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厦门大学

博 士 学 位 论 文

工程车辆降噪节能与声学舒适性的关键技术及其应用研究

Key Techniques and Applied Research on Engineering Vehicles' Noise Reduction, Energy Saving and Acoustic Comfort

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摘 要

当前，噪声已经成为衡量工程机械装备性能的一个重要指标。市场要求越来越高，相关的国家标准、国际标准日益严格。随着大功率产品的不断发展，整机噪声随之增加和热流密度不断提高，过低的冷却空气流量已满足不了发动机的热平衡要求，整机工作热流密度与逐渐降低的噪声限值的矛盾日益突出。同时，随着人们生活质量和品质追求的提高，整机声学舒适性也逐渐备受关注，对噪声的控制由最初的满足限值要求将转向声学舒适性的研究。因此，我国工程机械要发展并跻身世界市场，必须解决整机存在噪声偏大、热流密度高和声学舒适性差的共性问题。

针对以上问题，本文围绕工程车辆的噪声源分离与识别方法、多物理场耦合作用下降噪节能优化技术和声品质评价方法与预测及其控制策略等方面的问题展开研究，提出了基于改进后 FastICA 算法和 Scan&Paint 声源扫描定位系统的噪声源识别数值分析与试验研究方法；建立了基于多物理耦合分析和多学科参数优化模型；提出基于等级评分对比法的声品质主观评价方法并开发了软件系统，提高了主观评价试验的工作效率和可靠性；建立了与主观评价结果相一致的声品质评价模型，寻求主要声学评价参数与工程车辆噪声频谱特性之间的关系，提供合理的声品质的控制策略。通过平衡重式内燃叉车等实际应用案例，验证了以上提出的研究方法、技术路线和计算模型的可行性和准确性。论文主要研究内容如下：

1) 在确定工程车辆辐射噪声特点的基础上，提出综合运用独立分量分析、小波变换和声学成像技术的准确识别噪声源方法。针对 FastICA 估计存在排序、相位和幅值的不确定性，提出基于傅里叶变换和频谱最大相似度的校正方法，并通过数值算例对比改进前后的 FastICA 算法的分离结果，验证了改进后 FastICA 算法具有盲源分离的有效性和优越性。以平衡重式内燃叉车为例，在分析和确定采集到的噪声信号满足 ICA 分析独立性和高斯性的前提下，运用改进后的 FastICA 算法、连续小波变换和叉车动力舱的先验知识，分离和识别了怠速工况下的噪声源，并通过 Scan & Paint 声源定位系统验证了数值分析计算的准确性。

计算所有噪声信号和独立分量的噪声贡献度，确定了主次噪声源分别为发动机燃烧的基频噪声和排气系统的基频噪声。

2) 针对现有工程车辆存在降噪与散热的矛盾问题，提出基于多物理场耦合分析与多学科参数优化的方法。考虑到声波辐射过程中多物理场的相互影响，分析和推导了在非理想介质中声场、温度场和流速场相互耦合的控制方程，并引入了完美匹配层边界模拟声波在大气层的无反射现象。以降噪降温为目标函数，以结构几何参数为设计变量，以多物理场耦合的偏微分方程组及设计变量初始值为约束条件，提出多学科参数优化的数学模型和运用 COMSOL Multiphysics 平台进行数值计算。以同款叉车的动力舱为研究案例，以理论分析和试验数据为依据，建立动力舱的多物理场耦合模型，并进行数值计算。通过对比数值计算和试验测试得到了观测点声压级和温度，验证了所建模型的有效性。在此基础上，建立了动力舱的多学科参数优化模型，得到了较好的降噪降温效果，并对优化结果给出合理的解释，从而提出了动力舱结构创新的改进方案。

