申请XXXX大学博士学位论文

振动编码超材料结构设计与感知器件研究

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RESEARCH ON VIBRATION-CODED METAMATERIALS WITH STRUCTURE DESIGN AND SENSING DEVICE

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摘 要

当前我国正加快发展新型高端复杂装备平台技术，随着高端复杂装备向高速、轻质、重载和极端状态下运行的方向发展，其在制造、服役、维护过程中所遇到的振动问题尤为明显。通过对振动信息的感知来解决复杂的振动问题，对高端复杂装备的制造升级和智能运维至关重要。局域共振超材料是一种能够在亚波长尺度上调制振动信息的人工复合结构，其超常的物理特性在发展新型高效的振动感知技术中显示出潜力和优势，且兼具学术前沿研究价值和重大工程应用价值。由于局域共振超材料在振动感知领域尚处于起步阶段，仍面临理论机制认识不充分、器件研制技术不完善、缺乏有效的系统应用验证等问题。基于此，本文开展振动编码超材料结构设计与感知器件研究，以简化硬件电路和增强传感性能为目标，建立了振动编码感知超材料的基本设计框架。全文提出了局域振子排列无序有序的共振转换编码设计方法，研制了多源振动信息超材料感知器，发展了针对复杂故障激励的多源定位感知超材料技术，实现了单传感器轴上振动溯源；提出了局域振子频分多路复用的宽带增强编码设计方法，研制了宽频微动信息超材料感知器，发展了针对宽频微弱故障的超材料计算感知技术，实现了转子系统早期故障的精准监测。全文从结构设计、器件研制和系统应用三个部分系统开展了振动编码感知超材料研究，致力于突破振动信息感知的传统技术瓶颈，主要内容包括：

(1) 针对工程应用中的振动信息特征，基于矢量场弹性动力学理论和弹性波传播基本理论，建立了超材料的空间构型编码和振动信息编码之间的动力学关系。提出了局域振子排列无序有序的共振转换编码方法，构建了多源定位感知动力学系统。提出了局域振子频分多路复用的宽带增强编码方法，构造了宽频微动感知动力学系统。两种编码方法为结构器件研制和系统应用验证提供了理论支撑。

(2) 开展了局域振子排列无序有序的共振转换编码结构研究，受含羞草启

发制作了刺激响应超材料网络，研制了多源振动信息超材料感知器。受到振动刺激时，局域振子自适应地从无序共振状态转换为有序共振状态，振动刺激信息被自适应地编程到网络的全局动力学传输中，实现了信息驱动的弹性动力学编程。实验验证了信息交互场景的应用，在信息感知上融合了传感、控制和驱动为一体，有望将智能感知系统从复杂的硬件系统中解放出来。

(3) 开展了局域振子频分多路复用的宽带增强编码结构研究，受小鼠胡须启发制作了谐振特性不同的压电式单胞，研制了宽频微动信息超材料感知器。其在宽频范围内产生零等效质量，并在零质量频率附近产生了近无穷大的等效压电转换系数。相对于非谐振式的设计，最大灵敏度提高了 2 个数量级，工作频带实现了在 0-12 kHz 范围的定制化设计。在极端强噪环境下，实验验证了空时信息传感场景的应用，有望通过力学引导的超材料设计来实现高性能的微动传感。

(4) 开展了面向工程应用的振动编码超材料感知系统研究。以直升机的尾翼轴传动系统为案例，针对单传感器轴上振动溯源难题，搭建了一个类似直升机尾翼传动轴的缩比转子实验台，将定制化设计的超表面轴承座集成到转子实验台中，开发了轴上多源感知监测系统，实验验证突破了单传感器轴上振源辨识的瓶颈。针对宽频微弱故障感知难题，将宽频微动信息超材料感知器分别集成到转子实验台和车载系统中，开发了轴承和发动机宽频微弱故障监测系统，实验验证突破了宽频微弱故障感知的技术瓶颈。

