

学校编码: 10384

分类号 _____ 密级 _____

学 号: 19920120153879

UDC _____

厦 门 大 学

博 士 学 位 论 文

直流微电机建模及故障诊断方法研究

Research on Methods of Modeling and Fault Diagnosis
for Micro Direct-Current Motors

谢 志 平

指导教师姓名: 陈 文 芾 教 授

专 业 名 称: 机 械 电 子 工 程

论文提交日期: 2015 年 月

论文答辩时间: 2015 年 月

学位授予日期: 2015 年 月

答辩委员会主席: _____

评 阅 人: _____

2015 年 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果,均在文中以适当方式明确标明,并符合法律规范和《厦门大学研究生学术活动规范(试行)》。

另外,该学位论文为()课题(组)的研究成果,获得()课题(组)经费或实验室的资助,在()实验室完成。(请在以上括号内填写课题或课题组负责人或实验室名称,未有此项声明内容的,可以不作特别声明。)

声明人(签名):

年 月 日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

1. 经厦门大学保密委员会审查核定的保密学位论文，于 年 月 日解密，解密后适用上述授权。

2. 不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年 月 日

摘要

直流微电机以体积小、重量轻、便于控制等优点被广泛应用于生产消费领域，在微型精密仪器中尤为重要。为了保证产品出厂品质，生产过程必须对直流微电机进行 100% 检测。目前检测主要依靠人工的经验来判断电机的好坏，其工作量大，生产效率低，漏检现象严重，导致电机出厂质量不稳定。因此有必要寻找一种简便和可靠的直流微电机在生产线上的故障检测技术。该技术即可以对出厂前的直流微电机进行自动在线检测，以保证直流微电机的出厂合格率；又可以推广应用用于其他永磁直流电机的故障检测与诊断。

通过分析空载下直流电机的动态数学模型，假设稳态下 $d\omega/dt = 0$ ，推导出永磁直流电机稳态电枢电流的解析式，其揭示了电枢电流与电机内部的机电参数之间的规律。在分析有刷直流微电机的数学模型和运行机理上，结合 Matlab/Simulink 的功能模块和 S 函数，构建了有刷直流微电机系统仿真模型。探讨了直流微电机匝间短路、极间阻抗差异、线圈绕组开路、线圈绕组脱焊及磁铁回路异常的故障机理，建立了基于 Matlab/Simulink 的直流微电机匝间短路、极间阻抗差异、线圈绕组开路及线圈绕组脱焊的故障仿真模型，仿真结果与实验结果的一致，验证了该仿真模型的合理性和有效性，此仿真方法也适用于其他有刷永磁直流电机。

通过对直流微电机电枢电流的频谱数据统计分析，将直流分量 P_{DC} 、主频点 f_m 、主频点处的幅值 P_{f_m} 、带外频谱面积 A 和归一化因子 Q 定义为故障多特征量，利用提取的故障多特征量分析了六种生产中常见的直流微电机故障。对良品和典型故障电机的故障多特征量的分布规律进行了假设，采用 χ^2 检验和 $K-S$ 检验方法进行假设检验；对于服从多种假设分布的故障多特征量采用基于最大总体平均隶属优势准则进行模糊识别，从而确定故障多特征量的统计分布规律和阈值。将待测电机的故障多特征量值分别与已知故障多特征量的阈值比较，就可诊断待测电机的故障类型。该方法解决了直流微电机磁电参数离散性较大的问题。

为了验证直流微电机故障诊断方法的有效性，设计了基于稳态电流频谱分析的直流微电机故障诊断系统，搭建了基于 STM32F107VC 芯片的直流微电机诊断

装置。为拓展直流微电机故障诊断系统的应用范围，设计了自学习模块，即当被测电机的类型改变时，通过收集样本电机的故障多特征量值来估计分布参数值，重新确定和更新故障多特征量的阈值。以多台直流微电机为实验对象，进行故障诊断及分析，实验结果表明该方法可以有效的诊断直流微电机。

本方法只需要监测直流电机的电枢电流，不需要采集转速等其他更多的信号，对传感器等硬件要求小；采用基于统计模式识别的故障诊断方法，对硬件系统要求低，软硬件实现简单，成本低，但电机样本要求大。其在直流电机生产线的质量控制和直流电机的在线状态监测具有实用性。本文虽以直流微电机为研究对象，但其方法和理论可以应用于所有电枢电流具有正弦波形的直流电机。

