Process plant condition monitoring and fault diagnosis

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Abstract: The paper reviews current research work in the field of process condition monitoring and fault diagnosis. The review compares and contrasts the applicability and efficiency of different techniques, and concentrates on methods which monitor the main process variables. From the wide range of methods and process variables, temperature, flowrate and liquid level are used here in comparing the limitations and applications of each method. The scope of the paper ranges from basic, well established techniques to the latest reported monitoring strategies for each of the process variables.

Furthermore, the different methods of fault diagnosis deemed to be relevant in process plant are reviewed. The detection of the internal leakage in the control valves and motor faults are discussed in detail, as examples of the monitoring of vital process plant components.

The paper then outlines areas of future work, such as the development of a user friendly interface. This interface is based on state transition diagrams (STDs) as well as on the use of a knowledge based system (KBS) to model and diagnose faults in vital process plant components such as control valves.

Keywords: condition monitoring, fault diagnosis, process variables

1 INTRODUCTION

In any process such as oil refining, water treatment or aluminium production, several vital components are used to regulate and monitor process variables. The most commonly used components are:

(a) primary elements including orifice plates and sensors;
(b) electronic and pneumatic transmitters;
(c) controllers;
(d) control valves and actuators; and
(e) electric motors and pumps.

The process variables are not only influenced and regulated by the operators in the field and control rooms but also by the current condition of the above vital components within the plant.

It was reported by (**1**) that a petroleum refinery in Texas avoided a combined \$20 000 000 property damage and business interruption loss to a turbine/expander unit as a result of the early detection of high vibration levels. These were caused by the loss of two-thirds of the bolts, a circumferential crack in the coupling spacer approximately 75–100 mm long and a radial crack emanating from the initial break. If the fault had progressed and all of the bolts had sheared, the turbine would have been unrestrained with potentially disastrous consequences. This clearly illustrates why, particularly in large plants, it is vital to monitor critical components on a continuous basis to avoid the large cost of damage that may result if early fault detection is not carried out.

In addition, it is evident that if only process variables were monitored in a process plant then this early vibration would not have been detected and the damage would have been very large as explained earlier. Therefore, it is not sufficient to monitor just the process variables but rather the process variables as well as critical plant components.

The reliability and accuracy of a given condition monitoring system are dependent on the type of sensors used to monitor the process variables and the plant components as well as the location of the sensors and the suitability of the signal and data processing system used. In modern industries, where supervisory control and data acquisition systems (SCADAs) are used to monitor and control process variables, it is relatively easy to adapt these systems to monitor critical plant components in addition to the process variables.

One such example is described by (**2**) where a novel method was developed to monitor the condition of gas regulators within a high pressure natural gas transmission plant while carrying out the control of the gas pressure throughout the network.

This system utilized microprocessor based controllers to control the gas flow. These were then embedded in the required condition monitoring function, such that if a gas regulator fails for any reason, the controller carries out immediate action based on the condition of the regulator.

The study indicated that if any of the main gas regulators

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Table 1 Comparison table for thermocouples and resistance thermal detectors (RTDs)

No	Factor	Thermocouple	RTD
1	Temperature range	Wide range: from as low as −170 °C (type T) to as high as 1820 °C (type B)	Narrow range: • for 100Ω Pt, temperature range from −200 – +850 °C • for 120 Ni, from −80–+320 °C
2	Accuracy	• Tolerance band of ±2 °C exists when higher grade wires are used in the manufacturing of the thermocouples • Dependent on the type of the thermocouple and the temperature range	Higher than the best grade thermocouples Typically at 38 °C the tolerance band/errors is within ±0.7 °C
3	Sensitivity	• Sensitivity increases with temperature • It has very high sensitivity at temperature above 680 °C. It is therefore, the best sensor above this temperature for contact measurement at a distance	Almost constant value of 0.385 Ω/° C
4	Ambient temperature	Not sensitive to changes in the ambient temperature	Sensitive to changes in the ambient temperature. This effect is reduced by using four wire RTD system instead of two wire system
5	Drift	Prone to drift due to the oxidation of the thermocouples over a period of time, especially if used in a humid atmosphere	• Less prone to drift due to the excellent characteristics of platinum • The performance of platinum RTD is rapidly degraded if: – used in the presence of vapour from molten metals above 538 °C. – exposed to sulphur or silica
6	Response time	Extremely fast	Moderately fast
7	Sensor cost	Relatively cheap	More expensive
8	Ruggedness	More than RTDs	Less than thermocouples
9	Repeatability	Good	Extremely good
10	Installation methods and costs: • Direct wiring of the sensor to an indicating/ recording instrument	• Cheap but susceptible to pick-up electrical noise • Attenuation is produced in the low level signal, typical voltage produced is 20 μV/°C change in temperature • Extension leads are brittle and are not easy to bend or be pulled through conduits	• Do not require any special extension leads but also subject to electrical noise to a lesser extent than the thermocouples • Unbalanced extension leads can lead to measurement errors

Table 1 continued

No	Factor	Thermocouple	RTD
	• Using temperature transmitter	• Cost of installation increases but all the above disadvantages are eliminated	• Cost of installation increases but the accuracy of the measurement is improved • The effects of the variation in the ambient temperature are reduced

malfunctioned, the effect was detected in the form of an oscillating steam flow together with a corresponding oscillation in the controller output. This effect is usually undetectable, at an early stage, by the existing main site metering (including orifice installation) and it is only noticed when the fault has developed to such an extent that emergency action is required to rectify it.

It was also reported by (**2**) that the preliminary tests carried out at the British Gas high pressure testing station at Bishop Auckland, in order to prove the validity of the new approach, produced encouraging results.

The examples reported above emphasize the need for monitoring vital process plant components. In the following sections the methods of achieving this by monitoring temperature, level or flowrate are reviewed.

Details for two of the identified process plant components are then presented, with methods applied to (a) control valves and actuators and (b) motors and pumps described and compared. Within the consideration of control valves, the compatibility of a state-of-the-art and commercially available digital valve controller and associated diagnostic software are reviewed.

A comparison of eight different fault diagnosis methods is then made followed by an example in which a combination of a knowledge-based system, process variable monitoring and component condition monitoring can be integrated into a SCADA system.

2 MONITORING OF PROCESS VARIABLES

2.1 Temperature

Temperature is a critical process variable and its accurate monitoring is of paramount importance in process industries. Consequently, it is the intention of the authors to pay particular attention to temperature monitoring during the research programme. A common industrial example could be the monitoring and control of the temperature in a binary distillation column, in which the temperature of a mixture of two materials is increased to separate them by evaporating the lighter material and leaving the heavier one at the bottom of the column. The temperature is carefully monitored to ensure that it does not exceed a certain specified level, otherwise the quality of the final product may be affected.

Another example is the temperature monitoring of moving objects such as moving metal balls or bars. It is evident that the temperature sensor needed in each case is different due to the different range of temperature and the nature of the process.

A wide range of temperature sensors and measurement systems exists including: thermocouples, resistance thermal detectors also known as resistance thermometers (RTDs), thermistors, filled thermal systems, pyrometers, infrared thermography and glass thermometers. In industrial applications, temperature is usually monitored from a remote location such as the central control and monitoring room. This room could be quite far from the process plant, typically 2 km away. This is one of several factors that dictates the type of sensor and transmission system adopted to convey a signal which is proportional to temperature variations, without introducing noise or disturbance in the signal and to minimize transmission loss.

Non-contact temperature sensors exist but are expensive and for remote readout of temperature at an acceptable cost the choice is reduced to two main sensors, namely thermocouples and RTD. These sensors meet the industrial requirements as far as cost, accuracy and stability are concerned. A comparison between these sensors is drawn as shown in Table 1 and the choice of either of them is dependent on the given specifications.

