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Fault Detection and Diagnosis in Chemical and Petrochemical Processes

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PREFACE

Today, plants in the chemical and petrochemical industry are becoming larger and more complex. Corollaries of this trend imply that each hour of down time is more expensive, and that the source of a malfunction or fault is more difficult to locate. As industrial systems enlarge, the total amount of energy and material being handled increases, making early and correct fault detection and diagnosis imperative both from the viewpoint of plant safety as well as reduced manufacturing costs. The purpose of monitoring for faults is to reduce the occurrence of sudden, disruptive, or dangerous outages, equipment damage, and personnel accidents, and to assist in the operation of the maintenance program. Although the pressures for greater safety and reduced costs may superficially seem to create a conflict, more careful thought indicates that such is not the case.

The objective of this book is to present the analytical background and practical techniques of fault detection and diagnosis for practicing engineers. Some of the techniques have sound credentials. Others are more speculative but seem to have potential. Most of the literature on fault and failure detection seems to have little adequate analytical framework for the assessment of malfunction monitoring in the face of the uncertainty in measurements. My intention has been to present those quantitative aspects of theory that have proved useful in an engineering environment. Thus, rather than summarize the literature on applications to machinery and instrumentation, I have indicated how decisions are made, and have illustrated the procedures with examples involving chemical plant applications. The book has not been formulated as a textbook, for homework problems have been omitted, but it can be used as such if the instructor provides homework and examples.

With this goal in mind, there was some question as to how to organize the book. What developed is as follows. Background material is presented in the first three chapters followed by four chapters of techniques. The techniques in Chapter 4 pertain to process control charts, those in Chapter 5 to estimation of process variables and coefficients, those in Chapter 6 to pattern recognition, and Chapter 7 treats logical diagrams for fault and failure analysis. If your interest in fault detection focuses on a particular type of equipment, such as a heat exchanger, rather than a technique, then the subject index should be consulted, as one type of equipment may by analyzed in several ways.

Fault detection and diagnosis can be applied at many stages:

(1) detection of an incipient fault;

(2) early detection of an abnormal state;

(3) real time determination of the causes of a malfunction;

(4) prediction of the process trend toward abnormality;

(5) selection of a suitable course of action to take to rectify the abnormal state;

(6) post-failure diagnosis of the cause of failure.

Only the first four applications are treated here. Safety, reliability, and redundant systems are not discussed to any extent.

So many people have assisted in the preparation of this volume that it is difficult to thank each of them individually. To those who have provided examples of practical applications, I am most indebted. Such contributions have been cited individually in the examples.

D.M.H.

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CONTENTS

CHAPTER 1

INTRODUCTION

This chapter describes some of the purposes, objectives, and techniques of fault detection and diagnosis in a chemical plant, and indicates what types of faults might be experienced. It goes on to examine the design of systems for fault detection including the type of tests made and the role of the operator and the computer in both detection and diagnosis.

1.1 PURPOSES AND OBJECTIVES OF FAULT DETECTION AND DIAGNOSIS

Malfunctions of plant equipment and instrumentation increase the operating costs of any plant. Even more serious are the consequences of a gross accident, such as an explosion, because of faulty design or operation.

Chemical plants today are characterized by

(1) complex processes and equipment;

(2) high throughput;

(3) long sequential process trains with considerable recycle;

(4) high performance equipment;

(5) complex controls and instrumentation that compensate for and conceal faults;

(6) serious consequences for a catastrophic accident.

These features lead to a high cost of downtime. Operational reliability calls for expensive programs of maintenance as well as more reliable, and hence, more expensive, equipment. Any system of fault detection that permits the use of less expensive equipment, increases unit availability, and/or reduces maintenance costs merits serious attention. Thus, the detection and analysis of faults in process equipment are of definite economic significance in both the design and operation of a plant.

