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Exploring Cutting-Edge Technologies for Low-Frequency Broadband Vibration Isolation in High-End Equipment

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Abstract: With the development of high-end equipment towards higher precision, stability and integration, environmental vibration has become a significant factor restricting system performance. Traditional linear vibration isolators rely on fixed stiffness and damping parameters, and their vibration isolation effect is limited by the natural frequency: to achieve a lower vibration isolation starting frequency, the support stiffness must be reduced, but this leads to increased static deflection, decreased load-bearing capacity and deteriorated attitude stability, thus forming a typical "low-frequency vibration isolation - static load-bearing" contradiction. In recent years, nonlinear vibration isolation technology has provided a new path to break through the performance boundaries of linear vibration isolation by introducing geometric nonlinearity, magnetoelastic coupling, buckling flip structures and nonlinear energy transfer mechanisms; among them, the QZS vibration isolator can maintain a high static stiffness and load-bearing capacity while making the equivalent dynamic stiffness near the equilibrium point approach zero, significantly reducing the system's natural frequency and improving low-frequency vibration isolation performance. At the same time, bionic vibration isolators, by imitating the hierarchical compliance and multi-path energy dissipation characteristics of biological structures, have shown unique advantages in lightweight, robustness and working condition adaptability.

1. Introduction

With the continuously escalating stability demands of semiconductor lithography/inspection tools, space optical payloads, inertial navigation systems, ultra-precision machining platforms, and quantum metrology devices, vibration isolation has become a cornerstone technology in precision engineering and structural dynamics. In practical operating environments, disturbances are increasingly characterized by low-frequency dominance (0.5–10 Hz), six-degree-of-freedom (6-DoF) coupling, broadband randomness, and pronounced uncertainty caused by load variations, thermal drift, structural aging, and assembly imperfections [1]. Conventional linear isolators rely on lowering the natural frequency while maintaining sufficient damping within the isolation band; however, for ultra-low-frequency isolation they face a fundamental trade-off—enhancing load-bearing capacity and static stability typically requires higher stiffness, which raises the isolation onset frequency and leads to substantial transmission of low-frequency vibrations—thereby limiting the capability of purely linear spring–damper architectures for next-generation high-end systems [2]. To overcome this limitation, nonlinear vibration isolation leverages nonlinear restoring forces and/or nonlinear dissipation to improve low-frequency performance and broaden the effective isolation bandwidth without a proportional loss of static support [3]. Representative strategies include geometric nonlinearities (e.g., linkages, scissor mechanisms, arc springs, and compliant structures) that yield softening/hardening or piecewise force–displacement characteristics [4], magnetoelastic coupling that enables tunable negative-stiffness compensation, buckling and snap-through (flipping) mechanisms that create near-zero-stiffness regions or energy wells for enhanced isolation and impact mitigation [5], and nonlinear energy transfer via nonlinear energy sinks (NES) for broadband vibration suppression [6]. Among these approaches, quasi-zero-stiffness (QZS)/high-static–low-dynamic-stiffness (HSLDS) isolators have received sustained attention because positive–negative stiffness compensation can render the equivalent dynamic stiffness near equilibrium close to zero, substantially reducing the natural frequency while preserving load-bearing capability through the static stiffness pathway; typical implementations include inclined-spring configurations, X-shaped mechanisms, cam–roller compensation, magnetic negative-stiffness modules, and origami/metamaterial-inspired units [7]. Nevertheless, the majority of existing QZS studies remain concentrated on single-DOF or predominantly vertical isolation, whereas realistic disturbances are inherently multi-directional and coupled; unidirectional QZS designs may therefore fail to satisfy lateral/rotational requirements and can even amplify attitude errors. This has motivated growing interest in multi-directional QZS (M-QZS) platforms—often realized within parallel-mechanism frameworks (e.g., Stewart platforms) by embedding QZS units across multiple branches—yet their practical deployment introduces additional challenges, including multi-axis stiffness matching, workspace maintenance, avoidance of nonlinear instabilities, mitigation of friction/clearance effects, and system-level reliability assessment [8].

2. Development and Limitations of Traditional Linear Isolators

2.1 Basic Models and Isolation Performance Metrics of Linear Isolators

Traditional linear vibration isolators typically consist of linear elastic elements (metal springs, rubber, air springs, etc.) and linear damping elements (viscous dampers, material internal damping, etc.). For the most basic single-degree-of-freedom base excitation model, where load displacement is denoted as X and base displacement as Y, the equation can be written as:

$$m\ddot{x} + c(\dot{x} - \dot{y}) + k(x - y) = 0 \tag{1}$$

Where m is the equivalent mass, k is the linear stiffness, and c is the damping coefficient. Its natural frequency and damping ratio are:

$$\omega_n = \sqrt{k/m}, \qquad \zeta = \frac{c}{2\sqrt{km}} \tag{2}$$

The most commonly used indicator in engineering is the vibration transmission ratio. When the system operates at a ratio $r = \omega/\omega_n$ (where ω is the excitation frequency and ωn is the natural frequency) sufficiently large, the transmission ratio becomes significantly less than 1, entering the effective vibration isolation zone. To balance resonance peak suppression and damping zone attenuation, the damping ratio is typically set in the range of 0.05 to 0.2. Insufficient damping leads to excessively high resonance peaks, while excessive damping raises the transmission ratio in the damping zone, degrading high-frequency isolation performance.

