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博　士　学　位　论　文

基于机器学习和智能优化算法的压力传感器补偿技术研究

Research on Compensation Technology of Pressure Sensor Based on Machine Learning and Intelligent Optimization Algorithm

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摘 要

微机电系统（Micro Electro Mechanical System, MEMS）拥有功耗低、灵敏度高、体积小、制造标准化程度高以及性价比高等突出优势，基于 MEMS 制造工艺的压阻式压力传感器被广泛应用于汽车、航空、石油石化及消费电子的压力测量环节。伴随社会工业化水平的不断发展，对相应工业过程的压力测量性能也日趋严格。环境温度和静压压力作为全面影响高精度 MEMS 压力传感器整体测量特性的两个关键因素，已然成为压阻式压力传感器在高精度测量领域更进一步的瓶颈。

针对上述问题，本文以半导体材料的压阻效应和 MEMS 制造工艺为基础，以绝压压力传感器、差压压力传感器为研究对象，通过结合包括支持向量回归机（Support Vector Regression, SVR）、最小二乘支持向量机（Least Squares Support Vector Machine, LSSVM）与核极限学习机（Kernel Extreme Learning Machine, KELM）在内的机器学习模型以及包括自适应变异粒子群优化（Adaptive Mutation Particle Swarm Optimization, AMPSO）、混沌离子运动算法（Chaotic Ions Motion Algorithm, CIMA）和耦合模拟退火-单纯形搜索（Coupled Simulated Annealing-Simplex, CSA-Simplex）在内的智能算法为手段，对环境温度变化和静压压力影响导致的非线性输出特性、静压输出误差等关键问题展开研究。论文主要研究内容如下：

(1) 分析了温度漂移现象成因，表明传感器的输出非线性不仅是基于半导体材料压阻系数对温度变化的本质响应也同时受到制造工艺过程中许多其他因素的干扰。比较现有的硬件补偿方法和软件补偿方法，分析各种方法存在的优势和缺陷。

(2) 针对 250kPa 压阻式差压压力传感器的温度补偿问题，提出基于改进的 AdaBoost.RT 集成自适应变异粒子群优化支持向量回归机（Adaptive Muatation Particle Swarm Optimization Optimized Support Vector Regression, AMPSO-SVR）的方法。考虑温度对输出特性的非线性影响，温度补偿问题可以抽象为非线性函数的回归问题。支持向量回归机的结构风险最小化框架保证了良好的模型非线性

逼近能力和泛化能力。由于模型参数选择对于支持向量回归机的性能起到至关重要的作用，引入经典的智能优化算法——粒子群优化作为优化选参的策略。局限于传统粒子群算法存在的早熟问题和有限的寻优能力，结合 Levy 飞行阶段性调整粒子群运动轨迹避免早熟现象。为加速粒子群算法的收敛过程，在初始化种群阶段利用相对基初始化令种群在寻优空间中均匀分布等价于最大程度获取参数空间的结构信息。以精简标定过程为目的设计并完成了动态温度标定实验，结合实验数据与布谷鸟搜索优化支持向量回归机（Cukoo Search Optimized Support Vector Regression, CS-SVR）、飞蛾算法优化支持向量回归机（Firefly Algorithm Optimized Support Vector Regression, FA-SVR）、混合蛙跳算法优化支持向量回归机（Shuffled Leap Frog Algorithm Optimized Support Vector Regression, SLFA-SVR）、粒子群优化支持向量回归机（Particle Swarm Optimization Optimized Support Vector Regression, PSO-SVR）、结合 Levy 飞行粒子群优化支持向量回归机（Particle Swarm Optimization with Levy Flight Optimized Particle Swarm Optimization Optimized Support Vector Regression, Levy-PSO-SVR）以及自适应变异粒子群优化支持向量回归机（Adaptive Muatation article Swarm Optimization Optimized Support Vector Regression, AMPSO-SVR）的补偿算法相比较，结果表明所提出的自适应变异粒子群优化算法对支持向量回归机的优化程度强于其他优化方法。进一步比较 BP 神经网络、RBF 神经网络、AMPSO-SVR 模型与以 AMPSO-SVR 为基学习机的改进 AdaBoost.RT 集成模型，结果显示所提出的温度补偿方法在减少标定工作量的基础上获得了更为满意的补偿性能且更易于工程实现。

