Complex dynamics of a vibro-impacting capsule robot in contact with a circular fold

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Abstract. The circular folds in the lining of the small intestine provide the main source of resistance for the motion of capsule endoscopy. To reveal the capsule-fold dynamics, this paper presents bifurcation analyses for a vibro-impact self-propelled capsule robot contacting with a circular fold. Using the GPU parallel computing and the path-following techniques, one- and two-parameter bifurcation analyses are performed. It is found that the excitation parameters of the capsule robot and the fold's mechanical properties have significant influences on the bifurcation scenario. Performing the basin stability analysis, numerical results indicate that the period-one motion of the capsule-fold interaction and the crossing motion can dominate the global dynamics of the system in the small and large excitation amplitude regions, respectively. The findings of this work will be useful for the locomotion control of the capsule robot in the small intestine when encountering different types of circular folds.

Introduction

Self-propelled locomotion robots have attracted great attention from the research community in recent years, as they can move efficiently in complex environments. In the past decade, various locomotion mechanisms have been developed to provide active propulsive force for driving robots. For example, Guo et al. [1] presented an experimental study on a vibro-impact self-propelled capsule in mesoscale and discussed the feasibility of such a capsule under different frictional environments. The vibro-impact capsule robot is a non-smooth dynamical system driven by its internal vibration and impact in a rectilinear manner in the presence of environmental resistance. However, previous studies only considered capsule dynamics on a flat surface without the consideration of intestinal anatomy. While considering a series of circular folds of different sizes in the lining of the small intestine, the capsule's dynamics and locomotion will be significantly influenced. Thus, the present work will study the capsule's dynamics when encountering various types of circular folds.

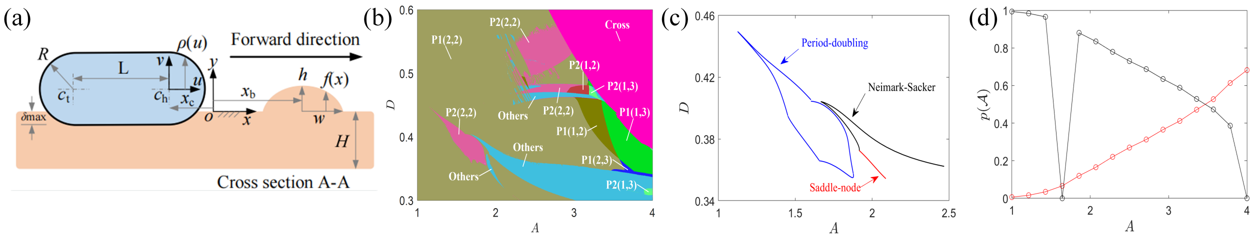

Figure 1: (a) Schematic diagram of the capsule moving on an intestinal substrate with a circular fold. (b) Two-parameter bifurcation diagram. (c) Continuation of bifurcation curves. (d) Occurrence probabilities of the $P1(2,2)$ (red) and fold crossing (black) motions.

Results and discussion

Modelling the contact force of capsule-fold interaction by a piecewise-smooth nonlinear force [2], the complex dynamics of the capsule robot were presented in Fig. 1(a-d). The two-parameter diagram obtained by GPU calculation in Fig. 1(b) indicated an initial view of the capsule–fold dynamics. Two basic attractors, the $P1(2,2)$ (a period-one motion with capsule sticking to the fold) and the fold crossing motions, were observed. In practice, the $P1(2,2)$ motion is one of the desired motions because of its simplicity for locomotion control. Continuation analysis was performed to uncover the bifurcation of the $P1(2,2)$ motion as shown in Fig. 1(c). Since bifurcation analysis can only provide local information, basin stability analysis was also conducted to characterise the capsule–fold dynamics from a global perspective. Fig. 1(d) showed that the $P1(2,2)$ motion dominated the global dynamics of the system with a high probability when the excitation amplitude of the robot was small. On the contrast, the fold crossing motion dominated the global dynamics of the system with a high probability when the excitation amplitude was large. Practically, such a high probability for the crossing motion is preferred, as the transit time of the capsule robot in the small intestine should be as short as possible. In summary, such results can provide essential guidance for the locomotion control of the capsule robot.

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References

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