关键词：直流微电机；故障诊断；建模仿真；频谱分析；故障多特征量

Abstract

Micro direct-current motors (MDCMs) are increasingly used in industry fields and consumption fields, especially in micro precision instruments. Compared to other motors, smaller size and simpler control scheme are achieved. MDCMs must be screened at 100% detection efficiency on the production line to ensure the quality of outgoing products. Currently, fault detection of motor is mainly based on the experiences of the individual. This method is heavy workload and low production efficiency. The leak phenomenon is serious. It leads to motor's quality is not stable. So it is necessary to find a simple and reliable fault detection technology of MDCMs on the production line. To ensure the ex factory product pass rate of MDCMs, the method which can be applied to fault diagnosis of other permanent magnet DC motor is used for fault detection of motor on-line before delivery

Assuming that $d\omega/dt = 0$ under steady state operation conditions, The analytical expression of armature current is obtained from the dynamic model of DC motor under no-load operation conditions. It reveals the rule between armature current and electromechanical parameters. According to the mathematical model and running mechanism of MDCM, A simulation model of MDCM based on SIMULINK and S function of MATLAB is established. The fault mechanisms of turn-to-turn short circuit, different coil resistance and inductance, opening of coil and sealing-off of coil are studied, and their faulty simulation models based on MATLAB/SIMULINK are established. The reasonability and validity of the method was testified by the coincidence of simulation and experimental results. The simulation methodology is also applicable to other permanent magnet brush DC motor.

Based on the statistical analysis of the spectral data for MDCMs, the DC component P_{DC} , the main frequency point f_m , the amplitude of the main frequency point P_f , the spectrum area outside band A and the normalized distortion factor Q are determined as multiple features of fault diagnosis for MDCM. The five multiple features extracted from the armature current of MDCM are utilized to analyze the six

kinds of faults for MDCMs in production. The distribution rules of multiple features for the healthy and typical faulty MDCMs are made assumptions. Their hypothesis distribution tests are performed using the χ^2 test and the $K-S$ test. Fuzzy pattern recognition based on the maximum overall average membership advantages criteria is adopted to confirm the distribution rules of multiple features which obey varieties of possible hypothesis distribution. Then, the distribution rules and threshold values of multiple features are obtained. The tested motors can be diagnosed by comparing the multiple features of the tested motors with the threshold values. The problem which the magnetoelectric parameters of MDCMs are discrete is solved by using this proposed method.

To demonstrate the feasibility of the proposed fault diagnosis method, fault diagnosis system of MDCM based on spectrum analysis of the steady-state current is designed. The diagnostic device of MDCMs based on STM32F107VC chip is set. In order to extend the application range of MDCM diagnosis system, the self learning module is designed. When the type of tested motor is changed, the self learning modules can estimate distribution parameters value by collecting the multiple features of tested motor and update the threshold of multiple features. The experiments of fault diagnosis on several MDCMs was studied and analyzed. The experimental results showed that this method can effectively diagnosis the MDCM.

This method only needs to monitor armature current of MDCM, doesn't need to collect speed and other signal and not high demand for sensors. The fault diagnosis method based on statistical pattern recognition has low requirement to the hardware, simple software and hardware and low cost, but it requires large motor data. This method has practicability in the quality control of DC motor on the production line and on-line condition monitoring. Although the MDCMs are studied, the proposed method can be applied to any of DC motors which have sinusoidal waveform.

Key Words: Micro Direct-Current Motor; Fault Detection; Modeling and Simulation; Spectrum Analysis; Faulty Multiple Features

目 录

第一章 绪论	1
1.1 课题研究的目的和意义	1
1.2 直流电机故障类型	2
1.3 直流故障电机的故障监测技术	4
1.3.1 基于电流故障监测	5
1.3.2 基于声音故障监测	7
1.3.3 基于振动故障监测	7
1.3.4 基于转矩的故障监测	8
1.3.5 基于转速的故障监测	8
1.3.6 基于温度的故障监测	8
1.4 直流电机故障诊断技术	8
1.4.1 基于数学模型的方法	8
1.4.2 基于统计模式的故障模式识别方法	10
1.4.3 基于人工智能的故障模式识别	10
1.5 直流电机信号处理技术	14
1.5.1 快速傅里叶变换	14
1.5.2 双谱分析	15
1.5.3 小波变换	15
1.6 本文主要研究工作	16
第二章 永磁直流电机数学模型	18
2.1 永磁直流电机电枢电流分析	18
2.1.1 直流电机稳态电枢电流分析	18
2.1.2 直流电机换向过程中的电枢电流变化	22
2.2 直流微电机	24
2.2.1 直流微电机结构	24
2.2.2 直流微电机电动势分析	25
2.3 直流微电机相电流分析	28