The degree of difficulty of fault detection and diagnosis depends very much on the nature of the fault. Complete malfunction of a piece of equipment is usually relatively easy to detect, but by the time it has occurred, considerable damage may have taken place. Detection of incipient or latent malfunctions, or process degradation, is more difficult, hence it is the focus of attention in this book. Some objectives of early detection of malfunctions include the prevention of sudden failure of equipment, the collection of higher-grade information on malfunctions, the improved planning of maintenance, and the achievement of more highly automated plants.

Malfunction detection is very relevant from the viewpoint of reliability engineering. Failures of instruments and key auxillary equipment, such as pumps or compressors, often can be prevented if the early signs of impending breakdown are recognized. The statistical approach to plant reliability usually assumes that an instrument or piece of equipment either works, or fails outright, in which case it is then replaced or repaired. With this assumption quite high reliabilities can be obtained. But computations become meaningless if an instrument incurs a fault which is allowed to go on undetected for a long period of time. This type of situation can very easily lead to a catastropic failure.

Malfunction detection and subsequent diagnosis also is of particular significance in computer control itself. Completion of a mass balance, or sequential optimization, requires functioning not only of the data collection system, but also of the process equipment if control algorithms are to be valid. The detection of incipient failures should initiate action to improve instrumentation and instrument maintenance as well as organize control systems so that they can make use of substitute measurements in the event of partial failure being detected. On-line malfunction detection techniques via the computer might well be considered equivalent to providing a redundant control system without incurring any further substantial costs.

1.2 DEFINITIONS

The terms fault, failure, and malfunction have many connotations in the literature as well as in general usage. We will use the words <u>fault</u> and <u>malfunction</u> in relation to equipment as synonyms to designate the departure from an acceptable range of an observed variable or calculated parameter associated with the equipment. As examples, the impulse response of a vessel might differ in some measureable way from a normal response, or the zero-pole pattern of a system transfer function might not be the same as that specified by the designer. Figure 1.1 illustrates different circumstances corresponding to different ranges of acceptable performance. Clearly, the prescription of the boundaries to delineate a fault is a subjective task, and even after the boundaries are established, the classification of faulty vs. nonfaulty is by no means clear-cut if the stochastic aspects of

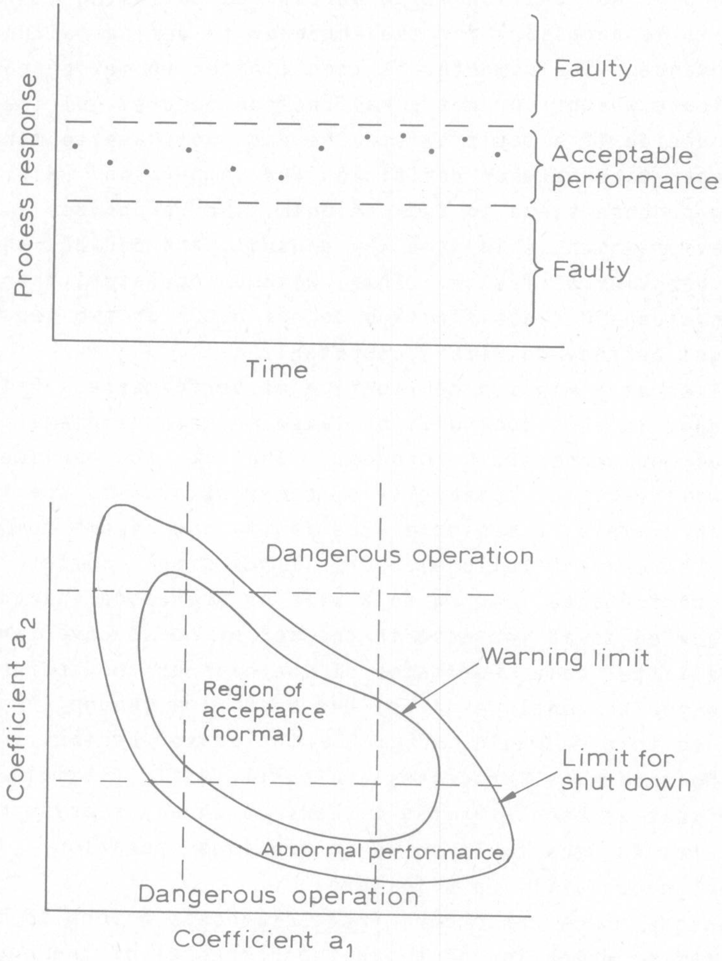

Fig. 1.1. Methods of prescribing the range of acceptable performance have a direct bearing on the definition of a fault. In the lower figure, the dashed lines might bound acceptable ranges for the individual coefficients.

