Bond graph model-based fault detection and isolation of loaded Jeffcott Rotor system

Ma, Shiao

2009

Ma, S. (2009). Bond graph model-based fault detection and isolation of loaded Jeffcott Rotor system. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/19270>

<https://doi.org/10.32657/10356/19270>

BOND GRPAH MODEL-BASED FAULT DETECTION AND ISOLATION OF LOADED JEFFCOTT ROTOR SYSTEM

MA SHIAO

School of Electrical and Electronics Engineering

A thesis submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of
Master of Engineering

2009

ACKNOWLEDGEMENTS

First, I must thank my supervisor Professor Wang Danwei for his invaluable advices, encouragements, and inspirations, for the best supervision I can receive during my postgraduate study, furthermore for providing financial support so that I can focus on research.

I would like to thank SIMTech for allowing me to carry out experiments on the machinery fault simulator, for providing funds to enable the purchase of sensors and engagement of contractors. Thanks also go to Dr. Luo Ming, Ms Zhang Dan Hong, Ms Zhou Jun Hong and Mr. Tan Gak Chee for all the helps I received from you all.

I would like to thanks Dr. Shai Arogeti, Mr. Yu Ming, Mr. Huang Lei and Mr. Vahid Hassani for all your discussions and suggestions. I really enjoy the lunch time conversations we had together. Our friendship will last forever.

I would like to thank KEPPEL SINGMARINE PTE LTD for allowing me to take a year of study leave and still awarding me the fat bonuses, which allowed me to free myself and focused on the study.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS.....	i
TABLE OF CONTENTS.....	ii
SUMMARY.....	iv
LIST OF FIGURES	v
LIST OF TABLES	x
NOMENCLATURE	xii
1 INTRODUCTION	1
1.1 Motivation.....	1
1.2 Objective.....	2
1.3 Major contributions of the thesis	2
1.4 Organization of the thesis	2
2 LITERATURE REVIEW	4
2.1 Fault detection and isolation (FDI).....	4
2.2 Model based FDI	6
2.3 Bond graph model based FDI	8
2.4 Fault diagnosis for rotating machinery	10
3 BACKGROUND THEORIES	12
3.1 Model based FDI	12
3.2 Basics of bond graph modeling	14
3.2.1 Bonds and bond variables.....	14
3.2.2 One-port elements and two-port elements	15
3.2.3 Junctions	16
3.2.4 Causality	17
3.2.5 Multiport transformer	18
3.3 DBG for residual generation.....	20
3.3.1 Definition	20
3.3.2 Purpose of DBG.....	21
3.3.3 Substitutions in DBG	21
4 LOADED JEFFCOTT ROTOR AND ITS BOND GRAPH MODEL.....	25
4.1 Overview of the loaded Jeffcott rotor system under study	25
4.1.1 Electrical motor.....	26
4.1.2 Jeffcott rotor.....	27
4.1.3 External load driven by the Jeffcott rotor	31
4.2 Bond graph modeling.....	32
4.2.1 Bond graph modeling of Jeffcott rotor.....	33

4.2.2	Bond graph modeling of external load.....	39
4.2.3	Integrating Jeffcott rotor and external load.....	40
5	FAULT DETECTION AND ISOLATION	44
5.1	Diagnostic bond graph (DBG)	44
5.1.1	Differential causality assignment.....	44
5.1.2	DBG derivation.....	47
5.2	Causal path analysis.....	49
5.3	Fault signature matrix	54
6	PARAMETER MEASUREMENT & IDENTIFICATION.....	57
6.1	Overview.....	57
6.2	Parameter measurement	57
6.3	Parameter identification	58
6.4	Estimation of eccentricity (u)	64
6.5	Parameters' values	65
7	EXPERIMENT & RESULT	66
7.1	Modification to DBG	66
7.2	Modification to FSM	67
7.3	Simulation.....	68
7.4	Test bed experiment.....	69
7.4.1	Laboratory equipment.....	69
7.4.2	Test bed experiment procedure.....	71
7.5	Results.....	74
7.5.1	Simulation.....	74
7.5.2	Test bed experiment.....	86
7.5.3	Reliability of residuals	106
7.5.4	Remarks on threshold selection	109
7.5.5	Remarks on residuals sensitivity in relation to operating speed.....	111
7.5.6	Comparison with other results	112
8	CONCLUSION AND RECOMMENDATION.....	116
8.1	Conclusion	116
8.2	Recommendation for future research.....	117
	BIBLIOGRAPHY	119

SUMMARY

Rotating machineries are commonly used in the industry and in our daily life. Their fault diagnosis deserves our uncommon attention. Data driven approach of rotating machinery fault diagnosis has been well developed, but there are still limitations to this approach. A bond graph model based fault detection and isolation of rotating machinery is proposed in this research. This report gives a brief introduction to physics of Jeffcott rotor system. A simple and effective bond graph model of Jeffcott rotor is developed and integrated with some rotational loads of the rotor. The model is further developed into a diagnostic bond graph model which is used to generate residuals for the purpose of fault detection and isolation. The proposed method is verified by simulation using Matlab/simulink and by test bed experiment using machinery fault simulator. Simulation and experimental results are presented, analyses are provided. It is found that the proposed method can be successfully applied to the machinery fault simulator to detect and isolate imbalance fault, loose belt fault and three sensors' fault. The proposed method can be used as an alternative to data driven approach of machinery fault simulator diagnosis, it has potential to be applied to real life rotating machinery as well.

LIST OF FIGURES

Figure 3-1 Bond between two elements.....	14
Figure 3-2 Modulated Multiport Transformer 1	19
Figure 3-3 Modulated Multiport Transformer 2	20
Figure 3-4 De assigned inverted causality	22
Figure 3-5 Substitute graph for causality inverted De	22
Figure 3-6 Df assigned inverted causality	23
Figure 3-7 Substitute graph for causality inverted Df	23
Figure 3-8 De assigned non-inverted causality.....	23
Figure 3-9 Substitute graph for causality non-inverted De.....	23
Figure 3-10 Df assigned non-inverted causality	24
Figure 3-11 Substitute graph for causality non-inverted Df	24
Figure 4-1 Schematic Diagram of Modeled System – top view	26
Figure 4-2 Jeffcott Rotor.....	27
Figure 4-3 Front view of stationary Jeffcott Rotor	28
Figure 4-4 Side view of stationary Jeffcott Rotor.....	29
Figure 4-5 Front view of rotating Jeffcott Rotor	30
Figure 4-6 Side view of rotating Jeffcott Rotor	31
Figure 4-7 schematic diagram of modeled system - side view	32
Figure 4-8 Orthogonal spring and dashpot physical model of Jeffcott rotor.....	33
Figure 4-9 Multiport transformer for geometry constraint 1	36
Figure 4-10 Multiport transformer for geometry constraint 2	37
Figure 4-11 Jeffcott rotor acausal bond graph model	39
Figure 4-12 External load acausal bond graph model	40
Figure 4-13 Loaded Jeffcott rotor acausal bond graph model	41
Figure 4-14 Loaded Jeffcott rotor system bond graph in integral causality	43
Figure 5-1 Loaded Jeffcott rotor system bond graph in differential causality.....	46
Figure 5-2 Loaded Jeffcott rotor system diagnostic bond graph	48
Figure 5-3 Causal paths for r1	51
Figure 5-4 Causal paths for r2	52
Figure 5-5 Causal paths for r3	53
Figure 6-1: Machinery fault simulator with belt removed.....	59
Figure 6-2: Machinery fault simulator with belt.....	59
Figure 6-3: Simulink block diagram of DSBG for step1	60
Figure 6-4: Simulink block diagram of DSBG for step 2.....	61
Figure 6-5: MATLAB code for Gauss-Newton optimization	62
Figure 6-6: Simulink block diagram for parameter verification.....	63

Figure 6-7: Verification result of para30	63
Figure 6-8: Verification result of para10	63
Figure 6-9: Verification result of para20	64
Figure 7-1: Simulink top level block diagram for simulation	69
Figure 7-2: Machinery fault simulator	70
Figure 7-3: Simulink top level block diagram for test bed experiment	71
Figure 7-4: Creation of imbalance fault	73
Figure 7-5: Creation of loose belt fault	73
Figure 7-6: sim, 20Hz, para20, lr1l inactive, $\varepsilon=0.00004$, fault free condition	77
Figure 7-7: sim, 20Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, fault free condition	77
Figure 7-8: sim, 20Hz, para20, lr3l inactive, $\varepsilon=0.3$, fault free condition	77
Figure 7-9: sim, 20Hz, para20, lr1l active, $\varepsilon=0.00004$, imbalance fault condition	77
Figure 7-10: sim, 20Hz, para20, r2 active, $\varepsilon=+-0.00006$, imbalance fault condition ..	77
Figure 7-11: sim, 20Hz, para20, lr3l inactive, $\varepsilon=0.3$, imbalance fault condition	77
Figure 7-12: sim, 20Hz, para20, lr1l active, $\varepsilon=0.00004$, loose belt fault condition	78
Figure 7-13: sim, 20Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, loose belt fault condition ..	78
Figure 7-14: sim, 20Hz, para20, lr3l active, $\varepsilon=0.3$, loose belt fault condition	78
Figure 7-15: sim, 20Hz, para20, lr1l active, $\varepsilon=0.00004$, Df:1 fault condition	78
Figure 7-16: sim, 20Hz, para20, r2 active, $\varepsilon=+-0.00006$, Df:1 fault condition	78
Figure 7-17: sim, 20Hz, para20, lr3l active, $\varepsilon=0.3$, Df:1 fault condition	78
Figure 7-18: sim, 20Hz, para20, lr1l inactive, $\varepsilon=0.00004$, Df:2 fault condition	79
Figure 7-19: sim, 20Hz, para20, r2 negatively active, $\varepsilon=+-0.00006$, Df:2 fault condition	79
Figure 7-20: sim, 20Hz, para20, lr3l inactive, $\varepsilon=0.3$, Df:2 fault condition	79
Figure 7-21: sim, 20Hz, para20, lr1l inactive, $\varepsilon=0.00004$, Df:3 fault condition	79
Figure 7-22: sim, 20Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, Df:3 fault condition	79
Figure 7-23: sim, 20Hz, para20, lr3l active, $\varepsilon=0.3$, Df:3 fault condition	79
Figure 7-24: sim, 10Hz, para20, lr1l inactive, $\varepsilon=0.000005$, fault free condition	80
Figure 7-25: sim, 10Hz, para20, r2 inactive, $\varepsilon=+-0.000015$, fault free condition	80
Figure 7-26: sim, 10Hz, para20, lr3l inactive, $\varepsilon=0.3$ at fault free condition	80
Figure 7-27: sim, 10Hz, para20, lr1l active, $\varepsilon=0.000005$, Df:1 fault condition	80
Figure 7-28: sim, 10Hz, para20, r2 active, $\varepsilon=+-0.000015$, Df:1 fault condition	80
Figure 7-29: sim, 10Hz, para20, lr3l active, $\varepsilon=0.3$, Df:1 fault condition	80
Figure 7-30: sim, 10Hz, para20, lr1l inactive, $\varepsilon=0.000005$, Df:2 fault condition	81
Figure 7-31: sim, 10Hz, para20, r2 negatively active, $\varepsilon=+-0.000015$, Df:2 fault condition	81
Figure 7-32: sim, 10Hz, para20, lr3l inactive, $\varepsilon=0.3$, Df:2 fault condition	81
Figure 7-33: sim, 10Hz, para20, lr1l inactive, $\varepsilon=0.000005$, Df:3 fault condition	81
Figure 7-34: sim, 10Hz, para20, r2 inactive, $\varepsilon=+-0.000015$, Df:2 fault condition	81
Figure 7-35: sim, 10Hz, para20, lr3l active, $\varepsilon=0.3$, Df:3 fault condition	81
Figure 7-36: sim, 10Hz, para20, lr1l active, $\varepsilon=0.000005$, imbalance fault condition ..	82
Figure 7-37: sim, 10Hz, para20, r2 active, $\varepsilon=+-0.000015$, imbalance fault condition ..	82
Figure 7-38: sim, 10Hz, para20, lr3l inactive, $\varepsilon=0.3$, imbalance fault condition	82
Figure 7-39: sim, 10Hz, para20, lr1l active, $\varepsilon=0.000005$, loose belt fault condition ...	82
Figure 7-40: sim, 10Hz, para20, r2 inactive, $\varepsilon=+-0.000015$, loose belt fault condition	82

Figure 7-41: sim, 10Hz, para20, lr3l active, $\varepsilon=0.3$, loose belt fault condition	82
Figure 7-42: sim, 30Hz, para20, lr1l inactive, $\varepsilon=0.00006$, fault free condition	83
Figure 7-43: sim, 30Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, fault free condition	83
Figure 7-44: sim, 30Hz, para20, lr3l inactive, $\varepsilon=0.3$, fault free condition	83
Figure 7-45: sim, 30Hz, para20, lr1l active, $\varepsilon=0.00006$, Df:1 fault condition	83
Figure 7-46: sim, 30Hz, para20, r2 active, $\varepsilon=+-0.00006$, Df:1 fault condition	83
Figure 7-47: sim, 30Hz, para20, lr3l active, $\varepsilon=0.3$, Df:1 fault condition	83
Figure 7-48: sim, 30Hz, para20, lr1l inactive, $\varepsilon=0.00006$, Df:2 fault condition	84
Figure 7-49: sim, 30Hz, para20, r2 negatively active, $\varepsilon=+-0.00006$, Df:2 fault condition	84
Figure 7-50: sim, 30Hz, para20, lr3l inactive, $\varepsilon=0.3$, Df:2 fault condition	84
Figure 7-51: sim, 30Hz, para20, lr1l inactive, $\varepsilon=0.00006$, Df:3 fault condition	84
Figure 7-52: sim, 30Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, Df:3 fault condition	84
Figure 7-53: sim, 30Hz, para20, lr3l active, $\varepsilon=0.3$, Df:3 fault condition	84
Figure 7-54: sim, 30Hz, para20, lr1l active, $\varepsilon=0.00006$, imbalance fault condition	85
Figure 7-55: sim, 30Hz, para20, r2 active, $\varepsilon=+-0.00006$, imbalance fault condition ..	85
Figure 7-56: sim, 30Hz, para20, lr3l inactive, $\varepsilon=0.3$, imbalance fault condition	85
Figure 7-57: sim, 30Hz, para20, lr1l active, $\varepsilon=0.00006$, loose belt fault condition	85
Figure 7-58: sim, 30Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, loose belt fault condition ..	85
Figure 7-59: sim, 30Hz, para20, lr3l active, $\varepsilon=0.3$, loose belt fault condition	85
Figure 7-60: exp, 20Hz, para20, lr1l inactive, $\varepsilon=0.3$, fault free condition	89
Figure 7-61: exp, 20Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.0004$, fault free condition ..	89
Figure 7-62: exp, 20Hz, para20, lr3l inactive, $\varepsilon=0.5$, fault free condition	89
Figure 7-63: exp, 20Hz, para20, lr1l inactive, $\varepsilon=0.3$, imbalance fault condition	89
Figure 7-64: exp, 20Hz, para20, r2 active, $\varepsilon=+0.0003/-0.0004$, imbalance fault condition	89
Figure 7-65: exp, 20Hz, para20, lr3l inactive, $\varepsilon=0.5$, imbalance fault condition	89
Figure 7-66: exp, 20Hz, para20, lr1l active, $\varepsilon=0.3$, loose belt fault condition	90
Figure 7-67: exp, 20Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.0004$, loose belt fault condition	90
Figure 7-68: exp, 20Hz, para20, lr3l active, $\varepsilon=0.5$, loose belt fault condition	90
Figure 7-69: exp, 20Hz, para20, lr1l active, $\varepsilon=0.3$, Df1 fault condition	90
Figure 7-70: exp, 20Hz, para20, r2 active, $\varepsilon=+0.0003/-0.0004$, Df1 fault condition ..	90
Figure 7-71: exp, 20Hz, para20, lr3l active, $\varepsilon=0.5$, Df1 fault condition	90
Figure 7-72: exp, 20Hz, para20, lr1l inactive, $\varepsilon=0.3$, Df2 fault condition	91
Figure 7-73: exp, 20Hz, para20, r2 negatively active, $\varepsilon=+0.0003/-0.0004$, Df2 fault condition	91
Figure 7-74: exp, 20Hz, para20, lr3l inactive, $\varepsilon=0.5$, Df2 fault condition	91
Figure 7-75: exp, 20Hz, para20, lr1l inactive, $\varepsilon=0.3$, Df3 fault condition	91
Figure 7-76: exp, 20Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.0004$, Df3 fault condition ..	91
Figure 7-77: exp, 20Hz, para20, lr3l active, $\varepsilon=0.5$, Df3 fault condition	91
Figure 7-78: exp, 10Hz, para20, lr1l inactive, $\varepsilon=0.5$, fault free condition	92
Figure 7-79: exp, 10Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.00003$, fault free condition	92
Figure 7-80: exp, 10Hz, para20, lr3l inactive, $\varepsilon=0.5$, fault free condition	92
Figure 7-81: exp, 10Hz, para20, lr1l, $\varepsilon=0.5$, imbalance fault condition.....	92