2.2 Typical Linear Isolator Types and Engineering Characteristics

Linear isolators can be categorized by their load-bearing medium and implementation method into rubber/elastomer, metal spring/wire rope, air spring/air-bearing platform, and active/semi-active isolation systems. Rubber isolators feature simple structures, low cost, and easy molding. They rely on material internal dissipation for damping and can attenuate resonance peaks. However, their temperature sensitivity, creep, and aging cause stiffness drift and performance degradation. Additionally, their inherent frequency limitations make them unsuitable for ultra-low-frequency isolation requirements. Metal spring isolators offer a wide linear range, high load-bearing capacity, and excellent durability, making them ideal for industrial foundations and heavy-load applications. Wire rope isolators combine elasticity with frictional energy dissipation, offering outstanding shock resistance. They are commonly used in naval vessels, military equipment, and transportation systems with impact environments. However, metal spring systems also face the trade-off between "reducing stiffness versus increasing static deflection." Achieving lower natural frequencies typically requires larger installation spaces and greater stroke allowances. Air springs utilize gas compression for elasticity, enabling low natural frequencies and high adjustability. They are commonly used for vibration isolation in precision machine tools, testing platforms, and optical equipment. However, the system relies on air sources and valve circuits, featuring complex structures and sensitivity to leaks and temperature drift. In multi-directional coupling conditions, attitude control and lateral constraints are also required. Active and semi-active isolation employ sensor-controller-actuator closed-loop suppression to significantly enhance low-frequency performance. Semi-active systems (e.g., variable damping) offer greater engineering feasibility, though both require power and control systems. In aerospace, high-radiation, or high-reliability applications, purely passive solutions retain advantages. Consequently, developing passive isolators with superior low-frequency and multi-directional performance remains a fundamental and critical research focus.

2.3 Fundamental Contradictions and Performance Boundaries of Linear Vibration Isolation

The fundamental limitations of linear vibration isolators can be summarized as follows:

(1) The starting point for low-frequency isolation is determined by the natural frequency. To lower the isolation starting frequency, ω_n must be reduced, which requires either decreasing stiffness k or increasing mass m.

(2) The contradiction between static deflection and load-bearing capacity. Under static load W, the static deflection δ of a linear spring is $\delta = W/k$. Reducing k to lower the natural frequency increases δ, leading to increased installation space requirements, amplified attitude errors, and reduced safety margins.

(3) The damping trade-off between resonance amplification and elevation of the isolation zone. Higher damping lowers resonance peaks but increases high-frequency transmission in the isolation range; lower damping improves high-frequency isolation but may produce unacceptable resonance peaks.

(4) Multidirectional coupling issues. Real-world systems often exhibit six-degree-of-freedom coupling. A linear unidirectional isolator may be effective in one direction but generate new resonance modes or coupling amplification in lateral/rotational directions.

(5) Parameter drift. Material aging, temperature variations, and load changes can cause stiffness and damping to deviate from design points, rendering isolator performance unpredictable.

These limitations make it challenging for traditional linear isolation to simultaneously meet the combined demands of “low frequency + heavy load + multidirectional” applications. This directly drives the development of nonlinear isolation and QZS/HSLDS approaches.

3. Theory and Types of Nonlinear Isolators

3.1 Descriptive stats Fundamental Concepts and Dynamic Description of Nonlinear Isolation

The core principle of nonlinear isolators is to ensure that the restoring force or dissipation energy no longer follows a linear relationship. A typical representation is expressed as:

$$m\ddot{z} + c\dot{z} + f(z) = F(t) \tag{3}$$

Here, z = x − y represents the relative displacement, and f(z) denotes the nonlinear restoring force. A common polynomial approximation is the Duffing model[9]:

$$f(z) = kz + \alpha z^3 \tag{4}$$

When $\alpha < 0$, the material exhibits softening nonlinearity (slightly softer, more conducive to low-frequency vibration isolation). When $\alpha > 0$, it exhibits hardening nonlinearity (significantly stiffer, enhancing large-amplitude stability but potentially causing jumps and frequency response bending). Additionally, practical engineering nonlinearities may manifest as:(1) Segmented stiffness (caused by gaps/end stops);(2) Friction/dry friction (Coulomb friction);(3) Magnetic nonlinearity (exponential/fractional characteristics);(4) Buckling/flip-flop (bistable or multistable potential energy);(5) Nonlinear damping (e.g., velocity-squared, hysteretic energy dissipation).

