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基于协同边界调控的载荷可调式准零刚度隔振器

摘要

准零刚度（QZS）隔振器在低频隔振方面具有显著优势，但其工程应用往往受限于对承载载荷的高度敏感性。针对这一问题，本文提出了一种基于协同边界调控的额定载荷可调式准零刚度隔振器。该隔振器由特定构型的曲梁与集成调节机构组成，可实现额定载荷的连续调节。通过协同调控曲梁端部的横向位移和转角，隔振器的准零刚度特性能够被重构，从而适应设计范围内的任意载荷。

本文首先采用非线性有限元分析，揭示边界条件对曲梁载荷-位移特性的协同影响机制；随后建立多目标优化设计策略，在满足预设载荷调节需求的同时兼顾结构强度约束。优化算例表明，该隔振器能够在一定载荷范围内通过结构重构保持准零刚度特性，例如优化设计可覆盖名义载荷 50% 至 150% 的变化范围。进一步地，本文开展了非线性动力学分析，评估不同边界条件和载荷工况下的隔振性能，结果表明协同边界调控能够有效恢复系统的低频隔振能力。最后，本文制作了 3D 打印样机，并通过静态和动态实验进行了验证。实验结果表明，借助额定载荷调节策略，该隔振器在三种显著不同载荷下均能保持基本一致的低截止频率。所提出的准零刚度隔振器兼具结构紧凑性、被动可靠性和载荷适应性，可为复杂工程环境中的高性能低频振动控制提供一种有效方案，尤其适用于有效载荷难以精确预测的应用场景。

关键词

准零刚度隔振器；低频振动隔离；非线性动力学；曲梁；额定载荷调节；边界条件调控

Abstract

Quasi-zero-stiffness (QZS) vibration isolators offer a superior solution for low-frequency vibration isolation; however, their application remains constrained by an inherent sensitivity to the supported load. To address this limitation, this paper proposes a novel QZS isolator comprising specifically shaped curved-beams and integrated regulation mechanisms to achieve a continuously tunable rated load. Through the synergistic regulation of the lateral displacement and the rotation angle at the curved-beam boundaries, the isolator's QZS characteristic can be reconfigured to accommodate arbitrary payloads within a design range. The research first employs nonlinear finite element analysis to elucidate the synergistic effects of boundary conditions on load–displacement characteristics of the curved-beam. Subsequently, a multi-objective optimization strategy is developed for designing the curved-beam, aiming to satisfy the predefined load-tuning requirements while adhering to strength constraints. In the optimization case presented herein, the isolator can be reconfigured to maintain QZS characteristics across a payload range–as exemplified by an optimized design spanning 50\% to 150\% of the nominal load. Nonlinear dynamic analysis is further conducted to evaluate the isolation performance under different boundary conditions and payloads, demonstrating the effectiveness of the synergistic regulation in restoring system performance. Finally, a 3D-printed prototype was fabricated and validated through comprehensive static and dynamic experiments. The results demonstrate that the isolator maintains a consistent low cut-off frequency under three significantly different loads through the rated-load tuning strategy. The proposed QZS isolator offers a compact and robust solution for high-performance passive vibration control in complex engineering environments, with its QZS characteristic reconfigurability ensuring practical viability in scenarios where precise payload prediction is challenging.

Keywords

Quasi-zero-stiffness isolator; Low-frequency vibration isolation; Nonlinear dynamics; Curved-beam; Rated-load tuning; Boundary-condition regulation

Authors: 宸, 张 (清华大学); Mr 华航, 许 (清华大学); 笑天, 李 (清华大学); 永鹏, 顾 (清华大学)

Presenter: 宸, 张 (清华大学)

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