(3) 针对 40kPa 压阻式差压压力传感器的温度补偿问题，提出混沌离子运动优化最小二乘支持向量机的补偿方案。最小二乘支持向量机将支持向量回归机中的二次优化问题转化为线性方程组，其中的正则化理论获得了建模能力与模型复杂度之间的平衡。分析了不同核函数对模型逼近能力的影响，构造了混合核函数。介绍了离子运动优化算法，引入混沌映射保证混沌离子运动算法中搜索过程的遍历性和随机性，提出了混沌离子运动算法选取混合核参数。结合静态标定实验数据，从静态划分和随机划分两种不同的训练集生成角度，与只含 RBF 核函数的支持向量机（RBF-SVM）、改进的粒子群优化支持向量机（Improved Particle Swarm Optimization Optimized Support Vector Machine, IPSO-RBF-SVM）、改进的粒子

群算法优化最小二乘支持向量机（Improved Particle Swarm Optimization Optimized Least Square Support Vector Machine, IPSO-RBF-LSSVM）以及考虑混合核函数的改进的粒子群算法优化最小二乘支持向量机（Improved Particle Swarm Optimization Optimized Least Square Support Vector Machine, IPSO-Hybird-LSSVM）、离子运动算法优化最小二乘支持向量机（Ions Motion Algorithm Optimized Least Square Support Vector Machine, IMA-Hybrid-LSSVM）和混沌离子运动算法优化最小二乘支持向量机（Chaotic Ions Motion Algorithm Optimized Least Square Support Vector Machine, CIMA-Hybrid-LSSVM）进行对比，仿真结果表明基于 LSSVM 的温度补偿方案相比 SVM 拥有计算效率高的优势，混合核函数相比单一 RBF 核函数具有更好的模型泛化能力，CIMA 优化算法具有良好的全局寻优能力。

(4) 针对数据量较大的情形提出一种新的量子粒子群最小二乘支持向量机稀疏化（Quatum Particle Swarm Optimization Sparsed Least Squares Support Vector Machine, QPSO-sparsed-LSSVM）策略。量子粒子群优化算法不仅能够以较大概率搜索到与当前稀疏化模型对应的最优模型特征参数，也避免了经典稀疏化算法顺序停止准则可能造成的早期停止效应。量子粒子群优化算法对 1MPa 绝压压力传感器的补偿效果都优于未稀疏化的最小二乘支持向量机和经典稀疏化最小二乘支持向量机。

(5) 提出耦合模拟退火结合单纯形搜索优化核极限学习机（Coupled Simulated Annealing and Simplex Optimized Kernel Extreme Learning Machine, CSA-simplex-KELM）框架以解决考虑静压和环境温度综合影响的差压压力传感器的补偿问题。利用极限学习机（Extreme Learning Machine, ELM）拥有令人满意的建模速度并将正则化方法和核方法纳入其中可迅速获得泛化性能良好的预测模型。对核极限学习机（KLEM）的参数寻优策略由耦合模拟退火算法（CSA）与单纯形搜索（simplex）组合的两阶段搜索构成，先由 CSA 算法在参数空间中获取局部最优或可能的全局最优位置，进而用单纯形搜索完成更小范围的局部精细搜索。结合实验数据与误差反传神经网络（Back Propagation Neural Network, BP）、径向基神经网络（Radial Basis Function Neural Network, RBF）、粒子群优化支持向量机（Particle Swarm Optimization Optimized Support Vector Machine, PSO-