Figure 7-82: exp, 10Hz, para20, r2 active, $\varepsilon=+0.0003/-0.00003$, imbalance fault condition	92
Figure 7-83: exp, 10Hz, para20, lr3l inactive, $\varepsilon=0.5$, imbalance fault condition	92
Figure 7-84: exp, 10Hz, para20, lr1l inactive, $\varepsilon=0.5$, Df:2 fault condition	93
Figure 7-85: exp, 10Hz, para20, r2 negatively active, $\varepsilon=+0.0003/-0.00003$, Df:2 fault condition	93
Figure 7-86: exp, 10Hz, para20, lr3l inactive, $\varepsilon=0.5$, Df:2 fault condition	93
Figure 7-87: exp, 10Hz, para20, lr1l inactive, $\varepsilon=0.5$, loose belt fault condition	93
Figure 7-88: exp, 10Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.00003$, loose belt fault condition	93
Figure 7-89: exp, 10Hz, para20, lr3l active, $\varepsilon=0.5$, loose belt fault condition	93
Figure 7-90: exp, 10Hz, para20, lr1l inactive, $\varepsilon=0.5$, Df:3 fault condition	94
Figure 7-91: exp, 10Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.00003$, Df:3 fault condition	94
Figure 7-92: exp, 10Hz, para20, lr3l active, $\varepsilon=0.5$, Df:3 fault condition	94
Figure 7-93: exp, 10Hz, para20, lr1l active, $\varepsilon=0.5$, Df:1 fault condition	94
Figure 7-94: exp, 10Hz, para20, r2, $\varepsilon=+0.0003/-0.00003$, Df:1 fault condition	94
Figure 7-95: exp, 10Hz, para20, lr3l active, $\varepsilon=0.5$, Df:1 fault condition	94
Figure 7-96: exp, 30Hz, para20, lr1l inactive, $\varepsilon=0.7$, fault free condition	95
Figure 7-97: exp, 30Hz, para20, r2 inactive, $\varepsilon=+0.0001/-0.001$, fault free condition	95
Figure 7-98: exp, 30Hz, para20, lr3l inactive, $\varepsilon=1$, fault free condition	95
Figure 7-99: exp, 30Hz, para20, lr1l inactive, $\varepsilon=0.7$, imbalance fault condition	95
Figure 7-100: exp, 30Hz, para20, r2 active, $\varepsilon=+0.0001/-0.001$, imbalance fault condition	95
Figure 7-101: exp, 30Hz, para20, lr3l inactive, $\varepsilon=1$, imbalance fault condition	95
Figure 7-102: exp, 30Hz, para20, lr1l active, $\varepsilon=0.7$, loose belt fault condition	96
Figure 7-103: exp, 30Hz, para20, r2 negatively active, $\varepsilon=+0.0001/-0.001$, loose belt fault condition	96
Figure 7-104: exp, 30Hz, para20, lr3l active, $\varepsilon=1$, loose belt fault condition	96
Figure 7-105: exp, 30Hz, para20, lr1l inactive, $\varepsilon=0.7$, Df:2 fault condition	96
Figure 7-106: exp, 30Hz, para20, r2 negatively active, $\varepsilon=+0.0001/-0.001$, Df:2 fault condition	96
Figure 7-107: exp, 30Hz, para20, lr3l inactive, $\varepsilon=1$, Df:2 fault condition	96
Figure 7-108: exp, 30Hz, para20, lr1l inactive, $\varepsilon=0.7$, Df:3 fault condition	97
Figure 7-109: exp, 30Hz, para20, r2 inactive, $\varepsilon=+0.0001/-0.001$, Df:3 fault condition	97
Figure 7-110: exp, 30Hz, para20, lr3l active, $\varepsilon=1$, Df:3 fault condition	97
Figure 7-111: exp, 30Hz, para20, lr1l active, $\varepsilon=0.7$, Df:1 fault condition	97
Figure 7-112: exp, 30Hz, para20, r2 active, $\varepsilon=+0.0001/-0.001$, Df:1 fault condition	97
Figure 7-113: exp, 30Hz, para20, lr3l active, $\varepsilon=1$, Df:1 fault condition	97
Figure 7-114: exp, 30Hz, para30, lr1l inactive, $\varepsilon=0.4$, fault free condition	100
Figure 7-115: exp, 30Hz, para30, r2 inactive, $\varepsilon=+-0.0004$, fault free condition	100
Figure 7-116: exp, 30Hz, para30, lr3l inactive, $\varepsilon=1.25$, fault free condition	100
Figure 7-117: exp, 30Hz, para30, lr1l active, $\varepsilon=0.4$, Df:1 fault condition	100
Figure 7-118: exp, 30Hz, para30, r2 active, $\varepsilon=+-0.0004$, Df:1 fault condition	100
Figure 7-119: exp, 30Hz, para30, lr3l active, $\varepsilon=1.25$, Df:1 fault condition	100

Figure 7-120: exp, 30Hz, para30, lr1l inactive, $\varepsilon=0.4$, imbalance fault condition	101
Figure 7-121: exp, 30Hz, para30, r2 active, $\varepsilon=+-0.0004$, imbalance fault condition	101
Figure 7-122: exp, 30Hz, para30, lr3l inactive, $\varepsilon=1.25$, imbalance fault condition...	101
Figure 7-123: exp, 30Hz, para30, lr1l active, $\varepsilon=0.4$, loose belt fault condition	101
Figure 7-124: exp, 30Hz, para30, r2 inactive, $\varepsilon=+-0.0004$, loose belt fault condition	101
Figure 7-125: exp, 30Hz, para30, lr3l active, $\varepsilon=1.25$, loose belt fault condition	101
Figure 7-126: exp, 30Hz, para30, lr1l inactive, $\varepsilon=0.4$, Df:2 fault condition	102
Figure 7-127: exp, 30Hz, para30, r2 negatively active, $\varepsilon=+-0.0004$, Df:2 fault condition	102
Figure 7-128: exp, 30Hz, para30, lr3l inactive, $\varepsilon=1.25$, Df:2 fault condition	102
Figure 7-129: exp, 30Hz, para30, lr1l inactive, $\varepsilon=0.4$, Df:3 fault condition	102
Figure 7-130: exp, 30Hz, para30, r2 inactive, $\varepsilon=+-0.0004$, Df:3 fault condition	102
Figure 7-131: exp, 30Hz, para30, lr3l active, $\varepsilon=1.25$, Df:3 fault condition	102
Figure 7-132: exp, 10Hz, para10, lr1l inactive, $\varepsilon=0.3$, fault free condition	103
Figure 7-133: exp, 10Hz, para10, r2 inactive, $\varepsilon=+0.0001/-0.00025$, fault free condition	103
Figure 7-134: exp, 10Hz, para10, lr3l inactive, $\varepsilon=0.6$, fault free condition	103
Figure 7-135: exp, 10Hz, para10, lr1l active, $\varepsilon=0.3$, Df:1 fault condition	103
Figure 7-136: exp, 10Hz, para10, r2 active, $\varepsilon=+0.0001/-0.00025$, Df:1 fault condition	103
Figure 7-137: exp, 10Hz, para10, lr3l active, $\varepsilon=0.6$, Df:1 fault condition	103
Figure 7-138: exp, 10Hz, para10, lr1l inactive, $\varepsilon=0.3$, imbalance fault condition	104
Figure 7-139: exp, 10Hz, para10,r2 active, $\varepsilon=+0.0001/-0.00025$, imbalance fault condition	104
Figure 7-140: exp, 10Hz, para10, lr3l inactive, $\varepsilon=0.6$, imbalance fault condition	104
Figure 7-141: exp, 10Hz, para10, lr1l active, $\varepsilon=0.3$, loose belt fault condition	104
Figure 7-142: exp, 10Hz, para10,r2 inactive, $\varepsilon=+0.0001/-0.00025$, loose belt fault condition	104
Figure 7-143: exp, 10Hz, para10, lr3l active, $\varepsilon=0.6$, loose belt fault condition	104
Figure 7-144: exp, 10Hz, para10, lr1l inactive, $\varepsilon=0.3$, Df:2 fault condition	105
Figure 7-145: exp, 10Hz, para10, r2 negatively active, $\varepsilon=+0.0001/-0.00025$, Df:2 fault condition	105
Figure 7-146: exp, 10Hz, para10, lr3l inactive, $\varepsilon=0.6$, Df:2 fault condition	105
Figure 7-147: exp, 10Hz, para10, lr1l inactive, $\varepsilon=0.3$, Df:3 fault condition	105
Figure 7-148: exp, 10Hz, para10, r2 inactive, $\varepsilon=+0.0001/-0.00025$, Df:3 fault condition	105
Figure 7-149: exp, 10Hz, para10, lr3l active, $\varepsilon=0.6$, Df:3 fault condition	105
Figure 8-1 Machinery fault simulator	118

LIST OF TABLES

Table 3-1 Fault Signature Matrix (FSM)	14
Table 3-2 Effort and Flow variables in different domains.....	15
Table 3-3 One port elements of bond graph	15
Table 3-4 Effort and Flow source elements	16
Table 3-5 Two-port elements	16
Table 3-6 Junctions	17
Table 3-7 Causal forms for basic one-port elements	18
Table 3-8 Causal forms for basic two-port elements and junctions	18
Table 5-1 Fault signature matrix 1	55
Table 5-2 Fault signature matrix 2.....	56
Table 6-1: Parameters identified at different shaft speeds.....	65
Table 7-1 Fault signature matrix 3.....	68
Table 7-2: Coherence vectors obtained at various fault conditions, sim, 30Hz, para20	75
Table 7-3: Thresholds used for the residuals evaluation, sim, 30Hz, para20	75
Table 7-4: Coherence vectors obtained at various fault conditions, sim, 10Hz, para20	75
Table 7-5: Thresholds used for the residuals evaluation, sim, 10Hz, para20	75
Table 7-6: Coherence vectors obtained at various fault conditions, sim, 20Hz, para20	75
Table 7-7: Thresholds used for the residuals evaluation in, sim, 20Hz, para20	75
Table 7-8: Coherence vectors obtained at various fault conditions, exp, 20Hz, para20	86
Table 7-9: Thresholds used for the residuals evaluation, exp, 20Hz, para20	86
Table 7-10: Coherence vectors obtained at various fault conditions, exp, 10Hz, para20	87
Table 7-11: Thresholds used for the residuals evaluation, exp, 10Hz, para20	87
Table 7-12: Coherence vectors obtained at various fault conditions, exp, 30Hz, para20	87
Table 7-13: Thresholds used for the residuals evaluation, exp, 30Hz, para20	87
Table 7-14: Coherence vectors obtained at various fault conditions, exp, 30Hz, para30	98
Table 7-15: Thresholds used for residuals evaluation, exp, 30Hz, para30	98
Table 7-16: Coherence vectors obtained at various fault conditions, exp, 10Hz, para10	99
Table 7-17: Thresholds used for the residuals evaluation, exp, 10Hz, para10	99

Table 7-18: Residuals status confidence level, exp, 10Hz, para10.....	106
Table 7-19: Residuals status confidence level, exp, 20Hz, para 20.....	107
Table 7-20: Residuals status confidence level, exp, 30Hz, para30.....	107
Table 7-21: Residuals status normalized confidence level, exp, 10Hz, para10.....	107
Table 7-22: Residuals status normalized confidence level, exp, 20Hz, para20.....	108
Table 7-23: Residuals status normalized confidence level, exp, 30Hz, para30.....	108
Table 7-24: Active residuals values at various fault conditions and different operating speeds, sim	111
Table 7-25: Values of residual r3 during Df:1 and Df:2 fault at different operating speeds, exp	112

NOMENCLATURE

Df:1	Representation of shaft speed encoder	Df:2	Representation of laser displacement velocity sensor
Df:3	Representation of minibeam sensor	MTF	Multiport transformer where imbalance is modeled in the bond graph model
TF ₁	Belt transfer ratio	TF ₂	Gearbox transfer ratio
R ₁ , R ₂	Air drag friction of Jeffcott rotor in horizontal and vertical direction	C ₁ , C ₂	Shaft stiffness in horizontal and vertical direction
I ₁ , I ₂	Rotor moment in horizontal and vertical direction	I ₃	Moment of inertia of the rotor
R ₄	Friction loss in gearbox	I ₄	Moment of inertia in gearbox
R ₃	Rotational friction loss in rotor	T	Torque provided from electrical motor
U	Disk eccentricity	δ	Shaft deflection
FSM	Fault signature matrix	MFS	Machinery fault simulator
FDI	Fault detection and isolation	DBG	Diagnostic bond graph
Db	Detection ability	Ib	Isolation ability
r1, r2 & r3	residuals	D _e	Effort detector in bond graph
D _f	Flow detector in bond graph	S _e	Effort source in bond graph
MC	Mass centre	GC	Geometry centre
DSBG	Diagnostic sensitivity bond graph	Para10	The set of parameters value identified at 10Hz shaft speed
Para20	The set of parameters value identified at 20Hz shaft speed	Para30	The set of parameters values identified at 30Hz shaft speed

Figures and tables showing simulation and experiment results are named in the following convention as shown in the example below.

1 INTRODUCTION

As the complexity of most engineering systems increase, their maintenance is becoming more expensive and more difficult to perform. Furthermore safety of people and environment friendliness has become important criteria when evaluating engineering systems. Techniques on process supervision have to be developed and improved to satisfy the demands from industry.

1.1 Motivation

Over past decades, vibration spectrum analysis had been widely used in rotating machines' fault diagnosis, but there are limitations. Model-based fault detection and isolation of rotating machinery is gaining more interests recently [12]. Real machines are never perfectly balanced, and most vibrations of rotating machine are excited by rotor imbalance. Jeffcott rotor is one of the most useful models for rotor dynamic analysis because of its capability to model rotor imbalance [19].

The capability of representing a large amount of structural, functional and behavioral information makes bond graph a good tool for model based fault detection and isolation, because this kind of representation can be used to create complex cause-effect reasoning [15].

Vibration-based fault detection and isolation of rotating machinery based on bond graph model is not yet sighted in the literature. A bond graph model of jeffcott rotor

was developed by Campos, et al. [3]. Experiment was done by the authors for model validation. However, the model was based on a special Lagrange Bond Graph which makes it difficult to understand, and its capability of model based fault detection and isolation is tested neither by experiment nor by simulation.

1.2 Objective

The objective of this research is to develop a simple and effective Jeffcott rotor bond graph model and to study the capability of the proposed bond graph model in model-based fault detection and isolation framework. It is also to provide an alternative to data driven approach of machinery fault simulator FDI.

1.3 Major contributions of the thesis

In this research, Bond Graph Model-based fault detection and isolation on a loaded Jeffcott rotor system is attempted. A Jeffcott rotor system coupled with rotational load is represented by bond graph model. The bond graph model is further developed into Diagnostic Bond Graph model which is used to generate residuals for fault detection and isolation of the Jeffcott rotor and rotational load system. Fault detection and isolation algorithm is verified by MATLAB/simulation and by test bed experiment using machinery fault simulator. The proposed method serves as an alternative to data driven approach of machinery fault simulator fault detection and isolation. It has potential to be applied to real life rotating machinery fault detection and isolation as well.

1.4 Organization of the thesis

In order to make the reading easier, an overview of each chapter is presented in this section.

Chapter 1 establishes the significance of the research, and present motivation, objective and major contributions of the research.

Chapter 2 provides an overview of the relevant researches e.g. fault detection and isolation, model based fault detection and isolation, and bond graph model based fault detection and isolation, and finally rotating machinery fault diagnosis.

Chapter 3 introduce some basic background theories about model based fault detection and isolation, bond graph modeling and diagnostic bond graphs. This basic background knowledge will help the reader understand the thesis better.

Chapter 4 describe the components and physics of loaded Jeffcott rotor, it also presents the modeling process of the loaded Jeffcott rotor using bond graph.

Chapter 5 applies diagnostic bond graph method to the model developed in the previous chapter. The loaded Jeffcott rotor diagnostic bond graph model which is used to generate residuals for fault detection and isolation is developed in this chapter; it presents the fault signature matrix derived from causal path analysis method also.

Chapter 6 describes how the parameters used in the model are obtained. Some verification of the parameters is done at the end of the chapter.

Chapter 7 presents the simulation and test bed experiment. Simulation and experiment procedures and equipments are introduced. Results are presented and analyses are provided. There are also some remarks on residual reliability, threshold selection and residual sensitivity. And finally some comparison with data driven approach is made.

Chapter 8 concludes the thesis by providing some insights on the findings. It also makes some recommendations for further research.

2 LITERATURE REVIEW

2.1 Fault detection and isolation (FDI)

Gertler defines some basic terms in fault detection and isolation frame work in his book [7]. When a component of a plant or process behaves differently from its normal behavior, the component is faulty. Fault detection finds out the presence of faulty component in a monitored process. Fault isolation determines which component is faulty after a fault occurrence. In order for a fault to be isolated, it must belong to a set of known possible faults. Novel fault can never be isolated, but sometimes it can be detected. Fault detection and isolation (FDI) performs both detection and isolation of faults. Fault identification determines the magnitude or severity of faults. Fault diagnosis performs both fault isolation and identification. FDI does not perform fault identification. This research deals with only fault detection and isolation (FDI), but not fault identification.

Various process fault detection and diagnosis techniques are available, such as fault tree analysis, analytical approaches, and knowledge based systems and neural networks [20][10].

The methods of FDI can be classified into two groups, namely model-free method and model-based method [7][17]. Model-free method, as the name implies, does not rely on any model of normal or faulty behavior of the plant or process under monitoring; it makes use of physical redundancy (redundant sensors), limit checking of measured process variables or outputs, spectrum analysis and other logic reasoning techniques to

perform FDI. On the other hand, model-based method utilizes a model that describe the normal or faulty operation of the monitored process or plant. The model runs in parallel with the actual process or plant and serves as a form of redundancy.

Regardless model-free method or model-based method, some kind of redundancy in the information sources is required for fault detection and isolation [17]. In order to obtain redundancy, there must be at least two sources for the same information. For example, the output of a process can be measured from sensor or it can be calculated from a behavior model of the process, in this case there are two sources of information for the process output and a redundancy can be obtained. Some sources of information are calculated output from behavior model, measurement from sensor, knowledge on fault symptoms obtained from past experience and etc. This research bases on analytical redundancy and it relies on an accurate process model.

Fault detection and isolation performs two tasks, namely alarm generation and alarm interpretation [17]. Alarm generation gives out alarm when there is detectable fault in the system. In order to generate alarm, the FDI algorithm must be able to detect the present fault in the system. If a fault cannot be detected, there will be no alarm generated. Alarm interpretation is performed after alarm generation; it performs fault isolation and identifies fault occurrence time, fault type and fault location.

Performance evaluation criteria of FDI algorithms are discussed in some literatures [20]. Some common evaluation criteria are false alarm, misdetection, fault isolation errors, delay in detection and etc. false alarm means FDI algorithm output alarms when there is no fault occurring in the system. Misdetection means FDI algorithm fails in giving alarm when there is fault in the system. Fault isolation error means FDI algorithm gives wrong information about fault type, fault location after a fault is detected. In order words, fault isolation error occurs when fault A occurs and the FDI tells that fault B instead of fault A is present in the system. Common performance evaluation criteria are important especially when there are many approaches and methods developed and being developed in the field of FDI.

2.2 Model based FDI

Model-based fault detection and isolation utilizes a model. The model describes the monitored system under normal or faulty operation conditions.

Various models are possible to describe operation of a system, for example fuzzy models [13], state space models [14], partial differential equations [5], bond graph models as in this report and etc.

In model based FDI, necessary redundancy is established between the actual process and the model. Process variables are measured from process using sensors or are calculated based on the model which is running parallel to the process. The differences between measured quantities and calculated quantities are residuals.

Alarm generation and alarm interpretation are two functions of fault detection and isolation (FDI) algorithms [17].

