

高阶累积量耦合性质在液压阀故障诊断中的应用研究

学校编码: 10384

分类号____密级____

学号: 23120090153694

UDC____

厦门大学

博士学位论文

高阶累积量耦合性质在液压阀故障诊断中的应用研究

Research on the application of HOC coupling properties in hydraulic faults diagnosis

指导教师姓名: 陈文芎

专业名称: 电路与系统

论文提交日期: 2012 年 月

论文答辩时间: 2012 年 月

学位授予日期: 2012 年 月

答辩委员会主席:

评阅人:

2012 年 月

厦门大学

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

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

厦门大学博硕士学位论文摘要库

摘 要

本文以液压系统常用的液压阀（溢流阀、减压阀、调速阀）为研究对象，基于高阶累积量和高阶谱，采用小波、分形和神经网络等理论方法对液压阀的振动信号进行分析，实现液压阀的故障识别。

液压阀在正常与不同故障状态下工作时，其振动信号通过双谱分析谱图各有差异。正常状态和故障状态的双谱相比，在分布范围和谱峰多少均体现出不同的特性。双谱 $1\frac{1}{2}$ 维切片较双谱更具体更直观地表征液压阀故障信息的频率位置，且计算量也相对减少。两种谱分析方法均十分有效地对液压阀进行故障识别。在此基础上，以高阶累积量的耦合性质理论为依据，将采集的原始信号变换为复数信号，再通过复数高阶累积量的各种不同的耦合方式分析各种故障产生的结果，将正常信号和故障信号按照某种相同的耦合方式进行故障辨别，以此寻找最佳故障判别效果。由于小波方法是分析机械振动信号有力工具，因此本文通过小波进行特征提取，再利用 BP 网络和支持向量机进行故障诊断，并和实数信号相应结果进行对比，进而分析原因。本文通过上述研究方法，取得了如下研究成果：

1：由于双谱计算的复杂性，在实际应用中难以兼顾计算复杂性和实际应用需要之间的矛盾，因此文章提出一种双谱的不对称绘制方法，并用实例说明这种方法的意义。

2：分别对原始信号、AR 功率谱、实数双谱对角切片的故障诊断效果进行对比，得出实数双谱对角切片优于 AR 功率谱，而 AR 功率谱又优于原始信号的结论，而这些结论和理论分析都是一致的。

3：对复数三阶累积量、复数双谱的各种不同耦合方式的故障诊断效果进行分析，并和实数双谱、实数三阶累积量的结果进行对比，得出在不同的耦合方式下，对于大多数故障，与实数状态的高阶累积量或者高阶谱相比，都能找到一种诊断正确率更高的方法的结论。

4：以容量维为工具，通过计算复数信号不同耦合方式下的各种切片的容量维数，再以计算出的容量维数进行故障判别，得出在某些故障形式下，复数形式切片的容量维数更有利于故障识别的结论。

关键词：高阶累积量；耦合；故障诊断

Abstract

In this paper, the usual hydraulic valves (reducing valve, overflow valve and speed-regulating valve) in hydraulic system were studied. Based on higher-order cumulants (HOC), higher-order spectrum (HOS) and its coupling features, wavelet, fractal and neural network theories were used to analyze the vibration signals extracted from hydraulic valves, and the fault recognition were accomplished.

Autoregressive (AR) model parameters based on higher-order cumulants of vibration signals from hydraulic valves were used to express the bispectrum and trispectrum. The vibration signals extracted from different working states of hydraulic valves were analyzed with bispectra. Results indicated that the spectral distributions were different under normal and different fault states. Compared with bispectra, the $1\frac{1}{2}$ -D slices of bispectra characterized the frequencies of fault information more specifically and directly, also, the amount of calculations was reduced. Futhurmore, based on the theory of HOS coupling, complex HOC were used to analyse various faults, the same coupling mode of normal signals and fault signals were used to diagnose faults. Because mechanical signal has the characteristics of nonlinear and nonstationary, and wavelet can deal with this kind of signals effectively, this paper used it to fetch features, then BP and LSSVM were used to judge faults. Through above works, some research achievements were obtained as follows:

1. Nonsymmetric bispectrum drawing method is proposed, this method can solve the contradiction between bispectrum complexity and actual needs to an extent.
2. The fault diagnosis effects of primitive signals、 AR power spectrum and real bispectrum diagonal slices are compared, the results demonstrate the effect of bispectrum diagonal slices is prior to AR power spectrum, and AR power spectrum is prior to primitive signals, these results coincide with relative theory.
3. The fault diagnosis effects of complex three order bispectrum and cumulants in various coupling modes are compared with real three order bispectrum and cumulants, the results show, for many faults, through different complex couplings, one

diagnosing method with higher correct rate can be found.

