Chapter 1

Introduction

1.1 Why Implement Condition Monitoring?

The rapidly changing industrial climate now almost demands that each facet of operation be closely examined with a view to, broadly, obtaining:

- the highest product quality
- efficiency optimisation
- improvement in the safety of operation
- maximum profitability

By way of an example consider a steel billet forging press system shown in Figure 1.1 with the hydraulic circuit schematic shown in Figure 1.2. These presses vary in complexity, particularly multi-axis systems, and the digital control approaches incorporate advanced monitoring and diagnostic support.

Considering one issue of many in such complex circuits, a pump failure will inevitably produce debris that could be carried to the press cylinders resulting in financially-damaging consequences:

- The cost of pump removal, pump repair/replacement, pump re-fitting is often tolerable.
- Main press cylinders can be up to 2 m bore diameter and the cost of replacement or refurbishment will be significantly higher than the pump and probably prohibitive in the case of a new cylinder; the cylinder may well be manufactured in another country with additional shipping implications. Whatever the course of action taken, a significant loss of press operation time will occur.
- Downtime losses in the case of a minor pump problem, due to material re-heating and lost production will still be financially damaging to the press operator.
- The loss of component supply to meet the demands of the end user could have consequential financial penalties to the press operator, and to a point that could be financially crippling.

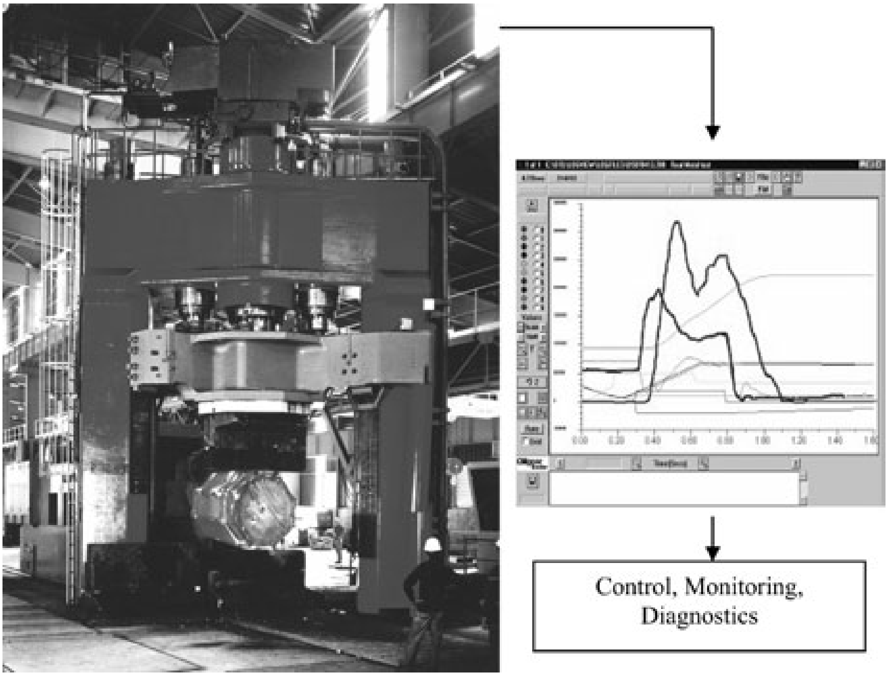


Figure 1.1. Forging press system (Courtesy of The Oilgear Company)

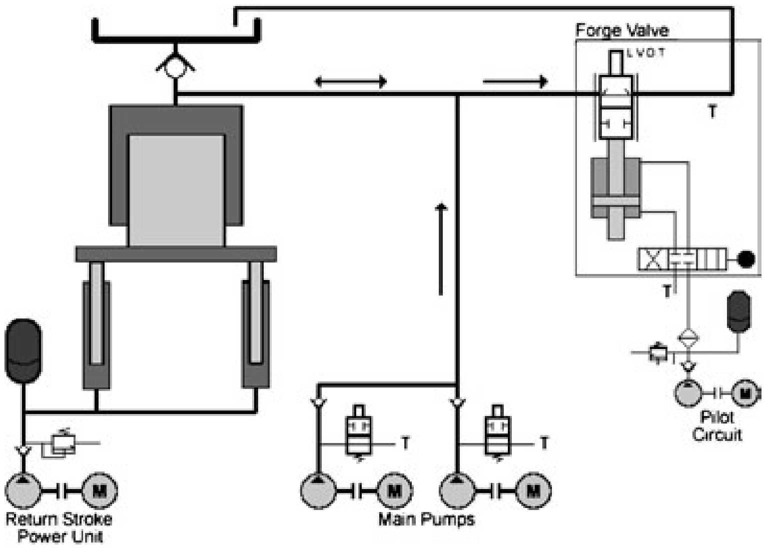


Figure 1.2. Forging press hydraulic circuit schematic (Courtesy of The Oilgear Company)

Clearly with systems such as this the main pumps must have specially designed debris filtering units to protect the circuit. Filtration is a key issue in fluid power and leads to perhaps the first rule for a hydraulic system:

> At the very least – provide adequate filtration and protect components from debris damage

Manufacturing profitability and efficiency are clearly connected, and in this context condition monitoring can play a vital part particularly when linked to a condition-based maintenance (CBM) policy. By monitoring the plant "health", potentially disastrous failures can be avoided, a corollary being that safety is also improved.