2.3.1 换向过程相电流分析.....	28
2.3.2 感应电动势与相电流.....	30
2.3.3 相电流数学模型.....	31
2.4 基于 Matlab 仿真的有刷直流微电机数学建模	40
2.4.1 直流微电机等效电路模型.....	40
2.4.2 Matlab/Simulink 平台上直流微电机的建模和仿真	43
2.4.3 仿真结果.....	45
2.5 直流微电机实验	48
2.5.1 实验方法.....	48
2.5.2 实验结果.....	48
2.6 本章小结	49
第三章 典型故障机理分析及仿真模型	51
3.1 匝间短路故障机理分析及仿真模型.....	51
3.1.1 匝间短路电机数学模型.....	51
3.1.2 匝间短路电机仿真模型.....	55
3.1.3 匝间短路故障电机实验.....	60
3.2 极间阻值差异故障机理分析及仿真模型.....	61
3.2.1 极间阻值差异故障电机数学模型.....	61
3.2.2 极间阻抗差异故障电机仿真模型.....	61
3.2.3 极间阻抗差异故障电机实验.....	65
3.3 绕组开路故障机理分析及仿真模型.....	66
3.3.1 绕组开路故障数学模型.....	66
3.3.2 绕组开路故障机理分析.....	67
3.3.3 绕组开路故障电机仿真模型.....	68
3.3.4 绕组开路故障电机实验.....	70
3.4 线圈绕组脱焊故障机理分析及仿真模型.....	71
3.4.1 线圈绕组脱焊故障机理分析.....	71
3.4.2 线圈绕组脱焊故障仿真模型.....	72
3.4.3 线圈绕组脱焊故障电机实验.....	74
3.5 磁铁回路异常故障机理分析.....	75
3.5.1 电磁场计算基本方程.....	75

3.5.2 直流微电机正弦气隙磁场.....	75
3.5.3 磁铁回路异常故障电机实验.....	76
3.6 本章小结.....	76
第四章 直流微电机故障多特征量研究.....	78
4.1 能量泄露分析.....	78
4.1.1 能量泄漏.....	78
4.1.2 栅栏效应.....	80
4.1.3 能量泄漏与栅栏效应的关系.....	80
4.2 故障多特征量概念.....	81
4.2.1 直流微电机电枢电流解析式.....	81
4.2.2 故障多特征量数学表达式.....	82
4.3 故障电机频谱特征提取实验.....	84
4.3.1 实验平台.....	85
4.3.2 实验设计.....	86
4.4 故障多特征量.....	87
4.4.1 故障多特征量提取.....	87
4.4.2 典型故障电机电枢电流频谱特征.....	89
4.4.3 故障多特征量变化率.....	95
4.5 本章小结.....	96
第五章 统计模式和模糊模式识别技术.....	98
5.1 参数估计.....	98
5.1.1 参数估计方法.....	98
5.1.2 故障多特征量统计分布的参数估计.....	100
5.2 拟合优度检验.....	101
5.2.1 χ^2 检验.....	102
5.2.2 $K-S$ 检验.....	102
5.3 故障多特征量分布的模糊模式识别.....	103
5.3.1 相关概念及理论.....	104
5.3.2 最大总体平均隶属优势准则.....	105
5.3.3 故障多特征量隶属函数的确定.....	106
5.3.4 基于最大总体平均隶属优势准则的模糊识别方法.....	107

5.4 本章小结	108
第六章 基于统计模式识别的直流微电机故障诊断方法	109
6.1 故障多特征量的分布规律	109
6.1.1 多特征量数据的获取	109
6.1.2 良品电机故障多特征量分布规律	109
6.1.3 典型故障电机故障多特征量分布规律	111
6.2 故障多特征量的阈值确定	119
6.2.1 良品直流微电机故障多特征量阈值	119
6.2.2 典型故障电机多特征量阈值	120
6.3 故障识别算法	127
6.4 直流微电机故障诊断系统设计及实验	128
6.4.1 直流微电机故障诊断系统设计	128
6.4.2 故障诊断系统实验装置	131
6.4.3 故障诊断系统性能实验结果分析	131
6.5 本章小结	134
第七章 总结与展望	135
7.1 总结	135
7.2 展望	136
参考文献	137
致谢	149
科研成果	150

