博士学位论文

（学术学位）

电磁双稳态隔振机制及低频调控方法研究

Research on Electromagnetic Bistable Vibration Isolation Mechanism and Low-frequency Regulation Methods

学科专业： 机械工程

完成日期：二〇二三年十二月

摘　要

有害振动会使航天装备稳定性变差、安全性降低，甚至永久损坏。随着以空间卫星天线为代表的航天装备向大型化和低刚度方向发展，其工作时引起的低频振动问题变得更为突出，尤其是 10Hz 以下的振动。为了保障航天装备的动态性能，应采取减隔振方法将振动控制在合理范围内。传统线性隔振系统的隔振频率受自身刚度限制，无法适用于低频隔振。准零刚度隔振系统具有高静低动刚度特性，可以平衡系统承载和隔振带宽之间的关系，但其仍然存在大幅复杂激励适应性不强、微幅下隔振性能差等问题。双稳态结构存在阱间和阱内两种运动模式，可为大幅和微幅激励下系统隔振性能的提升提供解决方案。然而，双稳态系统中的负刚度引起的隔振特性变化规律尚不清晰，双稳态隔振方法的低频隔振品质提升机理尚不明确，导致低频隔振理论难以取得突破。

针对以上问题，本研究建立了双稳态隔振系统的动力学模型，提出了电磁式双稳态隔振器的构型设计方法，揭示了双稳态隔振系统的低频隔振调控机理。论文的主要研究内容如下：

（1）建立了基于“三弹簧”结构的一般双稳态系统模型，推导了非线性恢复力和势能函数的表达式。建立了双稳态模型的动力学方程，推导了双稳态隔振系统的力传递率和位移传递率。通过解析解和数值解求解了双稳态隔振系统在高阶恢复力下的位移传递率，揭示了双稳态隔振系统的“谷”值响应机理。最后，也利用随机振动仿真分析证明了双稳态隔振系统理论模型的正确性。

（2）设计了一种具有轴向不对称永磁体的电磁式双稳态隔振器，对隔振器中的磁刚度模型进行了建模、仿真和测试。基于谐波平衡法推导了电磁双稳态隔振器的幅频响应方程，并分析了系统的复杂动力学行为。研制了电磁双稳态隔振器样机，设计了试验系统，验证了其多种运动模式（阱内运动、阱间运动、混沌运动等），同时也测试了其具备良好的隔振性能。

（3）建立了基于电磁分支电路的阻尼设计准则，将负电阻电磁分支电路阻尼振动控制方法引入至电磁双稳态隔振器。建立了基于负电阻电磁分支电路阻尼调控的电磁双稳态隔振器的力-电-磁耦合模型，阐明了参数对双稳态系统隔振特性以及动力学行为的调控规律。研究表明，电磁分支电路阻尼振动控制方法可以有效调控电磁双稳态隔振器的振动响应，抑制双稳态系统中可能会存在的不稳定动力学行为。对基于电磁分支电路阻尼的电磁双稳态隔振器隔振特性进行了试验研究，验证了负电阻调控的有效性。

（4）提出了电磁双稳态杠杆隔振器的质量调控方法。基于系统等效质量高效调控和能量耗散准则，优化了电磁非线性杠杆式隔振器中杠杆结构和磁耦合元件配置关系，进一步实现隔振品质提升。利用能量法建立了电磁非线性杠杆式隔振器的理论模型，研究了系统参数对电磁非线性杠杆隔振器隔振性能的影响规律。推演至电磁双稳态杠杆隔振系统模型的建立和幅频响应方程的求解，研究了电磁双稳态杠杆隔振器在不同参数下的隔振性能影响规律，杠杆结构可调控隔振器从阱间运动回到阱内运动，揭示了杠杆结构在双稳态隔振器中的低频隔振调控机理。

（5）研究了基于杠杆吸振结构的吸隔一体化双稳态隔振系统的调频方法。提出了基于杠杆吸振结构的吸隔一体化非线性隔振器设计方法，推导了其运动响应方程，研究了参数对隔振系统的影响规律。随之将研究拓展到吸隔一体化双稳态隔振器设计方法，对其进行了模型验证和参数分析。隔振系统传递率曲线的第二个峰所对应的频率随着杠杆比的增加向低频区域移动，高频区域的隔振性能也得到了提高，隔振带宽得到拓宽。利用动力学分析讨论了势能阱对吸隔一体化双稳态隔振器的隔振性能调控规律，进一步揭示了其低频隔振机理。

总之，本文建立了基于“三弹簧”结构的一般双稳态系统模型，提出了一种具有轴向不对称永磁体的电磁双稳态隔振器，建立了电磁双稳态隔振器的阻尼设计方法，发展了双稳态隔振器的杠杆质量调控研究，并阐明了基于杠杆吸振结构的吸隔一体化双稳态隔振器的调频规律。本研究丰富了低频非线性隔振理论，为双稳态隔振调控方法的实际应用提供理论基础和技术支撑，推动了非线性隔振技术发展。