关键词：局域共振超材料，动力学编码设计，机械故障诊断，振动感知器件，工程应用系统

RESEARCH ON VIBRATION-CODED METAMATERIALS WITH STRUCTURE DESIGN AND SENSING DEVICE

ABSTRACT

The development of new high-end complex equipment platform technology is currently being accelerated. As high-end complex equipment progresses towards high-speed, lightweight, heavy-load, and extreme operating conditions, the vibration issues encountered during manufacturing, service, and maintenance become particularly significant. Addressing complex vibration problems through the perception of vibration information is essential for the manufacturing upgrade and intelligent operation and maintenance of high-end complex equipment. Localized resonant metamaterials are a kind of artificial composite structure that can modulate vibration information on subwavelength scales. Their extraordinary physical properties show potential and advantages in developing new highly efficient vibration sensing technology, with both academic frontier research value and significant engineering application value. However, localized resonant metamaterials are still in their infancy in the field of vibration sensing, and there are still problems such as insufficient understanding of theoretical mechanisms, imperfect device development technology, and lack of effective system application verification. Based on this, this paper carries out research on the structure design and sensing devices of vibration encoding metamaterials, aiming to simplify hardware circuits and enhance sensing performance, and establishes the basic design framework of vibration encoding sensing metamaterials. The paper proposes a resonance conversion coding design method for disordered and ordered local oscillator arrangement, develops multi-source vibration information metamaterial sensors, and develops multi-source positioning sensing metamaterial technology for complex fault excitation, achieving single-sensor on-axis vibration source tracing. It proposes a broadband enhancement coding design method for frequency-division multiplexing of local oscillators, develops wideband micro-motion information metamaterial sensors, and develops

metamaterial computation sensing technology for wideband weak faults, achieving precise monitoring of early faults in rotor systems. The paper systematically carries out research on vibration encoding sensing metamaterials from the aspects of structure design, device development, and system application, and is committed to breaking through the traditional technology bottleneck of vibration information sensing. The main content includes:

(1) Aiming at the vibration information characteristics in engineering applications, based on vector field elastodynamics theory and basic theory of elastic wave propagation, the paper establishes the dynamic relationship between spatial configuration coding of metamaterials and vibration information coding. It proposes a resonance conversion coding method for disordered and ordered local oscillator arrangement, constructs a multi-source positioning sensing dynamic system, and proposes a broadband enhancement coding method for frequency-division multiplexing of local oscillators, constructing a wideband micro-motion sensing dynamic system. Both coding methods provide theoretical support for the development of structural devices and system application verification.

(2) Research on the resonance conversion coding structure of disordered and ordered local oscillator arrangement is carried out. Inspired by the sensitive plant (Mimosa pudica), a stimulus-responsive metamaterial network is fabricated, and a multi-source vibration information metamaterial sensor is developed. When stimulated by vibrations, the local oscillators adaptively switch from a disordered resonance state to an ordered resonance state, with vibration stimulus information adaptively programmed into the global dynamic transmission of the network, achieving information-driven elastic dynamics programming. The application of information interaction scenarios is experimentally verified, integrating sensing, control, and driving in information sensing, and potentially liberating intelligent sensing systems from complex hardware systems.

(3) Research on the broadband enhancement coding structure of frequency-division multiplexing of local oscillators is carried out. Inspired by the

whiskers of mice, piezoelectric cells with different resonant characteristics are fabricated, and a wideband micro-motion information metamaterial sensor is developed. It generates a zero-equivalent mass within a wide frequency range, and an almost infinite equivalent piezoelectric conversion coefficient is generated near the zero-mass frequency. Compared to non-resonant designs, the maximum sensitivity is increased by two orders of magnitude, and the working frequency band is customizable within the 0-12 kHz range. The application of spatiotemporal information sensing scenarios is experimentally verified in extreme high-noise environments, and high-performance micro-motion sensing is expected to be achieved through mechanically guided metamaterial design.

(4) Research on vibration encoding metamaterial sensing systems for engineering applications is carried out. Taking the tail rotor transmission system of a helicopter as an example, to address the difficulty of single-sensor on-axis vibration source tracing, a scaled-down rotor testbed similar to the helicopter tail transmission shaft is built, and the customized supersurface bearing seat is integrated into the rotor testbed, developing a multi-source sensing monitoring system for the rotor shaft, and experimentally verifying the breakthrough of the bottleneck in single sensor axis vibration source identification. To address the challenge of wideband weak fault sensing, the wideband micro-motion information metamaterial sensor is separately integrated into the rotor testbed and the vehicle-mounted system, developing a wideband weak fault monitoring system for bearings and engines. Experimental verification demonstrates a breakthrough in the technical bottleneck of wideband weak fault sensing.

Keywords: Local Resonance Metamaterials, Dynamic Encoding Design, Mechanical Fault Diagnosis, Vibration Sensing Device, Engineering Application System