3.2 Geometrically Nonlinear Isolators

Geometrically nonlinear isolators create regions of low equivalent stiffness within small displacement ranges through configuration changes. Common structures include: arc springs, compliant beams, scissor/link mechanisms, and X-shaped mechanisms. Among these, X-shaped isolators feature crossed links as their core component. As shown in Figure 1, Yang et al. [10]proposed a geometric nonlinear isolation structure based on a symmetrical geometric arrangement. This design incorporates nonlinear compliant characteristics while maintaining vertical load-bearing capacity, enabling the system to achieve low equivalent stiffness near the equilibrium position. It stands as one of the representative solutions in the research of geometric nonlinear quasi-zero stiffness isolation.

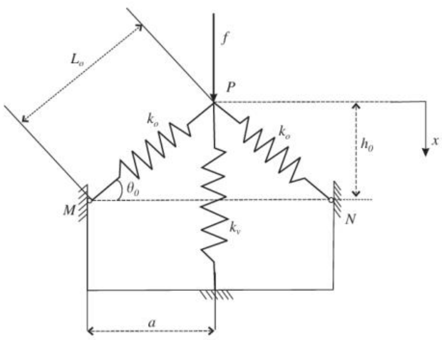

Figure 1: Schematic Diagram of the Three-Spring Structure

The advantages of geometric nonlinear isolators lie in their relatively intuitive structure, designable parameters, and ease of integration with traditional springs. However, their disadvantages include sensitivity to assembly errors, the presence of lateral forces and additional torques caused by geometric coupling, and the potential for hardening/instability at large amplitudes, necessitating the use of damping and limiting strategies.

3.3 Magnetoelastic Coupling and Magnetic Negative Stiffness Nonlinear Isolators

Magnetic components can generate strong nonlinear forces within a small displacement range, serving as a key means for achieving negative stiffness compensation and tunable vibration isolation. A typical approach involves superimposing a negative stiffness channel formed by magnetic repulsion/attraction onto a positive stiffness spring load path, enabling the system to exhibit near-zero equivalent dynamic stiffness near the equilibrium point.

As shown in Figure 2, Wang et al.[6] schematic of this three-dimensional isolator unit comprises upper and lower permanent magnet pairs, a central positive-stiffness spring, and a guiding constraint mechanism. The repulsive magnetic force between the permanent magnet rings provides an equivalent negative stiffness component under vertical displacement, which compensates for the positive stiffness provided by the central spring. This creates a quasi-zero stiffness operating zone near the static equilibrium position. By adjusting the spacing between magnetic rings, magnet dimensions, and magnetization intensity, the negative stiffness characteristics can be effectively modified to regulate the system's nonlinear mechanical response. This structure offers advantages such as minimal contact, low wear, compact design, and parameter adjustability, making it suitable for low-frequency vibration isolation applications.

This paper adopts the double-difference model as the main effect model, and takes the 2018 R&D expense deduction policy as an exogenous shock. The details are as follows:

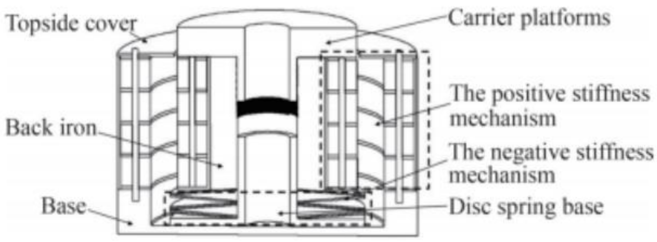

Figure 2: Cross-sectional schematic of the QZS isolator

3.4 Buckling/Flip Structures and Origami/Metamaterial Nonlinear Vibration Isolation

Buckling and flip structures exhibit negative or near-zero stiffness within specific displacement ranges, representing a key approach for constructing QZS/HSLDS. In recent years, origami structures and metamaterials have also been incorporated into isolator designs, primarily leveraging their programmable geometric nonlinearity and multiscale mechanical responses.

As shown in Figure 3, origami QZS Unit: The figure below illustrates a three-dimensional unit inspired by Kresling origami. Its key feature is the formation of a designable nonlinear mechanical curve through the coupling of torsional and axial deformation, offering potential for lightweight, foldable, and tunable vibration isolation units[11].

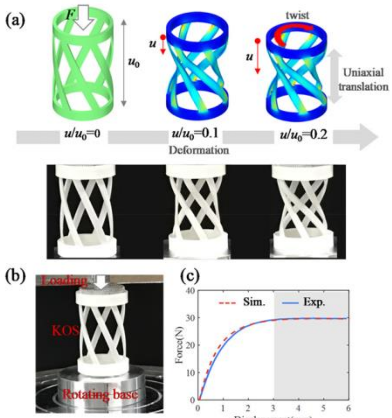

Figure 3: Three-dimensional model of an origami-inspired structure

As shown in Figure 4, QZS Metamaterial Lattice: The figure below illustrates a novel quasi-zero stiffness (QZS) metamaterial proposed by Liu et al.[12] based on a topological design combining positive and negative stiffness elements, achieving multifunctional integration of vibration damping and energy absorption. Composed of a periodic array of quasi-zero stiffness units, the material achieves low equivalent stiffness and broadband low-frequency vibration isolation at the macroscale through meticulous design of unit geometry (e.g., shell structures, curved beams, or arched components). The arrayed units not only create vibrational bandgaps at specific frequencies to suppress wave propagation but also integrate with energy absorption mechanisms. This enables synergistic optimization of vibration isolation and energy dissipation, making it suitable for lightweight and multifunctional vibration control applications.