classification are taken into account. Thus, the definition of a fault depends on the characteristics of the process chosen for measurement (or calculation), their acceptable range(s), and the accuracy of the statistic used for classification of a potential fault. Even though different criteria of process performance may be theoretically equivalent, they are by no means identical in practice, and consequently, a process that is "faulty" in one sense could easily be called "normal" in another.

If detection of a malfunction is to be carried out using a process computer, then it is necessary for the engineer to define malfunction precisely in advance. The computer is then limited to making comparisons which indicate whether or not a malfunction occurs. If the process operator is to decide if a fault exists, he does not have to make such a clear separation between definition and comparison. His decision-making process seems to include both. He recognizes a pattern of behavior which is in some way unusual, and decides whether to define this behavior as faulty. Thus, with an operator, the two stages of definition and classification do not occur in two separate, sequential stages as they do with a computer.

A fault implies at a minimum degradation of performance. Failure, on the other hand, in this book will be taken to mean complete inoperability of equipment or the process. That is, the equipment or an instrument will lack the capability of carrying out its specified function. As an example, a sensor may be faulty and become completely nonoperational ("hard-over" failure). Or, it may simply suffer degradation in performance leading to a bias or increased inaccuracies, which may be modeled as an increase in the sensor noise covariance matrix. In the latter case, estimates of the bias or the increase in noise may allow you to continue to use the sensor, although in a degraded mode, so that we would categorize the sensor as faulty but not failing. Most chemical processes are sufficiently flexible and well organized that as soon as a fault shows up in any subsystem, the system compensates for the fault so as to continue operation. Thus, a fault will not necessarily be a failure.

If more than one cause can occur, fault diagnosis refers to the determination (after detection of a fault occurrence) of the equipment, or portion thereof, that is causing the fault(s). That is, diagnosis is the determination of which of the subsystems, or the environment, is violating its given sufficient conditions for satisfying the process performance specifications. Because of the interaction between process components, it has been found to be very difficult to isolate causes that occur in complex systems. An engineer wants to obtain the maximum possible degree of discrimination using the available test data, with the least amount of computation. However, if the parameters used to classify the equipment among the possible faulty states are not unique, then there is little hope of determining which element among several is the source of the malfunction.

In addition to the problem of uniqueness, a satisfactory scheme for fault diagnosis has to be able to cope with the presence of noise in the measurements, as well as with the phenomenon of parameter drift. Diagnosis is a statistical decision problem much like signal detection. When the signal is weak, the matter is not so simple as either "seeing" it or "not seeing" it; rather, the observer must assess his degree of confidence that the signal exists, and then make a judgment about whether to proceed as if the signal is there, or not there. When the information received is ambiguous, other kinds of information, such as probabilities and risk, must be taken into account. Diagnostic resolution (distinguishability, detectability) refers to the precision with which a fault can be identified for the case in which multiple faults occur.

Finally, reliability is another word used extensively in both theory and practice that has many meanings. We will use the term infrequently, and when doing so, will use it in the sense of the probability that equipment will perform a required function under stated conditions for a stated period of time.

1.3 TYPES OF FAULTS AND THEIR PROBABILITY OF OCCURRENCE

It is clearly not possible here to catalog all the types of faults, and their expected occurrences, that can be experienced in the chemical industry. We can only cite a few examples. Reliability analysis requires data on failure rates of process equipment, and the equipment for instrumentation and control. The reliability of process equipment such as pumps, fans and compressors, control valves, heat exchangers, evaporators, condensers, furnaces, separation equipment, chemical reactors, etc., is very difficult to collect even from historical records because the failure rates and faults depend very much on the operating conditions of the equipment, namely the fluid properties, compositions, pressures, temperatures, and heat fluxes. Faulty operation depends not only on the steady state values of these operating conditions, but even more on the dynamics of disturbances which very often lead to temporary overload of the equipment.