In addition to the selection of an appropriate temperature sensor, the attention of the reader is drawn to the importance of selecting suitable methods of conveying the change in the temperature in industrial applications as accurately and as quickly as possible.

There are mainly two methods: direct wiring and transmitting the information using temperature transmitters mounted in the vicinity of the measuring points within the plant.

2.1.1 Direct wire method

This method involves extending the leads of a thermocouple or an RTD from the plant, where the sensor is located, to an indicating or a recording device which could be located 1 km away from the plant. The cost is relatively low, but has many drawbacks including the difficulty in transmitting low level signals long distance without being attenuated and losing most of the valuable information within the signal. In addition, when extending thermocouple leads to 1 km or more, the signal is highly susceptible to picking-up electrical noise since the extension wires act like an antenna. When this method is used with an RTD sensor, then another problem is added, namely the difficulty in balancing the resistance of the leads (2, 3 or 4 leads) and this leads to errors in the measurement.

2.1.2 *Temperature transmitter method*

Newly-developed temperature transmitters exist, which are commonly used in process industries, to transmit temperature variations over a long distance without reducing the accuracy of the measurement or introducing noise in the transmitted signal.

The temperature transmitter is located as close to the measuring point as possible to reduce the transmission loss. There is a tendency to pick-up induced voltages, which is due to an alternating magnetic field from electric motors and other large machines often found in process plants. However, this can be reduced by using twisted pairs of wires as extension leads.

The cost of monitoring temperature from a distance using temperature transmitters is higher than the direct wiring approach. It should be borne in mind that in industrial applications, factors such as accuracy, consistency and reliability of the measurement system are more important than the cost.

There are different types of transmitters: conventional analogue transmitters which transmit 4–20 mA d.c. signal over a distance and the latest 'smart' transmitters which are microprocessor-based devices. The smart transmitters are more expensive than the conventional ones but have many advantages including the following: versatility, capabilities to linearize the input signal, ambient temperature stability, automatic self-calibration, digital communication and high accuracy.

2.2 Level

It is an important and common process variable in many industries where raw material is converted into refined products. In these applications, an accurate level measurement is necessary to ensure that hazardous chemicals do not overflow storage tanks and cause a hazardous situation. In some applications, it is necessary to monitor the level of fluids in remote reservoirs from a central control room to ensure that supply meets the demand.

There are many techniques used in level measurement from the very basic dipstick level gauge to the most sophisticated ultrasonic level sensor incorporated into a microprocessor based digital signal conditioning and processing unit. The choice of a suitable level measuring system is dependent on many factors including; specifications, cost and the type of liquid or solid which is being measured. The fluid may contain slurries, may evaporate with time and could be acidic, while on the other hand, it could be pure distilled water. Therefore, it is necessary to consider all factors before selecting a particular level measurement system.

The most commonly used liquid level measurement instrument in industrial applications is the differential pressure (D/p) transmitter. This is because of its acceptable low cost and high accuracy. Recently, a study was carried out by (**3**). References (**3**), (**4**) and (**5**) are shown in Table 2. This indicated that after carefully considering the total cost of installing a D/p transmitter and considering all the risks involved during the routine calibration procedure and comparing it with the latest microprocessor based capacitance level measuring instrument, it is no longer feasible to install D/p transmitters. These are gradually being replaced by a capacitance level measurement system.

Consider the number of joints involved, and hence possible leakage points, in Fig. 1a and Fig. 1b. It is clear that for Fig. 1a, which is a D/p method of level measurement in a closed vessel, there are at least 29 places along the line to the transmitter in which the process fluid could leak into the atmosphere, while Fig. 1b, which is a typical hermetically sealed flange type capacitance level transmitter, has only one place in which the process fluid could leak. Hence from a health and safety point of view, it is much safer to use the capacitance level measurement system.

Another major advantage of using the capacitance level measurement system is the fact that this type of level measurement system does not require routine re-calibration as is the case for the D/p based measurement system and with the smart signal processing system that exists, it is a simple matter to calibrate the capacitance system from a distance. The accuracy and the reliability of the capacitance system are also higher.

Table 2 summarizes the main level measurement systems, and lists their advantages and limitations.

2.3 Flow

The measurement of flowrate is common in many processes, where it is necessary to monitor the fluid flowrate through various sections of pipelines and into the vessels.

A number of devices have been developed that could be used to measure either the mass or the volume flowrate, and the choice is dependent on many factors including specifications, type and the nature of the fluid which is being measured. A large number of researchers have studied these devices in detail and developed new methods of measuring flowrate.

The current research work on two of the common devices used in the process industries are highlighted in the following sections. A summary table, Table 3, is also provided which lists all the flow meters, their applications and limitations.

2.3.1 *Differential pressure transmitter*

Research work was carried out by (**6**) on the effects of the

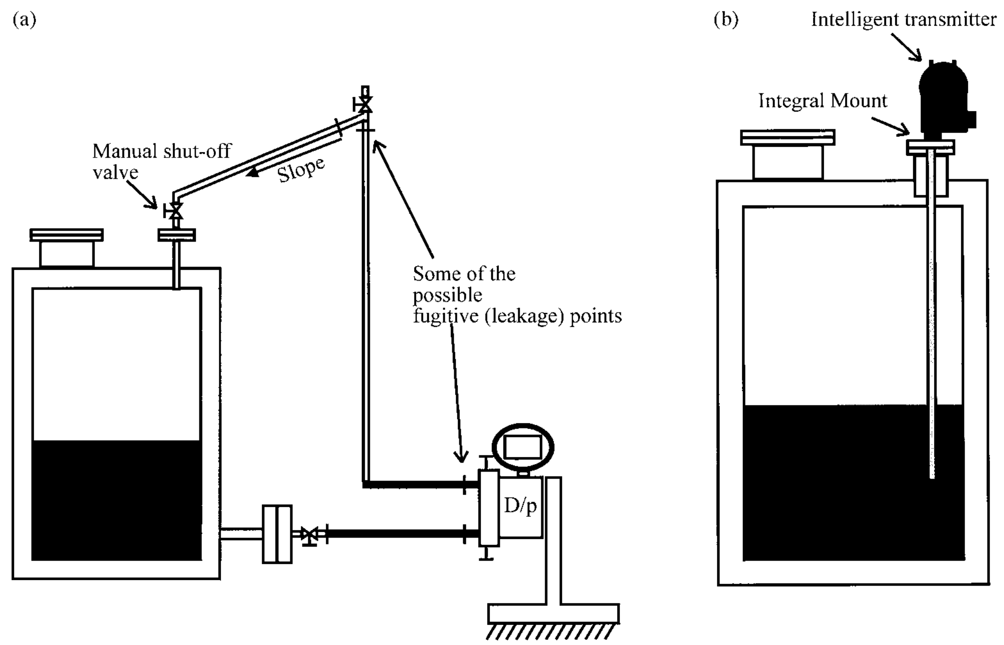


Fig. 1 (a) Remote mounted D/p for level measurement in a closed vessel. (b) Capacitance level transmitter for a closed vessel

orifice plates, D/p transmitter and the length of the connecting lines from the flanges of the orifice plates to the D/p transmitter on the measurement system. It concluded that in order to reduce the errors caused by the oscillating pressure at the orifice plates taps to a minimum value, the length of the connecting lines (gauge line length) must be kept to a minimum value. Moreover, the D/p transmitter must have a high frequency response to ensure that it is constant over the actual frequency range of the pressure oscillation and the gauge line connected to a D/p transmitter. It is desirable for this transmitter to have the smallest possible chamber.