3) 针对如何评价工程机械声学舒适性问题，提出了基于等级评分对比法的声品质评价方法，并设计和开发了基于该方法的评价系统。结合工程车辆自身特点，选取了线性声压级、A 计权声压级、响度、尖锐度、粗糙度、抖动度、音调度、语音清晰度和冲激量为心理声学客观参数，并以烦躁度为主观评价指标。介绍了基于多元线性回归法、标准 BP 神经网络和 GA-BP 神经网络的常见主客观建模方法后，提出基于 PSO-BP 算法的主客观非线性映射方法，并指出运用 Garson 算法确定主要客观参数。以 50 个叉车的噪声信号为样本数据，在提出评价系统的校验方法和确定对比样本及其对应等级后，组织评审团进行主观评价试验，并对评价数据进行可靠性和有效性检验，计算了所选的客观参数值和分析其与烦躁度的相关性。建立了基于多元线性回归、BP 神经网络、GA-BP 神经网络和 PSO-BP 神经网络的评价模型和对比了模型的预测精度，确定了 PSO-BP 模型为叉车噪声主客观评价的数学模型，并由此得到影响烦躁度的最主要客观参数为响度。分析了在怠速和额定转速下的响度与频率的对应关系，确定了叉车的声品质取决于低频，并据此提出可实现的声品质控制策略。

4) 根据以上的研究成果，提出基于减振和局部密封的应用样机改进方案。按照叉车的行业标准和要求进行试验测试，结果表明改进后样机的辐射噪声降低

2.4 dB(A)，热平衡水温降低 2.2°C，均满足了标准限值。改进后的烦躁度预测值较改进前的主观评价值均下降了 10%以上，样机的声学舒适性得到了明显的改善。样机的成功改进验证了本文提出的噪声控制理论、方法和关键技术的可行性和有效性。

论文将理论分析、数值计算与试验研究相结合，提出了工程车辆降噪节能和改善声学舒适性的关键方法与技术，并展开案例和样机改进研究，对于深化和完善工程领域的学科发展具有重要的理论意义和实际应用价值。

关键词：叉车；噪声源识别；热平衡；声学舒适性；FastICA 算法；PSO-BP 神经网络；多物理场耦合

ABSTRACT

At present, noise has become an important index to evaluate the performance of engineering machinery and equipment. Under the background of more higher market requires and stricter relevant international standards and the high power products continuously develop, the machine noise increases and heat flow density enhances unceasingly. The low cooling air flow can't satisfy the engine heat balance requirements, which causes the contradictions are increasingly protruding between heat flow density and gradually lower limit value of noise. In the meantime, as people life quality and quality pursuit improve, much attention has been paid to the whole machine acoustic comfort. The noise control research has been changed from the original meet limit to acoustic comfort. Therefore, in order to gain a foothold in the international market the common problems of higher engine noise, higher heat flow density and poor acoustics comfort must been solved.

To solve the problems mentioned above, the following aspects are studied, including noise source separation and identification methods, optimization technology of energy-saving noise-reduction based on multi-physical field coupling and sound quality evaluation method, prediction and its control strategy of engineering vehicles. The noise source identification method of numerical analysis and experimental study is proposed based on the improved FastICA algorithm and Scan & Paint system. The mathematical model is established based on multi-physical field coupling analysis and multidisciplinary parameters optimization. Sound quality subjective evaluation method based on rank score comparison method is proposed and a software system is developed to improve the work efficiency and reliability of the subjective evaluation experiment. The sound quality evaluation model consistent with the subjective evaluation results has been built to seek the relationship between main acoustical evaluation parameters and the sound quality spectral characteristics, and provide reasonable sound quality control strategy. The actual application case of internal

combustion balance forklift verifies the feasibility and accuracy of the above listed research methods, technical routes and calculation models. This study mainly contains:

1) Based on the determined radiated noise characteristics of engineering vehicle, this study proposes applying independent component analysis, wavelet transform and acoustic imaging technology comprehensively so as to identify the noise source accurately. Aiming at the uncertainty of ordering, phase and amplitude in FastICA estimation, the correction method based on Fourier transform and spectrum maximum similarity is brought about. In addition, it verifies the validity and superiority of the modified FastICA algorithm in blind source separation through comparing the separation results before and after improvement under simulation example: after analyzing and determining that the collected noise signals satisfy the independence and Gaussian of ICA analysis, the noise signal at idle speed can be separated and identified through comprehensively applying the modified FastICA algorithm, continuous wavelet transform and prior knowledge on forklift power capsule; furthermore, the accuracy of the numerical analysis can be verified with the use of Scan & Paint sound source localization system. After calculating the noise contribution of all noise signals and independent components, it can be determine that the primary and secondary noise sources are the fundamental frequency noise of engine combustion system and exhaust system respectively.