From alarm generation point of view, alarms are generated when residual deviates from zero. Alarm indicates that there are inconsistency between the actual process and the model running parallel to it, and this is due to the faults present in the process if the model is accurate. The fault occurred in the process must cause inconsistency between the actual process and the model so as to be detected. In other words, a fault is detectable only if it invalidates at least one redundancy between the process and the model.

In real life situations, due to the presence of noise, model errors and parameter uncertainty, residuals are never zero even when there are no faults,. This means some evaluation must be carried out in order to decide whether the residual is active or

inactive. One way of evaluating a residual is to test it against some threshold. If the absolute value of a residual exceeds the predetermined threshold, it is considered active, otherwise it is inactive.

When a fault occurs, it may have some effect on a certain residual, but the effect it have may be very small. The residual deviates slightly away from zero and this makes residual evaluation very difficult to perform. It is desirable to design residuals in such a way that they are very sensitive to faults and insensitive to noises, parameter uncertainty and modeling errors [7]. Sensitivity bond graph was developed by Gawthrop [6]; sensitivity of residuals to parameters change can be obtained; however sensitivity bond graph is used for optimization problems only, its potential in determining residuals' sensitivity to fault is not yet studied.

From alarm interpretation point of view, model based FDI makes decision on the type and location of fault based on status of residuals. There are statistical approach and analytical approach to alarm interpretation.

Statistical approach test the probability of each fault occurring in the process, the fault with the highest occurrence probability is interpreted as being present in the process. Normally fault observers of each possible faults are designed, the residuals from each fault observers are tested statistically, the one that most depict what is happening in the process is statistically determined, and fault corresponding to that fault observer is considered as being present in the process.

Analytical approach deduces the possible faults based on cause effect reasoning. In this approach, FDI makes used of analytical redundancy relations. Analytical redundancy relations are constraint equations of known variables, e.g. measurement from sensors or known process inputs, in the process. The values of residuals can be calculated from the analytical redundant relations equation. It is easy to deduce from the equation, what may cause the residual to deviate from zero and become active. In

other words, the faults that a residual is sensitive to can be analyzed based on the analytical redundancy relations equations.

Depending on the residuals sensitivity to each fault, fault signature is developed [8]. When a fault has unique signature compared to all other faults, the fault can be isolated. In order to make the job easier, these fault signatures are further arranged in a matrix form with the fault detection ability and fault isolation ability indicated in the matrix, Fault Signature Matrix is formed [16].

Fault signature matrix is a good tool for fault detection and isolation; however, fault signatures rely on the status of each residual. When the residuals' sensitivity to fault is low, residual evaluation algorithm may provide wrong information on the status of residual, which will lead to wrong identification of fault signature. If this happens, misdetection or isolation errors are likely to occur.

There is another class of model-based methods which relies on parameter estimation. A model structure is decided. Normal values of parameters are identified when the process is normal, and these parameter values are set as reference. Parameters of the actual process are identified continuously while the process is running. If there are any discrepancy between the identified parameter values and the reference parameter values, fault is detected in the process. The information of parameters change is used to make fault isolation decisions. Some introduction on parameter identification based fault detection and isolation can be found in [20] and [8]. An example can be found in [9].

2.3 Bond graph model based FDI

Bond Graphs were invented in 1959 by Henry Paynter after intensive use of block diagrams for servocontrols and simulation problems. They were further developed by

Dean Karnopp and Ronald Rosenberg, professors at the universities of California and Michigan respectively [18].

Bond graph is a modeling tool; it is suitable to model multidisciplinary state-determined systems. Bond graph model is similar to a state-space model in the sense that, it is able to model the evolution of states of the system. There are some advantages of bond graph model which make it very convenient to be used for model based fault detection and isolation.

1. Bond graph makes modeling of multidisciplinary system relatively simple.

A lot of industry processes are multidisciplinary, the modeling of multidisciplinary systems is very important for model based fault detection and isolation. Bond graph uses uniformed symbols (R element, C element and etc) to represent constitutive relations between variables and uses simple lines (bonds) to represent energy exchange between different components of a system [18]. This makes the modeling of multidisciplinary system relatively simple.

2. Bond variables and element parameters carry real physical meanings, which makes bond graph model intuitively understood.

Bond variables can be voltage and current in electrical domain, force and velocity, torque and angular velocity in mechanical domain, Magneto-motive force and flux rate in magnetic domain and etc, they carry real physical meanings.

Bond graph elements carry real physical meaning also. For example, the parameter of I element in bond graph model can be value of inductance in electrical domain, it can be moment of inertia of a mass in mechanical domain.

The bond variables and element parameters which carry real physical meanings makes bond graph a good tool for intuitive analysis and reasoning. It is much easier to be understood compared to a purely mathematic model.

3. Causality property of bond graph model makes cause and effect reasoning possible [15].

Causality between variables is an important aspect of system behavior, and is very useful for fault detection and isolation. Bond graph uses perpendicular line at the end of bonds to indicate direction of signal flow [18], the cause and effect relation between variables are explicitly indicated.

Residuals are generated from analytical redundancy relations when bond graph models are used for the purpose of fault detection and isolation, however, this method is difficult to apply when the system under monitoring is non-resolvable. Analytical Redundancy Relations (ARRs) need to be derived symbolically from bond graph model where all the unknown variables need to be eliminated in order to obtain the ARRs, this is not an easy task. Diagnostic Bond Graph [14] is developed by Samantaray and his colleagues to deal with this problem. Causal path analysis is used to obtain fault signature matrix based on diagnostic bond graph model, thanks to the causality property of bond graph model.

Some textbooks on bond graph modeling and bond graph application in model based fault detection and isolation are [18] [11] [15].

2.4 Fault diagnosis for rotating machinery

Many industry applications and mechanical equipments involve rotating machineries. The fault diagnosis of rotating machineries plays an important role in reducing maintenance cost and improving reliability of industry plants and equipments. Vibration spectrum analysis is the most commonly accepted techniques in rotating machinery fault diagnosis, yet there are shortcuts in this approach and sometimes the information obtained from spectrum analysis are not enough to make decision on fault of machinery [1]. “Determining reliable model-based strategies for monitoring the

health of machines is a huge challenge, but one that need to be addressed in the coming years.” [12] In recent past, model based fault diagnosis of rotating machinery has been found in the literatures. Problem of incipient fault detection and diagnosis for rotating machinery in a statistical model-based framework is formulated in Abdel-Magied’s work, nonlinear phenomena such as rub impact has been considered as an example using simulation method [1]. An analytical mathematical model of extended Jeffcott rotor (two-mass rotor system) is derived from Lagrange’s equation by Wu and Meagher; computer simulation was performed, the distinct vibration signatures predicted by the model can be used for shaft crack diagnostic purposes [21]. A Lagrange Bond Graph model of Jeffcott rotor was proposed by Joaquin Compos, et al. The model proposed was experimentally proven, however it is difficult for those who do not have a good knowledge of Lagrange bond graph and it is not tested in the framework of model-based fault detection and isolation [3].

In this research, a simple and effective bond graph model of Jeffcott rotor system is developed and it is further developed into a Diagnostic Bond Graph to perform fault detection and isolation. It is verified by simulation via MatLab/Simulink and by test bed experiment using machinery fault simulator. This research provides a first attempt to diagnostic bond graph model based fault detection and isolation of a Jeffcott rotor system coupled with rotational load on the rotor.

3 BACKGROUND THEORIES

3.1 Model based FDI

When the process model runs in parallel to the process and is driven by the same process inputs, it is reasonable to expect that the process variables produced by the process model will be the same like those process variables from the actual process when the process is normal or fault-free [4]. The process variables delivered by the process model form redundancies to the process variables from the real process. If fault occurs in the process, and it invalidates the redundancy, the process variables produced by the model and those from the actual process will be different. The difference indicates the presence of fault. The actual process variables must be measured by some sensors in order to be compared to those produced by the model.

Most model based FDI rely on the concept of analytical redundancy relation (ARR) [16]. ARR represent constraints between different variables in the process. They are static or dynamic constraints which link the time evolution of the know variables when the system operates according to its normal operation. ARR is normally represented in the form of mathematical equation. When the constraints represented by the ARR is satisfied, the equation will be valid, otherwise, it will be invalid. When the constraint equation is not valid, there will be difference between the two sides of the equation, this difference is referred to as residual. A residual is sensitive to a fault if the fault invalidates the respective ARR. There can be many ARRs, hence there can be many residuals also in the same process. Ideally, residuals are zero when the process is in fault-free condition and they become non-zero when faults occur in the process.

In the real life, it is not the case due to sensor noises, modelling errors, model parameters uncertainties and etc.

Effects of faults on analyzed residuals are called fault signatures [8]. Fault signatures are arranged into a matrix to form part of a Fault Signature Matrix (FSM). A FSM indicates the expected status of each individual residuals for different fault conditions, it also indicates the fault detection ability and fault isolation ability in the last two columns of the matrix. Fault detection ability tells whether a fault is detectable; fault isolation ability tells whether a fault is isolatable. It is useful to note that a fault must be detectable so as to be isolatable.

A binary coherence vector $C = [c_1 \dots c_m]$ is defined for the purpose of FDI. Each component c_i of the coherence vector C is obtained by (3-1)

$$C_i = \begin{cases} 1, & \text{if } |r_i| > \varepsilon_i \text{ for } i = 1, 2, \dots, m \\ 0, & \text{otherwise} \end{cases} \quad (3-1)$$

For each fault or parameter change, there is one corresponding coherence vector C . If there are no faults that the residuals are sensitive to, the binary coherence vector C will be zero. Otherwise, if there are faults that the residuals are sensitive to, the coherence vector will be nonzero. ‘1’ in the corresponding coherence vector indicates that the respective residual is sensitive to the fault/faults represented by the coherence vector. On the other hand, ‘0’ in the coherence vector represents the respective residual is insensitive to the fault/faults represented by the coherence vector.

Fault Signature Matrix (FSM) shows the effects of fault to each residual. A typical FSM is shown in Table 1, D_b and I_b represent fault detection ability and fault isolation ability respectively. $r_1, \dots, r_m$ represent the m residuals available. For each row, the entry under the columns $r_1, \dots, r_m$ is the coherence vector (fault signature) with respect to a fault. If at least a ‘1’ appears in the fault signature of a fault, the fault is detectable. This ability is represented by assigning $D_b = 1$ in the respective row. When the fault signature is unique

compared to all the other fault signatures in the FSM, the respective fault is isolable. This is denoted by $I_b = 1$ in the respective row. It is obvious that a fault must be detectable so as to be isolatable.

Table 3-1 Fault Signature Matrix (FSM)

	r_1	$\dots$	r_m	D_b	I_b
θ_1	1 or 0				
$\vdots$					
$\vdots$					
$\vdots$					
θ_p					

3.2 Basics of bond graph modeling

Bond Graph displays both energy and signal exchanges between components in systems by simple lines and symbols [18].

3.2.1 Bonds and bond variables

Energy is exchanged through bond connected between two elements. Figure 3-1 shows an example of bond.

Figure 3-1 Bond between two elements

There are two variables for each bond, namely effort and flow. They are directed in opposite directions. The power (P) conducted by the bond is the product of effort and flow.

$$P = e * f.$$

Bond graph utilizes a small set of basic elements to represent multi-domain system. Table 3-2 shows different efforts and flows in the respective physical domains.

Table 3-2 Effort and Flow variables in different domains

Domain		Effort (e)	Flow (f)
Electrical		Voltage (e)	Current (i)
Mechanical	Translational	Force (F)	Velocity (v)
	Rotational	Torque (τ)	Angular Velocity (ω)
Hydraulic	Incompressible Flow	Pressure (P)	Volumetric Flow Rate (Q)
	Compressive	Enthalpy (h)	Mass Flow Rate ($\dot{m}$)
Thermal		Temperature (T)	Entropy Flow Rate ($\dot{s}$)
Magnetic		Magneto-motive Force (F)	Flux Rate ($\dot{\phi}$)

3.2.2 One-port elements and two-port elements

One-port elements include resistance elements, called R-elements; inertia elements, called I-elements; and capacity elements called C-elements. In addition, there are effort sources and flow sources. Table 3-3 shows the R-elements, C-elements and I-elements' graphical representation and their constitutive relation.

Table 3-3 One port elements of bond graph

Name	Constitutive Relation (CR)	Graphical Representation
Resistance	$e_i = Rf_i$, $f_i = \frac{1}{R}e_i$
Capacitance	$e_i = \frac{1}{C} \int f_i dt$, $f_i = C \frac{d}{dt} e_i$
Inertia	$e_i = I \frac{d}{dt} f_i$, $f_i = \frac{1}{I} \int e_i dt$

The interaction of the system with the external can be represented by the ideal effort and flow sources. Table 3-4 shows the representation and constitutive relation of flow source and effort source.

Table 3-4 Effort and Flow source elements

Name	Constitutive Relation	Symbolization
Source of Flow	$f_i = Sf$	$Sf \xrightarrow[f_i]{e_i}$
Source of Effort	$e_i = Se$	$Se \xrightarrow[f_i]{e_i}$

Two-port elements are energy conserving and they consist of ideal transformer (TF) and ideal gyrator (GY). Table 3-5 shows the representation and constitutive relation of transformer and gyrator elements. A transformer relates output effort to input effort, and output flow to input flow; a gyrator relates output effort to input flow, and output flow to input effort.

Table 3-5 Two-port elements

Name	Constitutive Relation	Symbolization
Transformer	$e_j = re_i, f_j = \frac{1}{r}f_i$	$\xrightarrow[f_i]{e_i} \text{TF} \xrightarrow[f_j]{e_j}$
Gyrator	$e_j = \mu f_i, f_j = \frac{1}{\mu}e_i$	$\xrightarrow[f_i]{e_i} \text{GY} \xrightarrow[f_j]{e_j}$

3.2.3 Junctions

The elements of bond graphs are connected by junctions. Usually junctions connect three or more elements together, and they are classified as multi-port elements. There are only two types of junction, namely common effort junction (p-junction, 0 junction) and common flow junction (s-junction, 1 junction). Junctions are power conserving, the power transport of all bonds add up to zero at all time. Table 3-6 shows the representation and constitutive relation of common flow junctions and common effort junctions. Note that there can be two or more bonds at a common effort junction or common flow junction, the number of bonds is not limited to four.

Table 3-6 Junctions

Name	Constitutive Relation	Symbolization
Common flow Junction (serial)	$e_1 + e_2 + e_3 + e_4 = 0$ $f_1 = f_2 = f_3 = f_4$
Common effort Junction (parallel)	$e_1 = e_2 = e_3 = e_4$ $f_1 + f_2 + f_3 + f_4 = 0$

3.2.4 Causality

In bond graph, inputs and outputs are specified is by causal stroke. The causal stroke is a short, perpendicular line made at the end of a bond. It indicates the direction in which effort signal is directed. Table 3-7 shows the causal forms and causal relations for basic one-port elements; Table 3-8 shows the causal forms and causal relations of basic two port elements and junctions.

For 0-junction, there should be only one bond bringing effort input to the junction, all the other efforts are determined by the junction constitutive relations; similarly, for 1-junction, there should be only one bond bringing flow input to the junction, all the other flows are determined by junction constitutive relations. The bond that brings effort input to the 0-junction and the bond that brings flow input to a 1 junction are called strong bonds. There should be one and only one strong bond for each junction, otherwise the bond graph model is invalid and cannot be used.

Table 3-7 Causal forms for basic one-port elements

Element	Causal Form	Causal Relation	Remarks
Effort source	$Se \rightarrow$	$e(t) = E(t)$	
Flow Source	$Sf \rightarrow$	$f(t) = F(t)$	
Resistor	$R \leftarrow$	$e = \phi_R(f)$	
	$R \leftarrow$	$f = \phi_R^{-1}(e)$	
Capacitor	$C \leftarrow$	$e = \phi_C^{-1}\left(\int^t f dt\right)$	Integral causality
	$C \leftarrow$	$f = \frac{d}{dt} \phi_C(e)$	Differential causality
Inertia	$I \leftarrow$	$f = \phi_I^{-1}\left(\int^t e dt\right)$	Integral causality
	$I \leftarrow$	$e = \frac{d}{dt} \phi_I(f)$	Differential causality

Table 3-8 Causal forms for basic two-port elements and junctions

Element	Causal Form	Causal Relation	Remarks
Transformer	$\begin{array}{c} \text{---}^1 \text{---} \text{TF} \text{---}^2 \text{---} \\ \text{---}^1 \text{---} \text{TF} \text{---}^2 \text{---} \end{array}$	$e_1 = m e_2$ $f_2 = m f_1$	
	$\begin{array}{c} \text{---}^1 \text{---} \text{TF} \text{---}^2 \text{---} \\ \text{---}^1 \text{---} \text{TF} \text{---}^2 \text{---} \end{array}$	$f_1 = f_2/m$ $e_2 = e_1/m$	
Gyrator	$\begin{array}{c} \text{---}^1 \text{---} \text{GY} \text{---}^2 \text{---} \\ \text{---}^1 \text{---} \text{GY} \text{---}^2 \text{---} \end{array}$	$e_1 = r f_2$ $e_2 = r f_1$	
	$\begin{array}{c} \text{---}^1 \text{---} \text{GY} \text{---}^2 \text{---} \\ \text{---}^1 \text{---} \text{GY} \text{---}^2 \text{---} \end{array}$	$f_1 = e_2/r$ $f_2 = e_1/r$	
0-Junction	$\begin{array}{c} \text{---}^1 \text{---} 0 \text{---}^2 \text{---} \\ \text{---}^3 \text{---} \end{array}$	$e_2 = e_1$ $e_3 = e_1$ $f_1 = -(f_2 + f_3)$	Bond 1 is strong bond in this example
1-Junction	$\begin{array}{c} \text{---}^1 \text{---} 1 \text{---}^2 \text{---} \\ \text{---}^3 \text{---} \end{array}$	$f_2 = f_1$ $f_3 = f_1$ $e_1 = -(e_2 + e_3)$	Bond 1 is strong bond in this example

3.2.5 Multiport transformer

Multiport transformer is not a standard bond graph element; however it is used in this research to model geometry constraints in Jeffcott rotor system. Hence its representation, causality assignment and constitutive relation are introduced in this section.

Multiport transformer is described in textbook written by Karnopp, et al. [11]. Multiport transformers relate output efforts to input efforts, output flows to input flows, at the same time conserving power at both side of the multiport transformer.

Two general forms of multiport transformers representing two possible causality assignment are shown in Figure 3-2 and Figure 3-3. M & N are modulars of the multiport transformers, they are matrixes of appropriate dimentions.