Deviations from process operating specifications can be categorized in terms of the particular observations, such as:

(1) pressure deviations;
(2) temperature deviations;
(3) flow deviations;
(4) level deviations;
(5) excessive vibration;

and so forth. Other measureable characteristics might be: corrosion, erosion, fouling, cavitation, fluid hammer, loadings, expansion, contraction, fluid properties (viscosity, boiling point, density, appearance), catalyst activity, and many qualitative features.

Causes of deviations from specifications, i.e., causes of faults, can be ascribed to poor distribution, improper mixing, hot spots, overheating, resonances, stress on bearings and shafts, improper lubrication, vortex generation, blockage, sedimentation, adhesion, surging, syphoning, improper design, leakage, spillage, defects in construction, power failure, instrument failure, sticking valves, materials decomposition, catalyst poisoning, contaminants, failure to follow operating procedures, human error, climatic effects, and so on.

The causes of any specific event may be common from plant to plant, or they may not, but plant records are gold mines of information. Take, for instance, the collapse of tanks because the following conditions (ref. 8):

(1) the flame arrestor in the vent pipe was not cleaned for over two years;

(2) a loose plank was put over the vent to stop fumes coming out near a walkway;

(3) a polythene sheet was tied over the vent to stop dust getting in while the pressure/vacuum valve was being overhauled;

(4) a sudden thunderstorm occurred while a tank was being steamed, and the vent was not big enough to prevent the tank from collapsing;

(5) a quantity of cold liquid was added to a tank containing a hot liquid; the tank was fitted with a pressure relief valve but not a vacuum valve;

(6) the tank was boxed up with some water inside, and rust formation used up the oxygen in the air;

(7) a flex was connected to the vent, and the other end put into a drum of water. When the tank was emptied, water rose up the flex and the tank collapsed;

(8) tank A is vented through tank B. Tank B is slip-plated for entry. When liquid is pumped out by tank A, B collapses.

Such obvious causes of failures lead to improved operating and maintenance procedures, but cannot be detected in advance by observations of temperature, pressure, etc.

On the other hand, maintenance records, logs, and other plant data do contain information pertaining to causes of equipment and instrument failure that lead to off specification measurements. As an example, Table 1.2, collected by Anyakora from plant records, lists examples of a wide variety of symptoms and basic causes of faults and failures of control valves.

Unfortunately, there is not an extensive public data bank of information on the types of faults found in chemical plants, and their causes. This situation is particularly unfortunate with respect to the lack of failure rate data because knowledge of the probability of different modes of malfunction of various types of equipment is relevant to fault detection in two ways. First, there is little point in developing methods for the detection of faults which are either highly improbable or quite unimportant. Second, information on malfunction probabilities can be used in some detection schemes. Some information on failure rates of plant equipment has been given by Farmer (ref. 5). Table 1.3 (ref. 10) is a checklist of the causes of faults in centrifugal pumps.

Lees and his coworkers (refs. 2,3,4,6,7) have provided a substantial catalog of information on instrumentation malfunctions. Tables 1.1 and 1.4 have been condensed from Lees' work (ref. 7) to illustrate the type of information available.

TABLE 1.1
FAILURE MODES OF TWO INSTRUMENTS*

Instrument	Failure mode	Number of faults
Control valves		
	Leakage	54
	Failure to move freely:	
	Sticking (but moving)	28
	Seized up	7
	Not opening	5
	Not seating	3
	Blockage	27
	Failure to shut off power	14
	Glands repacked/tightened	12
	Diaphragm fault	6
	Valve greased	5
	General faults	27
Thermocouples		
	Thermocouple element faults	24
	Pocket faults	11
	General faults	20

*From ref. 7.