Contents

Chapter 1 Introduction.....	1
1.1 Purpose and significance of the research	1
1.2 Fault type of DC Motor.....	2
1.3 Condition monitoring techniques for DC motor	4
1.3.1 Condition monitoring based on current	5
1.3.2 Condition monitoring based on voice	7
1.3.3 Condition monitoring based on vibration	7
1.3.4 Condition monitoring based on torque	8
1.3.5 Condition monitoring based on angular speed.....	8
1.3.6 Condition monitoring based on temperature.....	8
1.4 Introduction of fault detection method of DC motor	8
1.4.1 Fault recognition method based on dynamic motor motor	8
1.4.2 Fault recognition method based on statistical model.....	10
1.4.3 Fault recognition method based on artificial intelligence.....	10
1.5 Signal processing of DC motor	14
1.5.1 Fast fourier transform	14
1.5.2 Bispectra analysis.....	15
1.5.3 Wavelet transform.....	15
1.6 Main Contents and Arrangement of Paper.....	16
Chapter 2 Mathematical model of PM DC motor	18
2.1 The theoretical analysis of armature current for PM DC motor	18
2.1.1 The analysis of armature current under steady-state operation condition ...	18
2.1.2 Change of armature current in the brush switching process	22
2.2 Micro direct-current motor	24
2.2.1 The constitute of MDCM.....	24
2.2.2 The analysis of induced electromotive force for MDCM.....	25
2.3 The analysis of phase current for MDCM.....	28
2.3.1 The analysis of phase current under the commutation process.....	28

2.3.2 The induced electromotive force and phase current	30
2.3.3 Mathematical model of phase current.....	31
2.4 Mathematical modeling of MDCM based on Matlab	40
2.4.1 Equivalent circuit model of MDCM	40
2.4.2 Modeling and simulation of MDCM based on Matlab/Simulink	43
2.4.3 Simulation result	45
2.5 Experiment of MDCM	48
2.5.1 Experimental facility.....	48
2.5.2 Experimental result	48
2.6 Summary of chapter.....	49
Chapter 3 Mechanism analysis and simulation model of typical faults	
for MDCMs.....	51
3.1 Mechanism analysis and simulation model of inter-turn fault.....	51
3.1.1 Mathematical model of inter-turn fault.....	51
3.1.2 Simulation model of inter-turn fault	55
3.1.3 Experiment of inter-turn fault	60
3.2 Mechanism analysis and simulation model of different resistance and	
inductance fault	61
3.2.1 Mathematical model of different resistance and inductance fault	61
3.2.2 Simulation model of different resistance and inductance fault.....	61
3.2.3 Experiment of different resistance and inductance fault.....	65
3.3 Mechanism analysis and simulation model of open-winding fault	66
3.3.1 Mathematical model of open-winding fault.....	66
3.3.2 Mechanism analysis of open-winding fault	67
3.3.3 Simulation model of open-winding fault	68
3.3.4 Experiment of open-winding fault	70
3.4 Mechanism analysis and simulation model of windings desoldering fault .	71
3.4.1 Mechanism analysis of windings desoldering fault	71
3.4.2 Simulation model of windings desoldering fault	72
3.4.3 Experiment of windings desoldering fault	74
3.5 Mechanism analysis of abnormal magnet circuit fault	75

3.5.1 Calculation equation of electromagnetic field	75
3.5.2 The sinusoidal magnetic field of MDCM	75
3.5.3 Experiment of abnormal magnet circuit fault	76
3.6 Summary of chapter.....	76
Chapter 4 Research on multiple features of MDCMs	78
4.1 Analysis of energy leak.....	78
4.1.1 Energy leak	78
4.1.2 Fence effect	80
4.1.3 The relation of energy leak and fence effect	80
4.2 Concept of the multiple features	81
4.2.1 The analytical expression of armature current for MDCMs	81
4.2.2 Mathematical expression of the multiple features	82
4.3 Experiment of frequency spectrum feature extract for faulty motor	84
4.3.1 Experimental platform	85
4.3.2 Experimental design.....	86
4.4 Faulty multiple features	87
4.4.1 Extraction of multiple features.....	87
4.4.2 Frequency spectrum feature of armature current for faulty motor	89
4.4.3 Relative Changes for multiple features.....	95
4.5 Summary of chapter.....	96
Chapter 5 The techniques of statistical pattern recognition and fuzzy pattern recognition.....	98
5.1 Parameter estimation	98
5.1.1 The method of parameter estimation	98
5.1.2 Parameter estimation of statistical distribution for multiple features	100
5.2 Test of goodness of fit	101
5.2.1 The test of χ^2	102
5.2.2 The test of $K-S$	102
5.3 Fuzzy pattern recognition of multiple features.....	103
5.3.1 Relevant concepts and theories	104