Equations (3-2) and (3-3) show relation between output variables and input variables for the multiport transformers in Figure 3-2.

$$\begin{bmatrix} e(1) \\ \vdots \\ e(m) \end{bmatrix} = M^T * \begin{bmatrix} e(m+1) \\ \vdots \\ e(m+n) \end{bmatrix} \quad (3-2)$$

$$\begin{bmatrix} f(m+1) \\ \vdots \\ f(m+n) \end{bmatrix} = M * \begin{bmatrix} f(1) \\ \vdots \\ f(m) \end{bmatrix} \quad (3-3)$$

Figure 3-2 Modulated Multiport Transformer 1

Equation (3-3) and (3-4) show relation between output variables and input variables for the multiport transformers in Figure 3-3.

$$\begin{bmatrix} e(1) \\ \vdots \\ e(m) \end{bmatrix} = N * \begin{bmatrix} e(m+1) \\ \vdots \\ e(m+n) \end{bmatrix} \quad (3-4)$$

$$\begin{bmatrix} f(m+1) \\ \vdots \\ f(m+n) \end{bmatrix} = N^T * \begin{bmatrix} f(1) \\ \vdots \\ f(m) \end{bmatrix} \quad (3-5)$$

Figure 3-3 Modulated Multiport Transformer 2

3.3 DBG for residual generation

3.3.1 Definition

Diagnostic bond graph (DBG) has known variables as input and residuals as outputs. It is obtained by substituting some sub-graphs into bond graph model [16]. This section develops DBG based on the above mentioned reference.

3.3.2 Purpose of DBG

The advantage of diagnostic bond graph to conventional bond graph model based residual generation is its ability to obtain computational model even when there are symbolically non-resolvable equations. Non-resolvable equations contain unknown variables which are difficult if not impossible to eliminate. Explanation of non-resolvable equations can be found in [16].

3.3.3 Substitutions in DBG

For FDI, differential causality assignment is preferred so that system initial conditions will not affect residuals obtained from ARR_s or generated directly from DBG. Hence, differential causality is assignment to bond graph model before substituting sub-graph to it.

Bond graph representation of sensors in inverted causality and non-inverted causality and their respective substitute graphs are shown from Figure 3-4 to Figure 3-11, De is effort detector or effort sensor, it measures the effort at 0 junction; Df is flow sensor or flow detector, it measures flow of 1 junction. DBG is derived by substituting effort and flow detectors in bond graph model with some sub-graphs. Effort detector and flow detectors neither consume nor store energy, hence their existence does not affect behavior of bond graph model. Normally the causality of effort sensor and flow sensor should be assigned in such a way that the measured variables flow into the detectors. When developing diagnostic bond graph, the causality assignment of sensors can be inverted if necessary depending on the causality assignment on other parts of the bond graph model.

Four possible compositions are

- Inverted causality in effort sensor (De)
- Inverted causality in flow sensor (Df)
- Non-inverted causality in effort sensor (De)

- Non-inverted causality in flow sensor (Df)

Note that inversion of signal detector to signal source is not mentioned here, details can be found in [16].

Df* and De* are virtual flow detectors and virtual effort detectors respectively, they have only computational existence. The value measured by Df* and De* are actually residuals.

Figure 3-4 De assigned inverted causality

Figure 3-5 Substitute graph for causality inverted De

Figure 3-6 Df assigned inverted causality

Figure 3-7 Substitute graph for causality inverted Df

Figure 3-8 De assigned non-inverted causality

Figure 3-9 Substitute graph for causality non-inverted De

Figure 3-10 Df assigned non-inverted causality

Figure 3-11 Substitute graph for causality non-inverted Df

4 LOADED JEFFCOTT ROTOR AND ITS BOND GRAPH MODEL

In this research, Bond graph model based FDI is done on a loaded Jeffcott rotor system. In this chapter, the structure and physics of the loaded Jeffcott rotor system are explained first. The modeling of the system using bond graph is explained after.

4.1 Overview of the loaded Jeffcott rotor system under study

An electrical motor can run at no load condition or it can run with some external mechanical load connected to it. When there is load connected to the motor, the motor is said to be loaded. Here we borrow the term 'loaded' to Jeffcott rotor. When there is load connected to the Jeffcott rotor, the rotor is said to be loaded.

The schematic diagram of loaded Jeffcott rotor system under study in this research is shown in Figure 4-1.

Figure 4-1 Schematic Diagram of Modeled System – top view

There are three major parts in the loaded Jeffcott rotor system, which are the electrical motor, the Jeffcott rotor system and the external load driven by the Jeffcott rotor

4.1.1 Electrical motor

Electrical motor is shown in the left of Figure 4-1, it provides torque to the Jeffcott rotor which is connected to the motor through a speed encoder. It is assumed that torque output of the electrical motor is constant and the rotor is suitable to rotate at any speed. With this assumption, the electrical motor can be modeled as a simple effort source (S_e) using bond graph. The speed encoder is used to measure Jeffcott rotor rotating speed, and it can be easily modeled as a flow detector (D_f) using bond graph. Faults in the electrical motor are not considered, only the speed encoder fault is considered.

4.1.2 Jeffcott rotor

Jeffcott rotor consists of two bearings, a flexible shaft and an imbalance disk as shown in the box named as 'Jeffcott Rotor System' in Figure 4-1. Ideally, if the disk is perfectly balanced, the disk will not vibrate when the rotor is rotating. However it is not possible to get a perfectly balance rotor in real life, hence some vibration of the rotor is unavoidable. A displacement velocity sensor is installed on the side of the imbalance disk; it measures the displacement velocity of the disk in horizontal direction. The sensor is not in contact with the disk and it will not affect the movement of the disk at all. Imbalance fault and displacement velocity sensor fault are considered in this research.

Jeffcott Rotor was first used in 1919 to analyze the response of high speed rotating machines to rotor imbalance by Jeffcott; the model is named after his name later [19]. It consists of a flexible shaft supported by two rigid bearings at the ends; a massive unbalanced disk is mounted in the middle of the shaft between the two bearings. The only friction to oppose absolute motions of the disk is air drag and it is approximated by viscous damping. A schematic of Jeffcott rotor is shown in Figure 4-2.

Figure 4-2 Jeffcott Rotor

As shown in Figure 4-3, X-Y-Z frame is located at the center between the two ball bearings. Then the disk is placed at the origin of X-Y-Z frame. The shaft as indicated by the thick line is in line with Z axis. The disk rotates with respect to Z-axis if the disk is perfectly balanced.

Figure 4-3 Front view of stationary Jeffcott Rotor

Looking along Z axis into the negative direction, as shown in Figure 4-4, the geometry center (GC) of the disk is located at the origin when the shaft is not moving. The center of mass (MC) is located a distance (u) away from GC. We define a phase angle (φ) of the imbalance as the angle between the line connecting GC to MC and X axis.

Figure 4-4 Side view of stationary Jeffcott Rotor

When the shaft rotates, the disk will deviate away from its original position as shown in Figure 4-5. That is due to centrifugal force acting on the mass center of the imbalance disk. The dark thick bent line represents flexible shaft of the Jeffcott rotor; it goes through the GC of the imbalance disk. Note that the GC of the disk is no longer at the origin as compared to that in Figure 4-3 and Figure 4-4.

Figure 4-5 Front view of rotating Jeffcott Rotor

The side view of the rotating Jeffcott rotor is shown in Figure 4-6. Z axis is pointing out of the paper. GC of the imbalance disk is located δ distance away from the origin. MC is located u distance away from GC with a phase angle of ϕ which is defined previously as the angle between X axis and the line connecting GC to MC.

Figure 4-6 Side view of rotating Jeffcott Rotor

4.1.3 External load driven by the Jeffcott rotor

The external load driven by the Jeffcott rotor consists of two wheels, a V belt and a Gearbox as shown in Figure 4-1. The side view of the modeled system is shown in Figure 4-7, which provides a better view to the arrangement of wheel 1, wheel 2 and the belt connecting the two wheels. Wheel 1 is driven by the flexible shaft of the Jeffcott Rotor; wheel 2 is driven by wheel 1 through the V belt connecting wheel 1 and wheel 2. Wheel 2 is connected to the input shaft of the gearbox and it provides torque input to the gearbox. The gearbox takes the input rotation and transfers it to output rotation at a fix ratio. A rotation speed encoder is installed at the input shaft of the gearbox to measure the rotating speed. As the gearbox input shaft is connected to wheel 2, gearbox input rotation speed is equal to wheel 2 rotation speed; hence rotation speed sensor measures both the

gearbox input shaft speed and wheel 2 rotation speed. The gearbox is not connected to any load.

Figure 4-7 schematic diagram of modeled system - side view

The value ratio of rotation speed of wheel 2 and that of wheel 1 is called transfer ratio of the system formed by the V belt and the two wheels. The transfer ratio is fixed when the V belt is tightly secured to both wheels. When the belt becomes loose, there will be slippage between the belt and the wheels, which will cause the transfer ratio to change. Loose belt is considered as fault and will be discussed in this research. Another fault to be considered in the load will be rotation speed encoder fault.

4.2 Bond graph modeling

For bond graph model based FDI, model of the system is required. In this section, bond graph will be used as modeling language to model the loaded Jeffcott rotor system. Jeffcott rotor bond graph model will be derived first, followed by the bond graph modeling of the external load. The two models will be integrated at last to form the complete bond graph model of loaded Jeffcott rotor system.

4.2.1 Bond graph modeling of Jeffcott rotor

Figure 4-8 shows a physical model of Jeffcott rotor system. Jeffcott rotor consists of two rigid bearings, an elastic shaft of no mass supported by the two rigid bearings and an imbalanced disk. The X-Y-Z frame is located at the center of the two rigid bearing. If the disk is perfectly balanced, the disk will rotate with respect to Z axis which is pointing out of the paper. When imbalance is present as it is for Jeffcott rotor, a centrifugal force will be acting on the mass center (MC) of the disk when the shaft rotates, which will cause the disk to shift away from the Z axis.

Figure 4-8 Orthogonal spring and dashpot physical model of Jeffcott rotor

Springs

As the shaft is elastic, when the disk deviates from Z axis, the shaft tends to bring the disk back to its origin of the X-Y-Z frame. Shaft goes through the geometry center (GC) of the disk; hence a force will be imposed at the GC of the disk. This force is decoupled into two orthogonal forces with one in X axis direction and the other one in Y axis direction. Two orthogonal springs in X axis and Y axis attached to the GC of the imbalanced disk are used to model the two component forces. When the disk is at the origin of the X-Y-Z frame, the two orthogonal springs are neither stretched nor

compressed, hence will not impose any force on the disk; when the disk deviate from the origin of the X-Y-Z frame, the spring will be either stretched or compressed, hence impose a force at the GC of the disk which tends to bring the disk back to its original position.

Each spring can be modeled by a C element using bond graph. The effort variable of the C element is the force imposed by the shaft at the GC of the imbalanced disk in X axis or Y axis direction; the flow variable of the C element is the displacement velocity of the disk's GC in X axis or Y axis direction.

Dashpots

The only friction to oppose absolute motions of the disk is air drag. The air drag force acts on the disk's GC and is approximated by viscous damping. This force is decoupled into two orthogonal forces in X axis and Y axis direction. Each of the two orthogonal forces is modeled by a dashpot which is placed parallel to the spring in the respective direction, and the dashpots are connected to the disk's GC.

Each dashpot can be modeled by a R element using bond graph. The effort variable of the R element is the friction force acting on the disk's GC in X axis direction or Y axis direction; the flow variable of the R element is the displacement velocity of the disk's GC in X axis or Y axis direction.

Mass & moment of inertia

The shaft of the Jeffcott rotor system is assumed to have no mass, but the disk possesses mass. According to Newton's law, $F = m * a$, where F is the force acting on a mass, m is mass and a is acceleration of the mass, the force acting on MC of the disk in X axis direction is equal to the mass of the disk multiplied by the acceleration of the MC in X direction.

The effect of disk's mass in the X axis and Y axis direction can be modeled by I element using bond graph. The effort variable is the force acting on the disk's MC in X axis or Y

axis direction, the flow variable is the velocity of the disk's MC in X axis or Y axis direction. According to the constitutive relation of I element, flow is differentiated to derive effort. When the velocity (flow variable) is differentiated it becomes acceleration and the acceleration is used to derive force (effort variable) acting on the disk's MC.

Imagine an axis which is passing through the disk's MC and is parallel to Z axis, and it is named as axis Z'. The disk's moment of inertia to axis Z' is considered. The torque required to accelerate the rotation of the disk can be calculated by multiply the disk's moment of inertia by the disk's angular acceleration. This relation can be modeled by I element using bond graph. The effort variable is the torque acting on the disk; the flow variable is the angular velocity of the disk's rotation with respect to axis Z'.

Rotational friction

Imagine an axis which is passing through the disk's GC and is parallel to Z axis, it is named as Z''. When the rotor rotates around Z'' axis, there is air drag friction around the disk. This friction creates torque which opposes the rotation of the rotor. This torque is defined with respect to axis Z''. Assuming the torque caused by the air drag friction can be approximated by viscous damping, it can be modeled by I element using bond graph. The effort variable is torque caused by air drag friction; the flow variable is the disk's angular velocity with respect to Z'' axis.

Input torque from electrical motor

The input torque from the electrical motor is assumed to be constant; it is acting on the shaft which is passing through the GC of the disk. This torque is considered as being applied to the disk and it is defined with respect to Z'' axis.

Geometry constraint

Geometry constraint refers to the relation between movement of disk's MC and that of disk's GC. Refer to Figure 4-6, location of MC can be represented as (x_{mc}, y_{mc}) ; location of GC is represented as (x_{gc}, y_{gc}) . ϕ & u carry the same meanings as defined previously. The following equations can be derived.

$$x_{mc} = x_{gc} + u^* \cos \varphi \quad (4-1)$$

$$y_{mc} = y_{gc} + u^* \sin \varphi \quad (4-2)$$

Differentiate both sides of (4-1) & (4-2), the following equations are derived:

$$\dot{x}_{mc} = \dot{x}_{gc} + \dot{u}^* \cos \varphi - u^* \varphi^* \sin \varphi \quad (4-3)$$

$$\dot{y}_{mc} = \dot{y}_{gc} + \dot{u}^* \sin \varphi + u^* \varphi^* \cos \varphi \quad (4-4)$$

Since u is constant, $\dot{u} = 0$, (4-3) & (4-4) can be reduced to (4-5) & (4-6).

$$\dot{x}_{mc} = \dot{x}_{gc} - u^* \varphi^* \sin \varphi \quad (4-5)$$

$$\dot{y}_{mc} = \dot{y}_{gc} + u^* \varphi^* \cos \varphi \quad (4-6)$$

If the angular velocity of the disk's rotation around MC is represented as $\dot{\varphi}_{mc}$, the angular velocity of the disk's rotation around GC is represented as $\dot{\varphi}_{gc}$, the relation between them can be represented by (4-7).

$$\dot{\varphi}_{mc} = \dot{\varphi}_{gc} = \dot{\varphi} \quad (4-7)$$

(4-5) , (4-6) & (4-7) define the motion of MC and the rotation of the disk around MC in relation to the motion of GC and the rotation of the disk around GC. The three equations can be arrange in matrix form as shown in (4-8), and they represent the geometry constraints of the rigid disk.

$$\begin{bmatrix} \dot{x}_{mc} \\ \dot{y}_{mc} \\ \dot{\varphi}_{mc} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -u^* \sin \varphi \\ 0 & 1 & u^* \cos \varphi \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{x}_{gc} \\ \dot{y}_{gc} \\ \dot{\varphi}_{gc} \end{bmatrix} \quad (4-8)$$

The above equation can be easily modeled as a multiport transformer using bond graph.

Figure 4-9 Multiport transformer for geometry constraint 1

In Figure 4-9, the flow variables and modular matrix M are shown in the following equations.

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} \dot{x}_{gc} \\ \dot{y}_{gc} \\ \dot{\phi}_{gc} \end{bmatrix} \quad (4-9)$$

$$\begin{bmatrix} f_4 \\ f_5 \\ f_6 \end{bmatrix} = \begin{bmatrix} \dot{x}_{mc} \\ \dot{y}_{mc} \\ \dot{\phi}_{mc} \end{bmatrix} \quad (4-10)$$

$$M = \begin{bmatrix} 1 & 0 & -u^* \sin \varphi \\ 0 & 1 & u^* \cos \varphi \\ 0 & 0 & 1 \end{bmatrix} \quad (4-11)$$

The effort variables for bond graph in Figure 4-9, are the respective forces or torques at MC and GC of the disk.

If motion of MC and disk's rotation around MC is used to derive Motion of GC and disk's rotation around GC, the following equation can be obtained.

$$\begin{bmatrix} \dot{x}_{gc} \\ \dot{y}_{gc} \\ \dot{\phi}_{gc} \end{bmatrix} = \begin{bmatrix} 1 & 0 & u^* \sin \varphi \\ 0 & 1 & -u^* \cos \varphi \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{x}_{mc} \\ \dot{y}_{mc} \\ \dot{\phi}_{mc} \end{bmatrix} \quad (4-12)$$

The above equation can be modeled by multiport transformer in Figure 4-10.

Figure 4-10 Multiport transformer for geometry constraint 2

The meaning of flow variables and the modular matrix N are shown in the following equations.

$$\begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} = \begin{bmatrix} \dot{x}_{gc} \\ \dot{y}_{gc} \\ \dot{\phi}_{gc} \end{bmatrix} \quad (4-13)$$

$$\begin{bmatrix} f_4 \\ f_5 \\ f_6 \end{bmatrix} = \begin{bmatrix} \dot{x}_{mc} \\ \dot{y}_{mc} \\ \dot{\phi}_{mc} \end{bmatrix} \quad (4-14)$$

$$N^T = \begin{bmatrix} 1 & 0 & u^* \sin \varphi \\ 0 & 1 & -u^* \cos \varphi \\ 0 & 0 & 1 \end{bmatrix} \quad (4-15)$$

Jeffcott rotor bond graph model

With the above explanations, the following Jeffcott rotor acausal bond graph model is developed as in Figure 4-11. Acausal bond graph model is bond graph model without causality assignment.

Figure 4-11 Jeffcott rotor acausal bond graph model

In Figure 4-11, C_1 & C_2 represent the two springs, R_1 & R_2 represent the dashpots, R_3 represents rotating friction, S_e is the input torque; I_1 , I_2 and I_3 represent the mass and moment of inertia. Geometry constraint is represented by the multiport transformer.

