



IFAC

International Federation of Automatic Control

**FAULT DETECTION,
SUPERVISION AND SAFETY
FOR TECHNICAL PROCESSES**

*IFAC Symposium
Espoo, Finland, 13 – 16 June 1994*

**Edited by
T. RUOKONEN**

Volume 2



PERGAMON

UK	Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK
USA	Elsevier Science Inc., 660 White Plains Road, Tarrytown, New York 10591-5153, USA
JAPAN	Elsevier Science Japan, Tsunashima Building Annex, 3-20-12 Yushima, Bunkyo-ku, Tokyo 113, Japan

Copyright © 1994 IFAC

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means: electronic, electrostatic, magnetic tape, mechanical, photocopying, recording or otherwise, without permission in writing from the copyright holders.

First edition 1994

Library of Congress Cataloging in Publication Data

Fault detection, supervision and safety for technical processes: SAFEPROCESS'94:
IFAC symposium, Helsinki University of Technology, Espoo, Finland, 13-16 June 1994/
edited by T. Ruokonen.

p. cm.

1. Fault location (Engineering)--Congresses. 2. Process control--Reliability--Congresses.

I. Ruokonen, T. (Tuula). II. International Federation of Automatic Control. III. IFAC

Symposium on Fault Detection, Supervision and Safety for Technical Processes (1994:

Helsinki University of Technology)

TA169.6.F37 1994

629.8'028--dc20

94-37925

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 0-08-042222 5

This volume was reproduced by means of the photo-offset process using the manuscripts supplied by the authors of the different papers. The manuscripts have been typed using different typewriters and typefaces. The lay-out, figures and tables of some papers did not agree completely with the standard requirements: consequently the reproduction does not display complete uniformity. To ensure rapid publication this discrepancy could not be changed: nor could the English be checked completely. Therefore, the readers are asked to excuse any deficiencies of this publication which may be due to the above mentioned reasons.

The Editor

Printed in Great Britain

Published and Forthcoming IFAC Postprint Volumes (IPPV)

<u>Title</u>	<u>Editor(s)</u>	<u>ISBN</u>
1993		
Real-Time Programming	Boullart & De La Puente	0 08 041894 5
System Structure and Control	Strejc	0 08 042057 5
Interactions between Process Design and Process Control	Perkins	0 08 042063 X
Intelligent Manufacturing Systems	Judd & Kheir	0 08 042037 0
Algorithms and Architectures for Real-Time Control	Fleming & Kwon	0 08 042050 8
Motion Control for Intelligent Automation	De Carli & Masada	0 08 042058 3
A Cost Effective Use of Computer Aided Technologies and Integration	Kopacek	0 08 042061 3
Methods in Small and Medium Sized Companies		
CIM in Process and Manufacturing Industries	Leiviska	0 08 042182 2
Intelligent Autonomous Vehicles	Chamley	0 08 042223 3
1994		
Modeling and Control in Biomedical Systems	Patterson	0 08 042224 1
Advanced Control of Chemical Processes	Bonvin	0 08 042229 2
Intelligent Components and Instruments for Control Applications	Banyasz & Boromisza	0 08 042234 9
Intelligent Manufacturing Systems	Kopacek	0 08 042235 7
Fault Detection, Supervision and Safety for Technical Processes	Ruokonen	0 08 042222 5
Real Time Programming	Halang	0 08 042372 8
Integration of Process Design and Control	Zafiriou	0 08 042358 2
Identification and System Parameter Estimation	Blanke	0 08 042225 X
Advances in Control Education	Ichikawa & Furuta	0 08 042230 6
Computer Software Structures Integrating AI/KBS Systems in Process Control	Arzen	0 08 042360 4
Transportation Systems: Theory and Application of Advanced Technology	Liu & Blosseville	0 08 042226 8
New Trends in Design of Control Systems	Huba & Mikles	0 08 042367 1
Automatic Control in Aerospace	Schaechter	0 08 042238 1
Robust Control Design	Correa	0 08 042228 4
Robot Control	Sciavicco <i>et al</i>	0 08 042227 6
Integrated Systems Engineering	Johannsen	0 08 042361 2
Distributed Computer Control Systems	de la Puente	0 08 042237 3
Artificial Intelligence in Real Time Control	Crespo & Morant	0 08 042236 5
Safety, Reliability and Application of Emerging Intelligent Control Technologies	Ng & Hung	0 08 042374 4
1995		
Computer Applications in Biotechnology	Kndy sa & .Baselt	0 08 042377 9
Dynamics and Control of Chemical Reactors, Distillation Columns and Batch Processes	Jorgensen	0 08 042368 X
Intelligent Autonomous Vehicles	Haltne & Harris	0 08 042366 3
Adaptive Systems in Control and Signal Processing	Banyasz	0 08 042375 2
Nonlinear Control Systems Design	Krener & Mayne	0 08 042371 X
Analysis, Design and Evaluation of Man-Machine Systems	Sheridan	0 08 042370 1
Modelling and Control of National and Regional Economies	Vlacic <i>et al</i>	0 08 042376 0
System Structure and Control	Guglielmi	0 08 042356 6
Large Scale Systems: Theory and Applications	Roberts & Ellis	0 08 042365 5
Youth Automation	Lei Guo	0 08 042369 8
Intelligent Autonomous Control in Aerospace	Liang Dong Liu	0 08 042373 6
Automation in Mining, Mineral and Metal Processing	Baker & Hulbert	0 08 042364 7
Low Cost automation	Weis & Paiuk	0 08 042239 X
Automated Systems Based on Human Skill	Brandt & Martin	0 08 042379 5
Supplemental Ways for Improving International Stability	Kopacek	0 08 042378 7
Information Control Problems in Manufacturing	Gu	0 08 042380 9
Control of Power Plants and Power Systems	Palomares	0 08 042362 0
IFAC PROCEEDINGS 1994		
12th IFAC Triennial World Congress on Automatic Control (5 vol. set)	Goodwin & Evans	0 08 042211 X