In addition to this, more information can be obtained relating to the plant operation, a by-product not always fully appreciated when embarking on a new monitoring venture. New, often unexpected, faults occur and information can often be acquired that contributes to improving the machine/plant operation. Unacceptable working practices can also be detected such as operating machines at incorrect speeds, sometimes near critical shaft frequencies. This is particularly aided by on-line computer-based monitoring where operators and technicians can readily see unacceptable trends.

The consequences of component failure, operator error, or lack of system integrity is sadly too well known in the public domain. Although the number of incidents are low when compared with the activity, the resulting loss of life is perceived as unacceptable when it occurs in areas such as air transport, chemical processing, and the energy supply industry. Condition monitoring and protection for safety-critical applications is now a necessity.

However, condition monitoring by itself will never eliminate major failures unless it is embraced within a "total quality" approach, particularly in industrial applications. This expression of total quality has evolved via the Japanese manufacturing industry and considers customer requirements, continuing education and training of the workforce and management, in addition to the technological aspects of the manufacturing operation. This total quality approach also appears under different descriptions such as Plant Asset Management and Total Product Maintenance, the latter representing yet another Japanese initiative in this field. Responsibilities are devolved to individuals as well as groups associated with areas of production.

Vast amounts of money, in some cases up to 15% of companies' sales, are spent maintaining assets. This clearly cannot be allowed to continue and Total Product Maintenance is proposed as a necessary approach to remain competitive in manufacturing industries.

There are various aspects that need to be considered ranging from the simplest of operator tasks through to advanced monitoring techniques and ease of maintenance when considering both existing and new designs. The simplest of tasks could be inspection for oil leaks, audible changes in noise levels or vibration, awareness of working temperatures etc., and these may be easily logged by the operator. Total Product Maintenance therefore represents an overall philosophy whereby all aspects are considered, success requiring a positive attitude from all concerned in the industry and with a high degree of motivation.

Another way of looking at a manufacturing operation is to study other companies with a view to defining the "Best World Practice". This may actually result in companies from different parts of the world agreeing to co-operate on such a scheme with reciprocal exchange arrangements being established. Once the Best World Practice has been defined, the company then examines its own procedures and then takes steps to improve where necessary. The paradox established by participating companies is of course resolved if they are supplying to different world markets and thus not in direct competition – this is now rapidly changing.

Modern industrial systems incorporating various subsystems tend to be highly interactive and hence a single component failure may have serious financial consequences. Condition monitoring is slowly replacing the common practice of regular preventative maintenance whereby components are replaced at pre-determined intervals before failure occurs – although it may not be impending. Even if the components are replaced there is a significant downtime with resultant costs and loss of revenue.

Failures inevitably occur at the most inconvenient time creating both technical, organisational and financial restrictions that could be minimised with condition monitoring. However, this suggests continual monitoring and a compromise has to be reached regarding whether it should be carried out hourly, daily, weekly or monthly. There is inevitably an element of experience required here since a manufacturing system could involve the monitoring of a large number of parameters resulting in a vast amount of data that has to be carefully analysed. This suggests the use of computer-based techniques, although there are now many powerful hand-held items of instrumentation that may well be the preferred option.

Fluid power systems often form a part of the total industrial operation and it is perhaps the area which is currently receiving the least attention, from a monitoring point of view. Fluid losses alone in such areas as mining and steel processing can result in hundreds of thousands of euros in replacement costs, apart from costs due to resulting failures or inefficiency of operation. It will therefore probably be consequential that fluid power systems will be monitored from the desire to initially concentrate on other components.

It is unfortunate that company boardroom decisions are often made on the basis of financial "payback" only, and this may be as short (or as sensible?) as 2 years. However, it is common experience, certainly that of the writer, that condition monitoring with its inherent "spin-offs" always exceeds the investment payback expectation.

When considering the cost of introducing CBM it is instructive to consider total maintenance costs as plant availability is improved due to reduced downtime resulting from the introduction of CBM. Figure 1.3 illustrates this point, in principle rather than detail, by the addition of reduced downtime costs with increased maintenance costs.

It follows from Figure 1.3 that increasing plant availability may well lead to increased costs at the higher end of the availability spectrum.