SVM）、粒子群优化优化最小二乘支持向量机（Particle Swarm Optimization Optimized Least Square Support Vector Machine, PSO-LSSVM）、极限学习机（Extreme Learning Machine, ELM）相比，在温度补偿问题和综合补偿问题上有了显著的精度提升，对压力传感器的测量特性具备较强的学习能力。

本文将理论分析、智能优化算法、机器学习理论与试验研究相结合，提出了改善有关 MEMS 硅压阻式压力传感器温度漂移问题和静压误差问题的关键方法与技术，对多样化压力测量领域的研究方法和深化学科发展具有重要的理论意义和应用价值。

关键词：压阻式压力传感器；温度补偿；智能优化算法；SVR；LSSVM；KELM

Abstract

As Micro Electro Mechanical System takes many advantages as low power consummation, high sensitivity, small volume, standardized manufacturing process and high cost performance ratio, piezo-resistive pressure sensor based on which has been extensively applied to the pressure measurement in almost all the industrial areas such as automobile, aviation, petrochemical and consumer electronics, etc. The requirement of the synthetic performance pressure sensor in industrial process increases rapidly with the improvement of the social industrialization level. However, the environmental temperature and the static pressure effect are two key factors which may bring some unsatisfied bias to measurement characteristics of high precision pressure sensor， which have become the technical bottleneck to provide more measurement accuracy.

To deal with these two issues, the research work in this paper is based on piezo-resistive effect and MEMS craft. The absolute pressure sensor and the relative pressure sensor are taken as the research objects. Some methods including Machine learning models as support vector regression (SVR), least squares support vector machine (LSSVM), kernel extreme learning machine (KELM) and intelligent optimization algorithms as adaptive mutation particle swarm optimization (AMPSO), Chaotic ions motion algorithm, coupled simulated annealing with simplex (CSA-Simplex) are combined to solve critical problems as nonlinear output characteristic caused by environmental temperature variation and static pressure output error derived from static pressure. The main research works are summarized as follows:

(1) By analyzing the reason for temperature drift, it indicates that the nonlinear output of the pressure sensor is not only rely on the response relationship of piezo-resistive coefficient of the semiconductor and the environmental temperature variation but also influenced by some other unsatisfied factors in the pressure sensor manufacturing process. Both hardware compensation methods and software compensation methods are reviewed to give the details

of advantages and disadvantages of these existed temperature compensation schemes.

(2) The improved AdaBoost.RT ensemble adaptive mutation particle swarm optimization optimized support vector regression (AMPSO-SVR) is proposed to compensate the temperature error of 250kPa piezo-resistive differential pressure sensor. Taking into consideration the nonlinear effect of the sensor output characteristic rise from the temperature variation, the temperature compensation problem could be deemed as a nonlinear function regression problem. The frame of structure risk minimum guarantees SVR good nonlinear approximation ability and generalization ability. Because the model parameters are important to the SVR the classical intelligent optimization algorithm——particle swarm optimization (PSO) is introduced in this research work to select appropriate model parameters. Nevertheless, classical PSO algorithm suffers from premature phenomena and relative limited searching ability, Levy flight is applied to adaptively adjust the particle swarm trajectory to avoid premature. To accelerate the convergence process of PSO, opposition-based initialization is used to uniformly distribute the swarm particles over the solution space to learn as much as possible about the solution space structure. A dynamic calibration experiment was designed and implemented to reduce the calibration time, several compensation models including Cuckoo Search Optimized Support Vector Regression (CS-SVR), Firefly Algorithm Optimized Support Vector Machine (FA-SVR), Shuffled Leap Frog Algorithm Optimized Support Vector Regression (SLFA-SVR), Particle Swarm Optimization Optimized Support Vector Regression (PSO-SVR) and Particle Swarm Optimization with Levy Flight Optimized Particle Swarm Optimization Optimized Support Vector Regression (Levy-PSO-SVR) are compared on the experiment data with Adaptive Mutation article Swarm Optimization Optimized Support Vector Regression (AMPSO-SVR), the results indicate the presented AMPSO is superior to other optimization scheme for SVR. Furthermore, the proposed improved AdaBoost.RT takes the

AMPSO-SVR as base learning machine. The result derived from the comparison between back-propagation neural network, radial basis function neural network, AMPSO-SVR and the proposed compensation scheme shows that the improved AdaBoost.RT ensemble AMPSO-SVR can provide more satisfied compensation performance than other compensation methods and more feasible for engineering realization.

