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A new design for bidirectional autogenous mobile systems with two-side drifting impact oscillator

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ABSTRACT

This paper proposes and validates a new design for autogenous mobile systems based on the combination of vibration and impact of an oscillating mass with two-side elastic constraints. The proposed system is driven by a two-side impact oscillator which is excited by a periodic pulsed force. The system can move backward and forward as desired by simply reverse the excitation force. A mathematical model has been developed to form a basis of the design process and to choose proper operational parameters. An experimental rig has been implemented to validate the proposed design. The mathematical model of the system with non-dimensional parameters allows extending the results to both large- and micro-scale autogenous drifting applications.

1. Introduction

Autogenous mobile systems have been widely employed in both large- and micro-scale sizes. Large scale mobile systems are preferable in remote and hostile environments to disaster rescues or pipeline inspection [1–3] and impact moling [4–6]. For micro-scale, locomotion systems can enhance the capabilities of the capsule endoscopy to deal with the problems of traditional systems such as inability to control and stop, and risk of capsule retention [7]. Of such movable dynamical systems, vibration-driven platforms are a new kind which is propelled by the periodic motion of internal masses or the periodic deformation of their bodies. The vibration-driven locomotion systems have been widely investigated from many aspects, such as modeling and theoretical analysis and control [8–11], design and experimental implementation [12–15]. The common issue of such vibration-driven systems is that, a complex control for the inertial mass motion is necessary to obtain the desired progression of the system. For example, a motion of the inertial mass must consist of four steps to move the capsule forward [8,9,13]. Driving the inertial mass in such way within a restricted dimension of a capsule would be a difficult problem in practice. In addition, the problem for the large-scale mobile platforms would be difficult to miniaturize the platform. A capsule system using vibro-impact device proposed by Liu et al. [16] addressed these issues. A similar mobile mechanism in a large-scale size, which can produce strong impact force for moling machines was also reported [6]. For capsule endoscopy applications, the system abilities for moving forwards and backwards are required. In order to address this issue, a position feedback control method for the vibro-impact capsule system was proposed [17]. By changing the control gain from negative to positive, the system response is transformed from period-one motion with one impact to period one with two impacts, and the direction of motion can change from backward to forward. However, the desired direction of the system motion as well as the motion itself can only be obtained by carefully choosing proper parameters.

This paper proposes a new design for autogenous mobile systems where the backward and forward motion of the system can be easily controlled. A 2-side piecewise-linear impact oscillator working with periodic excitation is employed to drive the whole system. The proposed system is inspired by the one-side drifting oscillator under a harmonic excitation proposed by Pavlovskaia et al. [18]. Several other drifting systems, see e.g. [6,14–17], were deeply scrutinized based on the model involving impacts and friction, as previously proposed in [18]. Recently, Depouhon et al. developed a drifting oscillator for analysis and prediction of percussive drilling. Most of such systems [6,14–16] considered only one-sided drift of motion. The study of two-sided drifting systems, with special emphasis on directional control have been recently investigated by Liu et al. [17] and Chávez et al. [19]. Such systems contain one-side elastic constrain and thus, the compulsory backward motion could only be achieved by suitably varying the oscillation parameters [17,19]. As mentioned in [19], determining the precise parameter values that allow changing the direction of the rectilinear motion is not straightforward, but can be done via dedicated studies of the dynamical response of the system. Other autogenous mobile systems without impact oscillator [8,9,13] could obtain a desired motion through a careful

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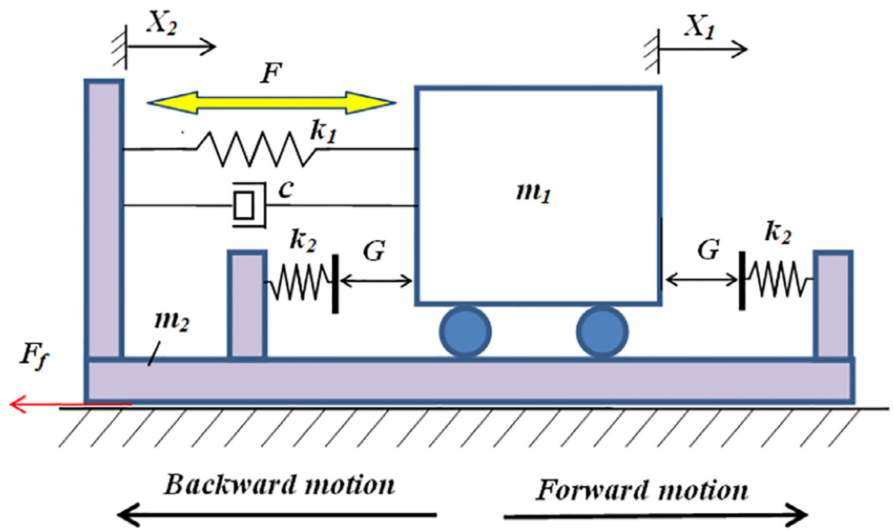