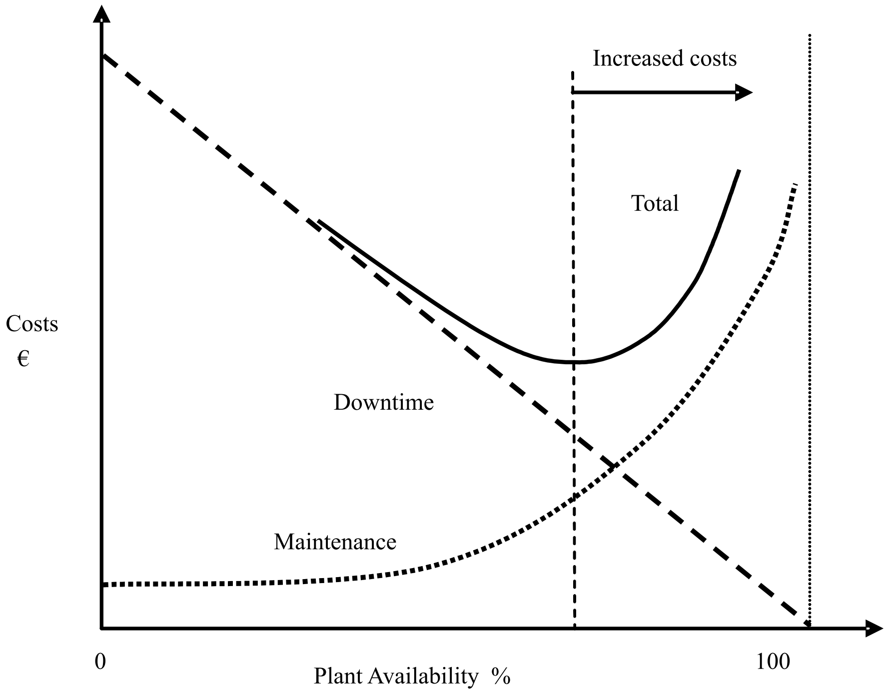


Figure 1.3. Maintenance/downtime cost variation

However, such a graph can only be derived by experience over many years of plant operation. The minimum cost point is also sensitive to individual cost fluctuations due to, for example, the current economic situation, world market share etc. Nevertheless, it seems to be common practice that companies continually strive to increase plant availability.

1.2 Three Maintenance Strategies

a) Breakdown Maintenance is the simplest of strategies to adopt since the plant is allowed to run without any rigorous supervision until it fails. Appropriate components are then repaired or changed on this ad hoc basis. This approach may actually be satisfactory for some subsystems such as a small pump circuit where often a standby pump is switched in, allowing the faulty pump to be repaired. Unfortunately there are more disadvantages than advantages of a breakdown maintenance approach when industry in general is considered. Some issues are as follows:

- Breakdowns often occur at the most inconvenient time creating undesirable disruption to operation.
- Mobile machine applications, for example, may result in considerable delay until replacement components are found, transported to site, and installed. This

is costly to the operating contractor and also introduces potential litigation costs, for example in large civil engineering operations such as road construction.

- The failure of a single component, for example a pump, can result in undesirable metallic particles being transported to other parts of the circuit and may cause further problems or even additional failures. This will almost certainly create high replacement costs.
- In a manufacturing system there will be critical components that need to be replaced quickly. This suggests that replacements must be held in store and represents an undesirable addition to capital expenditure.
- The replacement of a faulty component may not be carried out correctly. This can result in a further failure occurring rather more quickly than expected and is not helped by the absence of monitoring. This may be particularly the case for bearing and/or gearbox component replacements.
- Unexpected breakdowns may be a safety hazard in critical areas of operation and it may be necessary to install additional safety protection equipment or components which introduces additional costs.
- The maintenance effect/staffing will be irregular, and it is difficult to arrange a policy that utilises the manpower available and in an efficient manner. There will be a period of relative inactivity followed by a period of intense activity perhaps stretching the manpower resources available.

b) Preventative Maintenance represents a distinct improvement on breakdown maintenance. A strict maintenance schedule is established whereby components are replaced at pre-determined intervals, these intervals being established using a combination of manufacturers' data and operational experience. There can still be high costs associated with such an approach since the failure characteristic of a component can only be defined statistically. Figure 1.4 shows a typical failure distribution characteristic and illustrates three distinct regimes of totally safe operation, probable breakdown, and guaranteed breakdown.

Some important issues are as follows:

- Maintenance is planned in advanced, no matter what the plant condition is, and often the plant is shut down for perhaps one/two days in the case of a steel mill, such that the maintenance team (often sub-contracted) can be deployed.
- Clearly there are costs associated with premature replacement where breakdown will probably not occur. Components removed may still be functional and are often refurbished.
- There are also costs associated with a delayed replacement which, statistically, results in a higher system availability but with a potentially high breakdown cost.
- In situations where, in principle, failure is simply not allowed to occur, such as in aerospace applications, then the additional costs of premature replacement must be tolerated. In some applications this cost may be greater than that incurred due to a failure: experience must decide which approach is preferable.