Other studies carried out by (**7**–**10**) concluded that errors of several per cent are also introduced in the measurement due to the presence of swirl in the flow pipeline. The results obtained from a number of other researchers (**11**–**14**) agree with this and it could be stated that the effect of swirl on the orifice plates is in the order of 5 per cent.

A recent detailed study was carried out by (**15**). It produced results which largely agreed with the previous work and confirms the size of the errors produced.

2.3.2 Precision gas flow meter

Traditionally, volumetric technologies including differential pressure, turbine and vortex shedding have been used to measure gas flowrate. These methods are not suitable if accurate measurement is required, since errors are introduced in the measurement due to the compressible nature of gases and it was, therefore, necessary to compensate for gas density fluctuation in order to reduce the errors in the measurement.

Newly developed Coriolis mass flow meters, known as Micro Motion and manufactured by Fisher-Rosemount, can be used to measure the gas flowrate which is independent of temperature, pressure, density and composition.

They are designed in such a way that the tube vibration is reduced to 80 cycles per second with a peak-to-peak amplitude of less than 2.5 mm, and from material such as Hastelloy C-22 and Tantalum to improve their life cycle and enhance their resistance to corrosion fatigue as well as reduce the mechanical fatigue.

These flow meters are non-intrusive, have no rotating parts and are highly accurate, $\pm$ 0.5 per cent of actual mass flowrate (**16**). References (**17**) and (**18**) are in Table 3. In addition, they are immune to process noise and have an excellent low-flow capability. These devices not only measure mass flowrate accurately but also temperature and density at the same time, which reduces the number of possible leakage points along the pipeline.

In order to select the most appropriate flow meter for a given application it is recommended that the British Standard BS 7405 is used and studied in detail.

3 MONITORING OF VITAL PROCESS PLANT COMPONENTS

3.1 Control valves and actuators

Control valves are vital components in every process where fluid is handled and regulated. The common malfunction with control valves is internal leakage, which cannot be detected easily. The cause of the internal leakage could be due to one of several factors including eroded valve plug/ seat and insufficient seat load.

Conventionally, control valves are demounted

Table 2 List of level measurement methods and their limitations

No	Method/ Instrument	Application	Main advantages	Main disadvantages
1	Dipstick	Measurement of fluid level in vessels such as car engine oil level	• Cheapest method • Easily maintained • It has no moving parts	• Provides only an indication of level • Not very accurate • The dipstick must not be bent to avoid errors in the measurement • Cannot be used to measure solid level • The dipstick must be positioned vertically for level measurement against a reference point
2	Sight glass	Industrial tank level	• Cheap • Easily maintained • It has no moving parts	• The glass may break and cause a hazardous situation • Provides only an indication of level • Sight glass may be stained over a period of time • Parallax errors introduced in the measurement • Not very accurate
3	Static pressure head using differential pressure transmitter (electronic/ pneumatic)	Many industrial applications	• Signal can be transmitted over a long distance away from the plant • Very accurate measurement is achievable • Relatively cheap • Wide span is available • Suitable for most liquids • Smart transmitters are easily calibrated • Pneumatic transmitters could be used in hazardous situations to avoid any explosions	• Leakage of process fluid at the input ports • It has moving parts which must be maintained regularly • Typical working life of 5–7 years (**3**) • The sensing element may be damaged because it comes in contact with the process fluid • Level measurement is affected by density and temperature changes • Errors may be introduced in the measurement if the transmitter is not bled properly • Cannot be used to measure slurries • They need routine calibration, and during this process hazardous process fluid is released and the human operator is exposed
4	Capacitance probes with smart transmitters	• Non conductive fluids • Granular • Slurries	• Level measurement is independent of temperature and density • Only one possible leakage point in comparison with several possible leakage points when a differential pressure transmitter is used • With smart transmitter attached to the probe, any two points of level in a vessel can be used to calibrate the measurement system without emptying the vessel for zero level • If process material is not available for calibration, equivalent calculated capacitance value can be entered into the transmitter for calibration and capacitance box is not needed (**4**)	• Initial cost is high • Not suitable for conductive fluids • Comes in direct contact with the process fluid which may affect its performance in the long term

Table 2 Continued

No	Method/ Instrument	Application	Main advantages	Main disadvantages
5	Ultrasonic transceiver with digital signal processing	Many applications including: • Waste water • Solvent tank • Powdered product bins • Calcium carbonate • Citric acid (**5**)	• Can be used for a very wide range of applications of both solids and liquids • The transmitter and the receiver are not in contact with the material that is being measured • Can be used to measure solids and liquids over 60 m away from the transmitter (**5**) • Reliable • Very accurate	High cost

completely to replace the worn parts. This process requires the system or part of it to be shut down before the control valve is removed and taken for maintenance.

A study was carried out by Electricité de France (EDF) (**19**) to investigate the need for demounting control valves. It was concluded that 20 per cent of such demounting process was unnecessary and action was urged to develop condition monitoring techniques to monitor the internal leakage of valves and reduce the number of unnecessary demounting.

The methods used were: infrared thermography (IR) and acoustic emission (AE). Infrared thermography was less reliable than the acoustic emission and the AE was, therefore, used to monitor a large number of valves in their nuclear power units. The research work was limited to motor operated valves and valve signature analysis was given only for edge gate valve without giving any account of other types of control valves including check valves and butterfly valves.

For the AE technique, two measurements were taken: one with AE sensor applied to the body of the valve, and the other with the sensor applied to the process line a few feet away from the valve. The portable digital leak detector used had a frequency range of 0–500 kHz (**19**).

The IR technique was applied initially using hand-held IR cameras and IR images were compared for identical valves to observe any hot spots or areas along the pipeline upstream and downstream of the control valves.

The reliability quoted by the author was 90 per cent and an 80 per cent diagnosis was possible. It is recommended that similar investigations are carried out on other types of control valves, including check valves, and under different environmental conditions using different types of actuators, including diaphragm actuators.

Internal leakage was also investigated by (**20**). In their work the AE method was used to determine the relationship between the internal leakage rate and acoustic characteristics. The work was limited by the lack of availability of sensitive and suitable instrumentation.

It was deduced that for a 50.8 mm (2 in) ball valve at 275.8 bar air and another of 88.9 mm (3.5 in) gate valve at 41.4 bar steam the amplitude of the AE spectra at certain frequencies was an indicator of leak rate.

It was also observed that the amplitude was significant over a narrow range of frequency, 50–60 kHz for air and 45–50 kHz for steam. These two ranges of frequency were investigated to obtain a relationship between the leakage rate and the amplitude of the AE spectra.

Leakage through a 38.1 mm (1.5 in) spool type hydraulic valve at 193 bar hydraulic oil pressure can be quantified by AE amplitude but other system parameters would have to be controlled. Finally, leakage through a 101.6 mm (4 in) sea water ball valve could be detected but not accurately measured at 0.48 bar.

Some of the limitations associated with the reported results are:

1. The relationship between minimum measurable leakage rate to valve size was not known because all the valves used for each fluid were of similar sizes.
2. The reported measurable leakage through valves for different fluid may not be as low as was stated. This is due to the lack of understanding of the characteristics of background noise.
3. The reported laboratory results may not be accurate due to the fact that the effects of temperature and pressure on acoustic measurement of steam valve leakage rate was not fully understood at that stage. In addition, the expansion of the internal valve parts (trim) due to heat could have introduced some errors in the reported results which were not taken care of in the measurement.
4. The steam quality may affect both the acoustic emission and the condensate leak rate measurement. This factor was not considered when results were reported.

Another detailed study was carried out by (**21**) to diagnose internal valve leakage by vibration analysis. The experimental work was considered for three different valve sizes, namely 25, 50 and 75 mm and was limited to air and water leakage.