关键词：非线性振动；双稳态；负刚度；低频隔振；电磁式隔振

Abstract

Detrimental vibrations can compromise the stability and safety of aerospace equipment, potentially leading to permanent damage. As space satellite antennas evolve towards larger scales and lower stiffness, the issue of low-frequency vibrations, especially those below 10 Hz, becomes increasingly pronounced. To ensure the dynamic performance of aerospace equipment, vibration isolation methods are essential to keep vibrations within manageable limits. Traditional linear isolation systems, constrained by their inherent stiffness, are ineffective for low-frequency isolation. Quasi-zero stiffness isolation systems, characterized by high static and low dynamic stiffness, can balance the load-bearing capacity and vibration isolation bandwidth. However, they still face challenges such as poor adaptability to large amplitude complex excitations and subpar performance in isolating minute vibrations. There are two modes of motion in the bistable system: inter-well and intra-well, which can provide a solution for the improvement of the vibration isolation performance under large-scale and micro-amplitude excitation. However, the vibration isolation characteristics induced by negative stiffness in bistable systems are not yet clearly understood, and the mechanism behind the improvement of low-frequency vibration isolation quality using bistable isolation methods remains unclear, hindering breakthroughs in low-frequency vibration isolation theory.

To address the above issues, this study establishes the dynamics model of the bistable vibration isolation model, proposes the electromagnetic bistable vibration isolation configuration design method, and reveals the low-frequency vibration isolation regulation mechanism of the bistable vibration isolation system. The main research contents of the thesis are as follows:

A general bistable system model based on the "three-spring" structure is established, and expressions for the nonlinear restoring force and potential energy functions are constructed. The dynamic equations of the bistable model are solved. The force transmissibility and displacement transmissibility of the bistable vibration isolator are derived. The displacement transmissibility of the bistable vibration isolation system under the higher-order restoring force is solved, and the "valley" response mechanism of the bistable vibration isolation system is revealed. Finally, the correctness of the theoretical model of the bistable vibration isolation system is also proved by random vibration simulation analysis.

An electromagnetic bistable vibration isolation model with axially asymmetric permanent magnets is designed. The magnetic stiffness model in the vibration isolation system is modelled, simulated and tested. The harmonic balance method is used to solve the amplitude-frequency response relationship of the electromagnetic bistable vibration isolation system, and the dynamics and bifurcation analyses of the vibration isolation system are carried out to reveal its bistable characteristics. The correctness and tunability of the electromagnetic bistable vibration isolation system model are verified by experiments. Various motion modes (intra-well motion, inter-well motion, chaotic motion) are tested, and its vibration isolation performance is also tested.

Damping design guidelines based on nonlinear electromagnetic shunt damping are established. The damped vibration control method of nonlinear electromagnetic shunt damping is introduced to the electromagnetic bistable vibration isolation system. The force-electric-magnetic coupling model of electromagnetic bistable system based on nonlinear electromagnetic shunt damping is established. The parameter regulation of the vibration isolation characteristics and dynamic behaviors of the bistable system is elucidated. The nonlinear electromagnetic shunt damping vibration control method can effectively control the vibration pattern of the electromagnetic bistable vibration isolation system and suppress the unstable dynamic behaviors that may exist in the bistable system. The vibration isolation characteristics of the electromagnetic bistable system based on nonlinear electromagnetic shunt damping are experimentally investigated, and the effectiveness of negative resistance is verified.

An equivalent mass control method for electromagnetic bistable lever-type vibration isolation systems is proposed. The configuration of the lever structure and the magnetic coupling element is optimized. The equivalent mass control and energy dissipation of the system can be realized synchronously to further improve the vibration isolation performance. The theoretical model of electromagnetic nonlinear lever-type vibration isolation system is established by energy method. The influence of system parameters on the vibration isolation performance of the electromagnetic nonlinear lever-type vibration isolation system is investigated. Then, the electromagnetic bistable lever-type vibration isolation method is deduced. The influence of electromagnetic bistable lever-type vibration isolation system on the vibration isolation performance under different parameters is investigated. The lever structure can regulate the motion of the vibration isolation system from the inter-well motion back to the intra-well motion. The low-frequency vibration isolation regulation mechanism of the lever structure in the bistable vibration isolation system is revealed.

The frequency modulation method of bistable combined vibration isolation technology based on lever-type absorber is investigated. A design method of nonlinear combined vibration isolation system is proposed based on the lever-type absorber. The equivalent two-degree-of-freedom motion response equations of the nonlinear combined vibration isolation system are derived. The effects of parameters on the nonlinear combined vibration isolation system are investigated. The study is then extended to the bistable combined vibration isolation method, for which model validation and parametric analysis are carried out. The corresponding frequency to the second peak of the transmissibility curve of the vibration isolation system is shifted to the low-frequency region with the increase of the lever ratio. The dynamics analysis is used to discuss the regulation of the vibration isolation performance method for the bistable combined vibration isolation system by the potential energy well, which further reveals its low-frequency vibration isolation mechanism.

In conclusion, this paper establishes a general model of bistable system based on "three-spring" structure. An electromagnetic bistable vibration isolator with axially asymmetric permanent magnets is proposed. The damping design method of electromagnetic bistable vibration isolation system is studied. The lever regulation study of the bistable vibration isolator system is developed. And the bistable combined vibration isolation system based on lever vibration absorbing structure is studied. This study enriched the theory of low-frequency nonlinear vibration isolation, provided theoretical basis and technical support for the practical application of the bistable vibration isolation regulation method and to promote the development of nonlinear vibration isolation technology.

Keywords: Nonlinear vibration; Bistable; Negative stiffness; Low-frequency isolation; Electromagnetic vibration isolation