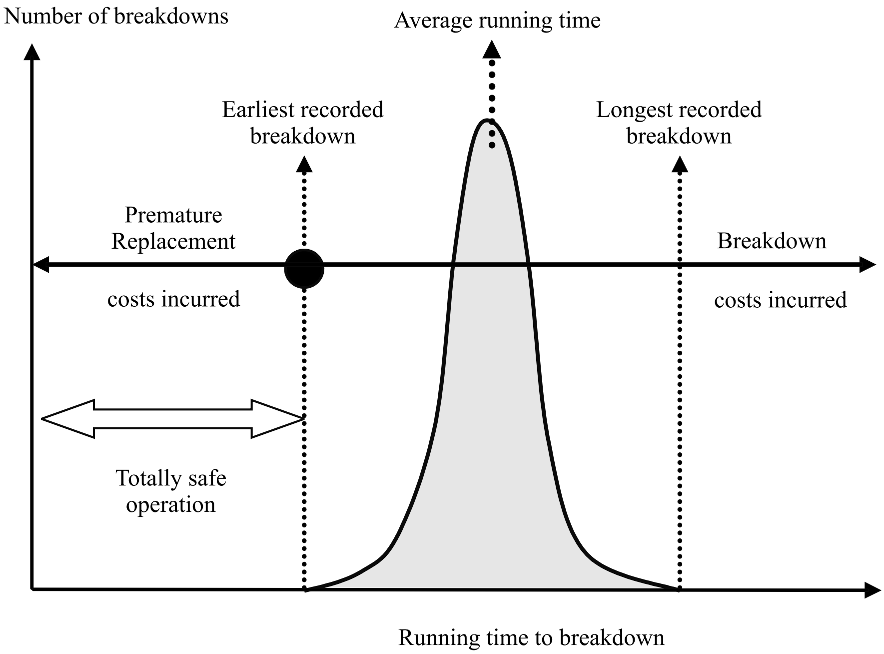


Figure 1.4. Typical component breakdown characteristic

- Experience, however, has also shown that the process of component replacement, often with a refurbished component that has previously been used, may lead to an unexpected premature failure. The reasons for this are varied, such as incorrect repair, oil contamination, incorrect re-assembly etc.
- However, there is no doubt that planned preventative maintenance is generally preferable to breakdown maintenance.

c) Condition-based Maintenance, incorporating condition monitoring with fault diagnosis in many cases, is generally now considered necessary for the optimum operation of modern plant.

- Condition-based maintenance involves the acquisition and analysis of data followed by some form of signal processing, further analysis and a decision-making policy. It may initially develop from the need to monitor just a few components, but inevitably it is expanded to cover complete systems.
- It is quite common for data to be obtained using hand-held instruments that are connected to appropriate test points around the plant. These may well be advanced electronic processing units where microcomputer technology has drastically reduced purchase cost. Data may then be transferred to a computer for analysis and trending of the appropriate parameter with operating time.
- On-line data acquisition provides the greatest flexibility since computer graphics combined with audible alarms make faults rapidly known to the operator.

Multi-channel systems are now commonplace and make the transition to on-line monitoring relatively easy to accommodate.

- The cost has to be carefully considered since computer hardware/software costs must be taken into account together with personnel training, system calibration and maintenance costs.

Consider, for example, the monitoring of a high-pressure axial piston pump. One parameter of interest is the case drain leakage flow rate, a natural feature of such a pump. A flow meter could easily be connected to the drain line when required and the flow rate could be checked to ensure that excessive leakage is not occurring. Figure 1.5 shows this set up with a possible measurement trend with time.

Some practical issues that need to be considered are:

- Experience will decide the flow loss value that indicates an unacceptable condition, the pump will then be removed and examined. A knowledge base is automatically developed and this allows fault indicator thresholds to be changed.
- A measurement such as this will not identify the cause of the increased leakage and more advanced measurements using pressure and/or vibration transducers