The results illustrated that it is possible to detect small air flows of less than 3 l/min through valves by vibration and analysis of the frequency spectra obtained. This flowrate was obtained when a certain valve was nominally closed. In the case of water, the results were less conclusive although the author stated that the leakage could be detected through ball plug valves by a general rise in vibration levels

Table 3 List of common methods of flow measurement and their limitations

No	Method/ Instrument	Application	Main advantages	Main disadvantages
1	Differential pressure flow meter with orifice plates (volume flowrate)	Clean liquids and gases	• Relatively cheap • Easily maintained • Signal can be transmitted long distance away from the plant	• Low accuracy • Pressure drop due to the orifice plates • Not suitable for liquids containing solids • Process fluid comes in contact with the primary sensor • The relationship between flowrate and differential pressure is non-linear • Errors produced in the measurement due to the oscillating pressure at the orifice plates taps • Some measurement errors due to swirl in the fluid
2	Magnetic flow meter	Suitable for conductive fluids only	• Good accuracy, $\pm 1\%$ of indicated flowrate • Calibration and operation are independent of viscosity, temperature, pressure and density • Non-invasive bi-directional flow measurement capability • Linear range • Fast response time	• Not suitable for gases or liquid hydrocarbons • Relatively expensive
3	Coriolis flow meter	Suitable for liquid and gases	• Direct mass measurement is achievable • Low pressure drop compared with orifice plates • Less maintenance is needed due to the absence of rotating parts • High accuracy • Gas flow measurement which is independent of temperature, pressure, composition and density	• Liquid flow measurement is affected by the environment: temperature, pressure and vibration • High initial costs
4	Turbine flow meter	Clean fluids including: water, petrol and other hydrocarbons, gases, corrosive liquids compatible with 316 stainless steel	• Suitable for a wide range of pipe diameters. Typically between 5 and 500 mm (**6**) • Intrinsically safe • Fast response time • Easy installation • Relatively long working life before changing the bearings Typically, greater than 5000 hours • Low initial cost • Produces better results than orifice plates and D/p transmitter • High accuracy especially when used to measure gas flowrate • Suitable for a wide temperature range and high pressure	• It has a moving part (rotor) which comes in contact with the process fluid. This may cause the bearings to be damaged or the rotor to be jammed or the pick-up to be defective • Viscosity dependent and not suitable for high viscosity fluids • Errors are introduced in the measurement if swirl is produced in the fluid flow. The percentage of error produced is dependent on the construction of the flow meter One turbine meter was in error by 5 per cent while another was almost unaffected by the swirl (**7**) • Suitable for clean fluids only

Table 3 Continued

No	Method/ Instrument	Application	Main Advantages	Main Disadvantages
5	Laser-Doppler method	Suitable for liquid and gases	• Very accurate measurement for both laminar and turbulent flow • Direct measurement of fluid velocity • Fluid flow is not disturbed by this method, no contact with process fluid • Suitable for a very small volume measurement (typically 0.2 mm^3) • High frequency response	• Can only be used to measure flowrate in transparent pipes and vessels • Artificial tracer particles are needed for gas flowrate measurement
6	Ultrasonic flow transmitter	Suitable for liquid and gases	• Measurement is independent of fluid medium • Provides both fluid speed and direction • Suitable for multiphase flow measurement • Small size and no moving parts • No need for particles for the sound waves to be reflected (as the case with Laser-Doppler method)	• Errors may be introduced in the measurement due to the installation of the transmitter (e.g. sound waves distortion could be produced) • High cost
7	Vortex shedding flow meter	Suitable for gases, liquids and superheated steam	Can be used to measure dirty and highly corrosive liquids	• Sensitive to vibration of pipe work which is compensated for in the new designs of flow meters • For accurate measurement, there is a need for a minimum length of straight pipe upstream and downstream of the sensing element • Accuracy is dependent on the type of fluid used as well as the Reynolds number. Typically: for liquid, Reynolds number 3800–2000 accuracy of ±0.75% of the full scale For gas or steam with the same Reynolds number accuracy of ±1% full scale
8	Hot-wire anemometer	Main applications: measurement of rapidly fluctuating velocities and directions such as the turbulent component of the fluid	Suitable for the measurement of fluid temperature and turbulent shear stresses as well as concentration of gases in the mixture (**8**)	• Problems associated with the limited strength of the fine wires: wires may break • Calibration changes occur rapidly (within a few minutes of operation if the fluid is not very clean) • Wires may vibrate when high speed measurement is carried out

across the frequency range 0–20 kHz. However, this initial research indicated that a high sensitivity accelerometer should be used to obtain reliable results. Figure 2a illustrates the results obtained for a 25 mm ball valve and Fig. 2b illustrates that for a 75 mm ball valve with air leakage at different pressure from Fig. 2a (**21**).

Extensive research work was carried out by (**22**), which was an extension to previously carried out work, to further investigate the applicability and reliability of vibration analysis technique in determining valve internal leakage. The experimental work was carried out utilizing more sensitive and accurate instruments, accelerometers and frequency analysers, than those utilized in the previous research work in order to reduce some of the uncertainties and improve the reliability of the results.

A series of tests carried out on a number of control valves with different sizes, indicated that air leakage rate as low as 0.5 l/min at 0.5 bar pressure through a 25 mm valve can be accurately detected by this technique.

After considering many factors that may affect the frequency spectra such as background noise, leakage rate, type and size of valve, it was deduced that the amplitude of the frequency spectra increased as the leakage rate increased and the frequency component that was excited by internal valve leakage was independent of these factors.

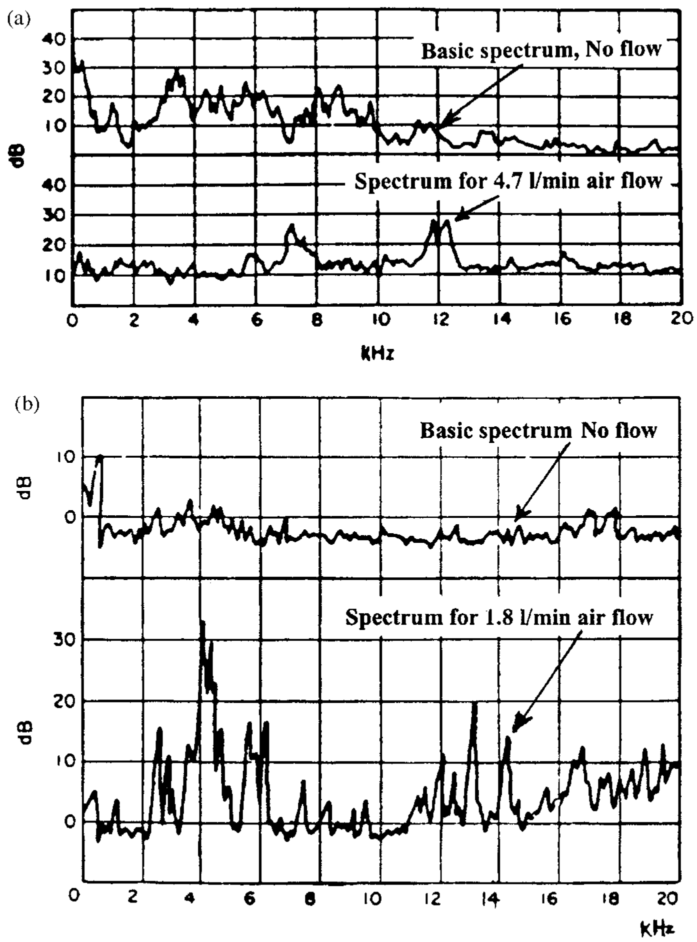


Fig. 2 (a) Variation in the amplitude against frequency for ball valve 25 mm, 13.6 bar air pressure. (b) Variation in the amplitude against frequency for ball valve 75 mm, 15 bar air pressure

The research work was extended to include different types of gases and it was observed that the spectrum produced for any particular type of gas was repeatable for a given leakage rate and pipe diameters. However, the excited frequency component was dependent on the type of gas used as well as the downstream pipe diameter.