4.2.2 Bond graph modeling of external load

The external load consists of a V belt system and a gearbox. The V belt system is driven by the Jeffcott rotor and it drives the gearbox to rotate.

The following assumptions are made on the V belt system and gearbox

1. There is no friction between the belt and the wheels
2. The friction in the gearbox can be approximated by viscous damping

3. The gear box pinions' moment of inertia can be represented as single moment of inertia

The load is represented in the following bond graph model.

Figure 4-12 External load acausal bond graph model

TF_1 represents the V belt system; TF_2 represents transfer ratio of the gearbox; R_4 & I_4 represents the friction loss of the gearbox and moment of inertia of the gearbox pinions respectively.

4.2.3 Integrating Jeffcott rotor and external load

The Jeffcott rotor bond graph model and the external load bond graph model have been developed above; they need to be integrated together to form bond graph model of the system in Figure 4-1.

Integration

The integrated bond graph is shown in Figure 4-13. The load as highlighted in bold font and thick lines is added to the 1 junction connected to bond 3.

Figure 4-13 Loaded Jeffcott rotor acausal bond graph model

One of the advantages to the Jeffcott rotor bond graph model developed in this research is that, it is easy to integrate with external load driven by the rotor. Refer to Figure 4-11, the load can be added to the junction that is representing the angular velocity of the rotor seen from GC of the disk. The simplicity of adding in external load to the Jeffcott rotor bond graph model makes the model easily incorporated into a bigger bond graph model. The effect of external load on rotor's rotation and shaft vibration are studied together in the same model.

Modeling sensors and causality assignment

There are three sensors in the system in Figure 4-1; they are modeled as flow detectors (D_f) in bond graph. D_f can be added to 1 junction connected to the flow variable which is to be measured, it does not consume nor store energy, hence behavior of the bond graph model will not be affected. The added flow detectors are highlighted in bold font in Figure 4-14.

Carry out causality assignment in the following steps. The causal strokes are highlighted in thick lines in Figure 4-14.

1. Assign fixed causalities to the effort source and flow detectors.
2. Assign integral causality to I_1 , I_2 & I_3 ; propagate the causalities through multiport transformer, junctions and transformers. If any bond has got causality such that it has become a strong bond for a junction, the causalities of all other bonds (weak bonds) are determined by laws for causality of junctions. After this step, all the causalities of the bonds are assigned in Figure 4-14. However I_4 can only be assigned differential causality.

I_4 cannot be assigned integral causality; this is due to assumptions in the model. In fact I_4 can be assigned integral causality by adding in a pad element as described in the referenced website [2]. Pad elements are normally representation of missing or unknown stiffnesses in the system. Although they ensure integral causality in the model, may turn out very stiff during numerical solution due to high frequency oscillations in the pad region.

Figure 4-14 Loaded Jeffcott rotor system bond graph in integral causality

5 FAULT DETECTION AND ISOLATION

5.1 Diagnostic bond graph (DBG)

5.1.1 Differential causality assignment

Causality assignment decides the inputs and outputs of junctions and of all other elements in the bond graph model. When I and C elements are concerned, the assignment of causality decides whether the constitutive relation between input and output of the element is in integral form or in differential form. This has some significance when fault detection and isolation is based on bond graph model. If the constitutive relations between variables are set in integral form, any integration of a variable will require the initial condition of the variable to be known. This is good for system simulation, because the initial conditions of the system can be considered during the simulation which makes the simulation more close to the real system. However it is not good when fault detection and isolation is concerned, if the calculation of residuals involve integration, the initial values of the variables to be integrated are needed, in real life, initial conditions are not easy to obtain, hence integral causality assignment is not preferred when doing fault detection and isolation.

The residuals used for fault detection and isolation are derived from analytical redundancy relations, as long as the constraints defined by the analytical relations are satisfied, the residuals are inactive, when the constraints cannot be satisfied, the residuals become active. The residuals status should not depend on the initial conditions of the

system variable. Bond graph model assigned in differential causality allow the constitutive relations between input and output of I and C elements to be defined in differential form, which means the output is calculated from the derivative of the input as in Table 3-7. The calculation of the residuals does not require the initial conditions of the variables to be known. Hence when Fault Detection and Isolation is concerned, differential causality is preferred.

When diagnostic bond graph is used, sensor's causality is allowed to be inverted if necessary. The bond graph in Figure 4-14 is assigned differential causality by allowing sensor causality inversion as in Figure 5-1. The causal strokes are highlighted in thick short lines. The sensors are highlighted using bold font, they are going to be replaced by substitution graphs discussed in section 3.4.3 in later part of this report to derive diagnostic bond graph model.

Figure 5-1 Loaded Jeffcott rotor system bond graph in differential causality

5.1.2 DBG derivation

As explained in section 3.3, DBG is obtained by substituting some sub-graphs into bond graph model. Refer to Figure 5-1, causality of sensor D_{f1} is inverted, causalities of sensors D_{f2} & D_{f3} are not inverted. Substitute the three sensors and the bonds connected to the sensor using respective substitutions discussed in section 3.4.3, diagnostic bond graph for the system in Figure 4-1 is obtained, and it is shown in Figure 5-2. The substitution graphs are highlighted in bold font and thick lines.

D_{f1} , D_{f2} & D_{f3} are measurements from process, and they are fed into diagnostic bond graph.

The three residuals $r1$, $r2$ & $r3$ are outputs of the diagnostic bond graph, $D_{e1}^* : r1$, $D_{f2}^* : r2$ & $D_{f3}^* : r3$ are virtual residual sensors, they measure values of the three residuals.

Figure 5-2 Loaded Jeffcott rotor system diagnostic bond graph

5.2 Causal path analysis

Numerical values of each residual can be obtained from the diagnostic bond graph shown in Figure 5-2. However, for FDI, fault signature matrix should be available. Analysis of the causal paths to each residual is used to generate fault signature matrix.

Fault signature matrix is derived from Analytical Redundant Relation constraint equations when conventional bond graph model is used. The constraint equations will not only facilitate the numerical calculation of the residuals but also provide an aid to generate fault signature matrix. When diagnostic bond graph model is used, numerical value of the residual can be obtained from the diagnostic bond graph itself, if the elements affecting each residual can be analyzed intuitively, derivation of analytical redundancy relation equations is not necessary.

Causal path analysis is to analyze how process inputs and variables propagate to the residuals. It will only tell what elements have effect on residuals, but it will not tell how much the effect will be. Causal path analysis is possible because of the causality property of bond graph models. Causality assignment defines the input and output of a bond graph element or junction. Input enters the element and is used to produce output based on the element's constitutive relations. This output becomes input of another element and propagate further until it ends in a virtual detector (residual).

Causal paths analysis for residual r1 is shown in Figure 5-3; the blue arrows indicate flow variable propagation, while the red arrows indicate effort variables propagation. The causal paths for r1 are listed below; the arrows indicate direction of information flow.

1. $D_{f1} \rightarrow f_{25} \rightarrow f_{12} \rightarrow f_{15} \rightarrow TF_1 \rightarrow f_{16} \rightarrow f_{18} \rightarrow TF_2 \rightarrow f_{19} \rightarrow f_{20} \rightarrow R_4 \rightarrow e_{20} \rightarrow e_{19} \rightarrow TF_2 \rightarrow e_{18} \rightarrow e_{16} \rightarrow TF_1 \rightarrow e_{15} \rightarrow e_{12} \rightarrow e_{24} \rightarrow r_1$

2. $D_{f1} \rightarrow f25 \rightarrow f12 \rightarrow f15 \rightarrow TF_1 \rightarrow f16 \rightarrow f18 \rightarrow TF_2 \rightarrow f19 \rightarrow f21 \rightarrow I_4 \rightarrow e21 \rightarrow e19 \rightarrow TF_2 \rightarrow e18 \rightarrow e16 \rightarrow TF_1 \rightarrow e15 \rightarrow e12 \rightarrow e24 \rightarrow r1$
3. $D_{f1} \rightarrow f25 \rightarrow f12 \rightarrow f13 \rightarrow MTF \rightarrow f10 \rightarrow I_3 \rightarrow e10 \rightarrow MTF \rightarrow e13 \rightarrow e12 \rightarrow e24 \rightarrow r1$
4. $D_{f1} \rightarrow f25 \rightarrow f12 \rightarrow f13 \rightarrow MTF \rightarrow f9 \rightarrow I_2 \rightarrow e9 \rightarrow MTF \rightarrow e13 \rightarrow e12 \rightarrow e24 \rightarrow r1$
5. $D_{f1} \rightarrow f25 \rightarrow f12 \rightarrow f13 \rightarrow MTF \rightarrow f8 \rightarrow I_1 \rightarrow e8 \rightarrow MTF \rightarrow e13 \rightarrow e12 \rightarrow e24 \rightarrow r1$
6. $S_e \rightarrow e14 \rightarrow e12 \rightarrow e24 \rightarrow r1$
7. $f11 \rightarrow R_3 \rightarrow e11 \rightarrow e12 \rightarrow e24 \rightarrow r1$
8. $f5 \rightarrow R_2 \rightarrow e5 \rightarrow e6 \rightarrow C_2 \rightarrow f6 \rightarrow f7 \rightarrow MTF \rightarrow f9 \rightarrow I_2 \rightarrow e9 \rightarrow MTF \rightarrow e13 \rightarrow e12 \rightarrow e24 \rightarrow r1$
9. $f2 \rightarrow R_1 \rightarrow e2 \rightarrow e1 \rightarrow C_1 \rightarrow f1 \rightarrow f4 \rightarrow MTF \rightarrow f8 \rightarrow I_1 \rightarrow e8 \rightarrow MTF \rightarrow e13 \rightarrow e12 \rightarrow e24 \rightarrow r1$

Causal paths for r2 are shown in Figure 5-4, blue arrows indicate flow variables propagation; red arrows indicate effort variables propagation. The causal paths for r2 are listed below.

1. $D_{f2} \rightarrow f22 \rightarrow f23 \rightarrow r2$
2. $f2 \rightarrow R_1 \rightarrow e2 \rightarrow e1 \rightarrow C_1 \rightarrow f1 \rightarrow f3 \rightarrow f23 \rightarrow r2$
3. $D_{f1} \rightarrow f25 \rightarrow f12 \rightarrow f13 \rightarrow MTF \rightarrow f8 \rightarrow I_1 \rightarrow e8 \rightarrow MTF \rightarrow e4 \rightarrow e1 \rightarrow C_1 \rightarrow f1 \rightarrow f3 \rightarrow f23 \rightarrow r2$

Causal paths for r3 are shown in Figure 5-5; blue color arrows indicate propagation of flow variables. The causal paths for r3 are listed below.

1. $D_{f1} \rightarrow f25 \rightarrow f12 \rightarrow f15 \rightarrow TF_1 \rightarrow f16 \rightarrow f17 \rightarrow f26 \rightarrow r3$
2. $D_{f3} \rightarrow f27 \rightarrow f26 \rightarrow r3$

Figure 5-3 Causal paths for r_1

Figure 5-4 Causal paths for r_2

Figure 5-5 Causal paths for $r3$

5.3 Fault signature matrix

The fault signature matrix is derived based on causal path analysis done in the previous section. The residual's value is affected by the elements which appear in the residual's causal paths. If any element appears in any causal path of the particular residual, the respective cell of the element and the residual in the fault signature matrix is updated as 1. If an element never appears in any causal path of a residual, the corresponding cell of the fault signature matrix should be updated as 0. Only parameters are shown in fault signature matrix, bond variables are not shown.

From the causal path analysis the following Fault Signature Matrix can be obtained as shown in Table 5-1. All the elements marked in red color which occurred in at least one of the causal paths derived in the previous section are indicated by a 1 in the cells corresponding to that residual in the fault signature matrix. The respective cells of the elements that didn't occur in any causal paths of the residual are indicated by 0.

A fault is detectable if there is at least one residual sensitive to the fault, in other words, there must be at least one 1 in the fault signature in order for the fault to be detectable. It is obvious from the FSM shown in Table 5-1 that all the faults listed in the first column can be detected theoretically. If a fault is detectable and its fault signature is unique compare to all other fault signatures in the fault signature matrix, the fault is isolatable. Fault related to D_{f1} , D_{f2} , D_{f3} and TF_1 are not only detectable but also isolatable. Faults related to D_{f1} , D_{f2} & D_{f3} are sensors' faults. Fault related to TF_1 is loose belt fault.

Table 5-1 Fault signature matrix 1

	r1	r2	r3	Db	lb
D_{f1}	1	1	1	1	1
D_{f2}	0	1	0	1	1
D_{f3}	0	0	1	1	1
R_1	1	1	0	1	0
C_1	1	1	0	1	0
R_2	1	0	0	1	0
C_2	1	0	0	1	0
R_3	1	0	0	1	0
S_e	1	0	0	1	0
MTF	1	1	0	1	0
I_1	1	1	0	1	0
I_2	1	0	0	1	0
I_3	1	0	0	1	0
TF_1	1	0	1	1	1
TF_2	1	0	0	1	0
R_4	1	0	0	1	0
I_4	1	0	0	1	0

In real life situation, it is not possible to consider all the possible faults that can occur in a system due to cost and technical constraints. In this research, it is assumed that only imbalance fault (MTF), loose belt fault (TF_1), shaft speed encoder fault (D_{f1}), laser displacement sensor (D_{f2}) and Minibeam sensor fault (D_{f3}) can occur in the system. All other faults are not possible to occur. It is further assumed that the system is either fault free or contains one fault only at one time; two or more faults are not possible to occur at the same time in the system. The new fault signature matrix is shown in Table 5-2.

Table 5-2 Fault signature matrix 2

	r1	r2	r3	Db	lb
D _{f1}	1	1	1	1	1
D _{f2}	0	1	0	1	1
D _{f3}	0	0	1	1	1
MTF	1	1	0	1	1
TF ₁	1	0	1	1	1

6 PARAMETER MEASUREMENT & IDENTIFICATION

6.1 Overview

In model based approach where a model is utilized for the purpose of fault detection and isolation, it is necessary to obtain accurate model parameters' values.

In this research, parameters are obtained by direct measurement and calculation, estimation using Gauss-Newton method, and trial and error.

6.2 Parameter measurement

Three parameters are obtained by direct measurement and calculation.

Disk mass is weighted when the disk is removed from the shaft. I_1 & I_2 are moment of the disk in horizontal and vertical direction, they equal to the mass of the disk.

Shaft stiffness (C_1 , C_2) is obtained by measurement and calculation. An additional weight (W) of 700g is hung at the center of the shaft. The change in shaft's deflection (δ) in vertical direction is measured. The stiffness of the shaft is equal to weight divided by change in shaft deflection, $C_1 = C_2 = W/\delta$.

Belt transfer ratio (TF_2) is obtained by measuring the driving shaft speed and driven shaft speed at the same time. The ratio between the two speeds is belt transfer ratio.

6.3 Parameter identification

Parameter estimation is done through a two-step approach.

In step 1, the belt is removed from the system, as shown in Figure 6-1, the system consists of an electrical motor, a rotor, and two bearings. Rotational friction (R_3) and rotor moment of inertia (I_3) are to be estimated.

In step 2, the belt is installed to the system, as shown in Figure 6-2, the system consists of an electrical motor, a rotor, two bearings, a belt system and a gearbox. Friction (R_4) and moment of inertia (I_4) of the gearbox are to be estimated; R_3 and I_3 are identified during step 1 and used in step 2 as known parameters.

Figure 6-1: Machinery fault simulator with belt removed

Figure 6-2: Machinery fault simulator with belt

Diagnostic sensitivity bond graph is used for calculating gradient, Gauss-Newton optimization method is used to estimate parameters. Two sensors are used in both step 1 and step 2, e.g. shaft speed encoder and shaft torque sensor. Three sets of parameters are identified when the shaft is running at 10Hz, 20Hz and 30Hz speed.

Diagnostic sensitivity bond graph is not the focus of this research. Interested readers can refer to [15] for details of diagnostic sensitivity bond graph. The simulink block diagram of the diagnostic sensitivity bond graph used in step 1 is shown in Figure 6-3.

Figure 6-3: Simulink block diagram of DSBG for step1

The simulink block diagram of the diagnostic sensitivity bond graph used in step 2 is shown in Figure 6-4

Figure 6-4: Simulink block diagram of DSBG for step 2

The m file used to implement Gauss-Newton optimization is shown in Figure 6-5.

```

Fb=inf;
ut1=[10 10];
ut2=[10 10];
F=1;
i=0;
while F>0.001
options=simset('solver','ode45','FixedStep',1e-3,'RelTol',1e-
10,'AbsTol',1e-12);
[t,x,r1,r1I,r1R]=sim('PI20090408experimentload',[0,50],options,ut1,
ut2);
F=transpose(r1)*r1;
g1=transpose(r1I)*r1;
g2=transpose(r1R)*r1;
g=[g1;g2];
h11=transpose(r1I)*r1I;
h12=0;
h21=0;
h22=transpose(r1R)*r1R;
H=[h11 h12; h21 h22];
i=i+1;
if i>200
    break
end

if F<Fb
    Fb=F;
    utb1=ut1;
    utb2=ut2;
    d=1*inv(H)*g;
    ut1=ut1-d(1);
    ut2=ut2-d(2);
else
    d=d/2;
    ut1=utb1-d(1);
    ut2=utb2-d(2);
end
end
disp(utb1);
disp(utb2);
disp(i);
disp(F);
disp(d);
disp(ut1);
disp(ut2);

```

Figure 6-5: MATLAB code for Gauss-Newton optimization

A model is built to verify the identified parameters, e.g. I3, R3, I4 and R4; the model is shown in Figure 6-6.

Figure 6-9: Verification result of para20

6.4 Estimation of eccentricity (u)

Eccentricity is estimated by trial and error. The optimization of parameter u is equivalent to the minimization of absolute value of residual r_2 when there is no fault in the machinery fault simulator. The measured and calculated shaft deviations are compared. If the measured shaft deviation is higher than the calculated, eccentricity parameter is adjusted higher; if the measurement is lower than the calculation, the eccentricity is adjusted lower. After several adjustments, the difference between measurement and calculation is smallest, that eccentricity is said to be optimum. Three sets of parameter are identified, when the shaft is running at 10Hz, 20Hz and 30Hz speed. Residual r_2 's value obtained during experiment when there is no fault in the system can be used as a verification of the correctness of parameter u estimation. As we can see in Figure 7-61, Figure 7-115 and Figure 7-133, values of r_2 are close to .