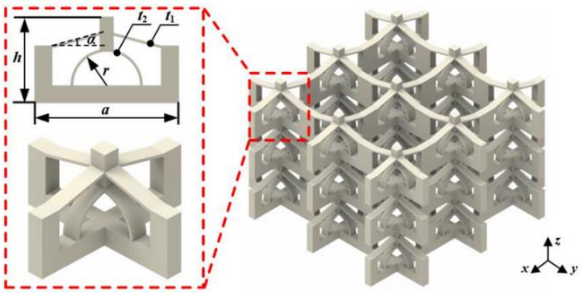

Figure 4: Three-dimensional model of a near-zero stiffness metamaterial isolator

3.5 Cam-Roller, Lever, and Mechanism-Based "Customizable Force-Displacement Curve" Isolators

Mechanism-based isolators generate target restoring force curves through the geometric relationships of moving pairs, exemplified by cam-roller compensation structures. Their core advantage lies in achieving "customizable" force-displacement relationships via cam profiles, enabling more precise construction of the quasi-zero stiffness (QZS) zone, control over nonlinearity levels, and expansion of effective working stroke.

As shown in Figure 5, Cam-Roller QZS[13] Compensation: The figure below depicts a cam-roller quasi-zero stiffness isolator primarily composed of upper/lower bases, a central positive stiffness spring, a cam-roller mechanism, and guiding constraint components. The system's vertical load-bearing capacity is primarily provided by the central spring. The cam profile's geometry is specifically designed to induce a nonlinear displacement-force relationship during roller tracking, thereby introducing an equivalent negative stiffness component in the axial direction. By paralleling the negative stiffness generated by the cam-roller mechanism with the positive stiffness of the spring, the system forms a quasi-zero stiffness operating zone near the static equilibrium position. A key feature of this isolator type is its highly tunable nonlinear mechanical characteristics. Adjusting cam profile parameters precisely controls the equivalent stiffness curve, making it suitable for applications demanding both low-frequency isolation performance and parameter controllability.

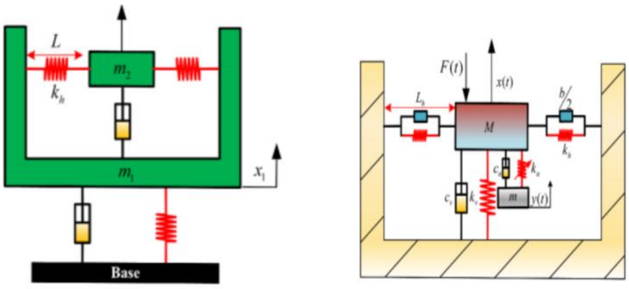

Figure 5: Planar Model of a Nonlinear Energy Transfer Isolator

3.6 Analysis Methods and Design Process for Nonlinear Isolators[14]

Common analysis and design approaches for nonlinear isolators include:(1) Harmonic balance method/incremental harmonic balance method: Suitable for steady-state periodic response and amplitude-frequency characteristic analysis;(2) Multiscale method/averaging method: Used for weak nonlinearity approximation and analytical expression;(3) Numerical continuation: Employed for bifurcation tracking and stability boundary identification;(4) Comparison of time-domain integration with sweep experiments: Used to validate multistable states and jump phenomena;(5) Parameter optimization: Multi-objective optimization targeting peak transfer ratio, isolation onset frequency, QZS band width, attitude error, etc.typical engineering workflow generally follows: Configuration selection → Modeling (including nonlinear restoring force/damping identification) → Steady-state response and stability analysis → Parameter optimization → Prototype validation testing (frequency sweep, random, impact) → Reliability and drift assessment (temperature/load cycling).

4. Development of Bionic Isolators

4.1 Design Philosophy and Mechanical Principles of Bionic Isolators

Bionic isolators draw inspiration from the evolutionary adaptations of biological structures in complex loading and vibration environments. Numerous biological structures—such as insect legs, mammalian joints, bamboo joints, and spinal columns—exhibit distinct hierarchical features, nonlinear compliance, and multi-path energy dissipation capabilities. These enable effective attenuation of external disturbances while maintaining load-bearing and motion capabilities. From a mechanical perspective, biomimetic vibration isolation does not involve simple replication of biological forms but rather abstracts their core mechanisms, including: Hierarchical compliant structures: Through series-parallel connections of multi-level components, the system's equivalent stiffness varies with deformation amplitude; Multi-path energy dissipation: Different components participate in vibration responses across distinct frequency bands, creating dispersed energy dissipation; Geometric-material nonlinear coupling: Nonlinear restoring forces and damping characteristics are jointly shaped by geometric configurations and material internal dissipation. These features endow biomimetic isolators with robust performance and adaptability despite their structural simplicity, establishing a new design paradigm for low-frequency broadband vibration isolation[15].

