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

Sponsored by
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Organized by
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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

MODEL BASED DIAGNOSIS I

MODEL BASED DIAGNOSIS II

MODEL BASED DIAGNOSIS III

APPLICATIONS: POWER PLANTS I

APPLICATIONS: POWER PLANTS II

APPLICATIONS: CHEMICAL PLANTS

RELIABILITY AND SAFETY ANALYSIS I

RELIABILITY AND SAFETY ANALYSIS II

ROBUST METHODS

PLENARY PAPER

MODEL BASED DIAGNOSIS IV

SPECIAL CASE PAPER

APPLICATIONS: COMPONENTS I

APPLICATIONS: COMPONENTS II

BENCHMARK

SPECIAL CASE PAPER

COMPARISON OF DIAGNOSIS METHODS

CASE: INVERTED PENDULUM

PLENARY PAPER

NEURAL NETWORKS

SUPPORT SYSTEMS

MAINTENANCE

APPLICATIONS: ELECTRIC MOTORS

SYSTEMS AND INSTRUMENTS I

SYSTEMS AND INSTRUMENTS II

A LOW COST TOOL FOR DIAGNOSIS OF ANTIFRICTION BEARINGS

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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 analyse 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).

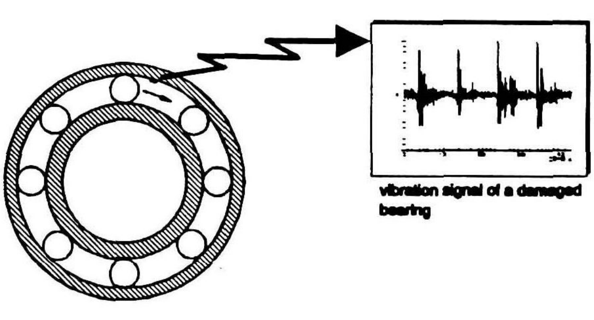

Fig.1 Run down of an outer race defect

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).

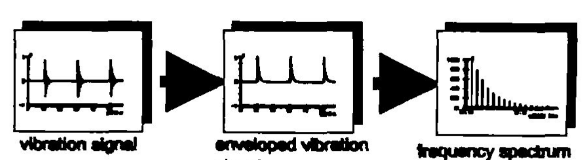

Fig.2 Envelope analysis

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 themself. 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).

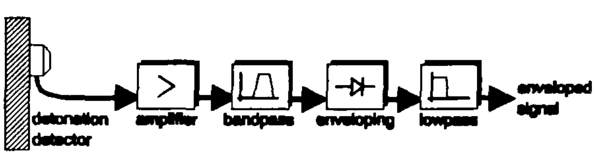

Fig.3 Low cost sensor system: dtect

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-diagnosekennwert 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 occured 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.

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Fault Diagnosis for Robots

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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).

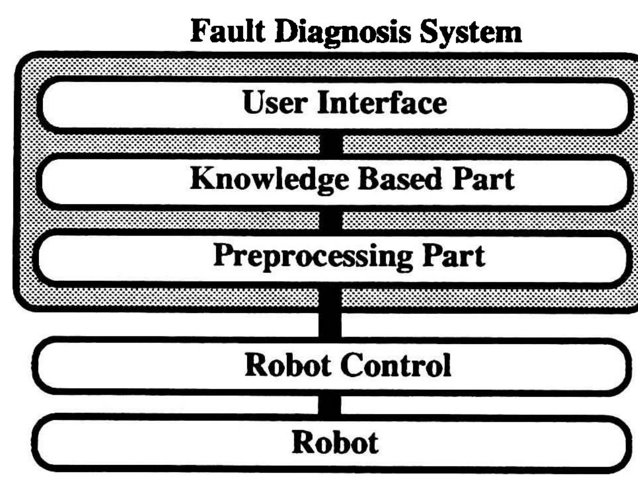

Fig. 1. Structure of the fault diagnosis system for robots.

$$\underline{M}_M = \underline{\Theta}(\underline{q})\,\ddot{\underline{q}} + \underline{M}_{CoCe}(\underline{q}, \dot{\underline{q}}) + \underline{M}_G(\underline{q}) + \underline{M}_F(\dot{\underline{q}}, \underline{\vartheta}) \quad (1)$$

with $\underline{M}_M$: Joint actuator torque vector
$\underline{\Theta}$: Inertia matrix
$\underline{\vartheta}$: Joint gear box temperature
$\underline{M}_{CoCe}$: Coriolis and centrifugal torques
$\underline{M}_G$: Gravity torques
$\underline{M}_F$: 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 $\ddot{\underline{q}}$ leads to

$$\ddot{\underline{q}} = \underline{\Theta}^{-1}(\underline{q})\left[K_M I_M - \underline{M}_{CoCe}(\underline{q},\dot{\underline{q}}) - \underline{M}_G(\underline{q}) - \underline{M}_F(\dot{\underline{q}},\underline{\vartheta})\right] \quad (2)$$

Joint speed and joint position are the integrated joint acceleration:

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

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.

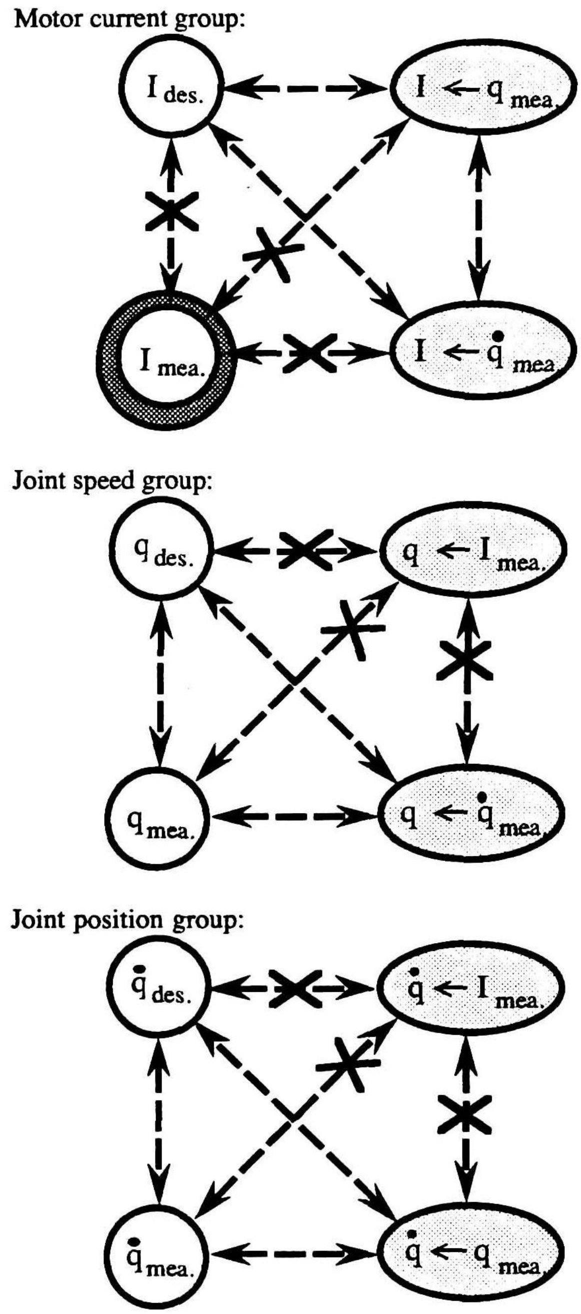

Fig. 2. Residuals for a fault in a motor current sensor using a sensor configuration of one motor current, one joint speed and one joint position sensor.

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