4. By means of calculating capacity dimensions, the dimensions of real bispectrum diagonal slices, real trispectrum diagonal slices and the slices of complex signals in various coupling modes were calculated, then those capacity dimensions were used to diagnose faults, the results shows, in some faults, complex signals capacity dimensions are more effective than that of real signals.

Keywords: Higher-order cumulants; Coupling; Fault diagnosis

目录

第一章 绪论	1
1.1 课题研究的背景和意义	1
1.2 液压阀故障分析方法概述	3
1.3 机械故障诊断技术现状概述	6
1.3.1 小波分析法.....	6
1.3.2 希尔伯特-黄变换	6
1.3.3 基于信号时域统计特性的方法.....	7
1.3.4 分形理论应用于故障诊断.....	8
1.3.5 高阶谱分析在故障诊断中的应用概况.....	8
1.3.6 基于支持向量机的故障诊断.....	9
1.3.7 非平稳、非线性、非高斯处理方法的特点及存在问题.....	10
1.3.8 本文工作的主要思路.....	10
1.4 本文的主要工作	11
第二章 液压阀的动态测试	13
2.1 溢流阀	13
2.1.1 溢流阀液压回路系统.....	13
2.1.2 溢流阀工作原理.....	14
2.1.3 溢流阀故障设定.....	14
2.2 减压阀	15
2.2.1 减压阀液压回路系统.....	15
2.2.2 减压阀工作原理.....	15
2.2.3 减压阀故障设定.....	16
2.3 调速阀	16
2.3.1 调速阀液压回路系统.....	16
2.3.2 调速阀工作原理.....	17
2.3.3 调速阀故障设定.....	17
2.4 动态测试系统	17

2.4.1	传感器与前置器.....	17
2.4.2	数据采集与动态测试程序.....	18
2.4.3	实验仪器及振动实验过程.....	20
第三章 小波、分形、HHT 理论和神经网络简介		21
3.1	小波理论简介	21
3.1.1	小波理论背景.....	21
3.1.2	连续小波变换.....	23
3.1.3	连续小波基函数的选择.....	23
3.1.4	小波分解树与小波包分解树.....	25
3.2	分形理论简介	26
3.2.1	分形理论背景.....	26
3.2.2	分形的定义.....	26
3.2.3	容量维数.....	27
3.3	Hilbert-Huang 变换 (HHT) 的基本原理	28
3.3.1	Hilbert-Huang 变换 (HHT) 概述	28
3.3.2	瞬时频率.....	29
3.3.3	特征尺度参数.....	29
3.3.4	固有模态函数.....	30
3.3.5	三次样条插值.....	31
3.4	SVM 理论简介.....	32
3.4.1	SVM 统计学习理论	32
3.4.2	SVM 分类算法	32
3.4.3	LS-SVM 分类算法	34
3.5	BP 网络简介	36
第四章 基于高阶谱的故障分析及其不对称绘制方法		37
4.1	高阶谱基本理论	37
4.1.1	高阶累积量.....	37
4.1.2	高阶谱.....	38
4.1.3	双谱切片.....	39

4.1.4	三谱切片.....	40
4.1.5	数据的预处理.....	42
4.1.6	AR 模型的参数估计.....	42
4.1.7	AR 模型的定阶.....	42
4.2.	不同液压阀故障的高阶谱分析.....	43
4.2.1	不同液压阀故障的 AR 双谱分析.....	43
4.2.2	不同液压阀故障的 AR 双谱 $1\frac{1}{2}$ 维切片分析.....	44
4.2.3	不同液压阀故障的 AR 三谱 $1\frac{1}{2}$ 维切片分析.....	46
4.3	不对称双谱绘制方法.....	47
4.3.1	双谱绘制步长的改变.....	47
4.4.2	两种双谱图对比.....	48
4.4.3	二维小波多尺度分解.....	49
4.4.4	特征提取.....	50
4.4.5	实验结果.....	51
4.4.6	结论.....	53
第五章	高阶累积量在故障诊断中的应用.....	54
5.1	小波包检测方法.....	54
5.2	基于 AR 参数的液压阀故障信号检测.....	55
5.3	减压阀故障信号的高阶统计量检测.....	56
5.3.1	偏度与峰度.....	56
5.3.2	实验结果分析.....	56
5.3.3	实验总结.....	57
5.4	AR 功率谱与原始数据诊断效果对比.....	58
5.5	功率谱和双谱切片诊断效果对比.....	60
5.5.1	功率谱和双谱表达式.....	60
5.5.2	功率谱和双谱图.....	60
5.5.3	实验结果分析.....	63
5.6	基于双相干谱的故障诊断.....	63