Customers wishing to purchase any of the above volumes and any IFAC Proceedings volume published prior to 1994 should send orders to their regular supplier or their nearest Elsevier Science office listed on the inside back cover of this volume.

IFAC SYMPOSIUM ON FAULT DETECTION, SUPERVISION AND SAFETY FOR TECHNICAL PROCESSES (SAFEPROCESS'94)

Sponsored by
International Federation of Automatic Control (IFAC)
Organized by
Finnish Society of Automation, Helsinki, Finland

International Program Committee

P. Lautala, (FIN) (Chairman)	J. König (D)
P. Albertos (E)	R. Lauber (D)
D. Barschdorff (D)	L. Ljung (S)
A. Benviste (F)	J.F. Magni (F)
M. Blanke (DK)	H. Matsuyama (J)
S. Bologna (I)	J. Morris (UK)
R.N. Clark (USA)	E. O'Shima (J)
S. Daley (UK)	R.J. Patton (UK)
B. Dubuisson (F)	V. Rouhiainen (FIN)
D. Filbert (D)	T. Ruokonen (FIN)
P.M. Frank (D)	G. Stephanopoulos (USA)
J. Gertler (USA)	A. Sturm (D)
A. Halme (FIN)	R. Tavast (ES)
D. Himmelblau (USA)	H. Toivonen (FIN)
R. Isermann (D)	S. Tzafestas (G)
L. Keviczky (H)	P. Uronen (FIN)
U. Kortela (FIN)	D. Wach (D)
M.A. Kramer (USA)	J. Vaurio (FIN)

National Organizing Committee

B. Wahlstrom (Chairman)
A. Halme
L. Hammarstrom
J. Holmberg
J. Jarvi
P. Lautala
T. Ruokonen
L. Vahtera (Secretary)

PREFACE

Fault detection, supervision and safety, being essential part of modern control engineering, are considered both as theoretical and practical problems at this second SAFEPROCESS Symposium, now taking place in Espoo, Finland. The first symposium held in Baden-Baden led the way for this important expert event.

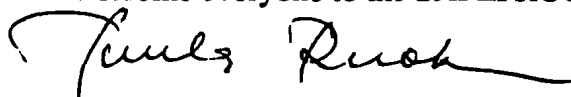
In this publication, some two hundred experts from various fields and application areas have joined forces, presented their latest results and discussed the important questions on reliability, availability and safety of technical processes. These questions are emphasised during all phases of design, start up, operation, maintenance and repair. Reliability, availability and safety imply continuous monitoring, diagnosing and fault detection of processes, sensors, control equipment and actuators. At the symposium, relevant methods and tools are being discussed and compared. Failure data collection and analysis, human factors and man-machine interfaces are increasingly important issues, because the results of the diagnostic systems are used as the basis of the decision making process, involving also important economical decisions.

At this symposium, the program is divided into two main session types: Methods and Applications. Understanding and developing the theory and algorithms are essential, but we have arrived to a point, where applying the methods to real problems and evaluating them is considered to be an important part of developing the methods. Model based methods have many more possibilities in the real practical problems than they so far have proved to have.

Development in this field calls for intense co-operation between researchers and industry: for the researchers to deal with the reality of practical world with noise and undeterministic, partly unknown processes and for the industry to be able to utilize all the possibilities of the modern technology in order to make their plants and equipment more reliable and safe.

The program of SAFEPROCESS '94 Symposium consists of three plenary sessions, 23 technical sessions, 2 special case sessions and one session dealing with a given benchmark problem. Modern maintenance is again included in the program as a discussion session. Altogether the program consists of 133 carefully selected papers, which are presented in parallel sessions.

I am sure all participants will find interesting results in the papers and carry out fruitful discussions with colleagues. On my behalf, I want to welcome everyone to the SAFEPROCESS '94 Symposium.



Tuula Ruokonen
Editor

CONTENTS

PLENARY PAPER

Robust Model-Based Fault Diagnosis: The State of the Art R.J. PATTON	1
---	---

MODEL BASED DIAGNOSIS I

A New Fault Diagnosis Approach in Stochastic Linear Systems J.Y. KELLER, L. CARMELLE, M. DAROUACH, G. KRZAKALA	25
Fault Detection by Continuous Deadbeat Observation A. MEDVEDEV	29
A Survey of Observer Based Residual Generation for FDI V. KRISHNASWAMI, G. RIZZONI	35
Design of Finite-Dimensional Observer-Based Fault Diagnosis for a Class of Distributed Parameter Systems H. RAFARALAHY, M. BOUTAYEB, M. DAROUACH, G. KRZAKALA	41