TABLE 1.2

CONTROL VALVE FAULTS*

Types of Failure	Symptoms	Causes
1 Fault in gland	Venting to atmosphere, when valve should have been in closed position.	Spindle seized in gland. P.T.F.E. chevron rings too tight in gland casing
2 Seat failure	Waste brine leaking up through valve spindle.	Chemical attack on diaphragm
3 Body failure - blocking	20 psi output from MOD 40 controller, and high level in caustic stock tanks	2 inch nail and metal bits blocking valve plug, in body
4 Blocking	No flow	Dirty material caused blockage in valve
5 Seat failure	Passing fluid when valve is closed	Poor fit of plug and seat; need to be regound
6 Seat and body failures	Bad leaks on body joint	Seat joint was found to be fractured
7 Relay body failures	Bad leak from body joint and slow action	Vibration and hydraulic hammering
8 Body failure	Bad leaks about the body	Internal corrosion
9 Inadequate packing	Valve passing when closed	Packing worn out
10 Other	Valve would not close	Large piece of PTFE wedged under seat of control valve

*Condensed from Malfunction of Process Instruments and Its Detection Using a Process Control Computer, Ph.D. Thesis, Loughborough Univ. of Technol., Loughborough, 1971.

TABLE 1.3
CAUSES OF FAULTS IN CENTRIFUGAL PUMPS*

1. Measuring instruments not correctly calibrated and/or incorrectly mounted.
2. Air entering the pump during operation, or the pumping system not completely deaerated before starting.
3. Insufficient speed.
4. Wrong direction of rotation.
5. Discharge pressure required by the system is greater than that for which the pump was designed.
6. Available NPSH too low (including suction lift too high).
7. Excessive amount of vapor entrained in liquid.
8. Excessive leakage through wearing surfaces.
9. Viscosity of liquid higher than viscosity of liquid for which the pump was originally designed.
10. Impeller and/or casing partially (or fully) clogged with solid matter.
11. Waterways of impeller and/or of casing very rough.
12. Fins, burrs, sharp edges, etc., in the path of the liquid.
13. Impeller damaged.
14. Outer diameter of impeller machined to a lower diameter than specified.
15. Faulty casting of impeller and/or casing.
16. Impeller incorrectly assembled in casing.
17. System requirements too far out on the head/capacity curve.
18. Obstruction in suction and/or discharge piping.
19. Foot valve jammed or clogged up.
20. Suction strainer filled with solid matter.
21. Suction strainer covered with fibrous matter.
22. Incorrect layout of suction and/or discharge piping.
23. Incorrect layout of suction sump.
24. The operation of one pump (in a system having two or more pumps operating either in parallel or in series, or in a combination of these) seriously affected by the operation of the other pumps.
25. Water level in suction sump (or tank, or well) below pump intake.
26. Speed too high.
27. Pumped liquid of higher specific gravity than anticipated.
28. Oversize impeller.
29. Total head of system either higher or lower than expected.
30. Misalignment between pump and driver.
31. Rotating parts rubbing on stationary parts.
32. Worn bearings.
33. Packing improperly installed.
34. Incorrect type of packing.
35. Mechanical seal exerts excessive pressure on seat.
36. Gland too tight.
37. Improper lubrication of bearings.
38. Piping imposing strain on pump.
39. Pump running at critical speed.
40. Rotating elements not balanced.
41. Excessive lateral forces on rotating parts.
42. Insufficient distance between outer diameter of impeller and volute tongue.
43. Faulty shape of volute tongue.
44. Undersize suction and/or discharge piping and fittings (sometimes causing cavitation).
45. Loose valve or disk in the system, causing premature cavitation in the pump.
46. Bent shaft.
47. Bore of impeller not concentric with its outer diameter and/or not square with its face.
48. Misalignment of parts.
49. Pump operates at a very low capacity.
50. Improperly designed baseplate and / or foundation.
51. Resonance between operating speed of pump and natural frequency of foundation and/or other structural elements of pumping station.
52. Rotating parts running off-center because of worn bearings or damaged parts.
53. Improper installation of bearings.
54. Damaged bearings.
55. Water-seal pipe plugged.
56. Seal cage improperly located in stuffing box, preventing sealing fluid from entering space to form seal.
57. Shaft or shaft sleeves worn or scored at the packing.
58. Failure to provide cooling liquid to water-cooled stuffing boxes.
59. Excessive clearance at bottom of stuffing box, between shaft and casing.
60. Dirt or grit in sealing liquid.
61. Stuffing box eccentric in relation to shaft.
62. Mechanical seal improperly installed.
63. Incorrect type of mechanical seal for given operating conditions.
64. Internal misalignment of parts, preventing seal washer and seal from mating properly.
65. Sealing face not perpendicular to shaft axis.
66. Mechanical seal that has been run dry.
67. Abrasive solids in liquids that come into contact with seal.
68. Leakage under sleeve due to gasket and O-ring failure.
69. Bearing-housing bores not concentric with water end.
70. Damaged or cracked bearing housing.
71. Excessive grease in bearings.
72. Faulty lubrication system.
73. Improper installation of bearings (damage during assembly, incorrect assembly, wrong type of bearings, etc.).
74. Bearings not lubricated.
75. Dirt getting into bearings.
76. Water entering the bearing housing.
77. Balancing holes clogged up.
78. Failure of balancing device.
79. Too-high suction pressure.
80. Tight fit between line bearing and its seats (which may prevent it from sliding under axial load).
81. Pump not primed and allowed to run dry.
82. Vapor or air pockets inside the pump.
83. Operation at too-low capacity.
84. Parallel operation of poorly matched pumps.
85. Internal misalignment due to too much pipe strain, poor foundations or improper repair.
86. Internal rubbing of rotating parts on stationary parts.
87. Worn bearings.
88. Lack of lubrication.
89. Rotating and stationary wearing rings made of identical materials with identical physical properties.