6.5 Parameters' values

TF_1 is the gearbox transfer ratio; it is obtained from the gearbox nameplate. R_1 , R_2 are representing friction losses due to air drag on the rotor, they are assumed to be ignorable and are set to zero.

Parameters value obtained from the above steps are listed below in Table 6-1.

Table 6-1: Parameters identified at different shaft speeds

	I_3	R_3	I_4	R_4	U	R_1 , R_2	I_1 , I_2	C_1 , C_2	TF_1	TF_2
10Hz	0.0012	0.0018	0.1431	0.2146	0.00035	0	0.7	659615	1.5	2.555
20Hz	0.0031	0.0018	0.0557	0.1152	0.00014	0	0.7	659615	1.5	2.555
30Hz	0.0025	0.0007582	0.0966	0.0844	0.000055	0	0.7	659615	1.5	2.555

7 EXPERIMENT & RESULT

7.1 Modification to DBG

The diagnostic bond graph developed as shown in Figure 5-2 is assigned differential causality to avoid residuals' dependency on process initial conditions as mentioned before. Residual r_1 and r_3 does not depend on any initial condition, however residual r_2 is depending on the initial imbalance phase angle of the imbalance disk, and differential causality assignment of the developed bond graph model cannot eliminate this dependency.

It is obvious for a person who knows bond graph that residual r_2 is the difference between flow variable of bond 22 (f_{22}) and that of bond 3 (f_3). ' f_{22} ' is obtained from D_{r2} sensor; it is the disk deviation speed, it does not require any information on imbalance phase angle. ' f_3 ' is the calculated disk deviation speed. It is obtained from the diagnostic bond graph model based on analytical relations between ' f_3 ' and other known variables. The process of calculating ' f_3 ' requires information about the imbalance phase angle. That is why ' f_3 ', hence r_2 , is depending initial phase angle.

This dependency makes practical implementation very difficult. In order to solve this difficulty, some modification is done on the generation of residual r_2 . The solution provided in this research is to generate r_2 by comparing the RMS value of ' f_{22} ' with that of ' f_3 '. In other words, the power of the vibration rather than the instantaneous value of the vibrating speed are compared. The above modification effectively eliminated residual r_2 's dependency on initial rotor imbalance phase angle, which makes it easier for practical implementation.

7.2 Modification to FSM

As will be shown later in the simulation results, residual r_1 's sensitivity to imbalance fault is very low. The fault signature matrix derived in chapter 5 as shown in Table 5-2 is still capable of isolating all the five faults listed, but it fails for the experiment. Residual r_1 fails to activate during imbalance fault in the experiment due to its low sensitivity to imbalance fault. This makes imbalance fault and Df:2 fault share the same coherence vector and become not isolatable.

Residual's sensitivity to fault is very much related to sensor's location in diagnostic bond graph model based FDI. Sensors placement is an on going research topic, and it is beyond the scope of this research. Due to time and cost constraints, sensors are not relocated to explore other possibilities of residual design. In this research, a tricky solution is proposed.

Different from residual r_1 and r_3 whose absolute values are evaluated against the respective thresholds, residual r_2 is evaluated against its thresholds directly. In this case, r_2 can be positive or negative, there are two thresholds for residual r_2 , one is positive, and the other one is negative.

When imbalance fault or D_{f1} fault occur, residual r_2 goes positive and exceeds the positive threshold, and becomes positively active; while when laser displacement sensor (Df:2) becomes faulty, residual r_2 goes negative and drop below the negative threshold, and becomes negatively active. In order for the above analysis to be valid, it is assumed that sensor (Df:2) fault is loss of sensor signal; and imbalance in a rotor will only grow and will not reduce as time goes by.

With the above modification, the new fault signature matrix is shown in Table 7-1. '-1' means residual r_2 is negatively active. It is easy to observe that all the five faults listed in the table are detectable and isolatable. The advantage of this new fault signature matrix is that even residual r_1 fails to activate during imbalance fault due to low residual

sensitivity, imbalance (MTF) fault and laser displacement sensor (Df:2) fault are still isolatable because of the usage of ‘-1’. In other words, all the five faults listed in the table are isolatable even when residual r1 is unreliable for imbalance fault.

Table 7-1 Fault signature matrix 3

	r1	r2	r3	Db	lb
D _{f1}	1	1	1	1	1
D _{f2}	0	-1	0	1	1
D _{f3}	0	0	1	1	1
MTF	1	1	0	1	1
TF ₁	1	0	1	1	1

7.3 Simulation

A simulation is set up to verify the effectiveness of the proposed method. Parameter’s uncertainty has adverse effects on bond graph model based fault detection and isolation. In the simulation, there will be no parameter uncertainty, the results obtained from simulation are compared with those obtained from experiment, and hopefully the comparison will tell the effects of parameter uncertainty on bond graph model based fault detection and isolation. It is also to study the effect of operating set point on residual sensitivity in the condition where there is no parameter uncertainty.

The behavior of machinery fault simulator is represented in simulink block “Behavior model”, the parameters used for normal machine operating condition are same as those parameters identified at 20Hz shaft speed in the test bed experiment. The torque input to the machinery fault simulator is set to 0.6Nm, 1.2Nm and 1.82Nm for shaft speed of 10Hz, 20Hz and 30Hz operating conditions in both the “Behavior block” and “DBG” block. Residuals values are obtained at fault free condition and various fault conditions at different operating set points, e.g. 10Hz, 20Hz and 30Hz.

Figure 7-1: Simulink top level block diagram for simulation

Imbalance fault and loose belt fault are simulated by modifying parameter's value in "Behavior model" block. Imbalance fault is simulated by changing parameter u from 0.00014 to 0.0014; loose belt fault is simulated by changing belt transfer ratio from 2.555 to 2.5. The three sensors' faults are simulated by disconnecting sensor input from the "DBG" block.

7.4 Test bed experiment

7.4.1 Laboratory equipment

The experiment makes use of a test bed called Machinery Fault Simulator (MFS). The machinery fault simulator is designed to facilitate developing understanding of predictive maintenance and learning to understand features of various machinery faults. Various faults can be introduced either individually or jointly in a totally controlled environment. In this experiment, machinery fault simulator is modified as shown in the photo to study bond graph model based fault detection and isolation of loaded Jeffcott rotor system.

Figure 7-2: Machinery fault simulator

The modified machinery fault simulator consists of an electrical motor, two sealed ball bearings, a 5/8 inch steel shaft with aluminum 6" round disk with two rows of tap holes on the shaft in the middle of the two bearings, double V-belt with tensional idler roller, three way straight tooth profile bevel gearbox with 1.5:1 ratio. The weight of the machinery fault simulator is approximately 130 lb, with a size of the following dimensions: L = 37", W = 20", H = 18.5".

The electrical motor is driven by a variable frequency drive; the speed of the rotor can be controlled from the variable frequency drive. It provides torque input to the system through the shaft. The torque is measured by a FUTEK TRS605 FSH02056 torque sensor which is installed in between the motor rotor shaft and the machinery fault simulator shaft through two flexible couplers. While the shaft is rotating, if there is any imbalance in the round disk, there will be a centrifugal force acting on the mass center of the disk

and the force will tends to pull the disk away from its original position, in other words, the disk and the shaft will vibrate. Keyence laser displacement sensor is installed to measure the vibration in horizontal direction. The rotation of the shaft is transmitted to the input of the gearbox through a V-belt at a certain transmission ratio. The rotation output speed is measured by Minibeam Scanner SM312LVMHS.

Sensors data are collected through Quanser Q4 hardware-in-the-loop control board and the board is integrated with MATLAB/Simulink/RTW via QuaRC software.

Figure 7-3 shows the Simulink block diagram which is used to take in sensors inputs and to generate residuals.

Figure 7-3: Simulink top level block diagram for test bed experiment

7.4.2 Test bed experiment procedure

A diagnostic bond graph model of the machinery fault simulator is developed for the fault detection and isolation of sensors' faults, loose belt fault and imbalance fault. It is assumed that if the machinery fault simulator becomes faulty, only one fault is present in

the system, multiple faults are not going to be present at the same time in the machinery fault simulator. When the machinery fault simulator is running at normal and various faulty conditions, sensors measurement data are collected and are saved in .mat files. These sensors measurement data are fed into the diagnostic bond graph model to generate residuals at normal and faulty operating conditions of the machinery fault simulator. If the generated residuals at various health conditions of the machinery fault simulator agree with the fault signature matrix obtained previously based on causal path analysis, they can be used as a positive verification of the designed fault detection and isolation algorithm.

The experiments are conducted at 10Hz, 20Hz and 30Hz shaft operating speed conditions separately using parameters identified at 20Hz shaft speed condition (para20). Fault free condition and all the five faults are simulated one by one; scopes displaying residuals value are saved for analysis.

Further experiments are conducted by simulating fault free condition and various fault conditions when the shaft is running at 10Hz and 30Hz. Fault detection and isolation is done using parameters identified at 10Hz (para10) and 30Hz (para30) respectively. Scopes displaying residuals' values are recorded.

The fault free condition and various fault conditions are generated in the following ways.

No fault condition

The MFS without any fault start at 0 speed, at around time 20s, the speed of the MFS is quickly increased to operating speed; at around time 50s, the data collection is stopped and sensors measurements are saved into .mat files.

Imbalance fault

Imbalance fault is created by adding imbalance mass on the round disk on the shaft as shown in Figure 7-4. Initially at time 0 the MFS is stationary, when time is about 20s, the

speed of the MFS is quickly increased to operating speed; after time 50s, the data collection is stopped. Sensors measurements are saved in .mat files.

Figure 7-4: Creation of imbalance fault

Loose belt fault

Loose belt fault is created by adjusting the position of tensional idler roller as shown in Figure 7-5. Initially at time 0 the MFS is stationary, when time is about 20s, the speed of the MFS is quickly increased to operating speed; after time 50s, the data collection is stopped. Sensors measurements are saved in .mat files.

Figure 7-5: Creation of loose belt fault

Laser displacement sensor fault

Laser displacement sensor fault is created by turning off the power supply to the laser displacement sensor when the machine is running. Initially at time 0, the MFS is stationary, at around time 20s the speed of the MFS is quickly increased to operating speed, at around time 30s, the power supply of the laser displacement sensor is turned off manually. After time 50s, the data collection is stopped. Sensors measurements are saved in .mat files.

Minibeam sensor fault

Minibeam sensor fault is created by turning off the power supply to the minibeam sensor when the machine is running. Initially at time 0, the MFS is stationary, at around time 20s the speed of the MFS is quickly increased to operating speed, at around time 30s, the power supply of the minibeam sensor is turned off manually. After time 50s, the data collection is stopped. Sensors measurements are saved in .mat files.

Speed encoder fault

The power supply to the speed encoder is taken from Quanser Q4 encoder connection socket; it is not possible to turn it off half way when the data collection is going on. The speed encoder fault is simulated by disconnecting the encoder measurement data from the diagnostic bond graph model in simulink block diagram before the simulation starts. The sensors data in healthy operating conditions are fed into the diagnostic bond graph model except the sensor measurement data from speed encoder which is disconnected.

7.5 Results

7.5.1 Simulation

Table 7-2 to Table 7-7 show the coherence vectors obtained in the simulation experiment and the thresholds used to evaluate the status of residuals. It is easy to see all the coherence vectors agree with the fault signature matrix derived from causal path analysis. All the five faults can be detected and isolated at 10Hz, 20Hz and 30Hz operating speeds. This means that when there are no parameter uncertainty and modeling error, the FDI algorithm designed in this research works well in detecting and isolating the selected faults.

Table 7-2: Coherence vectors obtained at various fault conditions, sim, 30Hz, para20

	r1	r2	r3	Db	lb
Fault free	0	0	0		
Imbalance	1	1	0	1	1
Loose belt	1	0	1	1	1
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-3: Thresholds used for the residuals evaluation, sim, 30Hz, para20

	r1	r2	r3
thresholds	0.00006	0.00006, -0.00006	0.3

Table 7-4: Coherence vectors obtained at various fault conditions, sim, 10Hz, para20

	r1	R2	r3	Db	lb
Fault free	0	0	0		
Imbalance	1	1	0	1	1
Loose belt	1	0	1	1	1
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-5: Thresholds used for the residuals evaluation, sim, 10Hz, para20

	r1	r2	r3
thresholds	0.000005	0.000015, -0.000015	0.3

Table 7-6: Coherence vectors obtained at various fault conditions, sim, 20Hz, para20

	r1	r2	r3	Db	lb
Fault free	0	0	0		
Imbalance	1	1	0	1	1
Loose belt	1	0	1	1	1
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-7: Thresholds used for the residuals evaluation in, sim, 20Hz, para20

	r1	r2	r3
thresholds	0.00004	0.00006, -0.00006	0.3

It is worth to note that, as shown in Figure 7-9, Figure 7-36 and Figure 7-54, sensitivity of residual r1 to imbalance fault is very low in all the three operating speeds. This

explains well why residual r_1 failed to activate during imbalance fault in the test bed experiments which will be shown later.

Figure 7-6: sim, 20Hz, para20, $r1|$ inactive, $\varepsilon=0.00004$, fault free condition

Figure 7-9: sim, 20Hz, para20, $r1|$ active, $\varepsilon=0.00004$, imbalance fault condition

Figure 7-7: sim, 20Hz, para20, $r2$ inactive, $\varepsilon=+-0.00006$, fault free condition

Figure 7-10: sim, 20Hz, para20, $r2$ active, $\varepsilon=+-0.00006$, imbalance fault condition

Figure 7-8: sim, 20Hz, para20, $r3|$ inactive, $\varepsilon=0.3$, fault free condition

Figure 7-11: sim, 20Hz, para20, $r3|$ inactive, $\varepsilon=0.3$, imbalance fault condition

Figure 7-12: sim, 20Hz, para20, lr1 active, $\varepsilon=0.00004$, loose belt fault condition

Figure 7-15: sim, 20Hz, para20, lr1 active, $\varepsilon=0.00004$, Df:1 fault condition

Figure 7-13: sim, 20Hz, para20, r2 inactive, $\varepsilon=\pm 0.00006$, loose belt fault condition

Figure 7-16: sim, 20Hz, para20, r2 active, $\varepsilon=\pm 0.00006$, Df:1 fault condition

Figure 7-14: sim, 20Hz, para20, lr3 active, $\varepsilon=0.3$, loose belt fault condition

Figure 7-17: sim, 20Hz, para20, lr3 active, $\varepsilon=0.3$, Df:1 fault condition

Figure 7-18: sim, 20Hz, para20, lr1 inactive, $\varepsilon=0.00004$, Df:2 fault condition

Figure 7-21: sim, 20Hz, para20, lr1 inactive, $\varepsilon=0.00004$, Df:3 fault condition

Figure 7-19: sim, 20Hz, para20, r2 negatively active, $\varepsilon=+-0.00006$, Df:2 fault condition

Figure 7-22: sim, 20Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, Df:3 fault condition

Figure 7-20: sim, 20Hz, para20, lr3 inactive, $\varepsilon=0.3$, Df:2 fault condition

Figure 7-23: sim, 20Hz, para20, lr3 active, $\varepsilon=0.3$, Df:3 fault condition

Figure 7-24: sim, 10Hz, para20, lr1 inactive, $\varepsilon=0.000005$, fault free condition

Figure 7-27: sim, 10Hz, para20, lr1 active, $\varepsilon=0.000005$, Df:1 fault condition

Figure 7-25: sim, 10Hz, para20, r2 inactive, $\varepsilon=\pm 0.000015$, fault free condition

Figure 7-28: sim, 10Hz, para20, r2 active, $\varepsilon=\pm 0.000015$, Df:1 fault condition

Figure 7-26: sim, 10Hz, para20, lr3l inactive, $\varepsilon=0.3$ at fault free condition

Figure 7-29: sim, 10Hz, para20, lr3l active, $\varepsilon=0.3$, Df:1 fault condition

Figure 7-30: sim, 10Hz, para20, lr1 inactive, $\varepsilon=0.000005$, Df:2 fault condition

Figure 7-33: sim, 10Hz, para20, lr1 inactive, $\varepsilon=0.000005$, Df:3 fault condition

Figure 7-31: sim, 10Hz, para20, r2 negatively active, $\varepsilon=+-0.000015$, Df:2 fault condition

Figure 7-34: sim, 10Hz, para20, r2 inactive, $\varepsilon=+-0.000015$, Df:2 fault condition

Figure 7-32: sim, 10Hz, para20, lr3 inactive, $\varepsilon=0.3$, Df:2 fault condition

Figure 7-35: sim, 10Hz, para20, lr3 active, $\varepsilon=0.3$, Df:3 fault condition

Figure 7-36: sim, 10Hz, para20, $r1$ active, $\varepsilon=0.000005$, imbalance fault condition

Figure 7-39: sim, 10Hz, para20, $r1$ active, $\varepsilon=0.000005$, loose belt fault condition

Figure 7-37: sim, 10Hz, para20, $r2$ active, $\varepsilon=+0.000015$, imbalance fault condition

Figure 7-40: sim, 10Hz, para20, $r2$ inactive, $\varepsilon=+0.000015$, loose belt fault condition

Figure 7-38: sim, 10Hz, para20, $r3$ inactive, $\varepsilon=0.3$, imbalance fault condition

Figure 7-41: sim, 10Hz, para20, $r3$ active, $\varepsilon=0.3$, loose belt fault condition

Figure 7-42: sim, 30Hz, para20, lr1 inactive, $\varepsilon=0.00006$, fault free condition

Figure 7-45: sim, 30Hz, para20, lr1 active, $\varepsilon=0.00006$, Df:1 fault condition

Figure 7-43: sim, 30Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, fault free condition

Figure 7-46: sim, 30Hz, para20, r2 active, $\varepsilon=+-0.00006$, Df:1 fault condition

Figure 7-44: sim, 30Hz, para20, r3l inactive, $\varepsilon=0.3$, fault free condition

Figure 7-47: sim, 30Hz, para20, lr3l active, $\varepsilon=0.3$, Df:1 fault condition

Figure 7-48: sim, 30Hz, para20, lr1 inactive, $\varepsilon=0.00006$, Df:2 fault condition

Figure 7-51: sim, 30Hz, para20, lr1 inactive, $\varepsilon=0.00006$, Df:3 fault condition

Figure 7-49: sim, 30Hz, para20, r2 negatively active, $\varepsilon=+-0.00006$, Df:2 fault condition

Figure 7-52: sim, 30Hz, para20, r2 inactive, $\varepsilon=+-0.00006$, Df:3 fault condition

Figure 7-50: sim, 30Hz, para20, lr3 inactive, $\varepsilon=0.3$, Df:2 fault condition

Figure 7-53: sim, 30Hz, para20, lr3 active, $\varepsilon=0.3$, Df:3 fault condition

Figure 7-54: sim, 30Hz, para20, $r1$ active, $\epsilon=0.00006$, imbalance fault condition

Figure 7-57: sim, 30Hz, para20, $r1$ active, $\epsilon=0.00006$, loose belt fault condition

Figure 7-55: sim, 30Hz, para20, $r2$ active, $\epsilon=\pm 0.00006$, imbalance fault condition

Figure 7-58: sim, 30Hz, para20, $r2$ inactive, $\epsilon=\pm 0.00006$, loose belt fault condition

Figure 7-56: sim, 30Hz, para20, $r3l$ inactive, $\epsilon=0.3$, imbalance fault condition

Figure 7-59: sim, 30Hz, para20, $r3l$ active, $\epsilon=0.3$, loose belt fault condition

7.5.2 Test bed experiment

Using parameters identified at 20Hz shaft speed

Figure 7-60 to Figure 7-113 show the absolute values of residual r1 and r3 and the value of residual r2 at fault free and various fault conditions.