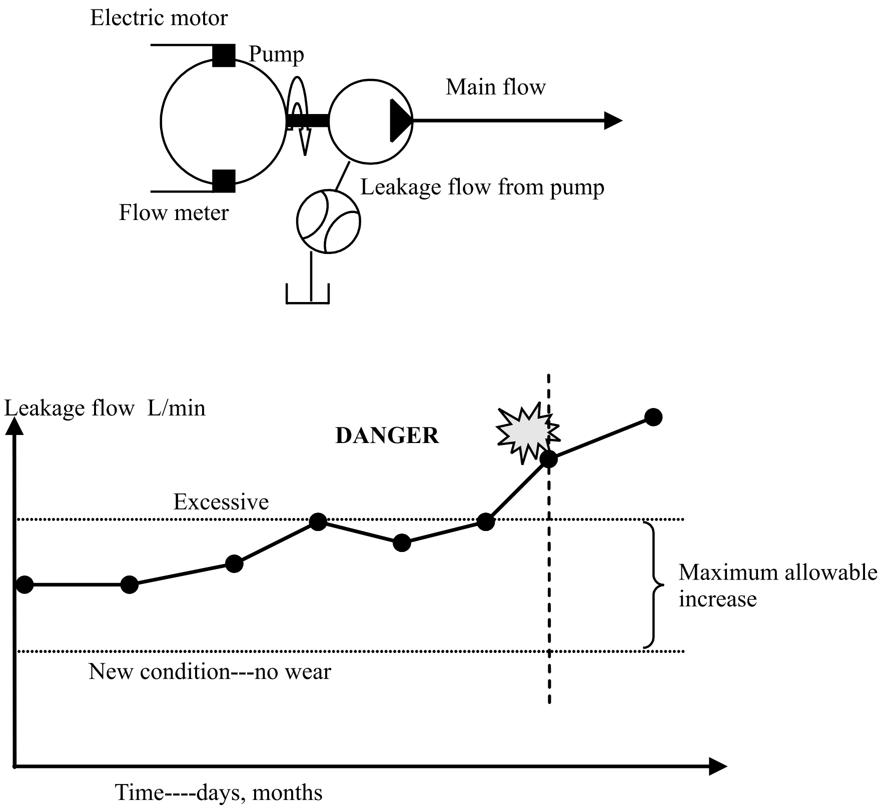


Figure 1.5. Leakage flow rate monitoring of an axial piston motor

together with oil contamination analysis may be necessary to pinpoint the actual fault.

- Off-line methods such as this are based upon cost effectiveness and the likelihood of the component failing together with additional consequences such as system failure and lead-time to repair.

To be able to make diagnostic predictions more measurements will inevitably be required thus increasing instrumentation costs and data analysis requirements. This suggests on-line monitoring with transducers hard-wired to a microcomputer which will have software written around the system in question. Pressure, flows, temperature etc., could be monitored and simply displayed on the computer screen with audible alarms being triggered as conditions deteriorate to a pre-determined unacceptable level.

More advanced on-line diagnostic applications are now implementing expert system concepts. Data is acquired in exactly the same way as previously described, and this data is then analysed using knowledge bases established within the expert system software. Various facts may then be interpreted using a set of rules that may be expanded as knowledge is gained from theoretical and operational experience. These are not explicit mathematical rules in the traditional sense as will be discussed later. An additional feature of this approach is that transducer integrity may also be checked in some cases since it cannot always be assumed that each transducer is indicating the correct parameter value.

Hence by incorporating a range of knowledge bases and analysis tools, a better estimate can be made of the system condition and the possible cause of a change in its condition. This is illustrated schematically in Figure 1.6.

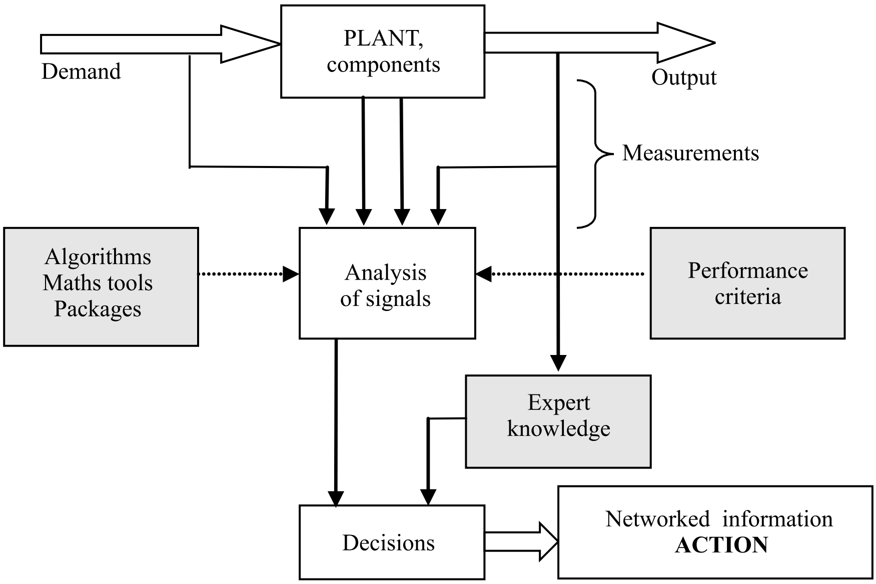


Figure 1.6. Expert system concepts for condition monitoring

1.3 Some Preliminary Conclusions

Some clearly defined steps may now be established when condition monitoring is being considered:

- The monitoring of complex fluid power systems will require some knowledge of the way components behave in that system. This may require characteristics and the way they change as components wear or, for example, as leakages occur between them.
- Understanding the performance of a system implies good design and the ability to predict the performance using appropriate computer software or CAD techniques.
- It is also important at the design stage to build appropriate monitoring points into the system so that sensors may be fitted at the building stage or later during operation. Sensors may therefore form a permanent feature or may simply be fitted when required if portable monitoring equipment is used.
- A monitoring strategy must be established together with presentation of data best suited to the application.
- It should be stated that whatever approach is adopted, there is generally no quick-and-easy solution to condition monitoring and fault diagnosis when applied to a large manufacturing plant.
- A range of techniques is available, some embracing advanced information technology. Commitment to detail is still required for technical, operational and management aspects.
- Improvements should be continually sought and it should also be realised that the dramatic improvements made by industry in recent years have not been instantly achieved. Investment payback can be as little as a few months, as experienced by the author, but may well be two to three years before the benefits of a new investment are fully realised.
- It has been suggested that an investment of typically 1% of the capital value of the plant is required, perhaps rising to 5% where safety risks must be eliminated.

1.4 Potential Benefits of CBM

There are many potential benefits of condition-based maintenance that have emerged over recent years, and may be broadly classified as follows, and not in any order of significance:

i) Reduced repair time and costs

- In some cases up to 80% reduction
- Labour and parts costs reduced with advanced knowledge
- Planned repairs less prone to problems than hurriedly-done repairs

ii) Improved plant operational knowledge

- Monitored data tends to reveal new fault information
- Monitored data can reveal incorrect plant operation due to either deliberate operator mis-use or the plant running at near-critical conditions

iii) A maintenance cost saving

- In some cases spares inventories have been reduced by up to 30% since advance warning allows just-in-time purchasing
- Priority action only on machines that need repair
- Actual number of failures reduced
- Planned maintenance reduced or possibly eliminated
- Reduced downtime hence reduced costs
- Maintenance teams arranged in advance and to suit the work needed

iv) Minimised revenue loss

- Impending failures detected and tracked, repairs carried out at a convenient and planned time
- Plant availability maintained or improved
- Revenue may actually increase with evidence of as much as 30%

v) Maintained product quality

- Monitored process parameters allow intelligent strategies to maintain product quality
- Causal effects on product quality changes can be tracked

vi) Improved plant life

- Serious damage avoided or minimised
- ‘Knock-on’ effects of damage transferred to other components avoided
- Longer running times for components normally changed under a planned maintenance scheme gives extended plant life

vii) Improved safety assurance, reduced personnel risk

- Data available to show improved performance, particularly on safety-critical aspects
- A demonstrable safer working environment gives added confidence to personnel
- Hospital and litigation costs reduced
- Improved safety assurance leads to minimised insurance premiums

viii) Improved plant design and operation

- CBM often produces much more information on plant behaviour and which parameters are crucial to efficient plant operation. This can often be valuable to the system designer and may lead to improved designs
- The monitored performance may also lead to improved ways of actually running the plant. In addition, the new databases developed can indicate whether or not unacceptable operating conditions are being approached

ix) Maintained customer relationship

- Maintenance of supply ensures customer satisfaction
- Maintenance of product quality aids customer satisfaction

1.5 Benefits Applied to Plant Economics

Output revenues, estimated over the plant life, must be compared against initial capital investment costs and daily operating costs as shown conceptually in Figure 1.7. Inflation, market price changes, revenue changes, planned scheduled maintenance, over the operating plant life has been neglected.

The effect of plant downtime is shown in Figure 1.8 and it can be seen that there are two major aspects, increased total costs and lost production revenue. Note that the lost profit interval is much greater than the downtime interval.

Once production has been lost, the investment return for the process can only be regained by either improving efficiency and/or extending plant operating life.