TABLE 1.4

INSTRUMENT FAILURE RATE DATA FROM THREE CHEMICAL PLANTS*

Instrument	Number at risk	Instrument years	Environment factor	Number of faults	Failure rate faults/year
Control valve	1531	747	2	447	0.60
Valve positioner	334	158	1	69	0.44
Solenoid valve	252	113	1	48	0.42
Current/pressure transducer	200	87.3	1	43	0.49
Pressure measurement	233	87.9	3	124	1.41
Flow measurement (fluids)	1942	943	3	1069	1.14
Differential pressure transducer	636	324	3	559	1.73
Transmitting variable area flowmeter	100	47.7	3	48	1.01
Indicating variable area flowmeter	857	409	3	137	0.34
Magnetic flowmeter	15	5.98	4	13	2.18
Level measurement (liquids)	421	193	4	327	1.70
Differential pressure transducer	130	62	4	106	1.71
Float-type level transducer	158	75.3	4	124	1.64
Capacitance-type level transducer	28	13.4	4	3	0.22
Electrical conductivity probes	100	39.8	4	94	2.36
Level measurement (solids)	11	4.38		30	6.86
Temperature measurement (excluding pyrometers)	2579	1225	3	425	0.35
Thermocouple	772	369	3	191	0.52
Resistance thermometer	479	227	3	92	0.41
Mercury-in-steel thermometer	1001	477	2	13	0.027
Vapor pressure bulb	27	10.7	4	4	0.37
Temperature transducer	300	142	3	124	0.88
Controller	1192	575	1	164	0.29
Pressure switch	549	259	2	87	0.34
Flow switch	9	3.59		4	1.12
Speed switch	6	2.39		0	
Flame failure detector	45	21.3	3	36	1.69
Millivolt-current transducer	12	4.78		8	1.67
Analyser	86	39.0		331	8.49
pH meter	34	15.8		93	5.88
Gas-liquid chromatograph	8	3.43		105	30.6
Impulse lines	1099	539	3	416	0.77
Controller settings	1231	609		84	0.14

*Condensed from ref. 7.