4.2 Typical Bionic Isolation Structures

Bionic Multi-Joint and "Leg-Like" Isolation Structures: Bionic multi-joint isolators typically mimic the segmented structure of animal limbs, composed of multiple alternating rigid-flexible "joint-segment" units. Each joint participates in deformation at different vibration amplitudes and directions, enabling the system to exhibit pronounced amplitude-dependent nonlinearity.

As shown in Figure 6, inspired by the coordinated motion of ankle, knee, and hip joints, Yan et al. [16]proposed a novel biomimetic multi-joint structure (BIMJS) and systematically investigated its favorable nonlinear characteristics for low-frequency vibration isolation. Two rigid rods simulate the femur and tibia, while three torsion springs mimic muscular functions within each joint. Based on the principle of virtual work, a static model accounting for the interactions of the three joints and leg posture was established to characterize its stiffness properties. The independent action mechanisms of each joint were revealed, and the influence of posture adjustment on the equivalent stiffness of the BIMJS was investigated. By adjusting appropriate postures and setting reasonable stiffness values for each joint, quasi-zero stiffness (QZS) can be readily achieved to realize low-frequency vibration isolation.

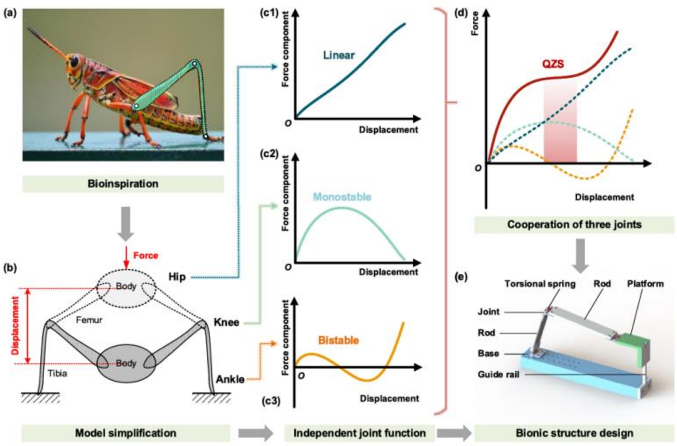

Figure 6: Novel Bionic Multi-Joint Structure Vibration Isolator

Bionic Hierarchical Skeletons and Multi-Level Nonlinear Vibration Isolation: Another class of bionic vibration isolation structures draws inspiration from bamboo joints, spinal columns, or polygonal skeletons, employing multi-scale components to generate segmented nonlinear mechanical responses. Low-frequency, small-amplitude vibrations are primarily absorbed by the outer compliant layer, while high-frequency or large-amplitude vibrations progressively activate the inner high-stiffness skeleton, achieving "passive adaptive" vibration isolation.

As shown in Figure 7, JIN et al.[17] observed that vibrations induced by human movement occur at very low frequencies, typically ranging from 2 to 5 Hz. Inspired by the human spine, a novel bionic quasi-zero stiffness (QZS) damper was proposed, composed of cascaded multi-level negative stiffness structures. Force and stiffness characteristics were investigated, a dynamic model was established using Newton's second law, and vibration isolation performance was analyzed via the Harmonic Balance Method (HBM). Numerical results indicate that increasing the number of negative stiffness stages, along with reducing damping and external force values, enhances the bionic damper's low-frequency isolation performance. Compared to linear structures and existing conventional QZS dampers, the bionic spinal damper demonstrates superior isolation capabilities in the low-frequency range.

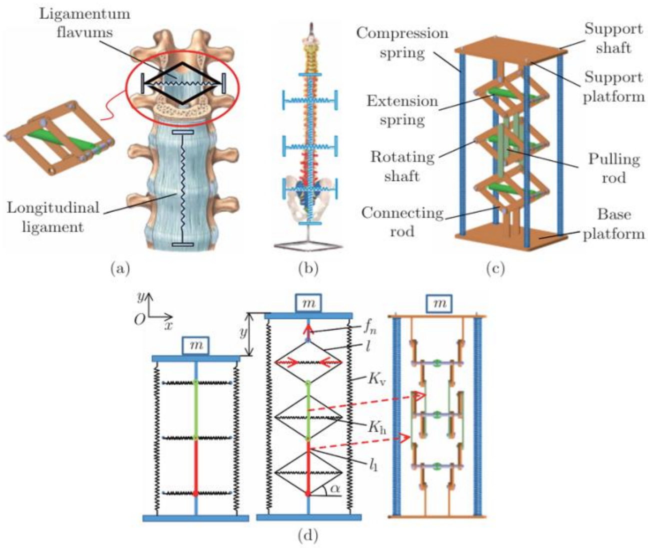

Figure 7: Novel Bionic Human Spine-Inspired Quasi-Zero Stiffness (QZS) Vibration Dampener

4.3 Application Scenarios of Bionic Isolators

Bionic isolation is currently applied in: vibration damping and cushioning for mobile robots and bionic platforms; landing cushioning and impact isolation for spacecraft; low-frequency disturbance suppression and safety protection for precision equipment. With advancements in manufacturing technologies (e.g., additive manufacturing, flexible materials), the engineering potential of bionic isolation in high-end equipment is gradually emerging.