MODEL BASED DIAGNOSIS II

Simultaneous Detection, Location and Identification of Faults for Dynamic Systems G. BLOCH, D. THEILLIOL, P. THOMAS	47
A Failure Detection Procedure for Bilinear Systems Based on a New Formulation of Unknown Inputs Bilinear Observers C. MECHMECHE, S. NOWAKOWSKI, M. DAROUACH	53
Fault Detection Observers for Systems with Unknown Inputs B. GADDOUNA, D. MAQUIN, J. RAGOT	59

MODEL BASED DIAGNOSIS III

Continuous and Discrete Time Identification for Fault Detection Th. SPROSSER, G.L. GISSINGER	65
Fault Detection/Diagnosis and Controller Reconfiguration in Dynamic Systems JIN JIANG	71
Fault Detection via Continuous-Time Parameter Estimation P. ALBERTOS, A. SALA	77
Fault Diagnosis in the Presence of Parametric Variations M.I. ARSAN, Ph. MOUYON, J.-F. MAGNI	83

Process Diagnosis of Jumping Parameters M. OULADSINE, A. KOBI, J. RAGOT	89
On Line Reconfiguration Strategy of Control Law for Degraded Systems C. AUBRUN, H. NOURA, D. SAUTER	95

APPLICATIONS: POWER PLANTS I

Statistical Diagnostics: A New Integrating Tool for Man-Machine Interfaces E.A. AVERBUKH, O. LESSI, L. OLIVI, P. PARISI	99
Fault Detection in a Control Loop I. MAIRET, M. ROBERT, T. CECCHIN, C. HUMBERT	105
Fault Detection and Diagnosis in a Real Power Plant: A Neural Approach G. GUGLIELMI, T. PARISINI, G. ROSSI, R. ZOPPOLI	111
Condition Monitoring and Diagnosis in Solid Fuel Gasification Process Y. MAJANNE, P. LAUTALA, R. LAPPALAINEN	117

APPLICATIONS: POWER PLANTS II

Long-Term Wear Monitoring and Wear Prediction by Means of Wear Models P. NEUENSCHWANDER, D. MAURER, L. RYCHLICKI	121
An Application of Gross Errors Measurements Detection in Nuclear Power Plants R. DORR, G. MOUROT, F. KRATZ, F. LOISY	127
An Integrated Approach to Fault Detection and Diagnosis in Power Plant J. KORBICZ, D. UCINSKI, A. PIECZYNSKI, G. MARCZEWSKA	133
Analytical and Experimental Investigations for Modelling the Fluid-Structure-Interaction in Annular Gaps G. GRUNWALD, E. ALTSTADT	141
A New Method for Acoustic Leak Detection at Complicated Geometrical Structures G. HESSEL, W. SCHMITT, F.-P. WEISS	147

APPLICATIONS: CHEMICAL PLANTS

Fault Detection of Large Parameter Changes in a Wastewater Plant M.J. FUENTE, P. VEGA, M.B. ZARROP	153
Model-Based Detection on One Particular Information Poor Process Plant J. HOWELL, S.J. SCOTHERN	159
Knowledge-Based Fault Detection and Supervision of Urban Sewer Networks K. SZAFNICKI, D. GRAILLOT, P. VOIGNIER	165
Fault Detection in a Multivariable Chemical Process by Monitoring Process Dynamics J.B. GOMM	171
Fault Detection and Isolation System Design for a Refinery Unit J.P. CASSAR, R. FERHATI, R. WOINET	177
Fault Detection by Using Process Functional States and Temporal Logic Nets A. HALME, A. VISALA, J. SELKAINAHO, J. MANNINEN	183

RELIABILITY AND SAFETY ANALYSIS I

Communicating the Safety Aspects of Industrial Plants K. KAARELA, J. OKSANEN	189
Use of Living PSA and Safety Indicators to Support Operational Safety Management E. LEHTINEN, J. HOLMBERG, K. LAAKSO, A. HOFFSTROM	195
A Qualitative Model-Based Approach to Integrate System and Hazard Analysis X. LAUFENBERG, P. FROHLICH	201

RELIABILITY AND SAFETY ANALYSIS II

Developments in Reliability Data Collection and Analysis J.K. VAURIO	207
Extending Fire PSA of NPP TVO I/II to Instrumentation Systems E. NIKULA, R. HIMANEN	213
Reliability-Directed Computer-Aided Design of Engineering Devices O.V. ABRAMOV, K.S. KATUYEV	219
Fault Tolerant Specification of Discrete Events J. PIK	223
A Practical Dependability Measure for Degradable Computer Systems with Non-exponential Degradation E. JONSSON, M. ANDERSSON, S. ASMUSSEN	227
Current State and Approaches to Further Development of Methods for Human Factors in Probabilistic Safety Assessments H.-P. BERG, H. SCHOTT	235

ROBUST METHODS

Robust Fault Detection and Isolation in Nonlinear Systems A. ZHIRABOK, O. PREOBRAZHENSKA	241
Robust FDI Systems and H_2 -Optimization-Tall Fault Systems and Example ZIYANG QIU, J. GERTLER	247
Modeling Errors as Unknown Inputs J. GERTLER	253
Fault Detection of an Industrial Actuator Benchmark R.W. GRAINGER, J. HOLST, A.J. ISAKSSON, B.M. NINNESS	259

PLENARY PAPER

Safety of Nuclear Power: Who Learns from whom? B. WAHLSTROM, P. HAAPANEN, K. LAAKSO, U. PULKKINEN	265
--	-----

