

博士学位论文

不倒翁惯性调制结构动力学设计
及自感知吸振方法研究

Research on Self-Sensing Vibration Absorption

and Dynamics Design of Tumbler-Inspired

Inertial Modulation Structures

摘 要

纤维复合材料的大量使用是新一代航空航天结构件实现轻量化、整体化、高可靠的必由之路。径向环形编织机是纤维复合材料高效、高精度成型的重要装备。径向环形编织机在工作时，电机转速通常在 400r/min 以内，其振动能量主要集中在低频区间。此外，编织机在编织过程中受到非线性、多周期激励及局部冲击等复杂动力学因素作用产生振动，容易导致设备“一快就抖、一抖就乱”，影响编织成品质量为保障编织机的稳定可靠运行，需采取必要的减振措施对有害振动进行抑制。吸振作为常用的减振手段，可实现主系统振动能量的转移与耗散，已在工程实践中得到了广泛应用。然而，传统吸振器存在适用频率范围窄、有效频带不可调、结构频率单一等问题，易发生失谐，导致吸振效果恶化。可调谐式吸振器能够在一定范围内调节系统参数以适应系统频率，但大多需要外部传感器对系统振动信号进行采集与识别。而在吸振器中引入非线性，可拓宽系统有效带宽并提升吸振性能，但同时也存在结构复杂、鲁棒性不足等问题。不倒翁作为一种惯性式结构，在受到激励后将围绕平衡位置发生低频摆动，将外部能量转换为自身摆动的机械能，并通过阻尼进行耗散，这为径向环形编织机的低频宽带吸振提供了一种新思路。然而，不倒翁结构的相关理论模型不完善，低频机理不清晰，调控方法不明确，制约了该结构的应用与发展。

针对以上问题，本研究建立了不倒翁惯性结构的理论模型，阐明了不倒翁惯性结构的宽频吸振机制，提出了不倒翁吸振结构的半主动磁控调控方法，基于长短期记忆（Long Short-Term Memory, LSTM）神经网络构建了不倒翁振动电磁自感知模型，建立了基于电磁式不倒翁的径向环形编织机自感知吸振模型。论文的主要研究内容如下：

（1）构建了不倒翁惯性结构的理论模型，建立了其动力学方程，定义了不倒翁惯性结构的近似共振频率。厘清了几何参数对系统响应的影响规律，阐明了系统等效质量与阻尼在响应中的作用，揭示了不倒翁结构的低频振动机理，探究了系统的非线性动力学行为。设计并搭建了原理样机与试验平台，试验结果表明不倒翁惯性结构具有 2.7Hz 的低频共振频率，验证了所建理论模型的有效性。

（2）提出了不倒翁惯性式吸振方法，设计了一种不倒翁惯性式宽频吸振器，建立了系统动力学模型，基于谐波平衡法推导了系统的幅频响应关系。通过解析解和数值解获取了不倒翁惯性式宽频吸振器的振幅放大系数，探究了系统关键参

数对系统幅值抑制与有效吸振带宽的影响，揭示了固有频率比对系统吸振性能的影响规律。采用多目标遗传算法对系统参数进行了优化。研制了不倒翁惯性式宽频吸振器样机，设计了试验系统，结果表明吸振器在固有频率比 0.25 至 1 的范围均表现出良好的宽频吸振特性。

(3) 提出了不倒翁吸振结构的半主动磁控调控方法，建立了线圈与不倒翁内部永磁体间的轴线非平行电磁力计算方法，构建了三自由度磁调控耦合模型，阐明了电磁力对系统固有频率以及吸振特性的调控规律，揭示了不倒翁结构的频率调控机制。对不倒翁式半主动吸振器的吸振特性进行了试验研究。结果表明，调控线圈电流可以实现主系统振幅 72% 的最大衰减，以及 3.7Hz 的有效减振频带。

(4) 提出了基于 LSTM 神经网络的不倒翁振动电磁自感知模型。建立了不倒翁振动电磁自感知结构的力-电-磁耦合模型，推导了系统电压响应关系，仿真分析了自感知结构的力电耦合特性。基于 LSTM 神经网络，构建了输出电压与输入激励之间的非线性映射关系，讨论了训练参数对模型识别精度的影响。并通过试验对比测试，验证所构建的不倒翁振动电磁自感知模型能够实现加速度幅值和频率的高精度识别，识别误差分别控制在 5% 和 10% 以内。

(5) 建立了基于电磁式不倒翁的径向环形编织机自感知吸振模型。提取了编织机关键模态参数，明确了其主要振动特征与频率分布，设计了能够反映编织机振动特征的缩比试验模型。建立了不倒翁式电磁自感知吸振器耦合系统模型，推导了系统幅频响应关系，通过解析与数值求解评估了其吸振效果。开展了试验测试，结果表明安装所提出的不倒翁电磁自感知吸振器后系统一阶模态振幅下降达 98.4%，有效减振频带可拓展至 9.8Hz，并可同步感知系统所受加速度激励特征，识别误差低于 7%。

总之，本文建立了不倒翁惯性结构理论模型，阐明了其低频振动机理。构建了三自由度不倒翁惯性吸振模型，揭示其宽频吸振规律。提出了不倒翁吸振结构的半主动磁调控方法，并设计了基于 LSTM 神经网络的不倒翁式电磁自感知模型。结合上述模型与方法形成了一种基于电磁式不倒翁的径向环形编织机自感知吸振技术。本研究丰富了非线性吸振理论，为不倒翁电磁自感知吸振技术的工程化应用提供了理论基础和技术支撑，推动了非线性可调谐低频宽带吸振技术的发展。

