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Human body inspired vibration isolation: Beneficial nonlinear stiffness, nonlinear damping & nonlinear inertia

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates, for the first time, a human body inspired anti-vibration structure (HBIAVS) for exploring its vibration isolation potential. The anti-vibration structure HBIAVS consists of an X-shaped supporting structure to simulate legs of human body and a rotational unit with mass to mimic rotational motion of arms and upper body during human walking. The nonlinear property of the HBIAVS can obviously improve the vibration isolation at low frequencies and/or in a broadband frequency range. With mathematical modeling, the influence incurred by different structural parameters on system isolation performance is systematically studied. It is revealed for the first time that, the HBIAVS has passive and very beneficial nonlinear stiffness, nonlinear damping and nonlinear inertia simultaneously and it can achieve a tunable ultra-low resonant frequency and an advantageous anti-resonance characteristic. All these beneficial properties are adjustable with respect to structural parameters, compared with other benchmark vibration isolation systems and validated by experimental results.

1. Introduction

Vibration isolation is often a critical issue in many engineering practices [1]. A typical example can be seen in the suspensions of vehicles, which play a major role in passenger comfort, driver fatigue, and overall vehicle performance. An ideal suspension is expected to achieve good vibration isolation in both low-frequency and broadband frequency range. To meet these different demands, many types of suspension systems are currently employed ranging from conventional spring-damper arrangements to sophisticated active suspensions [2–4]. Passive spring-damper vibration isolation is known for its high reliability, easy implementation and low development cost, while may not be effective for low-frequency or broadband frequency vibration isolation [5–7].

Traditionally, the design and analysis of vibration control are treated with linear system theory/methods. However, several limitations with linear vibration control systems are always encountered. For example, the resonant frequency is often expected to be smaller to achieve better isolation performance. But a smaller resonant frequency implies a smaller system stiffness (or much heavier mass) and thus a lower loading capacity or (a cumbersome system). Thus, nonlinear vibration isolation methods have been developed in several studies, which demonstrate excellent vibration isolation performance in low frequency range with high static stiffness [1,8–18]. These benefits can be achieved by nonlinear stiffness design of an isolation system leading to different nonlinear stiffness properties such as quasi-zero stiffness [1,8–16] and negative stiffness

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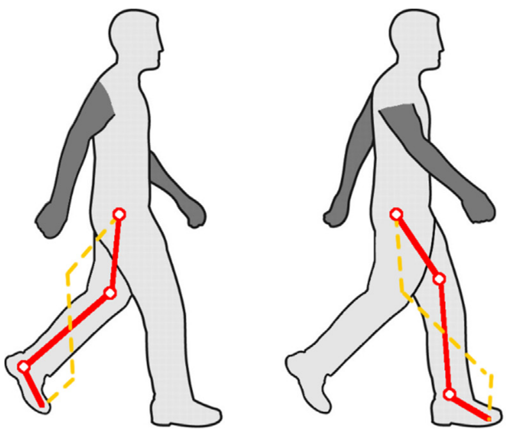
[17,18]. However, complicated nonlinear phenomena could happen, incurring potentially worse stability problems. Active control methods are often used to achieve low frequency and broadband frequency vibration isolation [19–23]. Several active control strategies are proposed to meet the various requirements of low and broadband frequency vibration isolation. However, high energy cost, expensive, actuation saturation, stability issues, and complexity in implementation etc. are still the problems that remain to be solved. Moreover, nonlinear damping characteristics are also shown to be superior to linear counterparts [24–26]. A series of frequency domain studies can be referred to [27–31] with a systematic parametric optimization method for system nonlinearity based on a novel nCOS or OFRF function. These results motivate the investigation of more engineering methods for realization of nonlinear vibration control systems.

Human bodies experience various types of whole-body vibration (WBV) in daily life: most commonly through a vibration surface or while walking, running and jumping [32]. The human body acts as a shock absorber to prevent brain injury caused by the vibration and impact [33]. Consequently, experimental studies of the biodynamic responses to vibration show that human bodies can provide excellent vibration isolation performance both in low and broadband frequencies. The resonance frequency of a human body is pretty low, dependent on various body postures [34]. Particularly, the peaks of transmissibility is even lower than 3 Hz when people stand with the bent knees. Meanwhile, human body is able to attenuate frequencies at 20 Hz and above [35].

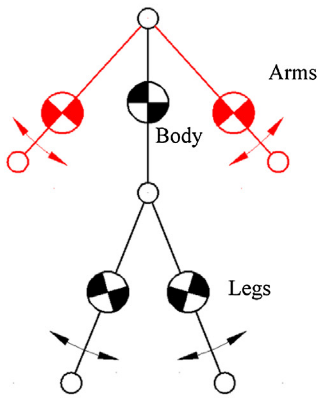
Moreover, human bodies tend to swing arms during walking, which is a curious behavior since the arms play no obvious role in bipedal gait. It might be costly to use muscles to swing the arms, and it is unclear whether potential benefits elsewhere in the body would justify such costs. To examine these costs and benefits, a study on whole-body vertical angular momentum and ground reaction moment when human walking indicates that arms swinging improve the walking stability [36,37]. Among measures of gait mechanics, vertical ground reaction moment is most affected by arms swinging and increased by 63 percent without it. The experimental research [38–40] also shows that arm swinging reduce the vertical displacement of the body center of mass.

The excellent vibration isolation characteristics of human bodies discussed above inspire a novel biomimetic approach to vibration control in this study, which potentially can achieve very good ultra-low-frequency isolation and excellent isolation performance over a broadband frequency range and thus possibly solve the problems as mentioned before Fig. 1. A human body inspired anti-vibration structure proposed in this study can be seen in Fig. 1 and Fig. 2. The novel structure consists of two parts: An X-shaped supporting structure which is to mimic human legs with bent knees; and a rotational disc or leverage which is to imitate the rotational motion of upper body or arms during human walking. The layout of the proposed anti-vibration system is shown in Fig. 2. The inherent structure nonlinearity of the proposed system is explored for superior low and broadband frequency vibration isolation performance.

In this paper, the human body inspired passive vibration isolation system is systematically studied for its nonlinear dynamic characteristics and special structural coupling effects. With mathematical modeling, analytical analysis and experimental validation, it is shown that (1) the novel human body inspired anti-vibration structure has beneficial nonlinear stiffness, nonlinear damping and nonlinear inertia simultaneously; (2) all nonlinear properties in stiffness, damping and inertia are adjustable via several easy-to-tune structural parameters and consequently lead to ultra-low resonant frequency and satisfactory transmissibility over a broadband frequency range; (3) the nonlinear rotational inertia can be employed to achieve a lower resonant frequency, a beneficial anti-resonance property and a tunable nonlinear damping property simultaneously, which are all advantageous to passive vibration control; (4) the inertia incurred nonlinear damping is purely produced by the rotational unit due to nonlinear coupling effect and has never been reported in the literature.



(a) Legs and arms motion [37]



(b) Lumped element model of human body

Fig. 1. Human body motion during walking.