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Accurate modeling and analysis of a bio-inspired isolation system: with application to on-orbit capture

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ABSTRACT

The accurate dynamical model of a bio-inspired isolation (BII) system with complete consideration of the kinetic and potential energies of all components is established for the first time. Owing to the inclusion of energies pertaining to the rods and joints in the modeling process, the equations of motion of the accurate BII model are virtually governed by a set of implicit ordinary differential equations (IODEs), which is totally different from the simplified model whose governing equations are standard ODEs. Since the accurate model cannot be transformed into the explicit form, viz. $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t)$, it cannot be handled via the traditional numerical integration methods, e.g. the Runge-Kutta method. In order to conquer this difficulty, the harmonic balance method and the Matlab's ODE15i code are employed to solve the periodic and aperiodic solutions, respectively. More importantly, the comparisons of dynamical responses as well as isolation performance between the accurate and simplified BII models are conducted in two situations. For the situation when system exhibits simple responses, the accurate and the simplified models generate qualitatively the same pattern of results. The only discrepancy is that the latter model produces an overestimated vibration. For the complex responses, an essential distinction occurs between the two models, indicating that using the accurate BII model is extremely important. Furthermore, the efficiency of the BII isolator is verified through comparing with the traditional spring-mass-damper (SMD) system. The influences of system parameters, such as damping, layer number, assembly angle, spring stiffness, etc., on the isolation performance have been investigated. Finally, numerical examples verify the efficiency of the present BII isolator in both ground and space environments.

1. Introduction

Normally, vibrations propagate via mechanical waves and linkages, and are undesirable in many domains [1–4]. To suppress vibration, isolators are required in various practical mechanical systems such as large-scale suspension bridges [5], aeroelastic structures [6–8], pipes that conveying fluids [9–11], on-orbit spacecraft [12,13] and so on. To fulfil this goal, a variety of methods have been developed to prevent vibration sources from transferring to the platform that needs to be stable.

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In general, there are three isolation approaches, namely, the passive, active and semi-active methods. Among them the passive one is the most frequently used, due to the fact that the latter two methods require sensors and actuators to produce destructive interference to cancel out vibrations, hence resulting in a much more complex system. The passive vibration isolation, however, making use of simple parts such as springs, dampers and mechanical linkages to absorb vibrations from the source, gains a growing attention in the past few years due to its simplicity and high reliability. The spring-mass-damper (SMD) isolator is a typical passive control method, which is pioneered by Ref. [14] wherein the properties of the SMD undergoing a variety of impacts were comprehensively analyzed. It is known that increasing the damping value in the SMD system can significantly reduce the vibration amplitude in the neighborhood of the resonant frequency, but may give rise to a stronger vibration beyond the resonant range.

To conquer this limitation, many nonlinear passive isolators have been proposed, where the nonlinearity has been exploited to achieve a better isolation performance. The quasi-zero-stiffness (QZS) isolator, attributed to Ref. [15], is a representative of the nonlinear isolators. Its main characteristic is the ability to show ultra-low stiffness, zero stiffness, and negative stiffness by smartly choosing different system parameters. The QZS isolator has been demonstrated to own a high-static-low-dynamic stiffness property and shows a better performance than the traditional SMD isolator in the neighborhood of the equilibrium point [15]. In addition, the QZS isolator works well in both low and high frequency ranges, and has been applied in many practical engineering problems [16–19]. Nevertheless, the QZS isolator is not robust and is prone to lose stability. Besides, it has a low loading capability at equilibrium point in case of negative stiffness [20], and very complex behaviors such as bifurcation and chaos may happen due to strong nonlinearity [11,21–23].

Recently, inspired by the smooth motions of a running kangaroo, a bio-inspired quadrilateral shape (BIQS) structure[1] (see Fig. 1) is proposed in Ref. [12] to simulate the vibration isolations of a free-floating spacecraft subject to both periodic and impulsive forces. The BIQS structure can be regarded as one of the scissor-like structures or *X*-shaped structures, which exploits the benefits of nonlinear damping and stiffness coming from the geometrical relations among the rods, rotation joints and springs. The development and applications of the *X*-shaped isolation system is attributed to Jing and his coworkers [12,17,24–29]. It is demonstrated that the BIQS isolator overcomes the major drawbacks of the traditional SMD and the QZS isolators. The BIQS isolation system is shown to be superior to the SMD isolator by about 10% in terms of vibration acceleration [12]. Nevertheless, for the sake of brevity the kinetic and gravitational energies[2] are not taken into account in the process of establishing governing equations due to the fact that the masses of the rods and joints are much smaller[3] than that of the platform and capture mechanism. Hence, the dynamical model of the bio-inspired isolation (BII) system in existing literature is essentially a simplified model.

However, a subtle model difference in the nonlinear system may arouse dramatically different responses [30–34]. For example, in Ref. [32], a typical two dimensional airfoil with freeplay nonlinearity undergoing subsonic flow is studied. The comparison of using the fourth-order Runge Kutta method (RK4) model and the accurate RK4Henon model is carried out in the analyses of simple periodic and complex motions. It shows that a very slight cross-over of the freeplay's switching point in RK4 model leads to a significant numerical inaccuracy, which seems to be amplified by the nonlinearity and eventually leads to an entirely different response. In Epureanu et al. [33], a panel forced by a supersonic unsteady flow is numerically investigated using an accurate model and a reduced order model. Structural non-linearity due to the nonlinear coupling between bending and stretching is considered. It was reported that various global characteristics of the dynamics, such as the main attractor governing the dynamics, can be accurately predicted by the reduced order model. However the reduced order model is sensitive to initial conditions in the chaotic regime, produces fake time histories in case of complex responses. Thus, motivated by the aforementioned suggestive results, the importance of using the accurate BII model rather than the simplified model has to be explored.

In the modeling, the equations of motion for the accurate BII model have been established via Lagrange's equations, which turn out to be a set of implicit ordinary differential equations (IODEs). The explicit expression of the IODEs illustrates that the inclusion of the rod mass m_0 and joint mass m_j causes the accurate model to be implicit as opposed to the standard ODEs of the simplified model. Since the traditional numerical integration methods cannot solve the IODEs, in this study, the harmonic balance method in conjunction with a Jacobian-inverse-free solver [35] and the Matlab's ODE15i solver [36] are employed to successfully solve the periodic and aperiodic solutions, respectively. Moreover, the differences of the responses between the accurate and the simplified BII models are thoroughly investigated in the ground environment. In case of simple responses, it is revealed that using the simplified model gives a smaller vibration, indicating that isolation performance predicted by the simplified model is over-estimated. In case of complex responses, the two models show essential distinctions, demonstrating the significant importance of using the accurate model. In addition, the comparison of the isolation performance of the present BII isolator in both ground and space environments are conducted, and very interesting discrepancies are observed between the two cases.

The rest of this paper is organized as follows. The equations of motion of the accurate model are formulated in Section 2. The solution method to the governing implicit ordinary differential equations is introduced in Section 3. Provided in Section 4

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[1] The two solid lines imitate the kangaroo's leg bones. The dotted lines and a spring are added for the purpose of imitating the functions of the tendons and muscles. The collision with the ground is represented by an impulsive force. Note that Fig. 1 is plotted to make the reader clearly understand the proposal background of the BIQS isolation system.

[2] In the ground environment the gravitational energies take effect.

[3] In fact, the rod mass m_0 and the joint mass m_j are about two to three orders of magnitude smaller than that of the capture mechanism m_1 and platform m_2.