5.6.1	双相干谱.....	63
5.6.2	双相干谱图分析.....	64
5.6.3	双相干谱特征提取.....	64
5.6.4	故障识别.....	66
5.7	双谱切片的分形特性在故障诊断中的应用	67
5.7.1	双谱对角切片.....	67
5.7.2	实验结果.....	68
5.8	基于高阶累积量和 HHT 的机械故障诊断	69
5.8.1	HHT 方法	69
5.8.2	高阶累积量.....	69
5.8.3	HHT 算法	69
5.8.4	EMD 分解图.....	70
5.8.5	实验结果分析.....	70
5.9	本章总结	72
第六章	基于复数高阶累积量耦合性质的故障诊断	73
6.1	$1\frac{1}{2}$ 维谱耦合性质在故障诊断中的应用.....	73
6.1.1	高阶累积量.....	73
6.1.2	$1\frac{1}{2}$ 维谱.....	73
6.1.3	谱图.....	74
6.1.4	实验结果.....	75
6.1.5	实验结果分析.....	75
6.1.6	结论.....	78
6.2	基于复三阶累积量切片谱的故障诊断	79
6.2.1	复数三阶累积量切片.....	79
6.2.2	谱图.....	79
6.2.3	实验结果.....	80
6.2.4	实验结果分析.....	81
6.3	基于机械故障诊断的 $2\frac{1}{2}$ 维谱耦合性能分析.....	84

6.3.1	三谱.....	84
6.3.2	$2\frac{1}{2}$ 维谱.....	84
6.3.3	谱图.....	85
6.3.4	实验结果分析.....	85
6.4	复数三阶累积量耦合性质在故障诊断中的应用	88
6.4.1	复数三阶累积量.....	88
6.4.2	复数三阶累积量图.....	89
6.4.3	特征提取.....	89
6.4.4	实验结果.....	89
6.4.5	实验结果分析.....	90
6.5	本章总结	93
第七章	总结与展望	94
7.1	全文总结	94
7.2	工作展望	95
	参考文献.....	96
	攻读博士学位期间参与的科研项目与发表论文情况.....	104

CONTENTS

Chapter 1 Preface	1
1.1 Background & Significance	1
1.2 Summary of hydraulic valve fault analysis methods.....	3
1.3 Overview of mechanical fault diagnosis technology	6
1.3.1 Wavelet method.....	6
1.3.2 Hilbert - Huang Transform.....	6
1.3.3 Method based on signal time domain statistical properties.....	7
1.3.4 Application of fractal theory in fault diagnosis.....	8
1.3.5 Survey of high order spectral analysis in fault diagnosis	8
1.3.6 Fault diagnosis based on support vector machine	9
1.3.7 Problems of non stationary, nonlinear, non Gauss process	10
1.3.8 The main ideas of this paper,.....	10
1.4 The main work of this paper	11
Chapter 2 Dynamic test of hydraulic valve	13
2.1 Overflow valve.....	13
2.1.1 Overflow valve hydraulic system.....	13
2.1.2 Overflow valve working principle	14
2.1.3 Overflow valve fault setting.....	14
2.2 Pressure relief valve	15
2.2.1 Relief valve hydraulic system	15
2.2.2 Relief valve working principle.....	15
2.2.3 Relief valve fault setting	16
2.3 Speed regulating valve	16
2.3.1 Regulating valve hydraulic system.....	16
2.3.2 Regulating valve working principle	17
2.3.3 Regulating valve fault setting.....	17
2.4 Dynamic testing system	17
2.4.1 Sensor and preamplifier	17