Fig. 1. The physical model.

design of the trajectory of the internal mass. However, the trajectory of the internal mass may be limited by the size of the capsule, leading to complications in practical design, and may also require a complex control strategy, as also mentioned in [19]. The new drifting system in this paper is proposed to address the above issues. The new device contains two-side symmetric constrains and is excited by an impulsed periodic force. As a result, the backward and forward motions can be easily achieved by applying the force in the desired direction.

As developed from the one-side drifting oscillator proposed by Pavlovskaia et al. [18], the proposed device belongs to the class of piecewise-smooth dynamical systems [20], similar to several other previous drifting systems [6,14–16,19]. The ability of obtaining desired motion of the new system is scrutinized numerically and then validated experimentally. A similar experimental study on a base-excited piecewise linear oscillator with symmetrical flexible constrains of high stiffness ratio (above 20), subjected to a harmonic base excitation, was devoted by Wiercigroch and Sin [21]. Nevertheless, the investigated experimental rig is not a drifting device thus is not applicable to the autogenous mobile system.

This paper presents a new design of an autogenous mobile system which can provide desired progressive directions simpler than previous drifting systems. Forward and backward motions can be easily obtained by simply applying the excitation force in the same desired direction. Mathematical model, dynamical response and experimental validation of the new system are also implemented.

The paper is organized as follows. In the next section, physical and mathematical models of the proposed system are briefly described as a basis of the design solution. Section 3 presents the dynamical response of the system under the effect of several key parameters, obtained numerically. An experimental case study is shown in Section 4 to validate the system designed. Lastly, major remarks and recommendations are given.

2. Modeling the new design

2.1. Basic of the design

The proposed design based on a two degrees-of-freedom impact system as depicted in Fig. 1.

A movable mass m_1 is connected with the system frame m_2 by a linear spring with stiffness k_1 and a viscous damper with damping coefficient c. Two rigid obstacle blocks are symmetrically located on both sides of the oscillatory mass m_1 with a predetermined distance G. The positive motion of the frame $X_2 > 0$ is considered as a forward movement. The impact stiffness of the obstacle blocks is simply modeled by a linear spring with stiffness k_2. The inertial mass m_1 is driven by a force F which is generated by a linear actuator. The actuator would be a linear motor, a pneumatic actuator or an electro-dynamic shaker. Hence, the force F is supposed to be an interaction force between the moving part and the body of the actuator and thus exerts on the both masses m_1 and m_2. In the proposed model, the force F is considered as a periodic impulse force with amplitude A and frequency Ω. The excitation amplitude, A is assigned as a positive value if it exerts on the mass m_1 in the forward direction and vice versa. The friction force F_f has direction opposite to the velocity of the frame body.

The hypothesis of the basic principle of the prototype are described as follows. Suppose the excited force has a constant positive amplitude, $A > 0$, i.e. the force exerts on the inertial mass in the forward direction (See Fig. 1). If the excited force is greater than the reaction force of the spring k_1, the inertial mass can be driven and hits the right obstacle block so as to create impacts. The impact force is required for the forward progression of the whole system. The reverse direction of the mass motion after impacting would be facilitated by the reaction force from the obstacle block in duo with the restoring force from the spring k_1. A new cycle of the motion is repeated and a steady oscillation can be realized. It is necessary to switch the force on and off at time intervals, thereby the force acts only to drive the mass forward. An impulse periodic force would satisfy well this requirement. Since $A > 0$, the force has not exerted on the mass in the backward direction, the mass motion would not reach the position of the left obstacle block. As a result, the system would be able to move in forward direction. The excitation frequency is chosen so as to have a harmonious relation with the natural motion of the impact mass.

Since the configuration is symmetric, the backward motion of the system can be obtained in a similar way, by applying an impulse periodic force with a negative amplitude.

The mathematical model is developed to validate this hypothesis.

2.2. Mathematical model

The impulse periodic excited force, F can be defined as

$$F = AH_0(\cos(\Omega t)) \tag{1}$$

where Ω is frequency and A is amplitude of the forcing function; $H_0()$ is the Heaviside function which can be depicted as

$$\begin{cases} H_0 = 1, & \cos(\Omega t) \geq 0 \\ H_0 = 0, & \cos(\Omega t) < 0 \end{cases} \tag{2}$$