(3) The chaotic ions motion algorithm (CIMA) optimized least squares support vector machine (LSSVM) is proposed to deal with the temperature compensation problem of 40kPa piezo-resistive differential pressure sensor. LSSVM converts the quadratic optimization to a linear equation system, in which the regularization theory is able to achieve the balance between modeling ability and model complexity. Constructing hybrid kernel function on the basis of analyzing the model approximation ability using different kernel functions. A new intelligent optimization method——ions motion algorithm (IMA) is introduced, moreover, the CIMA is presented to select appropriate hybrid kernel parameters. The chaotic mapping is embedded in the CIMA to promise the ergodicity and stochasticity of the searching process. Compared with SVM merely has RBF kernel (RBF-SVM), Improved Particle Swarm Optimization Optimized Support Vector Machine (IPSO-RBF-SVM), Improved Particle Swarm Optimization Optimized Least Square Support Vector Machine (IPSO-RBF-LSSVM), Improved Particle Swarm Optimization Optimized Least Square Support Vector Machine (IPSO-Hybrid-LSSVM), Ions Motion Algorithm Optimized Least Square Support Vector Machine (IMA-Hybrid-LSSVM) and Chaotic Ions Motion Algorithm Optimized Least Square Support Vector Machine (CIMA-Hybrid-LSSVM) on static experiment data from viewpoints of static partition and random partition. Three conclusion can be drawn from the simulation results: LSSVM framework is more efficient than SVM; hybrid kernel has better generalization ability than single RBF kernel; CIMA is more suitable than other referred optimization algorithms for searching global optima.

(4) A new sparse scheme named quantum particle swarm sparse least squares support machine (QPSO-sparse-LSSVM) is presented to deal with relative large sample dataset. QPSO-sparse-LSSVM can not only obtain the optimal model parameters of the sparse LSSVM model with high probability but also avoid the early stop caused by the order stop criterion of the classical sparse LSSVM algorithm. Compared with the LSSVM without sparseness and classical sparse LSSVM on different dataset, the proposed sparse LSSVM shows the most satisfied performance for the temperature compensation problem of 1MPa absolute pressure sensor.

(5) The coupled simulated annealing and simplex optimized kernel extreme learning machine (CSA-simplex-KELM) framework is proposed to solve the compensation problem result from synthetic influence of the static effect and environmental temperature. Extreme Learning Machine (ELM) is a prediction model with fast modeling speed and decent generalization ability which owes to the application of the kernel trick and regularization theory. The parameter optimization task is accomplished by a two steps searching strategy consists of coupled simulated annealing (CSA) and simplex. The CSA is employed to find a local optimal position followed by the simplex which would perform a more precise local search. Compared with Back Propagation Neural Network (BP), Radial Basis Function Neural Network (RBF), Particle Swarm Optimization Optimized Support Vector Machine (PSO-SVM), Particle Swarm Optimization Optimized Least Square Support Vector Machine (PSO-LSSVM) and Extreme Learning Machine (ELM), the proposed compensation strategy not only improves the compensation performance about the temperature compensation and synthetic compensation but also exhibits strong learning ability about the characteristic of pressure sensor.

Theoretic analysis, intelligent optimization algorithm, machine learning theory and experiment research are combined in this research. Some key methods are developed along with related work to eliminate the temperature error and synthetic error of the MEMS piezo-resistive pressure sensor which have important theoretical

significance and application value for the diversification of the research methods of the pressure measurement area and exploring the development direction of this discipline.

Keywords: piezo-resistive pressure sensor; temperature compensation; intelligent optimization algorithm; SVR; LSSVM; KELM

目 录