5. Development of Quasi-Zero Stiffness Isolators

5.1 Overview of Quasi-Zero Stiffness Isolation Principles

Quasi-zero stiffness isolators, also known as high-static-low-dynamic-stiffness isolators, operate on the core principle of achieving near-zero equivalent dynamic stiffness near the static equilibrium position through a rational combination of positive and negative stiffness, while maintaining high static load-bearing capacity. The key to designing quasi-zero stiffness isolators lies in incorporating negative stiffness structures. In passive isolation, these primarily include mechanical spring structures, buckling beam structures, magnetic structures, geometrically nonlinear structures, biomimetic structures, and novel material structures. Passive isolation requires no external energy supply, features simple structures, and is easy to implement, making it widely applied in engineering. Under ideal conditions, the equivalent restoring force of a QZS isolation system can be expressed as:

$$F(z) = \left(k_p - k_n\right)z + \mathcal{O}(z^3) \tag{5}$$

Here, k_p represents the positive stiffness component, and k_n denotes the negative stiffness component. When $k_p \approx k_n$, the linear term approaches zero, significantly reducing the system's natural frequency to achieve ultra-low-frequency vibration isolation, while static loads are primarily borne by the positive stiffness path. Compared to traditional linear isolators, the QZS isolator achieves low natural frequencies without significantly increasing static deflection, representing a key technological approach to resolving the “low-frequency isolation versus load-bearing capacity” trade-off[7].

5.2 Typical Structural Forms of Unidirectional QZS Isolators

Mechanism-Type Unidirectional QZS Isolators: Mechanism-type QZS isolators generate target restoring force curves through the geometric relationship of moving pairs, with cam-roller QZS isolators being representative examples. By precisely designing the cam profile, quasi-zero stiffness zones can be constructed within a predetermined stroke, and the matching of positive and negative stiffness offers high design flexibility. As shown in Figure 8, Le et al. [18]designed and fabricated a vibration-damping model aimed at enhancing the damping performance of vehicle seats at low excitation frequencies.

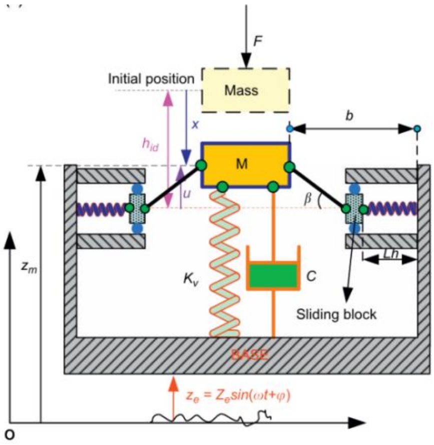

Figure 8: Planar Model of the Mechanism-Type Unidirectional QZS Isolator

Magnetic Negative Stiffness Unidirectional QZS Isolator: The magnetic negative stiffness QZS isolator utilizes repulsive or attractive forces between permanent magnets to generate negative stiffness, which is coupled in parallel with mechanical positive stiffness to form the QZS zone. Its key advantages lie in non-contact operation, tunability, and compact design potential, making it suitable for high-precision isolation applications. As shown in Figure 9, Wang et al. [19]proposed a multilayer quasi-zero-stiffness magnetic compensation isolator. To reduce static deformation and facilitate easy adjustment of isolation characteristics, this isolator employs magnetic pairs to generate nonlinear repulsive forces, thereby compensating for the structure's negative stiffness. This approach differs from conventional designs that use linear springs within each unit to provide positive stiffness compensation.

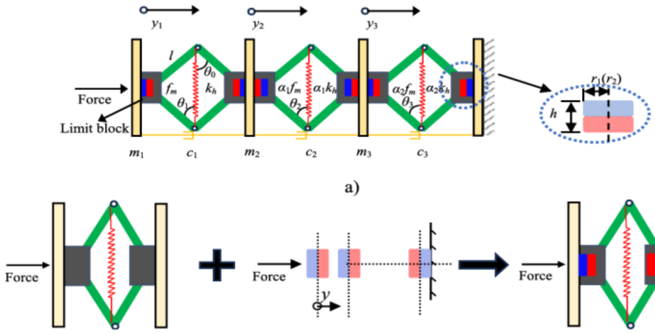

Figure 9: Multi-layer quasi-zero stiffness magnetic force compensation isolator

5.3 Multi-Directional QZS Isolators

Multi-Directional QZS in Parallel Mechanism Frameworks: Parallel mechanisms (e.g., Stewart/Gough platforms) inherently possess multi-degree-of-freedom load-bearing and motion capabilities. By incorporating QZS units into each branch, low equivalent stiffness zones can be formed in multiple directions. This approach offers advantages in full degree-of-freedom preservation and structural symmetry. However, its high parameter dimensionality complicates multi-directional positive/negative stiffness matching and coupling/decoupling design.