MODEL BASED DIAGNOSIS IV

Holistic Modelling as a Tool for the Diagnosis of Critical Complex Systems H.G. NATKE, C. CEMPEL	275
---	-----

Non-Probabilistic Reliability of Mechanical Systems YAKOV BEN-HAIM	281
Natural Redundancy and Fault Detection and Isolation in Dynamic Systems A.N. ZHIRABOK	287
A Fault Detection Method for a Nonlinear System and its Application to a Hydraulic Test Rig DINGLI YU, D.N. SHIELDS	293
On-Line Diagnosis of Dynamic-Stochastic Systems I.V. NIKIFOROV	299
Nonlinear Parity Equation Residual Generation for Fault Detection and Isolation V. KRISHNASWAMI, G. RIZZONI	305

MODEL BASED DIAGNOSIS V

Fault Detection for Sequentially Controlled Machines Using Temporal Constraint Nets M. MINAS	311
Fault Detection of Dynamical Systems with Nonstationary Inputs Th.D. POPESCU	317
Fault Detection-Location in Robots Using a Scheme of Observers F. NOUREDDINE, M.S. LAZEREGUE, D. NOYES	323

FUZZY AND KNOWLEDGE BASED METHODS

Causal Graphs for Model-Based Diagnosis J. MONTMAIN, L. LEYVAL	329
Approximate Reasoning Approaches for Diagnostic Decision M. ULIERU	339
A Methodology for Knowledge Acquisition and Reasoning about Faults in Conditions of Incomplete Information J. GRUNDSPENKIS	345
The Improvement of Fault Diagnosis Algorithm Using Signed Directed Graph K. TAKEDA, B. SHIBATA, Y. TSUGE, H. MATSUYAMA	351
Fault Diagnosis Based on Linguistic Equations Framework E.K. JUUSO	357
Advanced Design of the Decision Procedure in Failure Detection and Isolation Systems J.P. CASSAR, M. STAROSWIECKI	363

APPLICATIONS: COMBUSTION ENGINES

Fuzzy Classification of Internal Combustion Engine Faults Based on Neural Network HUA DENG, XIANG YUAN, YIFU WU	369
Monitoring the Combustion Set of a Gas Turbine M. BASSEVILLE, A. BENVENISTE, G. MATHIS, Q. ZHANG	375
Diagnosis of Exhaust Emissions Control Systems During the E.P.A. Tailpipe Inspection Program V. KRISHNASWAMI, GUAN CHUN-LUH, G. RIZZONI	381

Real Time Supervision for Diesel Engine Injection C. LUDWIG, S. LEONHARDT, M. AYOUBI	387
---	-----

SPECIAL CASE PAPER

Model-Based Diagnosis of Automotive Engines - Case Study on a Physical Vehicle J. GERTLER, M. COSTIN	393
---	-----

APPLICATIONS: COMPONENTS I

A Low Cost Tool for Diagnosis of Antifriction Bearings A. SEELIGER, B. GEROPP, H.-W. KESSLER	403
Fault Diagnosis for Robots T. SIEDLER	405
Automatic Supervision of Control Valves T. HAGGLUND	411
Model Based Fault Detection of Valves in Flow Control Loops R. DEIBERT	417

APPLICATIONS: COMPONENTS II

Sensor Fault Detection and Isolation on a Pilot Heat Exchanger X. SIMONART, M. KINNAERT	423
A SEVA Sensor - The Coriolis Mass Flow Meter M.P. HENRY	429
Fault Diagnosis and Wear Detection in the Control Loop of a Milling Machine H. NOLZEN	435
Fault Detection and Dynamic Behaviour of Pneumatic Valves G. BELFORTE, M. VELARDOCCHIA	441
A Rule- and Case-Based Hybrid System for Rotating Machinery Diagnosis Y. DING, D. WACH	447
Tool Wear Monitoring and Diagnosis in Milling Using Vibration Signal S. ZIEBA, M. SIDAHMED, B. DUBUISSON	451

BENCHMARK

Diesel Engine Actuator Fault Isolation Using Multiple Models Hypothesis Tests S.B. NIELSEN	457
Fault Detection and Isolation Using Eigenstructure Assignment R.B. JORGENSEN, R. PATTON, J. CHEN	463
Fault Detection for Diesel Engine Actuator - a Benchmark for FDI M. BLANKE, S.B. NIELSEN, R.B. JORGENSEN, R. PATTON	471
FDI by Extended Kalman Filter Parameter Estimation for the Industrial Actuator Benchmark B.K. WALKER, KUANG-YANG HUANG	481

Frequency Domain Approach to Residual Generation at the Industrial Actuator Benchmark Test E. ALCORTA GARCIA, B. KOPPEN-SELIGER, P.M. FRANK	489
Industrial Actuator Benchmark Test - A Systematic Approach to an Optimal FDI Th. HOFLING, Th. PFEUFER, R. DIEBERT, R. ISERMANN	495
Robust Fault Detection Based on Factorization Approach Y.X. YAO, J. SCHAEFERS, M. DAROUACH	501

SPECIAL CASE PAPER

Application of Fuzzy Logic to Process Supervision and Fault Diagnosis P.M. FRANK	507
---	-----