2) Aiming at the contradiction issue of current engineering vehicles' noise reduction and heat dissipation, this study proposes method based on multi-physical field coupling analysis and multi-disciplinary parameters optimization. Considering the interaction of multi-physical field during the sound radiation, the governing equation of mutual coupling under imperfect dielectric among sound field, temperature field and velocity field can be obtained. Furthermore, perfectly matched layer boundary is introduced to simulate the non-reflection phenomenon of sound wave in the atmosphere. Considering noise and temperature reduction as objective function; structural geometric parameters as design variables; the partial differential

equations of multi-physical fields coupling; and the initial value of design variables as constraint conditions, this study proposes the mathematical model of multi-disciplinary parameter optimization and adopts COMSOL Multiphysics platform to undertake the numerical calculation.With the same power capsule of forklift as case study, the multi-physical coupling model of power capsule is established based on theoretical analysis and experimental data, and then numberical calculation is carried out. Through comparing the sound pressure level and temperature in observation point from numerical calculation and experimental test respectively, the validity of the established model can be verified. Based on this, this study establishes the multi-disciplinary parameter optimization model of power capsule and gets relatively good effect in noise and temperature reduction. Furthermore, it provides reasonable explanation on the optimization results and thus puts forward modified proposal on power capsule structure innovation.

3) Aiming at issues about evaluating engineering machinery acoustics comfort, this study proposes sound quality evaluating method based on rating score comparison, and designs and develops evaluation system based on this method. Associated with the characteristics of engineering vehicles, psychoacoustics objective parameters including linear sound pressure level, A-weighted sound pressure level, loudness, sharpness, roughness, fluctuation, tonality, articulation index, impulsiveness are select, and annoyance is considered as subjective evaluation index. After introducing common subjective and objective modeling method based on Multiple linear regression, the standard BP neural network and GA-BP neural network, the subjective and objective nonlinear mapping method under PSO-BP algorithm is proposed and Garson algorithm is utilized to determine the main objective parameters. The forklift is taken as example again: firstly choose the noise signal of 50 forklifts as sample data; then organiz the jury to carry out the evaluation experiment after proposing the calibration method of evaluation system and determining contrast sample together with the corresponding level; check the reliability and validity of subjective evaluation data, and then calculate the selected objective parameter values

and analyze their correlation with annoyance. Based on multiple linear regression and BP neural network, GA-BP neural network and PSO-BP neural network, this study establishes evaluation models and compares the prediction accuracy of the models. After determining PSO-BP model to be the mathematic model of objective and subjective evaluation, loudness is found to be the most outstanding parameter in affecting annoyance. After analyzing the correspondence between loudness and frequency under the idle speed and rated speed, the sound quality of forklift is found to depend on low frequency. Based on this, realizable sound quality control strategy can be put forward.

4) Based on the above research results, this study proposes improvement project of applicative prototype under vibration reduction and local sealing. According to the industry standards and requirements of forklift, the experimental tests are carried out and results show that the radiation noise of improved prototype decreases 2.4 dB(A) and the thermal equilibrium temperature lowers 2.2°C, which both satisfy the standard limit. In addition, the modified annoyance prediction values all decrease more than 10% comparing to the former one with the acoustic comfort of prototype being improved remarkably. The successful improvement of prototype verifies the feasibility and validity of the proposed noise control theories, methods, key techniques in this study.

Combining theoretical analysis, numerical computation and experimental research, this study presents key methods and techniques in noise reduction, saving energy and acoustic comfort of engineering vehicles and carries out detailed case study and prototype improvement, which is of great theoretical significance and practical application value in deepening and improving the discipline development of engineering.

Keywords: forklift; noise source identification; thermal equilibrium; acoustic comfort; FastICA algorithm; PSO-BP neural network; multi-physical field coupling

目 录