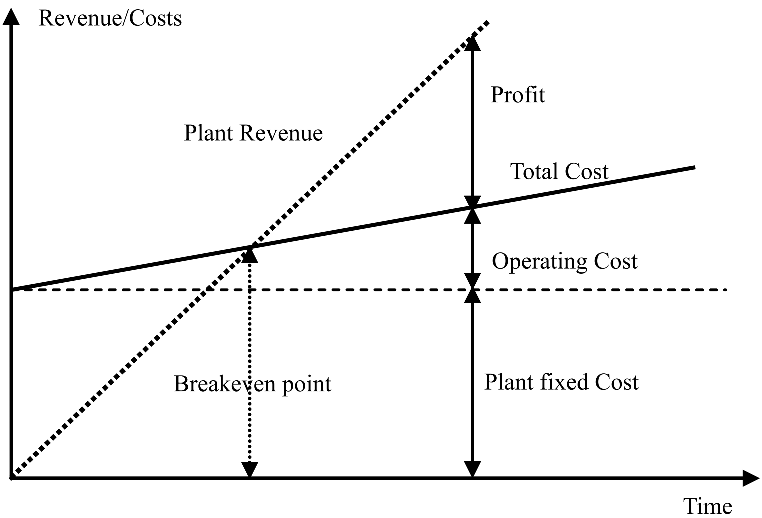


Figure 1.7. Ideal plant economics

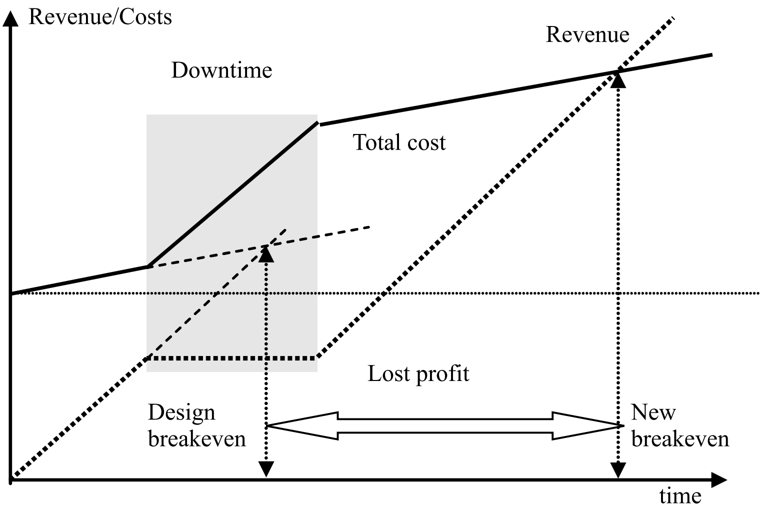


Figure 1.8. Effects of downtime on plant economics

A condition monitoring approach will then probably be crucial in meeting these new objectives.

There are many other issues to be faced at the same time such as switching to other production systems, the use of outside contract work, logistics of maintenance, all of which must be judged against a possible further downtime occurrence at a later date.

1.6 Types of Condition Monitoring Systems

The selection of the correct data acquisition approach is important and a number of possibilities exist depending on the complexity of the plant and the projected investment cost perceived as appropriate to the new condition monitoring strategy.

i) On-line multi-point systems

These are the most advanced data acquisition and signal processing systems and are usually 'hard wired' to the plant. These systems have the highest investment cost but offer a great deal of flexibility both for extending the number of monitoring points and adding new software fault diagnostic techniques. Computer terminals can be placed in appropriate plant offices giving direct access to a number of personnel. Fast transients may be captured allowing modern signal processing and identification to be used. Multi-point measurements are usually multiplexed to minimise cost.

ii) Surveillance systems

Data are again acquired on-line but the signal processing time is not so significant as with high-speed systems. They tend to be single-component dedicated systems (for example a tank level measurement), with high integrity, relatively low cost, and probably also hard-wired to the central monitoring system.

iii) Manual data collection systems
Data are acquired by handheld units from either single transducer monitoring points or multi-channel collection points around the plant. These handheld units can contain as much advanced processing power as many on-line computer systems and are capable of advanced diagnostics as well as simply recording quasi-static information such as temperatures, mean noise levels, etc. They can also be programmed to indicate the site route and which monitoring point is next on the route.

1.7 Methods of Condition Monitoring

Sensors are continually being developed, but the approaches may be broadly classified within the following areas:

i) Human – the senses – hearing, smell, touch (for example, temperature, vibration), are still quite common but based upon experience of working alongside the equipment or plant. Most of these "senses" may be replaced by "sensors".

ii) Steady-state measurements – changes in speed, torque, pressure, flow rates, temperature, vibration/noise dB readings, shaft alignment via laser measurement, etc. Process "outputs" such as product quality, throughput etc.

iii) Dynamic signal processing

- **Frequency analysis**
  A signal is analysed in terms of its frequency content allowing specific characteristics to be identified, usually from expected values such as rotation frequency of a machine. If the level increases at that known frequency then a changing condition is assumed. Vibration, in particular, may be measured with either accelerometers or acoustic emission sensors. In all cases, signal processing algorithms are required to convert the time signal into its frequency components. The usual method is to use the Fast Fourier Transform (FFT) algorithm. This is now standard software used in vibration measuring systems – simply measure and plot the results.
- **Time domain analysis**
  Methods are now available to actually characterise the time-varying signals. For example, step response tests or frequency response tests are well known from control theory, and apply to situations where known disturbances are applied and the output measured. However, new methods can work on the small fluctuations naturally occurring, and an important technique here is Time Encoded Signal Processing (TESP) analysis. Recent developments now embrace Artificial Neural Networks (ANNs) for data classification.