Table 7-8 shows the coherence vectors obtained from fault free and various fault conditions when the machinery fault simulator is running at 20Hz shaft speed. It is generated by comparing residuals values with their respective thresholds as listed in Table 7-9. It is easy to observe that all the coherence vectors obtained during normal and various faulty conditions agree with the fault signature matrix obtained from causal path analysis, except the status of residual r1 during imbalance fault. Residual r1 is supposed to be active during imbalance fault, however it failed to activate in the experiment. This is due to the low sensitivity of residual r1 to imbalance fault, and this agrees with the simulation results which were shown previously. This proves that residuals sensitivity to fault plays an important role in model based fault detection and isolation, and it is desirable to design residuals which have high sensitivity to faults.

Table 7-8: Coherence vectors obtained at various fault conditions, exp, 20Hz, para20

	r1	r2	r3	Db	lb
Fault free	0	0	0		
imbalance	0	1	0	1	1
Loose belt	1	0	1	1	1
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-9: Thresholds used for the residuals evaluation, exp, 20Hz, para20

	r1	r2	r3
thresholds	0.3	+0.0003, -0.0004	0.5

Although r1 failed to activate during imbalance fault, it is easy to see that all the five faults listed in the table are detectable and isolatable. In other words, the FDI algorithm works well at 20Hz shaft speed.

Table 7-10 & Table 7-12 show coherence vectors at fault free and various fault conditions when the machinery fault simulator is running at 10Hz & 30Hz shaft speeds respectively. Table 7-11 & Table 7-13 show the thresholds used to evaluate the status of the residuals at 10Hz and 30Hz shaft speed respectively. The residuals values are shown in Figure 7-78 to Figure 7-113.

Table 7-10: Coherence vectors obtained at various fault conditions, exp, 10Hz, para20

	r1	r2	r3	Db	lb
Fault free	0	0	0		
imbalance	?	1	0	1	1
Loose belt	0	0	1	1	1
Df1 fault	1	?	1	1	0
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-12: Coherence vectors obtained at various fault conditions, exp, 30Hz, para20

	r1	r2	r3	Db	lb
Fault free	0	0	0		
imbalance	0	1	0	1	1
Loose belt	1	-1	1	1	0
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-11: Thresholds used for the residuals evaluation, exp, 10Hz, para20

	r1	r2	r3
thresholds	0.5	$+3 \times 10^{-4}$, -3×10^{-5}	0.5

Table 7-13: Thresholds used for the residuals evaluation, exp, 30Hz, para20

	r1	r2	r3
thresholds	0.7	$+1 \times 10^{-4}$, -1×10^{-3}	1

‘?’ in Table 7-10 indicates that residual’s status cannot be determined; it is either active or inactive, because the absolute value of residual fluctuates around the threshold. This ambiguity of residual r1’s status at imbalance fault condition does not affect the isolation ability of imbalance fault.

It is observed that all the faults can be detected in both 10Hz and 30Hz shaft speed operating conditions. At 10Hz shaft speed operating condition, loose belt fault cannot be isolated; at 30Hz shaft speed operating condition, shaft speed encoder fault cannot be isolated, all the other faults in both 10Hz and 30Hz shaft speed operating conditions are isolatable. The failure in isolating the two faults might be due to parameters' change when operating speed changes. This is verified by simulation experiment, where there is no parameter uncertainty and will be verified again by FDI experiments using model parameters identified at respective operating speed as shown next.

Figure 7-60: exp, 20Hz, para20, r1 inactive, $\epsilon=0.3$, fault free condition

Figure 7-63: exp, 20Hz, para20, r1 inactive, $\epsilon=0.3$, imbalance fault condition

Figure 7-61: exp, 20Hz, para20, r2 inactive, $\epsilon=+0.0003/-0.0004$, fault free condition

Figure 7-64: exp, 20Hz, para20, r2 active, $\epsilon=+0.0003/-0.0004$, imbalance fault condition

Figure 7-62: exp, 20Hz, para20, r3 inactive, $\epsilon=0.5$, fault free condition

Figure 7-65: exp, 20Hz, para20, r3 inactive, $\epsilon=0.5$, imbalance fault condition

Figure 7-66: exp, 20Hz, para20, lr1 active, $\varepsilon=0.3$, loose belt fault condition

Figure 7-69: exp, 20Hz, para20, lr1 active, $\varepsilon=0.3$, Df1 fault condition

Figure 7-67: exp, 20Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.0004$, loose belt fault condition

Figure 7-70: exp, 20Hz, para20, r2 active, $\varepsilon=+0.0003/-0.0004$, Df1 fault condition

Figure 7-68: exp, 20Hz, para20, lr3 active, $\varepsilon=0.5$, loose belt fault condition

Figure 7-71: exp, 20Hz, para20, lr3 active, $\varepsilon=0.5$, Df1 fault condition

Figure 7-72: exp, 20Hz, para20, lr1 inactive, $\epsilon=0.3$, Df2 fault condition

Figure 7-75: exp, 20Hz, para20, lr1 inactive, $\epsilon=0.3$, Df3 fault condition

Figure 7-73: exp, 20Hz, para20, r2 negatively active, $\epsilon=+0.0003/-0.0004$, Df2 fault condition

Figure 7-76: exp, 20Hz, para20, r2 inactive, $\epsilon=+0.0003/-0.0004$, Df3 fault condition

Figure 7-74: exp, 20Hz, para20, lr3l inactive, $\epsilon=0.5$, Df2 fault condition

Figure 7-77: exp, 20Hz, para20, lr3l active, $\epsilon=0.5$, Df3 fault condition

Figure 7-78: exp, 10Hz, para20, $|r1|$ inactive, $\varepsilon=0.5$, fault free condition

Figure 7-81: exp, 10Hz, para20, $|r1|$, $\varepsilon=0.5$, imbalance fault condition

Figure 7-79: exp, 10Hz, para20, $r2$ inactive, $\varepsilon=+0.0003/-0.00003$, fault free condition

Figure 7-82: exp, 10Hz, para20, $r2$ active, $\varepsilon=+0.0003/-0.00003$, imbalance fault condition

Figure 7-80: exp, 10Hz, para20, $|r3|$ inactive, $\varepsilon=0.5$, fault free condition

Figure 7-83: exp, 10Hz, para20, $|r3|$ inactive, $\varepsilon=0.5$, imbalance fault condition

Figure 7-84: exp, 10Hz, para20, lr1 inactive, $\varepsilon=0.5$, Df:2 fault condition

Figure 7-87: exp, 10Hz, para20, lr1 inactive, $\varepsilon=0.5$, loose belt fault condition

Figure 7-85: exp, 10Hz, para20, r2 negatively active, $\varepsilon=+0.0003/-0.00003$, Df:2 fault condition

Figure 7-88: exp, 10Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.00003$, loose belt fault condition

Figure 7-86: exp, 10Hz, para20, lr3l inactive, $\varepsilon=0.5$, Df:2 fault condition

Figure 7-89: exp, 10Hz, para20, lr3l active, $\varepsilon=0.5$, loose belt fault condition

Figure 7-90: exp, 10Hz, para20, lr1 inactive, $\varepsilon=0.5$, Df:3 fault condition

Figure 7-93: exp, 10Hz, para20, lr1 active, $\varepsilon=0.5$, Df:1 fault condition

Figure 7-91: exp, 10Hz, para20, r2 inactive, $\varepsilon=+0.0003/-0.00003$, Df:3 fault condition

Figure 7-94: exp, 10Hz, para20, r2, $\varepsilon=+0.0003/-0.00003$, Df:1 fault condition

Figure 7-92: exp, 10Hz, para20, lr3 active, $\varepsilon=0.5$, Df:3 fault condition

Figure 7-95: exp, 10Hz, para20, lr3 active, $\varepsilon=0.5$, Df:1 fault condition

Figure 7-96: exp, 30Hz, para20, lr1 inactive, $\varepsilon=0.7$, fault free condition

Figure 7-99: exp, 30Hz, para20, lr1 inactive, $\varepsilon=0.7$, imbalance fault condition

Figure 7-97: exp, 30Hz, para20, r2 inactive, $\varepsilon=+0.0001/-0.001$, fault free condition

Figure 7-100: exp, 30Hz, para20, r2 active, $\varepsilon=+0.0001/-0.001$, imbalance fault condition

Figure 7-98: exp, 30Hz, para20, lr3 inactive, $\varepsilon=1$, fault free condition

Figure 7-101: exp, 30Hz, para20, lr3 inactive, $\varepsilon=1$, imbalance fault condition

Figure 7-102: exp, 30Hz, para20, lr1 active, $\varepsilon=0.7$, loose belt fault condition

Figure 7-105: exp, 30Hz, para20, lr1 inactive, $\varepsilon=0.7$, Df:2 fault condition

Figure 7-103: exp, 30Hz, para20, r2 negatively active, $\varepsilon=+0.0001/-0.001$, loose belt fault condition

Figure 7-106: exp, 30Hz, para20, r2 negatively active, $\varepsilon=+0.0001/-0.001$, Df:2 fault condition

Figure 7-104: exp, 30Hz, para20, lr3 active, $\varepsilon=1$, loose belt fault condition

Figure 7-107: exp, 30Hz, para20, lr3 inactive, $\varepsilon=1$, Df:2 fault condition

Figure 7-108: exp, 30Hz, para20, lr1 inactive, $\varepsilon=0.7$, Df:3 fault condition

Figure 7-111: exp, 30Hz, para20, lr1 active, $\varepsilon=0.7$, Df:1 fault condition

Figure 7-109: exp, 30Hz, para20, r2 inactive, $\varepsilon=+0.0001/-0.001$, Df:3 fault condition

Figure 7-112: exp, 30Hz, para20, r2 active, $\varepsilon=+0.0001/-0.001$, Df:1 fault condition

Figure 7-110: exp, 30Hz, para20, lr3 active, $\varepsilon=1$, Df:3 fault condition

Figure 7-113: exp, 30Hz, para20, lr3 active, $\varepsilon=1$, Df:1 fault condition

Using parameters identified at 10Hz and 30Hz shaft speeds

To verify the reason of failing to isolate the two faults discussed previously and to provide a solution to the problem, model parameters are identified when the machinery fault simulator is running at 10Hz and 30Hz shaft speeds respectively, and are used to carry out FDI for the respective operating speed. Parameters are shown in Table 6-1.

Table 7-14 shows the coherence vectors obtained at fault free and various fault conditions when the machinery fault simulator is running at 30Hz shaft speed. Table 7-15 shows the thresholds used to evaluate residuals status. It can be observed that all the faults can be detected and isolated successfully.

Table 7-14: Coherence vectors obtained at various fault conditions, exp, 30Hz, para30

	r1	r2	r3	Db	lb
Fault free	0	0	0		
imbalance	0	1	0	1	1
Loose belt	1	0	1	1	1
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-15: Thresholds used for residuals evaluation, exp, 30Hz, para30

	r1	r2	r3
Thresholds	0.4	0.0004, -0.0004	1.25

Table 7-16 & Table 7-17 show the coherence vectors obtained at fault free condition and various fault conditions when the machinery fault simulator is running at 10Hz shaft speed and the threshold values used to evaluate the status of the residuals. It is easy to observe that all the faults can be detected and isolated successfully.

Table 7-16: Coherence vectors obtained at various fault conditions, exp, 10Hz, para10

	r1	r2	r3	Db	lb
Fault free	0	0	0		
imbalance	0	1	0	1	1
Loose belt	1	0	1	1	1
Df1 fault	1	1	1	1	1
Df2 fault	0	-1	0	1	1
Df3 fault	0	0	1	1	1

Table 7-17: Thresholds used for the residuals evaluation, exp, 10Hz, para10

	r1	r2	r3
Thresholds	0.3	0.0001, -0.00025	0.6

The successful detection and isolation of all the faults at both 10Hz and 30Hz shaft speed using parameters identified at respective operating speeds verifies that the failure in isolating the two faults in Table 7-10 and Table 7-12 might be due to parameters' change when operating speed changes. It also shows that the parameter uncertainty problem can be solved by forming a lookup table of parameters at different shaft operating speeds. Hence the proposed approach is able to detect and isolate the selected faults successfully using parameters identified at respective operating speeds.

Figure 7-114: exp, 30Hz, para30, lr1 inactive, $\epsilon=0.4$, fault free condition

Figure 7-117: exp, 30Hz, para30, lr1 active, $\epsilon=0.4$, Df:1 fault condition

Figure 7-115: exp, 30Hz, para30, r2 inactive, $\epsilon=+0.0004$, fault free condition

Figure 7-118: exp, 30Hz, para30, r2 active, $\epsilon=+0.0004$, Df:1 fault condition

Figure 7-116: exp, 30Hz, para30, lr3 inactive, $\epsilon=1.25$, fault free condition

Figure 7-119: exp, 30Hz, para30, lr3 active, $\epsilon=1.25$, Df:1 fault condition

Figure 7-120: exp, 30Hz, para30, lr1l inactive, $\varepsilon=0.4$, imbalance fault condition

Figure 7-123: exp, 30Hz, para30, lr1l active, $\varepsilon=0.4$, loose belt fault condition

Figure 7-121: exp, 30Hz, para30, r2 active, $\varepsilon=+0.0004$, imbalance fault condition

Figure 7-124: exp, 30Hz, para30, r2 inactive, $\varepsilon=+0.0004$, loose belt fault condition

Figure 7-122: exp, 30Hz, para30, lr3l inactive, $\varepsilon=1.25$, imbalance fault condition

Figure 7-125: exp, 30Hz, para30, lr3l active, $\varepsilon=1.25$, loose belt fault condition

Figure 7-126: exp, 30Hz, para30, lr1 inactive, $\varepsilon=0.4$, Df:2 fault condition

Figure 7-129: exp, 30Hz, para30, lr1 inactive, $\varepsilon=0.4$, Df:3 fault condition

Figure 7-127: exp, 30Hz, para30, r2 negatively active, $\varepsilon=+0.0004$, Df:2 fault condition

Figure 7-130: exp, 30Hz, para30, r2 inactive, $\varepsilon=+0.0004$, Df:3 fault condition

Figure 7-128: exp, 30Hz, para30, lr3 inactive, $\varepsilon=1.25$, Df:2 fault condition

Figure 7-131: exp, 30Hz, para30, lr3 active, $\varepsilon=1.25$, Df:3 fault condition

Figure 7-132: exp, 10Hz, para10, lr1 inactive, $\varepsilon=0.3$, fault free condition

Figure 7-135: exp, 10Hz, para10, lr1 active, $\varepsilon=0.3$, Df:1 fault condition

Figure 7-133: exp, 10Hz, para10, r2 inactive, $\varepsilon=+0.0001/-0.00025$, fault free condition

Figure 7-136: exp, 10Hz, para10, r2 active, $\varepsilon=+0.0001/-0.00025$, Df:1 fault condition

Figure 7-134: exp, 10Hz, para10, lr3 inactive, $\varepsilon=0.6$, fault free condition

Figure 7-137: exp, 10Hz, para10, lr3 active, $\varepsilon=0.6$, Df:1 fault condition

Figure 7-138: exp, 10Hz, para10, lr1 inactive, $\epsilon=0.3$, imbalance fault condition

Figure 7-141: exp, 10Hz, para10, lr1 active, $\epsilon=0.3$, loose belt fault condition

Figure 7-139: exp, 10Hz, para10, r2 active, $\epsilon=+0.0001/-0.00025$, imbalance fault condition

Figure 7-142: exp, 10Hz, para10, r2 inactive, $\epsilon=+0.0001/-0.00025$, loose belt fault condition

Figure 7-140: exp, 10Hz, para10, lr3 inactive, $\epsilon=0.6$, imbalance fault condition

Figure 7-143: exp, 10Hz, para10, lr3 active, $\epsilon=0.6$, loose belt fault condition

Figure 7-144: exp, 10Hz, para10, lr1 inactive, $\varepsilon=0.3$, Df:2 fault condition

Figure 7-147: exp, 10Hz, para10, lr1 inactive, $\varepsilon=0.3$, Df:3 fault condition

Figure 7-145: exp, 10Hz, para10, r2 negatively active, $\varepsilon=+0.0001/-0.00025$, Df:2 fault condition

Figure 7-148: exp, 10Hz, para10, r2 inactive, $\varepsilon=+0.0001/-0.00025$, Df:3 fault condition

Figure 7-146: exp, 10Hz, para10, lr3 inactive, $\varepsilon=0.6$, Df:2 fault condition

Figure 7-149: exp, 10Hz, para10, lr3 active, $\varepsilon=0.6$, Df:3 fault condition

7.5.3 Reliability of residuals

The reliability of FDI algorithm is very important for its practical implementation. A good FDI algorithm should be able to tell the reliability of the FDI decisions. In this research, the reliability of the residual is estimated by the absolute value of the difference between the residual's actual value and its threshold value, this is called confidence level of residual's status in this research. The bigger the confidence level, the more reliable the residual is.

Table 7-18, Table 7-19, and Table 7-20 summarize the confidence level of residual's status of fault free and various fault conditions during 10Hz, 20Hz and 30Hz shaft speeds. The parameters used are the sets of parameters identified at 10Hz, 20Hz and 30Hz operating speeds respectively.