The vibration analysis method still has one main deficiency when considering the detection of internal valve leakage. This is its inability to determine precisely the leakage rate through the valve.

It was concluded that this method produced reliable results provided that the background noise is kept under control, otherwise the frequency component produced due to the internal valve leakage may be masked by this noise.

Industrially-based research work was carried out by (**23**) to diagnose faults in industrial control valves using newly developed diagnostic software and an interface module. Initial results indicated that with this system only certain parameters and faults, such as hysteresis, valve packing friction and damaged valve stem could be investigated in detail and the diagnostic system, software as well as hardware, must be developed further in order to be able to diagnose a range of common faults in control valves.

The existing software has other limitations including the fact that the results obtained from the diagnostic software are prone to misinterpretation since the results on their own cannot be used to diagnose faults precisely and the final judgement is based on the expertise of the engineer or the person interpreting the results.

Work has been started by (**24**) to develop a user friendly interface based on the historical graphs, characteristics of different types of control valves and common faults that may develop in these types of valves. MatLab has been used in conjunction with some of the historical graphs to develop data bases and eventually an expert diagnostic system.

The typical results of a test that was carried out to establish the relationship between the actuator pressure and the valve travel, mechanical movement of the valve in response to changes in the pneumatic signal applied to the actuator are illustrated in Fig. 3 and Table 4. These results could be used to assess the condition of the valve plug, packing, valve and actuator stems, actuator spring and the supply pressure.

The control valve used was a newly installed valve and the packing flange nuts were tightened to ensure that the process fluid did not leak from the packing. The frictional force produced was well below the expected packing friction for a graphite type of packing and the valve moved smoothly during the complete cycle. These were due to the condition of the valve and the settings including the gain and the supply pressure which were selected to be the optimum values.

It is vital to monitor the control valve closely to determine its condition and ensure that all its elements are functioning normally, and that both the static and the dynamic valve characteristics are as specified.

A control valve with an abnormally high packing friction could be the cause of a control loop cycling (**25**). If the valve's condition is not monitored to identify the cause of the loop cycling then it is very common to rectify the problem by re-tuning the controller in order to reduce the loop gain or increase the integral time. This approach, unfortunately, only solves the cycling problem temporarily by masking the root cause of it but creates a more serious problem in the future. This is due to the damage that may be done to the valve packing as well as the actuator spring rate as a result of the frictional force being too high.

The study investigated the characteristics of the cycling wave forms produced by high valve friction in comparison with that produced by an incorrectly tuned controller. It was deduced that the cycling wave forms produced by the high valve friction have unique characteristics even when the controller is re-tuned provided that the control signal as well as the measurement signal (flowrate signal) are carefully examined.

Two of the main symptoms of internal valve leakage or damaged valves are increased level of noise and vibration. Hence the following section discusses types of noise and vibration produced by control valves.

3.1.1 *Control valve noise and vibration*

When control valves are in operation, the sound of valve stroking and other noises are produced. The noise level could be high if the valve is not operating under an optimum condition and it could result in structural damage if not diagnosed and reduced quickly.

When a control valve is emitting an undesirable noise its cause could be traced back to one of the following:

1. Horizontal movement of the plug in the guide post.
2. Valve plug or some other components vibrating at its natural frequency.
3. Valve plug instability. This is caused by a vertical oscillatory movement of the valve plug at a frequency of about 30–60 Hz (**26**).
4. Noise of the flowing media.
   It is recommended by (**26**) that to reduce this type of noise the following should be considered:
   (a) acoustical absorbing material such as a silencer placed downstream;
   (b) use of heavy wall piping;
   (c) placing acoustical absorbing material in the air path on the outside of the piping; and
   (d) burying the pipe underground and allowing the fill dirt to absorb the sound.
5. Noise produced when liquid flows in valves: this type of noise is called cavitation noise.

3.2 Pumps and motors

Traditionally, vibration monitoring is used to determine the condition of rotating machinery. However a study carried out by (**27**) illustrated that vibration alone is not sufficient to monitor the health of rotating machinery especially when large industrial machines are concerned.

It was observed that an electric machine's temperature and current drawn from the supply increase if the machine is overloaded well before any vibration is detected. This suggests that for an early fault diagnosis of electric

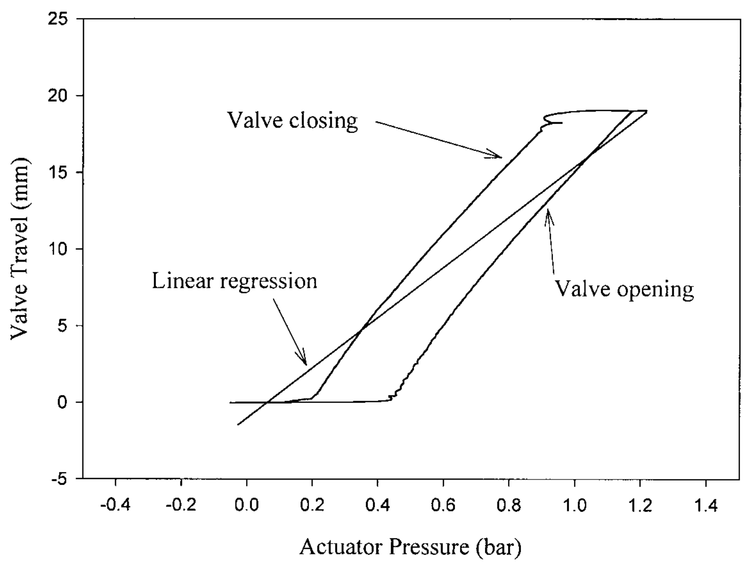


Fig. 3 Actuator pressure versus valve travel

Table 4 Result of the valve diagnostic test

Result	
Minimum friction	497.4 N
Maximum friction	554.0 N
Average friction	522.8 N
Spring rate	179.5 N/mm
Bench set	0.27–1.04 bar
Seat load as tested	1.01×10^3 N
Service seat load	743.6 N
Required seat load	488.5 N
Expected packing friction	981.0 N
Control valve database	**Description**
Valve:	
Type	GL
Class	300
Size	25.4 mm (1 in)
Rated travel	19.1 mm
Actual travel	19.1 mm
Stem diameter	12.0 mm
Packing type	Graphite
Inlet pressure	6.9 bar
Outlet pressure	0 bar
Trim:	
Seat type	Metal
Leakage class	IV
Port diameter	22.2 mm
Port type	Unbalanced
Push down to	Close
Flow direction	Up
Flow tends to	Open
Unbalanced area	387 mm^2
Actuator:	
Type	667
Size	34
Effective area	445.2 cm^2
Air	Opens

machines it is necessary to monitor other parameters simultaneously in addition to vibration. Also, if only vibration analysis is used then it may be difficult to establish the real cause of the vibration.

This is certainly the case when a motor is used to drive a pump. In this case, both vibration and the overall pump performance must be carefully monitored to obtain a more reliable diagnosis. It is important to realize that the vibration produced by an electric motor is not a fault on its own but rather a symptom of developing failure and gives early warning. Moreover, when measuring electric motor vibration, the location of the vibration sensor is vital to avoid introducing errors in the measurement and it was observed that the best location for these sensors is at the bearing or bearing housing.