关键词：不倒翁；吸振；非线性振动；自感知；编织机

Abstract

The extensive use of fiber-reinforced composites is essential for achieving lightweight, integrated, and highly reliable structures in next-generation aerospace engineering. The radial circular braiding machine is a critical piece of equipment for the efficient and precise forming of these composites. During operation, the motor speed of a radial circular braiding machine usually remains below 400 rpm, resulting in vibration energy being concentrated primarily in the low-frequency range. Furthermore, the braiding process is influenced by complex dynamic factors such as nonlinear effects, multi-period excitations, and local impacts, all of which induce vibrations. Such vibrations can readily lead to instability and process disruption, thereby impairing the quality of the braided products. To ensure stable and reliable operation, it is necessary to implement effective vibration control measures. As a widely used technique, dynamic vibration absorption enables the transfer and dissipation of vibration energy from the primary system and has been extensively applied in engineering practice. However, traditional absorbers suffer from limitations such as a narrow effective frequency range, non-tunable bandwidth, and a single structural frequency, which make them prone to detuning and lead to rapid deterioration of absorption performance. Tunable absorbers can adjust system parameters within a certain range to match the frequency, but they generally rely on external sensors to acquire and identify vibration signals. Alternatively, introducing nonlinearity into absorbers can broaden the effective bandwidth and enhance vibration suppression performance, though at the expense of increased structural complexity and reduced robustness. The tumbler, as an inertia structure, exhibits low-frequency oscillations around its equilibrium position under external excitation, converting input energy into mechanical energy of its swinging motion and dissipating it through damping. This unique energy transfer mechanism offers a new perspective for realizing low-frequency broadband vibration suppression in radial circular braiding machines. However, the theoretical models of tumbler structures are underdeveloped, the low-frequency mechanisms are unclear, and effective control strategies remain lacking, all of which hinder broader application and development.

To address these issues, this research establishes a dynamic model of the tumbler structure, clarifies its broadband vibration absorption mechanism, and proposes a magnetically tuned semi-active absorber. It also develops an electromagnetic self-sensing model based on a Long Short-Term Memory (LSTM) neural network and designs a self-sensing absorber tailored for the radial circular braider. The main contributions of this work are as follows:

The study developed a theoretical model for the tumbler structure. It derived its dynamic equations and calculated an approximate resonance frequency. The effects of geometric parameters, equivalent mass, and damping on system response were analyzed. The mechanism of low-frequency vibration absorption was revealed. The nonlinear dynamic behavior of the system was investigated. A prototype and test platform were constructed, and results showed a low-frequency resonance at 2.7 Hz, validating the theoretical model.

A tumbler-inspired dynamic vibration absorber was designed. Its motion equations were derived. The amplitude-frequency response was obtained using harmonic balance methods. Both analytical and numerical solutions were solved to evaluate amplitude magnification factors. The effects of key parameters were analyzed. The role of frequency ratios in vibration suppression was clarified. System parameters were optimized using a multi-objective genetic algorithm. Prototype tests showed that the absorber exhibited excellent broadband performance over a natural frequency ratio range of 0.25 to 1.

A semi-active magnetic control method for the tumbler vibration absorber was proposed. A calculation approach for electromagnetic forces with non-parallel axes between the coil and the internal permanent magnet of the tumbler was established, and a magnetically tuned coupling model of the tumbler was constructed. The regulatory effects of electromagnetic forces on the system's natural frequency and vibration absorption characteristics were clarified, thereby revealing the frequency tuning mechanism of the tumbler structure. Experimental studies on the semi-active tumbler absorber demonstrated that adjusting the coil current achieved a maximum reduction of 72% in the primary system amplitude and an effective vibration reduction bandwidth of 3.7 Hz.

An electromagnetic self-sensing model based on an LSTM neural network was developed. A coupled force-electric-magnetic model was built. The voltage response

was derived, and the electromechanical coupling characteristics were analyzed. A nonlinear mapping between output voltage and input excitation was established using the LSTM network. Experimental validation showed that the model could accurately identify acceleration amplitude and frequency, with identification errors controlled within 5% and 10%, respectively.

The self-sensing vibration absorption model for radial circular braiding machines was established based on an electromagnetic tumbler structure. Key modal parameters were extracted. Vibration characteristics and energy distribution were analyzed. A scaled experimental model was built. A coupled system model was established to derive amplitude-frequency responses. Performance was evaluated analytically and numerically. Experimental results showed that the absorber reduced the first-mode vibration amplitude of the machine by up to 98.4%, extended the effective bandwidth to 9.8 Hz, and could simultaneously sense acceleration excitation with errors below 7%.

In summary, this study establishes a theoretical model of the tumbler structure and elucidates its low-frequency vibration mechanism. A tumbler-inspired dynamic vibration absorber model is further constructed to reveal its broadband vibration suppression characteristics. A magnetic tuning method for the absorber is proposed, and an electromagnetic self-sensing model based on the LSTM neural network is developed. By integrating these models and methods, a self-sensing vibration absorption technology for radial circular braiding machines is developed based on the electromagnetic tumbler-inspired structure. This research enriches the theoretical framework of nonlinear vibration absorption, provides both a theoretical foundation and technical support for the engineering application of electromagnetic tumbler-inspired self-sensing absorbers, and promotes the advancement of tunable nonlinear broadband vibration suppression technologies.

Keywords: Tumbler; Vibration absorption; Nonlinear vibration; Self-sensing; Braiding machine