Passive negative-stiffness Stewart platforms, characterized by simple structure, reliable operation, and excellent vibration isolation, have become a research focus. However, the inherent limitation of non-adjustable stiffness restricts its application prospects. To address this issue, As shown in Figure 10, Wang et al. [20]proposed an adjustable electromagnetic negative stiffness (AENS) Stewart platform. This platform facilitates seamless stiffness matching and delivers outstanding vibration isolation performance across all six degrees of freedom. The three-dimensional structure of the isolator is illustrated below.

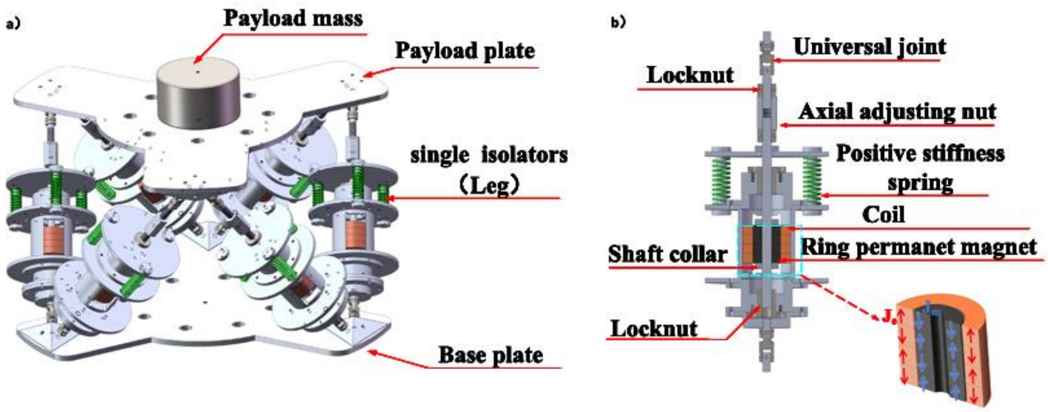

Figure 10: Schematic Diagram of the Three-Dimensional Model for an Adjustable Electromagnetic Negative Stiffness (AENS) Isolation Platform

Spatially Distributed Unidirectional QZS Combination: Another approach involves spatially combining multiple unidirectional QZS units, such as multiple inclined springs or scissor mechanisms acting simultaneously in different directions. This method offers relatively compact structures suitable for moderate loads and limited space conditions, though consistency and stability across multi-directional QZS zones remain challenging to ensure.

As shown in Figure 11, a typical configuration is the scissor mechanism (SLS) proposed by Sun & Jing et al[21]. to achieve tridirectional QZS—it precisely combines “unidirectional/element-level nonlinearity” through spatially symmetric arrangement to form multidirectional (3D) QZS. Compared to traditional quasi-zero stiffness isolation systems, this isolator exhibits superior three-dimensional isolation performance, specifically manifested as high static stiffness - quasi-zero dynamic stiffness characteristics, and a larger displacement adaptation range near the equilibrium position. The research results provide a novel and efficient solution for multidirectional vibration isolation technology—achieving excellent isolation effects solely through passive components by leveraging structural nonlinearity.

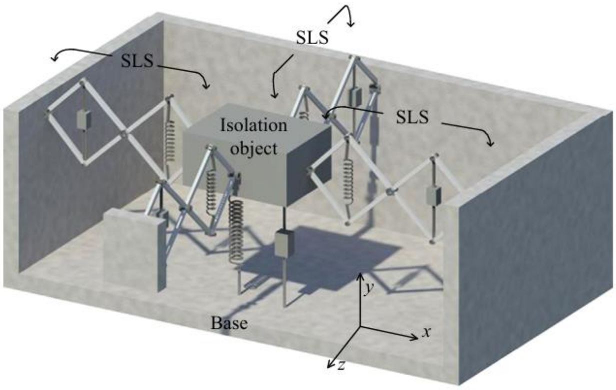

Figure 11: Three-dimensional model of the QZS multi-directional shear-type vibration isolator

Multi-directional magnetic levitation QZS isolators generate negative stiffness in multiple directions through magnetic field coupling, offering non-contact and low-friction advantages suitable for isolating aerospace precision payloads. However, they demand stringent electromagnetic environment and control precision requirements, significantly increasing system complexity.

As shown in Figure 12, LIU et al. [22]developed a multi-degree-of-freedom analytical model for composite magnet structures (CMI) based on equivalent charge theory. Using this model, they analyzed how magnetic suspension force and stiffness vary with vibration displacement, magnet geometric parameters, and air gap conditions. Employing a combination of experimental and theoretical methods, they quantitatively evaluated the vibration transmission characteristics of CMI structures using Volterra series and conditional spectral analysis (CSA).