A recent study carried out by (**28**) indicated that for low speed rotating machinery, such as rotating biological contactors (RBC) which rotates with a constant speed of 1 r/min, vibration analysis is not suitable to detect any degradation, while acoustic emission sensors which are strategically located on the machine can lead to a successful early detection of any deterioration of the machine.

Comprehensive electrical monitoring equipment is available which could be used to monitor: short circuit, open circuit, unbalanced coil impedance, leaks to ground and hot spots in the windings of electric motors. Electric motors fail if these faults are not detected early and may cause a loss of production or deterioration in the quality of the production line.

One of the most common factors that drastically affects the performance of hydraulic pumps is cavitation, which can damage the internal parts of a pump if not detected quickly.

A series of experiments was carried out by (**29**) to establish whether acoustic emission (AE) could be used to detect incipient cavitation in large, 75 kW, centrifugal pumps. The sampling rate of the data acquisition system used to capture the unprocessed AE signals was 2.5 MHz.

From the results obtained, it is clear that the AE spectra produced for a pump with lower efficiency due to cavitation was remarkably different from that produced for a completely healthy pump. In addition, it was observed that this method could be adopted to provide early warning of the drop in the net positive suction head (NPSH) well before it reaches the 3 per cent criteria, which determines that serious cavitation has occurred at the inlet of the pump.

It implies that if the AE method is used on-line to continuously monitor the performance of an industrial pump, then cavitation problems can be solved as soon as they commence without causing any disruption to the fluid system.

4 SYSTEMATIC FAULT DIAGNOSIS METHODOLOGIES

Several fault diagnostic systems for individual plant components have been investigated. However in process plants, it is desirable to develop a diagnostic system which can diagnose faults in the entire system. A wide range of fault diagnosis techniques exists and could be used to detect and diagnose faults. The ideal diagnostic system is one which records plant signatures for condition monitoring. It should be capable of diagnosing intermittent as well as regular and gradual faults.

Modern process plants are complex and involve using high technology machines and computers. To develop an acceptable diagnostic system for such plants, it is important to consider the underlying principles of fault diagnosis in general, and to try to develop a computer-based fault diagnostic system which satisfies the specifications and demands. An acceptable diagnostic system could be developed if in-depth knowledge of the process plant is known and good communication is established with the technicians and the operators who work on these plants. They know the type of faults that occur and their frequency of occurrence.

Experienced technicians often cure faults on plants without knowing detailed plant operation simply based on their previous knowledge of the fault. This approach is not systematic and does not solve most of the unpredicted faults.

The following is a summary of some of the most commonly available fault diagnostic techniques:

4.1 Logical method

One method reported by (**30**) uses detailed knowledge of the plant, academic knowledge of component behaviour and known common failures to form a list of possible causes of an observed symptom. Then, one possible cause is selected based on probability and ease of testing. Tests are then performed to confirm or deny this hypothetical cause. This technique is known as the hypothesis and test.

4.2 Algorithmic method

A typical example from a manufacture's manual (**31**) is shown in Fig. 4. These are particularly attractive as they can be stored as a routine for that item and requested from many diagnostic programmes for different parts of the plant.

4.3 Functionally Identifiable Maintenance System (FIMS) /Functional Systems Documentation (FSD)

FIMS was first developed at the HMS Collingwood (**32**) to aid fault diagnosis on Royal Navy warships. It was renamed FSD and adopted by British Steel (**33**) and GEC (**34**) to provide diagnostic documentation for electrical and hydraulic equipment.

FIMS is a documentation system based on the divide and test approach. The plant is divided into blocks with testable inputs and outputs which can be used to identify a faulty block. This block is then expanded to illustrate further blocks within the block with testable inputs and outputs. The division is continued until a simple circuit is reached. This method has two major limitations/disadvantages namely, that it can only be used when a plant could be divided into separate identifiable blocks, which is not the case in most real plants. The second limitation is the cost of documentation involved, which could be high.

4.4 Knowledge-based System (KBS)/Expert System (ES)

A KBS is based on acquiring an in-depth knowledge of the plant which is being monitored, and developing rules which are used as reasoning tools for fault diagnosis. It is, therefore, important to gather as much information about a particular plant as possible before designing a useful KBS for fault diagnosis. The KBS will be used by the operators but will be developed by the engineers (**35**). Hence the KBS should be developed in consultation with the users, operators and technicians, to ensure that the graphical displays developed for fault diagnosis are suitable for them. This is particularly important for large process plants where previous knowledge of possible fault symptoms and causes is vital in developing a KBS, which covers most faults and at the same time is not too complicated for the operators to interpret.

An expert system (ES) is a special kind of a KBS that uses knowledge acquired from one or more experts rather than from other sources. It includes a knowledge base, inferential engine and database. On the other hand, a KBS employs other forms of knowledge and good common sense. Hence, both conventional and fuzzy rules could be incorporated into a KBS to develop a diagnostic system which may be superior to a traditional ES, which utilizes rule-based and conventional logic for its inferential engine. Recently, many researchers have developed the inferential engine and a recent paper was published by (**36**) which integrated fuzzy logic and case-base reasoning techniques into the inferential engine and developed an ES for diagnosing faults in turbomachinery. The authors reported that the fuzzy rule-based reasoning technique can identify the underlying cause(s) of a real problem and the case-base technique can provide useful and reliable information to reinforce the results of rule-based diagnosis.

A detailed comparison between the first and the second generation ES is described by (**37**). It is an excellent review paper on ES since the author outlines the two generation ES in detail and proposes future work to develop the ES in order to be suitable for a wider range of industrial applications.

The main drawbacks of the first generation ES, which include its rigidity in reasoning (monolithicity), human-computer interaction limitations and maintainability, have been eliminated. A considerable amount of work is still needed to develop the second generation ES that possesses all the desired characteristics including the capabilities to resolve the conflicts between the different depth of knowledge required by users with different levels of expertise and skills.

In addition, a major deficiency of this type of fault diagnosis system is its dependence on the operator's/user's knowledge of the plant and if this is not sufficient and does not describe all the operations and possible faults, then the KBS/ES developed may not be very useful and needs continuous upgrading to include information about the newly developed faults which were not included in the initial stages of the development.

This method also has the inherent limitations including the inability to learn or dynamically improve its performance and loss of quantitative information from plant measurements.

4.5 Statistical technique

This method utilizes the statistical properties of the monitored signals such as the mean value, standard deviation, variance and density function to determine the condition