COMPARISON OF DIAGNOSIS METHODS

Detection of Additive and Multiplicative Faults - Parity Space vs. Parameter Estimation Th. HOFLING, Th. PFEUFER	515
FDI Residual Generators - A Comparison D. VAN SCHRICK	521
A Comparison of Fault Detection Filters Using Multiple Inputs, Parallel Observers and Residual Processing K.F. MARTIN, M. MOAVENIAN	527
Comparison of Observer-based Fault Detection Approaches X. DING, P.M. FRANK	533

CASE: INVERTED PENDULUM

Fault Detection and Isolation in Mechanical Systems Using Adaptive Friction Compensation D. SAUTER, C. FONTE, H. NOURA	539
Comparison of FDI-Methods at the Inverted Pendulum B. KOPPEN-SELIGER, Th. SPROSSER, P.M. FRANK, G.L. GISSINGER	545
Exponential Observer Based Fault Detection and Correction Method Applied to an Inverted Pendulum S. NOWAKOWSKI, M. BOUTAYEB, M. DAROUACH	551
Identification Based Sensor Fault Detection and Localisation. Application to an Inverted Pendulum Th. SPROSSER, G.L. GISSINGER	555
Comparison of the Data Reconciliation and Finite Memory Observer at the Inverted Pendulum S. BOUSGHIRI, F. KRATZ, J. RAGOT	561
A Re-Examination of Fault Detectability and Isolability in Linear Dynamic Systems JIE CHEN, R.J. PATTON	567

PLENARY PAPER

Integration of Fault Detection and Diagnosis Methods R. ISERMANN	575
---	-----

NEURAL NETWORKS

Using Neural Networks in Nuclear Power Plants for State Diagnosis J.P. BONFERT	591
Fault Diagnosis with Dynamic Neural Structure and Application to a Turbocharger M. AYOUBI	597
Application of a Neural Network to Condition Monitoring and Fault Diagnosis in a Pressure System T. JUUMA, R. PARKKINEN	603
Incipient Fault Detection in Rotating Machinery by Using Artificial Neural Networks N.M. ROEHL, C.E. PEDREIRA, M.S. FIALHO	611
A Neural Network Approach to the Detection and Diagnosis of Faults in a Hydraulic Test Rig S. DALEY, H. WANG	617

SUPPORT SYSTEMS

Diagnosing Faults Co-operatively and in Context M. HOLLENDER	623
Sextant: An Interpretation System for Continuous Processes B. LUCAS, J.M. EVRARD, J.P. LORRE	629
The Integration of Fault Detection within Plant-wide Data Quality Management M.P. HENRY	635
A Multi-Model Approach to Operative Fault Diagnosis of Mechatronic Systems M. KURKI	641
An Expert Knowledge Oriented Approach for the Evaluation of the Man-Machine Interface O. STRATER	647

MAINTENANCE

Optimum Replacement and Maintenance Decisions for Marine Systems with Deterministic Markovian Deterioration and Capital Rationing Constraints B. INOZU, N. KARABAKAL	653
Application of RCM for Industrial SME's in Foundry Sector D. RICHET, N. COTAINA, M. GABRIEL, K. O'REILLY	659
An Overall Machine Monitoring and Maintenance Management System M. STREICHFUSS, P. BURGWINKEL	665
Condition-Based Maintenance of Electrical Power Installations A. STURM, H.-J. PETERS	671

APPLICATIONS: ELECTRIC MOTORS

A Total Least Squares Approach of Pattern Recognition for Model Based Fault Detection T. MARCU, M. VOICU	677
Structured Generation of Analytical Redundancy Relations for the Detection of Control Loop Failures C.S. BERENDSEN, J.P. CASSAR, G. CHAMPENOIS, M. STAROSWIECKI	683

Fault Diagnosis on Bearings of Electric Motors by Estimating the Current Spectrum D. FILBERT, C. GUHMANN	689
Unsupervised Classification of Universal Motors Using Modern Clustering Algorithms K. ROPKE, D. FILBERT	695
Parameter Estimation and Residual Analysis: A Comparison C. SCHNEIDER, D. FILBERT	701
Simulation Environment - A Tool for Analysis and Design of a System for Fault Detection and Diagnosis M. RAK, E. KRASEVEC, D. JURICIC	707

SYSTEMS AND INSTRUMENTS I

Optimal Allocation of Sensors for Fault Diagnosis System Using the Signed Directed Graph S. TATENO, B. SHIBATA, Y. TSUGE, H. MATSUYAMA	713
Fault Detection and Bond Graph Modeling M. VERGE, D. JAUME	719
Observability Analysis and Sensor Placement D. MAQUIN, M. LUONG, J. RAGOT	725
Toward an Intelligent Evolutionary Signal Processing Based Failure Monitoring and Diagnostic System for Complex Plants L. KEVICZKY, J. BOKOR, A. SOUMELIDIS, A. EDELMAYER, P. GASPAR, Zs. CSAKI, E. VARGA	731
Classification and Placement of Measurements Through LP/MIP Algorithms P.J. IMMONEN	737

SYSTEMS AND INSTRUMENTS II

The Methods for Ensuring Fault-Tolerance of Distributed Control Systems E. TOUROUTA	743
Two Strategies for Improved Availability in Partitioned Computerized Systems A. ADLEMO, S.-A. ANDREASSON	749
An Alarm Processing System Using Distributed Artificial Intelligence Techniques K. KHOUALDI, M. DUMAS	755
The 'Diag' System for Fault Detection and Isolation in Industrial Processes J.M. KOSCIELNY, D. SEDZIAK, A. SIKORA	761
A Fuzzy Diagnosis Process to Detect Evolutions of a Car Driver's Behavior M.-A. PELTIER, B. DUBUISSON	767
Model-based Performance Monitoring of Process Equipment in an Automation System J. HARTIKAINEN	773
Author Index	777

