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厦门大学

博 士 学 位 论 文

机械结构工作模态参数盲源分离辨识方法研究

Research on Operational Modal Parameter Identification of Mechanical Structures Based on Blind Source Separation

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摘　要

随着国家机械制造工业的迅速发展，各类工程机械设备广泛地应用于日常生活、生产和建设过程中，机械结构的运行安全越来越受到国家的重视。模态分析是机械结构设计、状态监测和性能评估的重要基础，对机械结构的安全运行起到至关重要的作用。有别于传统的频域模态分析方法，工作模态分析仅利用时域输出信号，能够真实反映机械结构运行过程中的性能指标，因此准确可靠地提取机械结构工作状态下的模态参数具有十分重要的意义。

论文在总结传统模态分析方法的基础上，将盲源分离技术应用于机械结构在环境激励下的工作模态参数提取方法研究。提出了基于盲源分离技术的复模态系统模态参数提取方法和欠定系统的模态参数提取方法。论文的主要工作包括以下几个方面：

1、对模态分析方法的应用领域进行了介绍，总结了环境激励下的时域模态分析方法的基本原理及优缺点，并对盲源分离技术的发展过程进行了总结，指出了盲信号处理技术应用于模态参数分析的可行性。

2、阐述了盲源分离技术的一般模型及基本原理，讨论了盲源分离与独立量分析之间的关系及数据预处理方法。针对线性瞬时混合模型，归纳了盲源分离算法的基本分类。重点分析了特征矩阵联合近似对角化方法（JADE）、二阶统计量盲源分离方法（AMUSE）和稳健二阶盲辨识方法（RSOBI）的算法形式和原理。

3、对比例阻尼的实模态系统和一般粘性阻尼的复模态系统进行讨论，从理论角度分析了多自由度振动系统与盲源分离模型之间的关系。根据广义脉冲响应函数，描述了随机激励下系统输出响应的数字特征。将 JADE 方法、ASUME 方法和 RSOBI 方法应用于一个包含座椅的单轮车辆模型三自由度系统的模态识别。在自由响应和随机激励两种情况下分别对三自由度系统进行仿真，在不同噪声条件下对 JADE 方法、ASUME 方法和 RSOBI 方法的分离性能进行验证。结果表明这三种盲源分离方法对振动系统均具有一定的模态分离能力，但基于二阶统计量的 ASUME 方法和 RSOBI 方法分离能力优于基于独立量分析的 JADE 方法。

4、讨论了传统二阶盲源分离方法对复模态振动系统和欠定振动系统的模态分离能力。推导了复模态振动系统的连续状态空间模型及其离散状态空间模型，

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分析了随机离散状态空间模型输出量的相关函数分解形式。针对复模态系统的源信号数判断问题，提出了基于最大差值变比的源信号数量估计方法。并在此基础上进一步提出了基于平均特征矩阵的复模态系统分析方法（SOBIMUC 方法）和基于平均特征矩阵的欠定系统模态分析方法（SOBIMUC-UDH 方法）。分别利用 3 自由度复模态系统和 7 自由度欠定系统对 SOBIMUC 方法和 SOBIMUC-UDH 方法进行模态参数识别，均获得了良好的识别效果。

5、分别采用悬臂梁结构和路面随机激励作用下轿车正常行驶过程振动信号对盲源分离欠定复模态方法在模态辨识中的性能进行验证，并与传统盲源分离方法和随机子空间方法的分离效果进行对比，结果表明基于平均特征矩阵的欠定系统模态分析方法对自由响应下的悬臂梁结构和随机激励下的轿车振动信号均具有良好的模态参数识别能力。

关键词：机械结构；工作模态；盲源分离

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ABSTRACT

With the rapid development of machinery manufacturing industry, all kinds of engineering machinery and equipments are widely used in the process of daily life, production and construction. The operational safety of mechanical structures has been paid more and more attention to. Modal analysis is an important basis of mechanical structure design, status monitoring, performance assessment, which plays a vital role on the safe operation of the mechanical structures. Different from the traditional modal analysis methods in frequency domain, operational modal analysis only uses time domain output signal, which can reflect the actual performances of the mechanical structures in the operation processes, so accurate and reliable modal parameters extraction under the operational state of mechanical structure has very important significance.

This paper firstly summarized the traditional modal analysis method, and then discussed the research about blind source separation technique applied to modal parameter extraction of mechanical structure under ambient excitation. The modal parameter identification methods of complex modal system and underdetermined system based on the blind source separation technique were proposed. The main work of this paper includes the following aspects:

Firstly, the paper introduced the application fields of modal analysis method, summarized the basic principle, the advantages and disadvantages of time domain modal analysis method under ambient excitation, and analyzed the development process of blind source separation techniques, pointed out the feasibility of blind signal processing technique applied to modal parameters identification.

Secondly, the paper expounded the general model and basic principle of blind source separation technique, discussed the data preprocessing method and the relationship between blind source separation and independent component analysis. For the linear mixed model, the paper summarized the basic classification of blind source separation algorithm, Emphatically analyzed the principle of JADE method, AMUSE method and RSOBI method.

Thirdly, the real mode system of proportional damping and the complex mode system of viscous damping were discussed. From the theoretical point, the relationship between multiple degree of freedom vibration system and the blind source separation model were analyzed. Based on the generalized impulse response

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function, the system response characteristics under random excitation were described. Modal identification of a three degree of freedom system come from a single wheel vehicle model including a seat was analyzed used the JADE method, ASUME method and RSOBI method. Under the cases of free response and random excitations, simulations of the three degrees of freedom were carried out. In different noise conditions, the separation performance of JADE method, ASUME method and RSOBI method had been verified. The results showed that the three methods were all suit for the modal separation of the vibration system. But the ASUME method and RSOBI method were superior to the JADE method.

Fourthly, the paper discussed the modal separation ability of traditional BSS methods for complex mode system and underdetermined system. The continuous state space model and discrete state space model of complex mode system were deduced, the decomposition form of correlation function of random discrete state space model's output was analyzed. Aiming at the sources number judgment problem of the complex modal system, a method for estimating the number of sources based on the maximum difference ratio was proposed. Furthermore, a complex modal analysis method based on average characteristic matrix(SOBIMUC) and a underdetermined system modal analysis method based on average characteristic matrix(SOBIMUC-UDH) were proposed. The 3 DOF complex modal system and 7 DOF underdetermined system were respectively used to verify the separation performance of the above two methods, which obtained good identification effect.

Fifthly, the vibration response signals of a cantilever beam and a running car under random road excitation were respectively used to verify the modal identification performance of the SOBIMUC-UDH method, by contrasting with the traditional blind source separation method and stochastic subspace method, the results showed that the SOBIMUC-UDH method had well modal identification performance.

Key Words: Mechanical Structure; Operational Modal Analysis; Blind Source Separation.

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