

<https://doi.org/10.69646/1csst07>

LOW-FREQUENCY BROADBAND VIBRATION ISOLATION OF AEROSPACE STRUCTURES BASED ON METASTRUCTURES

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ABSTRACT

Vibration is a major factor that degrades critical performance metrics of high-precision spacecraft, including pointing accuracy and imaging quality. At present, major aerospace platforms represented by high-resolution Earth observation satellites and crewed space stations are in urgent need of effective vibration suppression solutions. Owing to the constraint imposed by the mass law, it remains highly challenging to achieve broadband low-frequency vibration isolation while simultaneously maintaining lightweight and compact structural designs. In recent years, metastructures have attracted extensive attention because they can exhibit unconventional mechanical properties that are unattainable in conventional structures. However, most existing metastructures are still based on linear systems, which generally result in relatively narrow operating bandwidths and increased structural mass, thereby limiting their applicability in lightweight systems requiring broadband vibration attenuation. Consequently, recent research has increasingly turned to nonlinear engineered systems, whose rich dynamic characteristics offer new opportunities to realize unconventional wave phenomena and overcome the inherent limitations of their linear counterparts.

First, we propose a forward design and optimization strategy for a monolithic quasi-zero-stiffness (QZS) unit cell without negative-stiffness compensation. By assembling different QZS unit cells in series and parallel,

we construct one- to three-dimensional metastructures that combine broadband low-frequency vibration isolation, load-bearing capability, and lightweight integration. Experiments show up to 90% vibration suppression above 60 Hz with only a 4.5% mass increase. Vibration isolation tests on a spacecraft control moment gyro (CMG) further demonstrate up to 90% isolation over 100–600 Hz, confirming the potential of the proposed 3D QZS metastructure for lightweight and compact broadband isolators.

Second, we investigate broadband vibration attenuation in nonlinear locally resonant metastructures. Unlike linear systems with narrow bandwidths and adjacent resonance peaks, hardening and softening nonlinearities can markedly broaden the attenuation band, achieving nearly twice the bandwidth of the linear counterpart. We further develop a continuous microstructural design with tunable nonlinearity, where different nonlinear behaviors can be switched through a single geometric parameter. Experiments confirm amplitude-dependent broadband attenuation. To further suppress resonance peaks, we design a nonlinear metastructures with two-degree-of-freedom resonators, which preserves the broadband bandgap while introducing an additional tunable low-frequency attenuation region. Its effectiveness is verified experimentally on an air-track platform.

These results establish new design routes for lightweight broadband low-frequency vibration isolators and demonstrate strong potential for aerospace engineering applications.