A LOW COST TOOL FOR DIAGNOSIS OF ANTIFRICTION BEARINGS

A. SEELIGER*, B. GEROPP* and H.-W. KESSLER*

**RWTH Aachen, Institut für Bergwerks- und Hüttenmaschinenkunde (IBH),
Wüllnerstraße 2, 52062 Aachen, Germany*

Abstract. Sound conducted through solids has been used to diagnose failures of machines for a long time. Many companies offer expensive equipment to measure and analyze vibrations. Faults in antifriction bearings can be detected at an early stage of failure using this equipment. In this paper the effect of faults in antifriction bearings on signal analysis methods will be discussed. The results lead to a new tool for low cost diagnostic equipment which is based on enveloped signals and uses a low cost acceleration sensor.

Key Words. Acceleration measurement, Vibration measurement, Sensors, Envelope analysis, Bearing diagnosis

1. EFFECTS OF DAMAGED BEARINGS ON VIBRATION SIGNALS

If the rotational speed has a constant value, pittings on the path of rolling or on the roll bodies of bearings are periodically run down. Each of these run downs excites resonances of machine parts adjoining the damaged bearing (Fig.1).

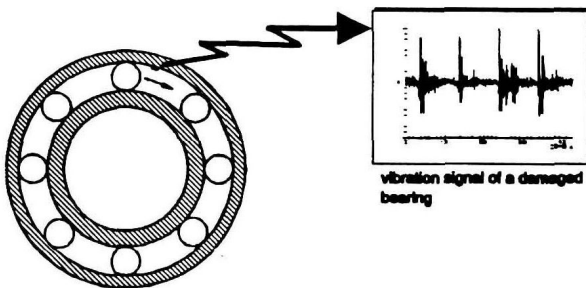


Fig.1 Run down of an outer race defect

The adjoined machine parts can be described by a simplified mechanical system [see McFadden (1984), Su (1992)]. The impulse excitations represent an interference term in the dynamical equation of this system. The solution of the dynamical equation shows that periodic impulse excitations lead to a kind of amplitude modulation of the resonance frequencies. The resonance frequencies may be considered as the carrier frequencies and the run down frequency as the modulation frequency.

2. SIGNAL ANALYSIS TECHNIQUES

Based on these concepts, vibration data was simulated on a personal computer and examined by several techniques of signal analysis. In particular, the techniques of spectrum and cepstrum analysis, autocorrelation and enveloping were assessed. Envelope techniques turned out to give the best results for diagnosis of amplitude modulations, not only with simulated data, but also with real data. Especially if the vibration signal of the bearing is strongly disturbed by other vibration sources, a reliable bearing failure detection is only possible by analysing the spectrum of the enveloped vibration signal (Fig.2).

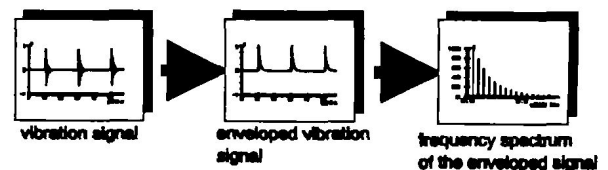


Fig.2 Envelope analysis

3. LOW COST ACCELERATION SENSOR

For failure detection of antifriction bearings some companies offer monitoring systems working with vibration analysis using envelope techniques [see Comes (1991)]. Especially if many bearings have to be diagnosed these systems are quite expensive because an expensive acceleration sensor is needed for each measuring point. Acceleration sensors,

commonly employed for vibration analysis, are usually used in a frequency range where they have a very linear frequency response characteristic. This linearity is necessary for reliable spectrum analysis [see Serridge (1986)].

Detonation detectors are accelerometers which are usually used in cars. They act as a part of a control device which regulates the combustion process of the engine. Due to the high number of units *detonation detectors* are offered at a unit price of below US \$ 20. Compared to *detonation detectors*, conventional accelerometers for failure detection cost at least US \$300 per unit.

The frequency response characteristic of *detonation detectors* is very nonlinear. This is the reason why they are used for detecting shocks but not for precise spectrum analysis. However, the envelope spectrum of *detonation detectors* is nearly the same as the envelope spectrum of common acceleration sensors. The nonlinearity of the *detonation detector* has only a small influence upon the envelope signal, because the periodic repetition of the resonance excitations forms the enveloping signal and not the resonance frequencies themselves. In terms of modulation: the modulation signals (in our case the run down frequencies) are important, not the carrier signals (in our case the resonance frequencies).

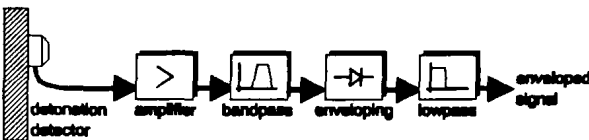


Fig.3 Low cost sensor system: dtect

At the 'Institut für Bergwerks- und Hüttenmaschinenkunde (IBH), Aachen University, a processing unit was developed for the proper enveloping of the *detonation detector's* output signal. This very low price sensor system is called dtect (Fig.3) and has demonstrated its ability for reliable bearing diagnosis in several fields of application. Patent is pending.

