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Experimental investigation of the vibro-impact capsule system

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Abstract

This paper presents an experimental investigation of the vibro-impact capsule system, which has potential applications in capsule endoscopy and engineering pipeline inspection. The experimental results obtained using novel test rig are used to verify the modelling approach where non-smooth multibody dynamics is applied to describe the motion of the system, and comparisons between numerical simulations and experiments are given. After an appropriate re-scaling, the findings of this work could provide a better insight into the behaviour of such systems which are subject to harmonic excitation.

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1. Introduction

Developing small-size robots with accessibility of the complex environment, such as pipeline^{1,2,3} and gastrointestinal tract^{4,5,6,7} for diagnosis, has been a challenge task over the past decade, particularly in the design of the external driving mechanisms (e.g. leg) for locomotion⁸. The complicated design of such tools and difficulties in their control are the bottlenecks that restrict their development in microsize. Alternatively, the self-propulsion robots driven by autogenous internal interactive forces is a promising solution with growing interests in recent years^{9,10,11,12,13}. The driving principle of these systems originally proposed by Chernousko¹⁴ is that the rectilinear motion of a system can be obtained through overcoming external resistance described as dry friction force using a periodically driven internal mass interacting with the main body of the system (see Fig. 1(a,b)). The advantage of this method is that no external driving mechanism is required, so the system can be encapsulated and move independently in the complex environment¹⁶. This paper presents an experimental study for this type of capsule system by using a newly designed test bed which allows one to investigate the influence of control parameters, such as impact stiffness, excitation frequency and amplitude, on system dynamics. The findings in this paper have significance in prototype design and fabrication which could be scaled up/down for the systems in any size.

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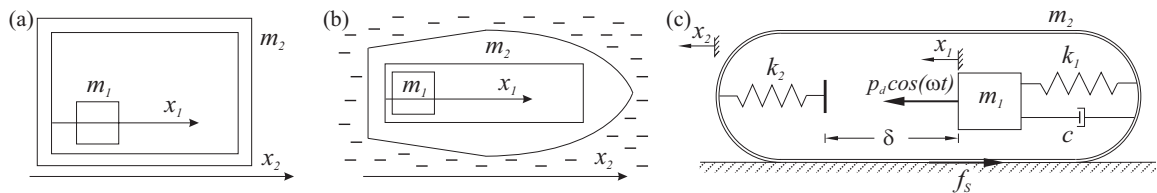


Fig. 1. Physical models of the capsule system: (a) on a resistive surface; (b) in a resistive medium¹⁵; (c) the vibro-impact capsule system

In the recent years, vibro-impact driven robots have attracted great attention from the robotics community. Nagy *et al.*⁹ studied the motion of a complex micro-robot exhibiting impacts and friction numerically and experimentally. They have found that the stiction and sliding of the robot are governed by excitation frequency and friction, while impact around the resonant frequency of the oscillator does not contribute to robot's propulsion. In this paper, we will also consider both non-smooth nonlinearities (i.e. friction and impact) numerically and experimentally, and further investigate the dynamical responses of this type of robot under variations of different control parameters. One of the notable differences between the micro-robot⁹ and the capsule system studied in this paper is that, the former is operated in the kilohertz range of oscillation and direct observation of the non-smooth phenomena at the micro-scale is impossible, while the later is controlled at a much lower frequency so that vibro-impact responses of the system can be easily observed. Hence after an appropriate re-scaling, the findings of this paper could provide a better insight for these micro-sized robots subject to high frequency excitation, and the novel experimental test bed can be used to predict the dynamical behaviour of these robots.

A major obstacle of current miniature capsule robots is the limited amount of power which restrains its operational duration. A multi-coil inductive powering system¹⁰ was designed for a vibratory driven capsule robot to address the power shortage issue in capsule endoscope, and a frictional reduction approach of this robot using a rotational vibratory motor was studied¹¹. Since only partial power contributes to the rectilinear motion of the robot, rotational vibration is not considered as an efficient way of driving. A capsule robot driven by a linear vibratory actuator was designed¹⁷, and its friction resistance in gastrointestinal tract was modelled¹⁸. In order to enhance the rectilinear progression of the capsule robot, we introduce a stop for the linear vibratory actuator which could produce notable impacts for the system. The dynamics of such a vibro-impact capsule system was studied numerically, and it has found that the control parameters for the best progression and for the minimum energy consumption are different, and therefore, a trade-off between the best progression and the energy consumption is required in order to optimize the capsule motion¹². A preliminary experimental study was carried out¹⁹, and an experimental verification of the vibro-impact capsule model was presented which showed a good agreement in a broad range of control parameters²⁰. The conducted bifurcation analysis indicated that the behaviour of the system was mainly periodic and that a fine tuning of the control parameters can significantly improve system performance. In this paper, we focus on the comparison of numerical and experimental results, and elucidate the discrepancies encountered by Liu *et al.*²⁰.

2. Mathematical Modelling

The vibro-impact capsule system is modelled as a two degree-of-freedom dynamical system depicted in Fig. 1(c), where a movable internal mass m_1 is driven by a harmonic force with amplitude p_d and frequency ω generated by a linear actuator. The actuator contains a movable part connected to the internal mass and a fixed part mounted on the rigid capsule m_2 . We simplify the model of the actuator here and represent the interaction between the internal mass and the capsule by using a linear spring with stiffness k_1 and a viscous damper with damping coefficient c . x_1 and x_2 represent the absolute displacements of the internal mass and the capsule, respectively. The internal mass contacts a weightless plate connected to the capsule by a secondary linear spring with stiffness k_2 when the relative displacement $x_1 - x_2$ is larger or equals to the gap δ . When the force acting on the capsule exceeds the threshold of the dry friction force f_s between the capsule and the supporting environmental surface, bidirectional motion of the capsule will occur, and the dynamic friction force f_d will be applied to the capsule. The comprehensive equations of motion for the

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