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面向航天器地面验证的垂向微低 重力环境模拟方法研究

学位申请人：X X

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指导教师：X X 教授

XXX 教授

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**A Dissertation Submitted in Partial Fulfilment of The Requirements
for The Degree of Doctor of Engineering**

**Research on Vertical Micro/Low-Gravity Simulation
Method for Spacecraft Ground Verification**

Ph.D. Candidate: XX

Major : Mechanical Engineering

Supervisor : Prof. XX

Prof. XX

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摘 要

随着技术不断发展，航天任务复杂度持续提升。为确保任务顺利执行，发射前的精确地面验证至关重要。航天器服役于微/低重力环境，其动力学特性与地面存在显著差异，因此微低重力环境模拟是保证其地面验证有效的关键环节。现有方法已可实现高精度的五自由度微低重力模拟。但在重力作用的垂向上，综合支承刚度难近零，且存在多种复杂扰动，难以在大行程内实现高精度微低重力模拟，这已成为制约航天器地面验证乃至航天事业跨越式发展的瓶颈。

本文提出一种将准零刚度机构与伺服随动系统串联的垂向微低重力模拟方法，可消除复杂支承扰动，大幅提高模拟精度。该方法包括两个关键环节：一是使用永磁准零刚度机构支承模拟对象，在小行程内被动释放其垂向自由度；二是通过对模拟对象的伺服随动控制，在大行程内完成重力卸载与附加质量补偿。

通过将永磁负刚度弹簧与主承载弹簧并联，可实现重载下的准零刚度支承；其难点在于突破磁场非线性限制，构建宽域高线性永磁负刚度弹簧。为此，探索编辑永磁体外形的永磁弹簧设计新范式。具体而言，首先构建适用于一般形状永磁体的微元叠加模型，并引入卷积算法实现三维磁力的高效求解；然后提出基于反卷积运算的磁体调制方法，将高维的几何设计难题转化为多个独立二维优化问题的组合，在显著降低求解复杂度的同时，保持极高的设计自由度，从而实现磁力/刚度特性的可编程逆向设计。应用该方法，可将永磁弹簧线性行程大幅拓展至数十毫米量级。

实现垂向大行程高精度微低重力模拟的关键，在于构建具备精准重力卸载与稳定附加质量补偿能力的随动控制系统。本文基于高精度位移反馈，设计包含 PID 控制、扰动观测补偿与零点矫正环节的随动控制器，实现对模拟对象的准零变形随动，从而精准卸载其重力。在控制器中嵌入局部反馈回路，依据加速度指令实时调整准零刚度机构变形量，以施加附加质量补偿所需的等效惯性力。进一步地，为抑制局部回路引发的系统振荡，引入包含模型信息的线性扩张状态观测器，完成系统柔性跟踪与高抗扰性的解耦设计，从而实现高精度重力卸载与无振荡附加质量补偿的兼顾。

为验证所提方法的有效性，研制了垂向微低重力模拟样机，并对其开展频域特性

和时域响应测试。结果表明，该样机可精准模拟航天器在微低重力环境下的自由漂浮状态与触碰反弹行为，具备多工况适应的高精度微低重力模拟能力。在此基础上，面向“XX-2”小天体探测任务的地面验证需求，研制重载垂向微低重力模拟装置，并将其集成至探测器模拟系统中，使其具备六自由度模拟能力，有力支撑了探测器着陆缓冲工况的地面验证。

综上，本文所提方法有以下优势：其一，采用无摩擦的永磁准零刚度机构支承模拟对象，可在小行程内被动释放其垂向自由度；同时，提出永磁弹簧的逆向设计方法将该行程大幅拓展，从而显著降低对伺服系统性能的要求。其二，基于位移反馈构建无残差随动控制系统，规避了重载下力传感器精度不足的限制，可实现吨级负载的高精度重力卸载。其三，在控制器内引入局部反馈回路，可有效消除附加质量引起的系统性误差，且无需新增传感器和执行器，保持了系统简洁。本研究为未来各类新型航天任务的地面验证提供方法借鉴与技术支撑。