4. A LOW COST TOOL FOR BEARING DIAGNOSIS

For reliable diagnosis of machines, it is advisable to measure the vibration of the machine with a permanently mounted sensor. The dtect sensor allows a low cost diagnosis of machines regarding bearing failures. It is now a reasonable proposition to monitor plants with a lot of measuring points.

For easy monitoring, a characteristic value for bearing diagnosis, called *LdZ* (Lager-diagnose-

kennwert zur Zustandsüberwachung), has been developed at the IBH. By checking the *LdZ*-value and evaluating the trend of the value it is possible to diagnose defects of bearings even at an early stage of failure. In contrast to known characteristic values such as Spike Energy, *SPM* or *BCU*, the *LdZ*-value works properly even at very low speeds of revolution.

It should be stressed that monitoring systems using only characteristic values do not lead to a reliable failure detection. In cases where these values increase, a further analysing is necessary. It is strongly recommended that spectrum analysis of the enveloped signal is carried out to determine the precise cause of the characteristic value increase. Only with such additional analysing it is possible to decide if a bearing failure has occurred or if some other factor caused the change of the characteristic value.

5. FUTURE DEVELOPMENTS

At the IBH a monitoring system for bearing diagnosis is being developed, which may use as many as 256 *dtect* sensors. The system is PC based and it is able to automatically diagnose machines with the help of an expert system based on a Neural Network.

6. REFERENCES

- Comes, K., Thureau, M.(1991). Lagerschäden vermeiden durch Überwachung der Wälzlager während des Betriebs *Wälzlagertechnik Industrietechnik (FAG) 1991 - 502*
- McFadden, P.D., Smith J.D. (1984). Model for the vibration produced by a single point defect in a rolling bearing" *Journal of Sound and Vibration* 96 (1), p.69-82
- Serridge, M., Licht, T.R. (1986). Piezoelectric Accelerometers and Vibration Preamplifiers, Theory and Application Handbook *Brüel & Kjaer*
- Su, Y.-T., Lin, S.-J. (1992). On initial fault detection of a tapered roller bearing: frequency domain analysis *Journal of Sound and Vibration* 155 (1), p.75-84

Fault Diagnosis for Robots

T. Siedler

Stockumer Str. 430, D-44227 Dortmund, GERMANY

Abstract: This paper presents a comprehensive fault diagnosis system for robots. The basic idea is a real time supervision of the robot simultaneously in time, frequency and parameter domain. In time domain a set of nonlinear equations is used to describe the dynamic behavior of the robot. In every joint each measured sensor signal is calculated from all other measured sensor signals. Due to this, for every measured sensor signal several independently signals of the same signal type are available for generation of residuals.

Key Words. Failure detection, Industrial robots, Nonlinear system, Frequency domain, Time domain, Parameter estimation, Parameter optimization

1. INTRODUCTION

Diagnosis of faults in automated processes using analytical redundancy has become a field of increasing interest. Especially fault diagnosis in universal handling machines as robots gain more and more importance due to increasing complexity in modern plants and increasing safety requirements.

The most fault diagnosis systems use Kalman filters or system state observers. For a theoretical background the interested reader is referred to survey papers of Gertler (1991) and Isermann (1991).

In this paper a nonlinear calculation approach for fault detection and isolation in robots is presented. Here a preprocessing and a knowledge based parts are working together to find the diagnoses. The preprocessing part receives the native sensor signals from the robot control and performs signal processing operations in time, frequency and parameter domain in real time. If the actual state of the robot differs from the calculated fault free state in any of the domains, the appropriate symptoms are activated and send to the knowledge based part. Here the symptoms are automatically written into the knowledge base and the inference machine starts checking the diagnosis and hypothesis rules. Any information from the robot control and the diagnosis system is displayed on the window based user interface.

2. PREPROCESSING PART

2.1. Time Domain

The calculation of the sensor signals of a robot requires a description of his dynamic behavior by a set of *equations of motion*. The equations of motion describe the dynamic response of the robot to input joint torques. This relationship is expressed by a set of nonlinear differential

equations, which includes the coupling forces and torques between the links. The derivation of the equations of motion is described in Asada (1986).

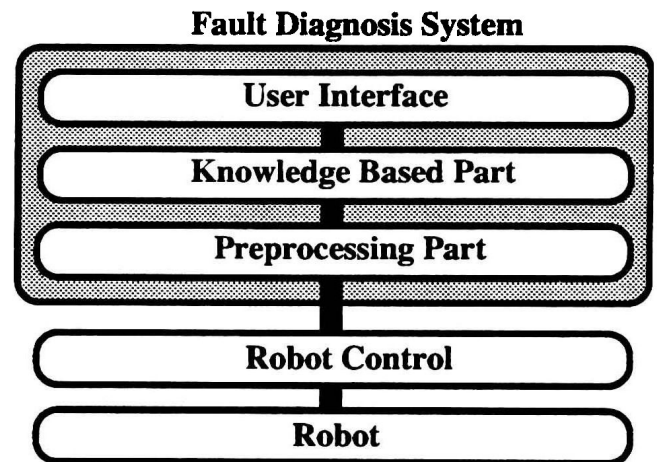


Fig. 1. Structure of the fault diagnosis system for robots.