Table 7-18: Residuals status confidence level, exp, 10Hz, para10

	fault free	imbalance	loose belt	Df:1	Df:2	Df:3
r1	0.25	0.2	0.2	0.7	0.2	0.2
r2	0.00005	0.00005	0.00002	0.0001	0.00002	0.0002
r3	0.4	0.5	0.4	23	0.5	23

Table 7-19: Residuals status confidence level, exp, 20Hz, para 20

	fault free	imbalance	loose belt	Df:1	Df:2	Df:3
r1	0.25	0.15	0.3	0.8	0.22	0.2
r2	0.00025	0.0002	0.0001	0.0002	0.00008	0.0003
r3	0.4	0.3	0.3	45	0.4	45

Table 7-20: Residuals status confidence level, exp, 30Hz, para30

	fault free	imbalance	loose belt	Df:1	Df:2	Df:3
r1	0.325	0.3	0.1	0.8	0.35	0.3
r2	0.0004	0.0006	0.00008	0.0001	0.00008	0.00035
r3	0.7	0.75	0.75	70	0.75	70

To make the reliability of residuals easier to judge, the confidence level is divided by the threshold value of the respective residual, this new value is called normalized confidence level of residual's status. Table 7-21, Table 7-22, and Table 7-23 show the normalized confidence level of residual's status at fault free and various fault conditions during 10Hz, 20Hz, and 30Hz shaft speeds.

Table 7-21: Residuals status normalized confidence level, exp, 10Hz, para10

	fault free	Imbalance	loose belt	Df:1	Df:2	Df:3
r1	0.833	0.667	0.667	2.333	0.667	0.667
r2	0.2	0.5	0.08	1	0.08	0.8
r3	0.667	0.833	0.667	38.333	0.833	38.333

Table 7-22: Residuals status normalized confidence level, exp, 20Hz, para20

	fault free	imbalance	loose belt	Df:1	Df:2	Df:3
r1	0.833	0.5	1	2.667	0.733	0.667
r2	0.833	0.667	0.25	0.667	0.2	0.75
r3	0.8	0.6	0.6	90	0.8	90

Table 7-23: Residuals status normalized confidence level, exp, 30Hz, para30

	fault free	imbalance	loose belt	Df:1	Df:2	Df:3
r1	0.8125	0.75	0.25	2	0.875	0.75
r2	1	1.5	0.2	0.25	0.2	0.875
r3	0.56	0.6	0.6	56	0.6	56

As shown in Table 7-21, residual r_1 and r_3 have good reliability for fault free condition and various fault conditions. The reliability of residual r_2 is relatively low, as it is easy to observe, normalized confidence level of r_2 status for loose belt fault and Df:2 fault is only 0.08. In 10Hz shaft speed operating condition, loose belt fault and Df:2 fault might be prone to false alarm, misdetection or isolation error.

As shown in Table 7-22 and Table 7-23, all the normalized confidence levels of residual's status are good. The normalized confidence level for loose belt fault and Df:2 fault are relatively low compared to those of other faults at both 20Hz and 30Hz shaft speeds. Low reliability of r_2 for the two faults can be the direct cause. But they are still good enough to make a fault detection and isolation decision.

In general, the reliability of the FDI algorithm at higher speed is better than that at lower speed based on the above tables of normalized confidence level of residual's status. This is consistent with the analysis based on simulation results which will be shown later in this section; the residuals are more sensitive to faults at higher operating speed according to simulation, this explains why the reliability is better at higher speed in this experiment.

7.5.4 Remarks on threshold selection

In the proposed approach, it is not possible to determine threshold level during the design stage. Threshold value determination has to be done after simulation or experiment. In other words, simulations or experiments have to be conducted in order to determine a suitable threshold level of each residual. This remains a problem to be solved in future.

In this research, threshold levels are determined after simulations and experiments at fault free conditions and various fault conditions. Residual values at each condition are recorded.

There is one threshold for each residual. A residual is classified into two groups, e.g. supposedly active and supposedly inactive. This classification is done base on fault signature matrix obtained from causal path analysis. Among the group of values when the residual is supposed to be active, the lowest value is selected to represent the group. Among the values when the residual is supposed to be inactive, the highest value is selected to represent that group. The threshold for this particular residual must lie in between the previously mentioned two values, in order words, the threshold must be able to distinguish the two groups.

In order that the above mentioned procedure works, the lowest value of the residual when it is supposed to be active should be higher than the highest value of the same residual when it is supposed to be inactive.

In the simulation, the threshold selection is straight forward. In the experiment, it is difficult to determine residuals r_1 's threshold value. Residual ' r_1 ' is supposed to be active during imbalance fault, however its value is as if it is inactive. This is due to low sensitivity of residual ' r_1 ' to imbalance fault as shown in the simulation results. In order that the threshold will work well for all other situations, r_1 's value during imbalance fault is not considered during threshold selection. With this consideration, the procedure mentioned previously can be used to determine residuals threshold value in the experiment, except that r_1 's status during imbalance fault cannot be reliably determined.

Residual r_2 is bi-directional. The main idea about r_2 's threshold selection is the same; the group of values when the residual is supposed to be active should be distinguishable from the group of values when the residual is supposed to be inactive. ' r_2 ' is bi-directional in the sense that when r_2 is active, it shall be distinguishable whether value of r_2 is positive or negative. There are two threshold values for r_2 , one of them is positive, the other one is negative.

In order to determine the threshold values of r_2 , the values of residual r_2 are classified into three groups, namely inactive group, positively active group and negatively active group. The positive threshold value must be higher than all the values in inactive group and lower than all the values in positively active group; the negative threshold value must be lower than all the values in inactive group and higher than all the values in negatively active group. In this way, the positive and negative threshold of residual r_2 can be determined.

7.5.5 Remarks on residuals sensitivity in relation to operating speed

Table 7-24 summarizes values of each residual at various fault conditions during simulation. We can see that the values of active residuals are proportional to the operating speed of the machinery fault simulator. Keep in mind that the fault simulated, and the parameters used are exactly the same in each operating condition. It is reasonable to say that the residuals sensitivity is proportional to operating speed in this experiment. This also explains the reason why the thresholds used are different when the operating speed changes.

Table 7-24: Active residuals values at various fault conditions and different operating speeds, sim

fault	residual	10Hz	20Hz	30Hz
Df:1	R1	0.6	1.2	1.8
	R2	0.000025	0.0002	0.00075
	R3	24	49	75
Df:2	R2	-0.000027	-0.00022	-0.00078
Df:3	R3	24	49	75
Imbalance	R1	0.000007	0.00005	0.0002
	R2	0.00022	0.0018	0.0065
Loose belt	R1	0.02	0.035	0.065
	R3	0.5	1	1.55

Consistency can be found in experiment also. Sensitivity of residual r_3 to Df:1 and Df:3 faults are proportional to operating speed of the machinery fault simulator in the experiments. This can be known by observing residual r_3 's value at the above mentioned two fault conditions when the shaft is running at 10Hz, 20Hz and 30Hz speed respectively. Residual r_3 's values are shown in Figure 7-71, Figure 7-77, Figure 7-119, Figure 7-131, Figure 7-137 and Figure 7-149. They are summarized in Table 7-25.

Based on causal path analysis done previously, residual r_3 is only depending on parameter TF_1 . Parameter TF_1 does not vary when the operating speed changes. That means there are no uncertain parameters affecting r_3 . Furthermore the sensors fault is simulated by a total loss of sensor signal; this means the amount of fault is the same. The residuals value will well represent the sensitivity to fault. Other residuals are affected by parameter uncertainty in the experiment, and they are not used to show the consistency between experiment and simulation in the relation between residual sensitivity and operating speed.

Table 7-25: Values of residual r_3 during Df:1 and Df:2 fault at different operating speeds, exp

fault	residual	10Hz	20Hz	30Hz
Df:1	R3	24	47	70
Df:3	R3	24	48	72

7.5.6 Comparison with other results

The most commonly used and well established approach to rotating machinery fault diagnosis is data driven approach. Among various data driven approaches, vibration spectrum analysis, operating deflection shape, phase analysis are commonly used methods. It will be meaningful to compare the FDI algorithm developed in this research with those well established methods, to find out what are the advantages and improvement opportunities of bond graph model based approach on rotating machinery fault diagnosis.

Imbalance fault

It is well known in the literature that imbalance fault will produce 1x vibration in the rotating machinery. It is most difficult to do fault detection and isolation when the spectrum analysis reveals high 1x vibration, because there are many faults that lead to 1x vibration. Imbalance fault is diagnosed by eliminating all other possible faults using other techniques, e.g. time-waveform measurement, phase analysis, operating deflection shape, first. If all other faults are not present in the monitored system, the high 1x vibration is caused by imbalance [23].

In the bond graph model based method proposed in this research, diagnosis of imbalance is based on a comparison between measured and calculated 1x vibration amplitude. The same problem is encountered as in data driven approach. For example, when misalignment fault occurs in the machinery fault simulator, the FDI algorithm might mistakenly conclude that imbalance fault has occurred. This wrong decision may happen because misalignment effect is not considered in the model of the machinery fault simulator with which the FDI algorithm is designed based upon, or in other words, the model is imperfect. In practical implementation, it is difficult, if not impossible, to get a perfect model of a complex system, what we can do is to live with the imperfectness of the model and use them with an understanding of their limitations. FDI algorithm designers should keep in mind that there are unknown factors or parameters which may affect the behavior of residuals. It might seem certain that a certain fault signature will indicate a certain fault, but in real life, no one is sure that the model is complete and perfect, things look certain, might not be certain really. In this research, it is assumed that except imbalance fault, all other faults that may produce 1x vibration are not possible to occur in the machinery fault simulator.

Loose belt fault

Only one paper is found on excessive belt slippage fault diagnosis using data driven

approach [22]. The idea is same like that used in the method proposed by this research. The belt transfer ratio is calculated based on the speed at the driving shaft and driven shaft. In the paper mentioned, the driving shaft is controlled at constant speed. The speed of driven shaft is obtained by measuring vibration at the driven shaft bearing. The ball pass frequency is proportional to and is used to calculate the driven shaft speed.

Loose belt fault can be detected and isolated in this experiment. The experiment shows that when loose belt fault occurs, there is slippage between the belt and the wheels, and the belt transfer ratio will change.

When loose belt fault occurs, residual r_2 will deviate away a lot from zero. This is possibly because when the belt becomes loose, the tension in the shaft will change, and this cause the shaft stiffness to change, in other words, this fault will cause other parameters in addition to belt transfer ratio to change when it occurs. The model used in this experiment does not model this aspect, but luckily, this imperfectness can be accommodated by setting the threshold of residual r_2 in such a level when loose belt fault occurs residual r_2 is still considered as inactive. However this will affect the reliability of residual r_2 , because confidence level of active residuals will be reduced.

Sensors fault

Redundant sensors are used to detect sensor failure and provide back up for mission critical systems. Sensors fault diagnosis is normally based on analytical redundancy [24]. Model based approaches, including the method proposed in this research, do have advantage over data driven approach in sensors fault detection and isolation because of its cost saving capability.

In this research, shaft speed encoder (Df:1), laser displacement sensor (Df:2) and minibeam sensor (Df:3) faults can be detected and isolated successfully.

There is an advantage of the proposed FDI algorithm which is worth mentioning. When

minibeam sensor is out of function, the sensor fault can be detected and isolated. The proposed FDI algorithm is able to provide an estimate of the variable that the minibeam sensor is measuring. This will be able to serve as virtual sensor. In fact many other bond variables in diagnostic bond graph can be used as virtual sensors; this is an advantage of bond graph model over other conventional mathematical models. It is because bond graph variables carry real physical meanings.

8 CONCLUSION AND RECOMMENDATION

8.1 Conclusion

A bond graph model of Jeffcott Rotor system with rotational load is developed in this report. This model is built into a diagnostic bond graph for residuals generation for the purpose of fault detection and isolation. Fault signature matrix is obtained through causal path analysis where derivation of analytical redundancy relations equations is not required. Test bed experiment and simulation experiment are performed to verify the proposed fault detection and isolation method, modification to diagnostic bond graph model is made so that fault detection and isolation will not depend on machine's initial conditions. This research serves as the first attempt (to the author's best knowledge) to rotating machinery fault detection and isolation using bond graph model based approach. It is found that

1. Imbalance fault, loose belt fault and sensors' fault can be successfully detected and isolated based on the developed bond graph model and diagnostic bond graph method. The proposed method is able to serve as an alternative to data driven approach of rotating machinery fault detection and isolation, it also opens possibility to overcome limitations of data driven approach which is well established method for rotating machinery fault detection and isolation.
2. Jeffcott rotor bond graph model developed in this report is able to serve as a foundation for rotating machinery modeling using bond graph, it can be conveniently integrated into a bigger system. In other words, the developed Jeffcott rotor bond graph model serves as a basis for bond graph model based fault detection and isolation of rotating machinery whose rotor can be modeled as Jeffcott rotor.

3. Residual's sensitivity to fault plays an important role in reliability of bond graph model based fault detection and isolation. Threshold selection must take residual sensitivity into consideration so as to be able to evaluate residuals status accurately. It is found that residual sensitivity is related to operating condition of the machine in model based approach, this must be considered when selecting thresholds for residuals and when designing adaptive thresholds.
4. Model parameters may change when machine normal operating conditions changes. This is probably due to the imperfectness of model which can be common during practical implementation. This research indicates that parameter uncertainty issue can be solved by forming a parameter look up table for different operating conditions

8.2 Recommendation for future research

Reliability is the key if a fault detection and isolation system wants to make a contribution to cost saving for industry processes. It is never an easy task to design a reliable FDI system. If the FDI is able to tell the reliability of each decision it makes, it will be very helpful in practical implementation although the best is still making the FDI system itself reliable.

Threshold selection is very important for the performance of model based FDI, if a standard procedure can be develop so that the threshold can be reliably determined during the FDI algorithm design stage, model based approach will exhibit obvious advantage over data driven approach.

Figure 8-1 Machinery fault simulator

BIBLIOGRAPHY

- [1] Abdel-Magied M., Loparp K. A., Lin W., (1998), “Fault detection and diagnosis for rotating machinery: a model-based approach”, *Proceedings of the American control conference*, Philadelphia, Pennsylvania, USA, Vol. 6, pp. 3291 – 3296.
- [2] About Bondgraphs - The system modeling world. Retrieved 24th November, 2006, <http://www.bondgraphs.com/about2.html>
- [3] Campos J., Crawford M., Longoria R., (2005), “Rotordynamic modeling using bond graphs: modeling the Jeffcott rotor”, *IEEE transactions on magnetics* , Vol. 41, Issue 1, pp. 274 – 280.
- [4] Ding S. X., (2008), “Model-based fault diagnosis techniques - design schemes, algorithms, and tools”, Springer-Verlag Berlin Heidelberg.
- [5] El-Farra N. H., (2006), “Integrating model-based fault detection and fault-tolerant control of distributed processes”, *Proceedings of American control conference*, Minneapolis, Minnesota, USA, pp. 6014-6019.
- [6] Gawthrop P. J., (2000), “Sensitivity Bond Graphs”, *Journal of the franklin institute* ,Vol. 337, pp. 907-922.
- [7] Gertler J., (1998), “Fault detection and diagnosis in engineering systems”, Marcel Dekker.
- [8] Isermann R., (1984), “Process fault detection based on modeling and estimation methods - a survey”, *Automatica* ,Vol. 20, Issue 4, pp. 387-404.
- [9] Isermann R., Appel W., Freyermuth B., Fuchs A., Janik W., Neumann D., Reiss Th., Wanke P., (1991), “Model based fault diagnosis and supervision of machines and drives”, *Proceedings of the 11th triennial world congress of the international federation of automatic control*, Tallinn, USSR, Vol. 4, pp. 1-12.

- [10] Isermann R., Balle P., (1997), "Trends in the application of model-based fault detection and diagnosis of technical processes", *Control engineering practice*, Vol. 5, Issue 5, pp. 709-719.
- [11] Karnopp D. C., Margolis D. L., Rosenberg R. C., (2006), "System dynamics: modeling and simulation of mechanical systems", Hoboken, N.J.: John Wiley & Sons.
- [12] Lees A.W., et al., (2008), "Model-based identification of rotating machines", *Mechanical systems and signal processing*, doi:10.1016/j.ymssp.2008.08.008
- [13] Mendonsa L. F., Sousa J. M. C., Sa da Costa J. M. G., (2005), "Fault detection and isolation of industrial processes using optimized fuzzy models", *Proceedings of the IEEE international conference on fuzzy systems*, Reno, NV, USA, pp.851-856
- [14] Nejari F., Perez R., Escobet T., (2006), "Diagnosability analysis using quasi-static models", *Proceedings of 32nd annual conference on IEEE industrial electronics*, Paris, France, pp. 529-524.
- [15] Samantaray A. K., Ould Bouamama B., (2008), "Model-based process supervision: a bond graph approach", Springer London.
- [16] Samantaray A. K., Medjaher K., Ould Bouamama B., Staroswiecki M., and Dauphin-Tanguy G., (2006), "Diagnostic bond graphs for online fault detection and isolation", *Simulation modelling practice and theory*, Vol. 14, Issue 3, pp. 237-262.
- [17] Staroswiecki M., (2000), "Qualitative and quantitative models for fault detection and isolation", *Mechanical systems and signal processing*, Vol. 14, Issue 3, pp. 301 - 325.
- [18] Thoma S. J., (1975), "Introduction to bond graphs and their applications", Pergamon Press.
- [19] Vance J. M., (1988), "Rotordynamics of turbomachinery", Wiley-interscience.
- [20] Venkatasubramanian V., Rengaswamy R., Yin K., Kavuri S. N., (2003), "A review of process fault detection and diagnosis, part 1: quantitative model-based methods", *Computers & chemical engineering*, Vol. 27, pp. 293-311.

- [21] Wu X., Meagher J., (2008), “A two-disk extended Jeffcott rotor model distinguishing a shaft crack from other rotating asymmetries”, *International journal of rotating machinery*, Vol. 2008, Article ID 846365, doi:10.1155/2008/846365
- [22] Hajime Y., Susumu O., Isao K., (1996), “Development of a diagnosis technique for failures of V-belt by a cross-spectrum method and a discriminant function approach”, *Journal of intelligent manufacturing*, Vol. 7, pp. 85-93
- [23] A El-Shafei, (2008), “Fan diagnosis in the field”, *Proceedings of ninth international conference on vibrations in rotating machinery*, Vol. 2, University of Exeter, UK, pp. 719-730
- [24] Gary G., Wei F., (2000), “Winner take all expert network for sensor validation”, *Proceedings of the 2000 IEEE international conference on control applications anchorage*, Alaska, USA, pp. 92-97