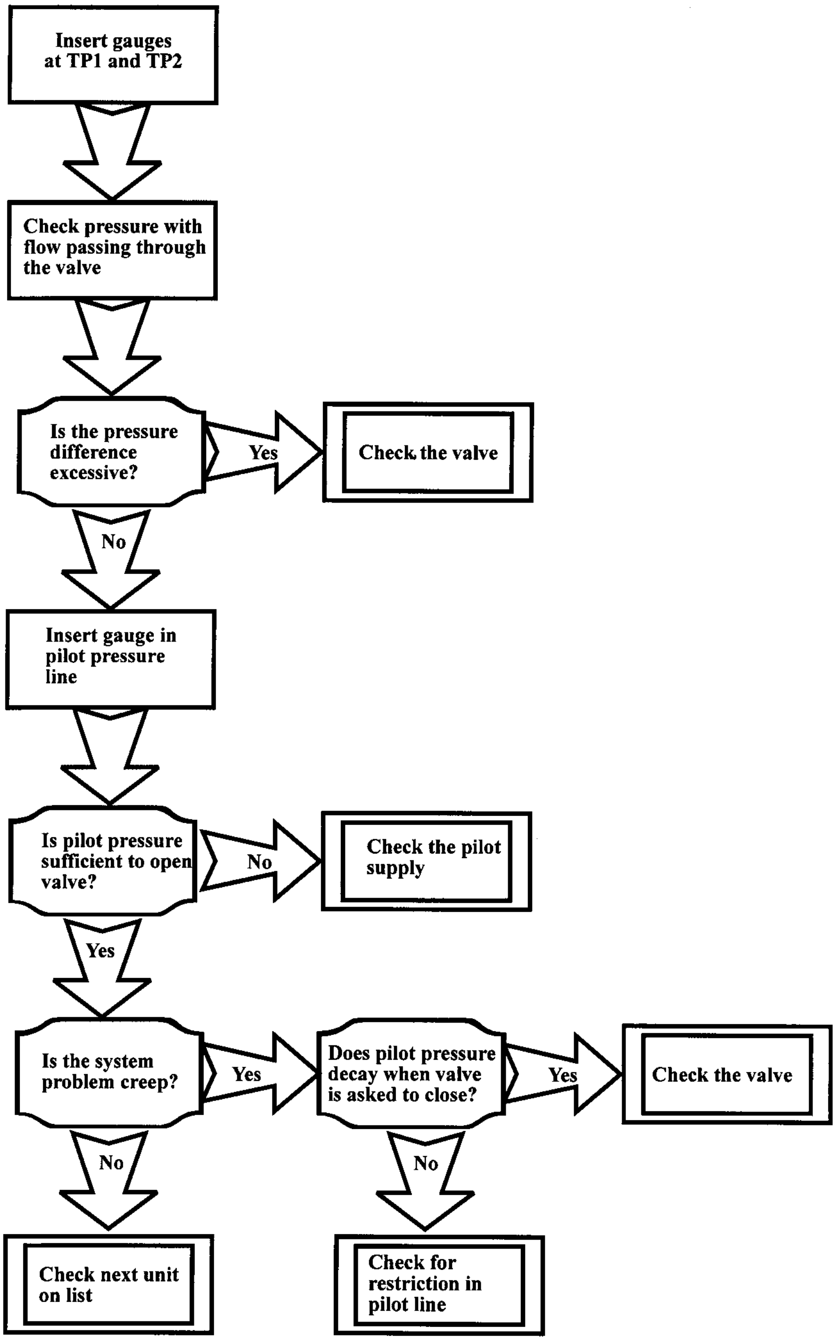


Fig. 4 Tree-based algorithm

of a plant. Hence, faults could be detected if the statistical properties of the monitored signals deviate from the normal values. It is, therefore, suitable for applications where signal statistics change.

An example could be the monitoring of a pressure signal across a section of a pipeline which has an amount of process material deposited on the inner walls of the pipeline, or the section is corroded hence the pipe diameter is reduced. In this case, if the pressure signal is measured along the section of the pipeline before and after the area where the diameter is reduced then the standard deviation as well as other signal properties of the measured signal will be affected. Under this condition, statistical technique is suitable to monitor the condition and diagnose faults along the pipeline.

The statistical method of condition monitoring and fault diagnosis is also used in process control. This is known as multivariate statistical process control (MSPC). This method can be used to monitor the performance of process plants and detect early deviations in the monitored parameters.

It is based on developing an intelligent operator support system which is especially useful in abnormal condition monitoring. The MSPC considers all the available plant data simultaneously and considers the behaviour of one variable relative to the others. Monitoring charts are developed by acquiring plant data under normal operating condition, and then future behaviour of the plant is referenced against these data sets to investigate any malfunctioning of plant components.

The reader's attention is directed to a detailed review paper written by (**38**) for further details of the applications of MSPC in process monitoring and fault detection which includes its first reported application in monitoring the performance of a high speed continuous polymer film production line.

4.6 Model-based

This technique involves the development of dynamic models of plants that are under surveillance. It may not be possible to model large industrial plants accurately since real plants are generally non-linear, and in order to develop mathematical relationships between various parameters it may be necessary to use linear approximation in order to model certain elements of the plants. This will introduce some errors in the results obtained from these models.

The performance of the model-based diagnostic system can be improved considerably by integrating the statistical technique and the Kalman filter into the model-based system. The Kalman filter eliminates any undesirable components of the monitored signal such as noise and the statistical technique considers the statistical properties of the monitored signals.

The model-based technique is further improved by utilizing fuzzy models to model non-linear process plant components where conventional models are not suitable.

Detailed research was carried out by (**39**) on a steel plant to investigate the feasibility of using model-based system in monitoring the condition of the plant and diagnosing faults. It was reported that for large plants that cannot be modelled precisely it is not feasible to develop a model-based diagnostic technique and if developed it may fail to diagnose faults as desired. Further, the author reported that rule-based technique was used to develop a diagnostic system for the plant and that the knowledge-based diagnostic system was found to be superior in performance to a similar system that was developed using model-based technique.

The paper did not consider the robustness of the model-based in comparison with the rule-based technique and it was clear that the author did not have an in depth knowledge of the steel plant, otherwise the model-based technique might have been selected instead of KBS. If plants are modelled using mathematical models then it is easy to simulate the changes in any of the parameters and investigate its overall effects. However, to model a plant satisfactorily it is necessary to have sufficient understanding of the plant in order to be able to model it using linear or non-linear models as appropriate.

4.7 Artificial neural network (ANN)

ANN can be used on-line to diagnose faults in process plants, and is particularly useful in non-linear applications. The training data for the ANN consists of pairs of symptom and fault. After the training is completed, the network will have classified the relationship between symptoms and their corresponding faults. Then, the trained ANN can be used to diagnose faults by associating any observed abnormalities with the appropriate faults. To utilize ANN in fault diagnosis, it is necessary to have a large amount of training data.

The ANN can also be used to diagnose multiple faults provided the network is trained to diagnose a single fault. The initial approach is dependent on the structure of ANN used, but basically an ANN can predict faults based on previously trained data. One advantage of ANN is that it is not necessary to know details of the process plant as long as the inputs and the outputs are known.

In certain applications including non-linear plants, it is recommended that in order to develop an improved fault diagnostic system based on ANN, the non-linear elements or the uncertainties in the plants are modelled using a combination of fuzzy models and fuzzy rules.

4.8 State transition diagrams (STDs) also known as Petrinets

This method is suitable for applications which involve a sequence of events which is the case when programmable logic controllers (PLCs) are used to control or monitor a sequence of industrial events.

The problems associated with these types of industrial applications can be traced on the dynamic display on a PLC screen. This screen illustrates the current state that the system is in and the next states. It is, therefore, used by technicians to identify the signal that has not been received and the technician can then trace the fault (**40**).

A comprehensive windows based Petrinet programme was developed by (**41**) to monitor the machining cycle of flexible manufacturing system (FMS). It has an editor which enables the user to develop custom made Petrinets, and an analyser which enables the user to sort out the communication between various Petrinets in addition to reading the desired digital hardware inputs necessary to drive them. Figure 5 illustrates an example in which a windows based Petrinet is used to identify a fault in the FMS.

It is expected that the programme will be used to develop a novel Petrinet programme to monitor and diagnose faults in a process system. A test rig is currently under investigation to develop an appropriate monitoring and diagnostic system.

5 APPLICATION OF PROCESS CONDITION MONITORING AND FAULT DIAGNOSIS

Consider Fig. 6, which is a typical arrangement for a supervisory monitoring and control system, in which a computer is used in a supervisory mode to monitor the process variables in this case: flowrate, temperature, liquid level and composition (ratio of fluid A and B).

The supervisory computer could be used to vary the set point of the single loop controllers as well as other parameters and display the real time and the historical trends.

Fluid A flows into the process tank via control valve 1(CV1) and fluid B is added to the tank via CV2. An agitator is used to mix the two fluids and produce a homogeneous mixture.

The temperature of the mixture is increased by allowing steam to flow through the outer tank and hence heat is transferred from the steam to the fluid mixture by conduction.