$$\mathbf{M}\ddot{\mathbf{q}} = \mathbf{Q}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{M}_{CoCe}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{M}_G(\mathbf{q}) + \mathbf{M}_F(\dot{\mathbf{q}}, \mathbf{q}) \quad (1)$$

with \mathbf{M}_M : Joint actuator torque vector

\mathbf{Q} : Inertia matrix

\mathbf{q} : Joint gear box temperature

\mathbf{M}_{CoCe} : Coriolis and centrifugal torques

\mathbf{M}_G : Gravity torques

\mathbf{M}_F : Friction torques (Coulomb and Stokes)

The motor torque is simply described by the motor current I_M and the motor constant K_M . Solving equation (1) for the joint acceleration $\ddot{\mathbf{q}}$ leads to

$$\ddot{\mathbf{q}} = \mathbf{Q}^{-1}(\mathbf{q})[\mathbf{K}_M \mathbf{I}_M - \mathbf{M}_{CoCe}(\mathbf{q}, \dot{\mathbf{q}}) - \mathbf{M}_G(\mathbf{q}) - \mathbf{M}_F(\dot{\mathbf{q}}, \mathbf{q})] \quad (2)$$

Joint speed and joint position are the integrated joint acceleration:

$$\dot{q} = \int \ddot{q} \, dt + \dot{q}_0, \quad q = \int \dot{q} \, dt + q_0 \tag{3), (4)}$$

Calculation methods have a high degree of inherent robustness due to the important fact, that no feedback exists. This is the main advantage of the calculation method to all other nonlinear fault detection and isolation methods.

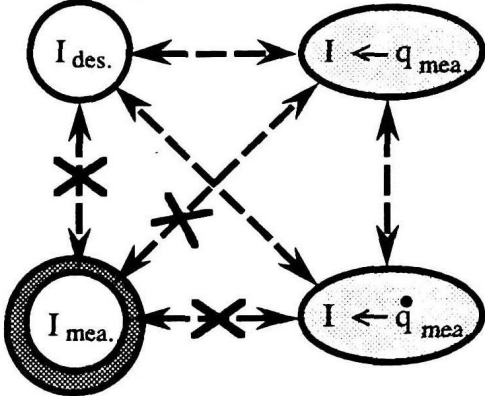
Depending on the sensor configuration with a motor current, a joint speed and a joint position sensor in each joint six independent models for each joint can be distinguished:

- Joint actuator model:
Calculation of the joint speed from the measured motor current with the numerically solved equation (2) and equations (3) and (4). The calculated joint position is used to calculate the coupling terms in equation (2).
- Joint drive model:
Calculation of the joint position from the measured motor current with the numerically solved equation (2) and equations (3) and (4).
- Joint gear model:
Calculation of the joint position from the measured joint speed with equation (4).
- Inverse joint gear model:
Calculation of the joint speed from the measured joint position with the inverse of equation (4).
- Inverse joint model:
Calculation of the motor current from the measured joint position with the inverse of equations (3) and (4) and equation (1).
- Inverse joint actuator model:
Calculation of the motor current from the measured joint speed with the inverse of equation (3) and equation (1).

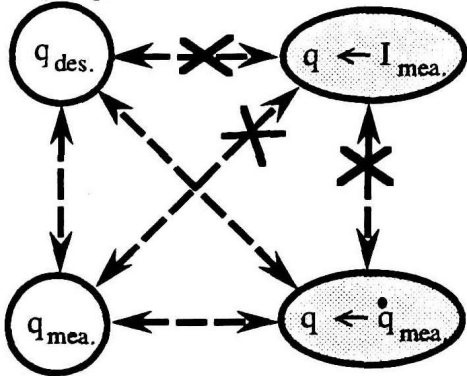
If a sensor configuration with an additional sensor for joint acceleration is used, the number of independent models increases to twelve. Other types of sensor configurations are build by using more than one sensor of the same type (e.g., two joint position and one motor current sensors). These configurations are easy to integrate into the presented fault diagnosis system because for all types of sensors the calculation functions are already implemented. Merely simple extensions to the residual functions are necessary to integrate the additional calculation signals. In the following paragraphs an extended standard sensor configuration of one motor current, one joint speed and one joint position sensor in each joint is discussed.

All the symptoms are activated if the related residual, which is the difference between the calculated and the measured signal, exceeds a predetermined threshold. For an illustration of the residual generation an example with an assumed fault in the motor current sensor is shown in Fig. 2 with the residuals in all signal groups.

Motor current group:



Joint speed group:



Joint position group:

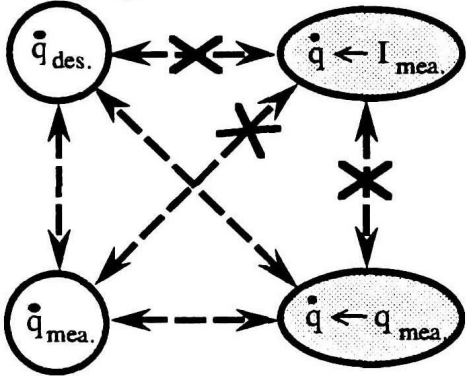


Fig. 2. Residuals for a fault in a motor current sensor using a sensor configuration of one motor current, one joint speed and one joint position sensor.

The residuals are shown as a dashed line with arrows on both ends. The discussed sensor configuration has eighteen residuals and therefore eighteen symptoms defined in each