5.3.2 The maximum overall average membership advantages criteria.....	105
5.3.3 Membership function of multiple features.....	106
5.3.4 Fuzzy pattern recognition based on the maximum overall average membership advantages criteria.....	107
5.4 Summary of chapter.....	108
Chapter 6 An approach to detection in MDCMs based on statistical pattern recognition.....	109
6.1 Law of distribution for multiple features	109
6.1.1 Data acquisition of multiple features	109
6.1.2 Law of distribution for multiple features in the healthy motor.....	109
6.1.3 Law of distributions for multiple features in the typical faulty motors	111
6.2 Threshold of multiple features	119
6.2.1 Threshold of multiple features for the healthy motor	119
6.2.2 Threshold of multiple features for the typical Faulty motors	120
6.3 Fault recognition algorithm.....	127
6.4 Design of fault diagnosis system and performance experiments	128
6.4.1 Design of fault diagnosis system for MDCMs	128
6.4.2 Experimental platform of fault diagnosis system	131
6.4.3 Experimental result of fault diagnosis system	131
6.5 Summary of chapter.....	134
Chapter 7 Conclusions and prospects.....	135
7.1 Conclusions	135
7.2 Prospects.....	136
References	137
Acknowledgements	149
Achievements.....	150

第一章 绪论

1.1 课题研究的目的是和意义

随着现代科技的飞速发展和工业自动化程度的提高,电机已广泛应用于国民经济各个领域,电机根据电磁感应定律将电能转换成机械能,使生产机械完成人们期望的各种运动。电机是系统设备主要的动力传动部件和执行部件,通常是系统设备的核心组成部分之一。其安全运行直接决定了生产过程的效益,生产线的安全以及产品的质量。在某些特殊的场合,电机的安全运行直接影响着生产人员的生命安全。因此,电机故障检测与诊断一直是众多学者、工程技术人员、电机制造厂商和普通用户所关注的热点问题。国内外学者对电机故障在线检测与诊断研究较多,其研究重点放在大功率电机及交流感应电机上^[1-4],已取得了一系列的研究成果。相对于大功率电机,小功率直流电机的检测技术研究相对较少^[5]。较少有文献涉及直流微电机的故障检测,尤其在产品生产线上电机故障检测。

直流微电机是由永磁体建立磁场的直流电机。它除了具有一般电磁式直流电机所具备的良好的机械特性和调节特性,可以用于要求起动转矩高和转速变化范围较大的场合外,还具有体积小、效率高(无激磁损耗)、控制方便和制造成本低廉等优点。因此,直流微电机被广泛应用于消费领域、工业领域和军事领域,从家用电器(如电动自行车、剃须刀、除尘器、汽车等)到一些要求良好动态性能的精密速度和位置驱动系统即增量运动系统(如计算机外部设备、精密机床及宇航等领域)都大量使用直流微电机。

我国的直流微电机制造企业通过自主研发、引进先进技术、合作生产、购买设备和培训工程技术人员等方法,已经逐步掌握电机的先进制造技术。为了保证这些产品的出厂合格率,出厂前必须对电机进行严格的质量检验。而现在没有高效的自动化检测设备,电机出厂质量检测全部依靠人工检测。常见的方法是通过观察电机运行时其端电压的波形以及听取运行声音,依据积累的经验来判断电机的好坏。这种检测方法完全依赖于操作者的知识经验,检测结果分散,检测标准不统一,检测结果受操作者的情绪影响严重,而且效率低,无法满足现代直流微电机厂商大批量生产、高合格率出厂的要求。因此有必要寻找一种可靠的直流微

Degree papers are in the “[Xiamen University Electronic Theses and Dissertations Database](#)”.

Fulltexts are available in the following ways:

1. If your library is a CALIS member libraries, please log on <http://etd.calis.edu.cn/> and submit requests online, or consult the interlibrary loan department in your library.
2. For users of non-CALIS member libraries, please mail to etd@xmu.edu.cn for delivery details.