The fluid level in the tank is measured by a level transmitter (LT) and the measured value is transmitted to the level indicator and controller (LIC) to compare the measured value with the desired value (set point). The output of the level transmitter is simultaneously applied to the input module of the supervisory computer for monitoring purposes. A real time liquid level trend is displayed on the computer's screen.

The flowrate of fluid A is measured by flow transmitter (FT 1) and its value is displayed on the computer for monitoring the variation in the flowrate. If the fluid level and the ratio of the two fluids A and B in the tank reach the desired level set by the operator, then the position of the valves (CV1 and CV2) should be maintained by the controllers.

Consider the case where there is an internal valve leakage through valve1 (CV1), due to a damaged valve seat. Clearly this will allow more of fluid A to be added to the tank and the level transmitter (LT) transmits a signal to the level indicator and controller (LIC) while the LIC in turn transmits an action signal to the control valve CV1 to close the valve. If there is an internal leakage in the valve then fluid A continues to flow through it to the tank despite the signal from the controller to close the valve completely.

This will have at least two undesirable effects namely, an increase in fluid level in the tank and the ratio of fluid A with respect to B. The undesirable effects are observed on the supervisory computer's screen and an action can be taken to correct them. The time taken to diagnose the cause of the deviation may be too long, which may lead to financial losses and could cause a hazardous situation.

If, however, appropriate sensors and an internal valve leakage system were used to detect any internal valve leakage, then this kind of problem could be detected well in advance before causing any damage. An example of an internal valve leakage detection system could be AE sensor and signal processing system, which detects any internal leakage by comparing the signal spectrum produced at critical frequencies.

The AE technique together with a KBS could be incorporated in the existing SCADA system in order to reduce the costs. This could be achieved since the SCADA provides a large number of plant data for monitoring and control purposes. If these signals as well as those from the AE sensor are carefully integrated into a well designed KBS, which may include fuzzy rules, then internal valve leakage and other component faults can be diagnosed.

6 CONCLUSION

The study has outlined the significance of selecting appropriate condition monitoring techniques for a given application and new methods of monitoring critical process plant components. It is, therefore, feasible to install suitable sensors and data acquisition systems to detect and diagnose

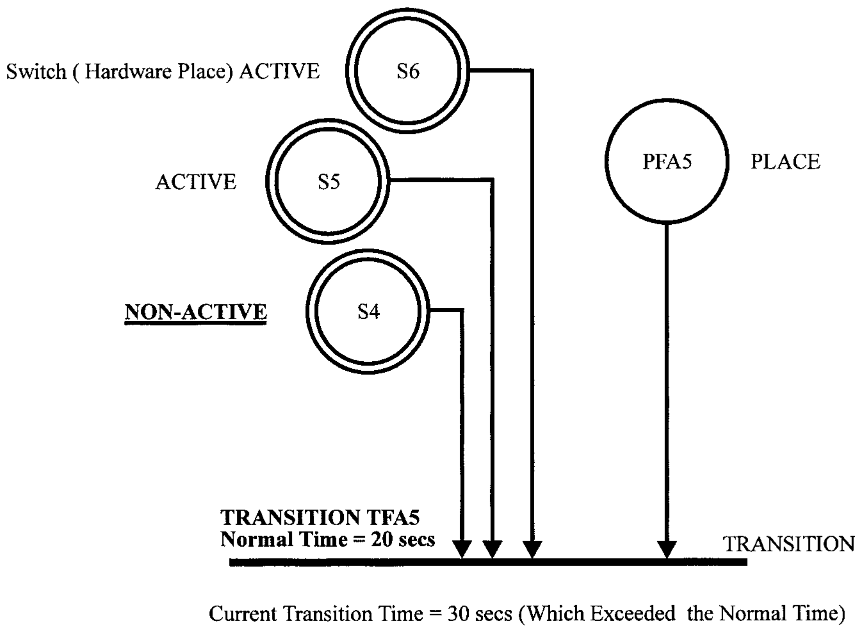
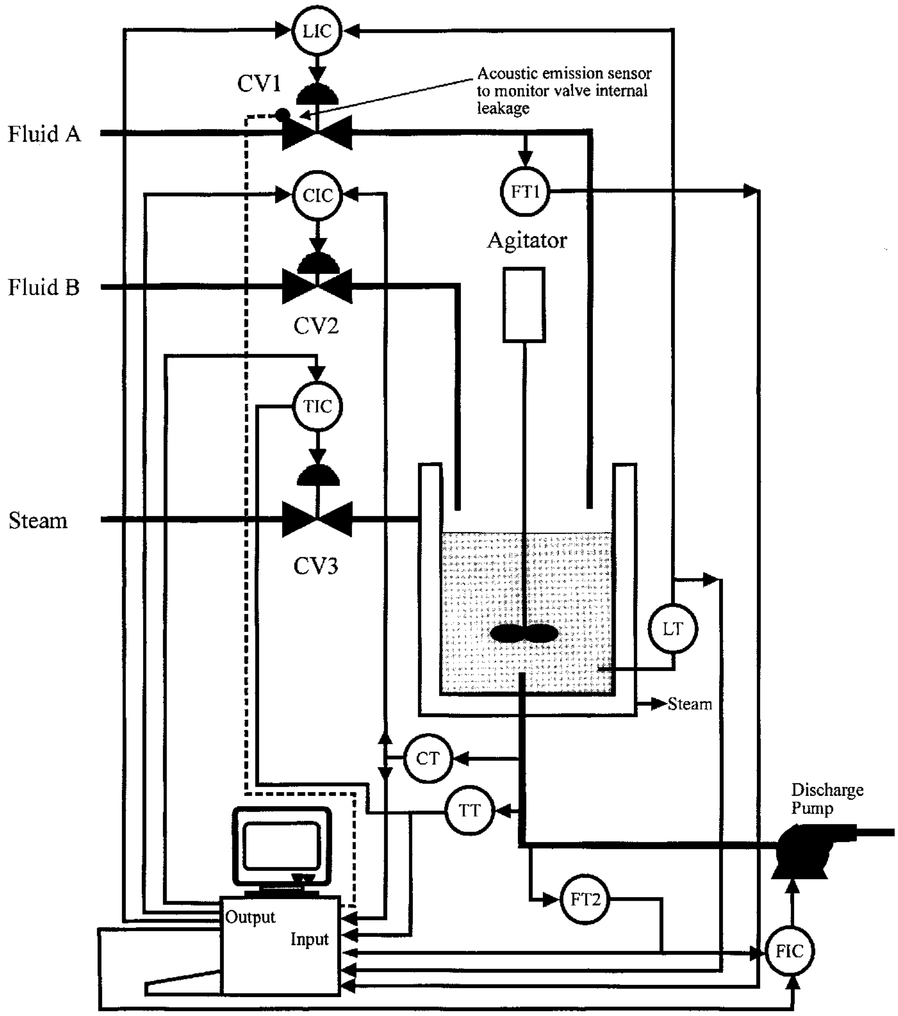


Fig. 5 Example of a Petrinet fault log template



TT : Temperature Transmitter
FT : Flow Transmitter
LT : Level Transmitter
CT : Composition Transmitter
TIC : Temperature Indicator and Controller
CIC: Composition Indicator and Controller
LIC: Level Indicator and Controller
CV1, CV2 and CV3: Control Valves

Fig. 6 Supervisory monitoring and control system

faults early, well before any irreversible damage is encountered.

It is recommended that the most appropriate techniques for diagnosing faults in critical plant components are the state transition diagrams (STDs) and knowledge based system (KBS). These methods together with the existing diagnostic software will be investigated further to develop suitable models for a typical process loop and diagnose critical faults more accurately.

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