关键词：航天器地面验证；微低重力模拟；永磁准零刚度；重力卸载；附加质量补偿

Abstract

With the rapid advancement of space technology, space missions have become increasingly complex, significantly elevating the risk of failure. Accurate ground verification is therefore essential. The key challenge lies in replicating the micro-/low-gravity condition, where current air-bearing simulators can achieve high-precision five degree-of-freedom (DOF) micro-/low-gravity simulation. However, in the gravity-affected vertical axis, the support stiffness is difficult to reduce to near zero, the stable working stroke is limited, and various complex disturbances exist. As a result, it is difficult to provide a high-precision constant force over a large stroke to accomplish gravity offloading, which has become a bottleneck restricting ground verification of spacecraft and even the leapfrog development of the space industry.

This dissertation proposes a vertical microgravity simulation method for high-precision ground verification of spacecraft. The method integrates a permanent-magnet quasi-zero-stiffness (QZS) mechanism in series with a servo follow-up system and effectively eliminates disturbances in vertical support and enables high-precision simulation over a large stroke range. It consists of two key components: (1) a permanent-magnet QZS mechanism that passively releases the vertical DOF of the simulated object within a small stroke; and (2) a servo follow-up system that performs gravity offloading and parasitic mass compensation during large-stroke motion.

By paralleling magnetic negative-stiffness springs with primary springs, a heavy-load QZS support can be achieved. To overcome the challenge of designing wide-range, highly linear negative-stiffness magnetic springs under magnetic nonlinearity, we propose a new inverse design paradigm of magnet shaping. A microelement model and convolution algorithm are developed for efficient 3D force computation between arbitrarily shaped PMs. Crucially, a deconvolution-based magnet modulation method is proposed, which further reduces the high-dimensional magnet design problem into a series of two-dimensional optimizations, enabling programmable force and stiffness characteristics with extensive design freedom. This extends the effective QZS stroke to the order of tens of millimeters.

A displacement-based servo control scheme is developed to eliminate simulation errors

caused by residual stiffness and parasitic mass, which are critical for high-precision vertical microgravity simulation. The controller integrates PID feedback, disturbance observation, and zero-pole correction to maintain quasi-zero deformation of the QZS mechanism during large-stroke motion for gravity offloading. Building on this, a local feedback loop is introduced into the controller for parasitic mass compensation, where the deformation of the QZS mechanism is adjusted according to the acceleration commands. In conjunction with a linear extended state observer, the control system achieves decoupled disturbance rejection and compliant tracking, effectively suppressing loop-induced oscillations and ensuring both high-precision gravity offloading and stable mass compensation.

To validate the proposed method, a vertical microgravity simulation prototype is developed and tested. Results show that the prototype accurately simulates spacecraft free-floating and contact-rebound behaviors in microgravity, with high-precision performance adaptable to various scenarios. Furthermore, a heavy-load vertical microgravity component is developed to meet the ground verification needs of the “XX-2” small body exploration and sampling mission. This component is integrated into the simulation system, enabling 6-DOF simulation and providing strong support for ground verification of the probe landing buffer conditions.

In summary, the proposed method offers three outstanding advantages: (1) a frictionless QZS mechanism that passively releases vertical DOF within a small stroke and, through the inverse design of magnetic spring, extends the stroke to ease servo performance requirements; (2) a displacement-based follow-up control system that bypasses the accuracy limits of heavy-load force sensors, enabling high-precision gravity offloading over large strokes; and (3) a controller-level local feedback loop that generates virtual mass without additional sensors or actuators, effectively eliminating inertia errors from parasitic mass. This study provides valuable methodological insights and technical support for future ground verification of advanced space missions.

Key words: Spacecraft ground verification; Micro-/Low-gravity simulation; Magnetic quasi-zero stiffness; Gravity offloading; Parasitic mass compensation