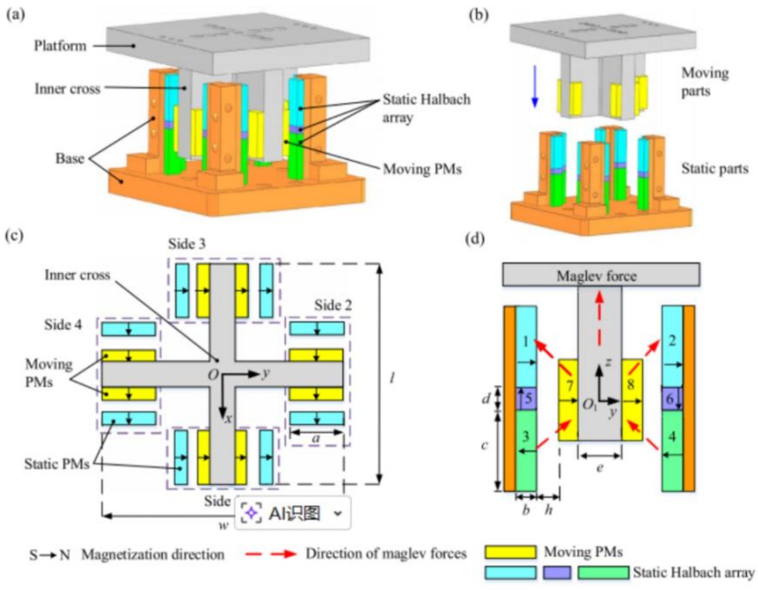

Figure 12: Composite Magnet Structure (CMI) Configuration

5.4 The Imperative and Challenges of Transitioning from Unidirectional to Multidirectional QZS Isolation

Multi-directional QZS isolation represents a crucial future development direction for high-end equipment vibration isolation technology. Practical engineering vibrations typically exhibit multi-directional coupling characteristics, encompassing both three-axis translational and three-axis rotational motions[23]. Single-directional QZS isolators are generally effective only in the vertical or a specific direction, potentially leaving significant resonance in lateral and rotational directions. Structural coupling may even amplify attitude errors. Therefore, while unidirectional QZS isolation resolves the “low-frequency-load-bearing” contradiction, it fails to meet the comprehensive requirements of high-end equipment for multidirectional low-frequency isolation and attitude stability. This directly drives the development of multidirectional QZS isolators.

Compared to single-direction QZS, multi-directional QZS isolators face more complex technical challenges: synchronous matching and maintenance of positive and negative stiffness in multiple directions; nonlinear coupling and stability control across multiple degrees of freedom; robustness of the QZS zone under load variations and temperature drift; and verification of engineering manufacturability and long-term service reliability[24].

6. Conclusion

Although quasi-zero stiffness (QZS/HSLDS) isolators demonstrate significant advantages in resolving the traditional trade-off between “low-frequency isolation and static load-bearing capacity” in conventional isolation systems, and have yielded abundant research outcomes in single-direction low-frequency isolation, their engineering application still faces numerous challenges. These issues become more pronounced during the expansion to multi-directional isolation. QZS isolators rely on precise matching of positive and negative stiffness to form a near-zero dynamic stiffness zone. Factors such as load variations, temperature fluctuations, material aging, and assembly errors can disrupt this matching relationship, causing QZS operating point drift and significant degradation in isolation performance. For multidirectional QZS isolators, each direction must simultaneously satisfy the QZS condition. The effects of parameter drift exhibit superposition and amplification, substantially increasing the complexity of system design and calibration.

Furthermore, QZS isolators are inherently highly nonlinear systems prone to multistable responses, abrupt transitions, and bifurcation phenomena. Under frequency sweeping or random excitation, stable solution switching may occur, leading to uncertain or even failed isolation performance. In multi-degree-of-freedom QZS systems, nonlinear coupling between different directions can also trigger internal resonance and complex dynamic behavior, further complicating stability analysis and control. Simultaneously, multi-directional QZS isolators typically employ parallel or spatially combined configurations, inevitably introducing stiffness-damping coupling issues. Achieving effective decoupling while maintaining low equivalent stiffness in multiple directions and preventing attitude error amplification remains a core challenge in their engineering implementation.

Under real-world engineering conditions, non-ideal factors such as friction, backlash, hysteresis, material nonlinearity, and manufacturing errors are ubiquitous. These factors often significantly diminish the performance advantages demonstrated by QZS isolators in theoretical models[25]. Particularly in micro-vibration isolation scenarios, even minute friction or backlash can dominate system response, becoming critical constraints on low-frequency isolation effectiveness. Concurrently, existing research predominantly focuses on performance validation using prototype models or under laboratory conditions. Systematic testing addressing long-term service life, adaptability to complex environments, and reliability remains limited. This constraint hinders the engineering application of QZS isolators—particularly multi-directional QZS isolators—in fields such as aerospace, high-end manufacturing, and precision measurement.

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