2.4.2	Data acquisition and dynamic testing programs.....	18
2.4.3	Instruments and vibration experimental procedures.....	20
Chapter 3 Wavelet, fractal, HHT theory and neural network		21
3.1	Wavelet theory.....	21
3.1.1	Wavelet backgrounds	21
3.1.2	Continuous wavelet transform	23
3.1.3	Continuous wavelet functions choice.....	23
3.1.4	Trees of Wavelet and wavelet packet decomposition.....	24
3.2	Fractal theory	26
3.2.1	Fractal backgrounds	26
3.2.2	Fractal definition	26
3.2.3	Capacity dimension.....	27
3.3	Hilbert-Huang Transform.....	28
3.3.1	Summary of Hilbert-Huang Transform	28
3.3.2	Instantaneous frequency.....	29
3.3.3	Scale parameters.....	29
3.3.4	Intrinsic mode function	30
3.3.5	Three times spline interpolation.....	31
3.4	Summary of SVM theory	32
3.4.1	SVM Statistical learning theory	32
3.4.2	SVM classification algorithm.....	32
3.4.3	LS-SVM classification algorithm.....	32
3.5	Summary of BP network.....	36
Chapter 4 Fault analysis based on HOS and its asymmetric drawing method		37
4.1	HOS theory	37
4.1.1	HOC	37
4.1.2	HOS.....	38
4.1.3	Bispectrum slices	39

4.1.4	Trispectrum slices.....	40
4.1.5	Data preprocessing.....	42
4.1.6	Parameters estimation of AR model.....	42
4.1.7	Order determination of AR model.....	42
4.2.	HOS Analysis of different valves.....	43
4.2.1	AR bispectrum analysis.....	43
4.2.2	$1\frac{1}{2}$ -D slices analysis of AR bispectrum.....	44
4.2.3	$1\frac{1}{2}$ -D slices analysis of AR trispectrum.....	46
4.3	Asymmetric bispectrum drawing method.....	47
4.3.1	Step size changing of bispectrum drawing.....	47
4.3.2	Comparison of two kinds of bispectrum.....	48
4.3.3	2-D multi-scale wavelet decomposition.....	49
4.3.4	Features fetching.....	50
4.3.5	Experimental results.....	51
4.3.6	conclusions.....	53
Chapter 5	HOS' application in fault diagnosis.....	54
5.1	Wavelet packet detecting method.....	54
5.2	Fault signals detecting of valve based on AR paramters.....	55
5.3	Fault signals detecting of valve based on high-order statistics.....	56
5.3.1	Skewness and kurtosis.....	56
5.3.2	Analysis of experimental results.....	56
5.3.3	Summary of tests.....	57
5.4	Diagnostic effects comparison of power spectrum and primitive datum.....	58
5.5	Diagnostic effects comparison of power spectrum and bispectrum.....	60
5.5.1	Expressions of power spectrum and bispectrum.....	60
5.5.2	Figures of power spectrum and bispectrum.....	60
5.5.3	Analysis of experimental results.....	63
5.6	Fault diagnosis based on bicoherence spectrum.....	63
5.6.1	Bicoherence spectrum.....	63

5.6.2	Analysis of Bicoherence spectrum diagrams	64
5.6.3	Features fetching of bicoherence spectrum	64
5.6.4	Fault identification	66
5.7	Applicatipn of bispectral slices characteristics in fault identification	67
5.7.1	Bispectral diagonal slices	67
5.7.2	Experimental results	68
5.8	Mechanical fault diagnosis based on HOC and HHT	69
5.8.1	HHT methods	69
5.8.2	HOC	69
5.8.3	HHT algorithm	69
5.8.4	EMD decomposition maps	70
5.8.5	Analysis of experimental results	70
5.9	Conclusions	72

Chapter 6 Fault diagnosis based on coupling properties of

complex HOC

6.1	Application of $1\frac{1}{2}$ -D spectrum in fault detecting bispectrum	73
6.1.1	Complex HOC	73
6.1.2	$1\frac{1}{2}$ -D spectrum	73
6.1.3	$1\frac{1}{2}$ -D spectral diagrams	74
6.1.4	Experimental results	75
6.1.5	Analysis of experimental results	75
6.1.6	conclusions	77
6.2	Fault diagnosis based on complex three order cumulants silces	79
6.2.1	Complex three order cumulants silces	79
6.2.2	Spectral diagrams	79
6.2.3	Experimental results	80
6.2.4	Analysis of experimental results	81

Degree papers are in the "[Xiamen University Electronic Theses and Dissertations Database](#)". Full texts 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.

厦门大学博硕士学位论文摘要库