscillations of internal masses, the system could achieve effective locomotion providing that the

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working media is resistive. Such locomotion systems have received much attention because they reasonably reflect the locomotion mechanisms of certain crawling animals and can be employed for developing micro locomotion robots without external propelling components (such as wheels, legs, and propellers) [23–28]. Considering the discontinuous characteristics of the dry friction force, piecewise procedures can be adopted to solve the system's steady-state motions if the internal mass is actuated by piecewise constant accelerations or piecewise constant velocities [29,30]. However, such methods become extremely complex or incapable of analyzing systems with multiple modules or with other internal actuations. To deal with these scenarios, the method of averaging was employed to analyze the steady-state motions of single-module systems [31,32] and multi-module systems [32–35], with the assumption that the sticking motion is absent or negligible. However, sticking and stick-slip motions are characteristic features of dynamical systems with dry friction that cannot be overlooked. Particularly, in vibration-driven locomotion systems, sticking can arise not only at the beginning but also during the movement as well as at the end. In a single-module system with acceleration-controlled internal mass, the system's steady-state motions were classified into eight types corresponding to different stick-slip phenomena [31]. Complicated stick-slip motions were also observed in a three-module system with dry-friction contact; their occurrence is closely related to the internal actuation phase-differences [34].

On the other hand, systems with dry friction can be described as nonsmooth dynamical systems of *Filippov type* [36], that is, systems with discontinuous vector field. The characteristic features of Filippov systems are *sliding* and *sliding bifurcations* [36–39]. If the discontinuity comes from dry friction in mechanical systems, *sliding* is also referred as *sticking*. Dry friction oscillators have been the most studied Filippov systems so far, where the oscillators were always modeled as harmonically excited spring-mass systems on a rough horizontal plane or on a driving belt [38,40–45]. Through numerical procedures, a 2-parameter sliding bifurcation diagram [44], codimension-2 bifurcations [45], and even routes to chaos [38] have been identified. Sliding bifurcation theory has also been employed for understanding the stick-slip effects in a single-module vibration-driven locomotion system with dry-friction contact [46]. When the internal mass is harmonically excited, the system's locomotion is categorized into four types with qualitatively different stick-slip characteristics. Transitions between different types of stick-slip motions correspond to certain sliding bifurcations. Theoretically, a two-parameter sliding bifurcation diagram is presented, where the bifurcation branches are derived in view of classical mechanics. With this bifurcation diagram, the occurrence of different stick-slip motions becomes predictable.

Note that in vibration-driven locomotion systems, instead of being a negative factor, dry friction turns into an essential factor for the system to take effect; and in particular, the dry-friction induced sticking motion can become a beneficial factor to improve locomotion performance, including directed locomotion without backward slip and higher average locomotion speeds [31,46]. However, in previous designs and experiments on vibration-driven locomotion systems, sticking was always avoided by applying large actuation amplitude or high actuation frequency so as to achieve smooth motion [23,47,48]. Such processing, although avoiding the additional procedures to predict and analyze the possible stick-slip motions, would give rise to an unavoidable backward slip in each locomotion cycle which is undesired in many applications. Considering that the sliding bifurcation offers a good theoretical tool to categorize and predict stick-slip locomotion, it is worth studying and utilizing the stick-slip effects in vibration-driven locomotion systems for wider actuation range and better locomotion performance. Nevertheless, except the abovementioned theoretically progress, there is a lacking of experimental efforts on achieving and understanding the vibration-driven stick-slip locomotion, qualitatively and quantitatively categorizing the stick-slip motions, and verifying with the sliding bifurcation theory.

Based on the above discussions, the goal of this research is to advance the state of the art by experimentally addressing the stick-slip effects in vibration-driven locomotion systems. More specifically, we focus on experimentally achieving and categorizing the stick-slip locomotion, as well as verifying the categorization from the sliding bifurcation perspective. In this paper, after a brief review on stick-slip motions and sliding bifurcations (Section 2), we design and build a vibration-driven locomotion prototype based on an internal piezoelectric cantilever and by making use of the mechanical resonance effect (Section 3). Then we carry out systematic locomotion tests on the prototype, from which four types of stick-slip locomotion are identified and an experimental stick-slip categorization diagram is generated (Section 4). After that, Section 5 establishes an equivalent two degree-of-freedom (DoF) lumped-mass model and a further simplified 1-DoF model; based on the measured relative accelerations, a numerical stick-slip categorization is obtained, which shows good agreement with the experiments. We also discuss the rationality of simplifying the 2-DoF model to 1-Dof model at the end of Section 5 and summarize the paper in Section 6.

2. Stick-slip motion and sliding bifurcation: a brief review

In this section, we briefly review the categorization of stick-slip motions in a single-module vibration-driven locomotion system based on the sliding bifurcation theory. This review is not redundant but beneficial for the following analysis and experiments by providing the basic concepts and theoretical results. The readers are referred to [46] for details.

Fig. 1(a) shows the mechanical model of a single-module vibration-driven locomotion system, which consists of a rigid body with mass M and an internal mass m. The internal mass is assumed to perform a sinusoidal oscillation relative to the rigid body, which drives the overall system to move along a straight line on a resistive horizontal plane. The friction force at the contact surface between the system and the resistive plane is assumed to obey the Coulomb dry friction law (Fig. 1(b)). Hence the equation of motion of the system yields