iv) Wear debris/fluid contamination analysis – particles are generated under wear or fault conditions, and any increase in particle generation rate down to micron size levels can now be detected either on-line or by sampling off-line. Also, the particle type can be determined to indicate from which part of the machinery it probably originated.

v) Fluid leakage detection – this may be simply visual. More advanced approaches will use on-line flow sensors or other sensors, such as pressure, which may serve to indicate flow losses via further systems analysis.

vi) Thermography – this is quite an expensive "camera" technique that converts the radiation spectrum into a colour coded pattern using infrared detection. It is a valuable tool for hot-spot detection, particularly in large-scale production systems utilising high-energy machines and processes.

vii) Corrosion – this occurs, for example, due to either:

- environmental effects
- internally within fluid components (such as pumps/pipelines, control valves etc.) due to chemical effects
- due to combustion chemical reactions
- bacteria effects, particularly in water-based fluids

viii) Erosion of a material can also occur due to localised fluid cavitation effects:

- Cavitation must be minimised by careful component and systems design, and it may be necessary to monitor a component if cavitation could be a problem.
- Sensors, particularly acoustic/stresswave, may be used for detecting incipient cavitation.

1.8 Failure Modes and Effects Analysis (FMEA)

When considering a large plant operation, with its inevitable distribution of faults, a methodological approach is required that seeks to prioritise the order in which faults are investigated and resolved. The FMEA approach does this by combining carefully considered fault data and the experience of the plant operations team. It is a process requiring continual investigation and action, and often leads to improved knowledge about the behaviour of the plant. The FMEA process in practice is typically as shown in Figure 1.9.

The FMEA method is a structured approach to fault diagnosis, fault correction, quality improvement, and has the following main advantages:

- it aims to recognise and evaluate the ***actual*** and ***potential*** failure modes
- it aims to recognise the cause of the failure modes
- it identifies sections that could eliminate or reduce the chance of failure
- it documents the corrective process

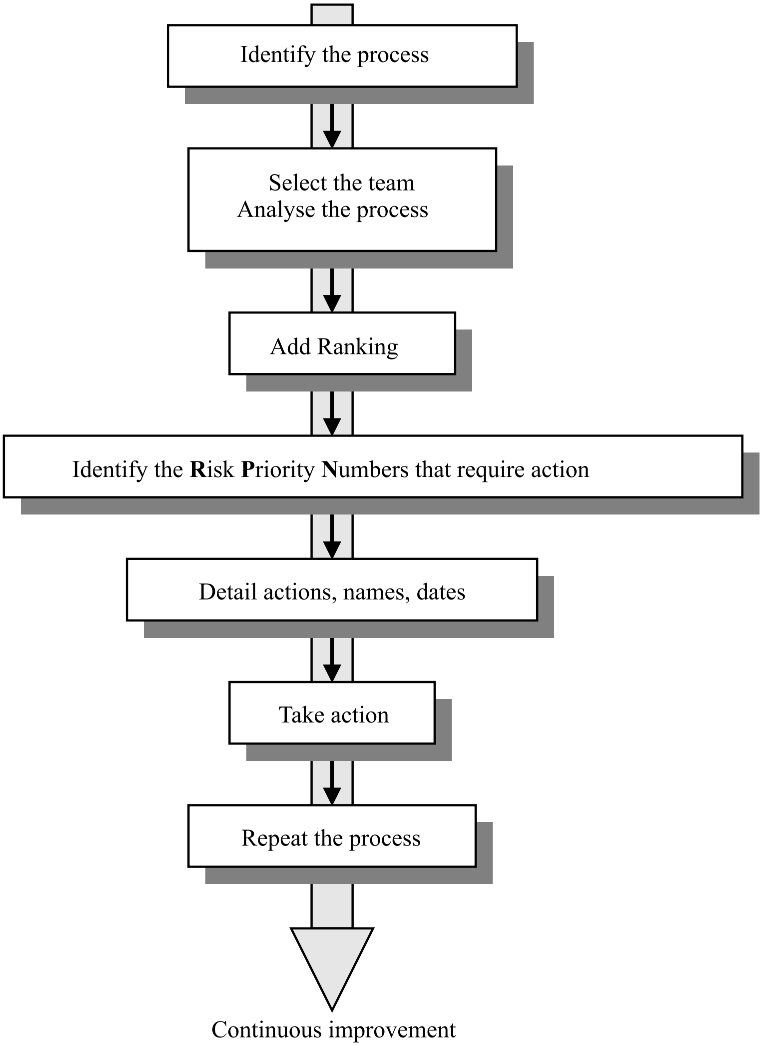


Figure 1.9. Essential steps in the FMEA approach to fault prioritisation

Now consider some details of the FMEA process:

i) Potential failure modes

It is important to continually ask the question – "what can go wrong"? It is also important to recall two key aspects:

- A potential failure mode is the way in which a process ***could fail*** to achieve objectives defined in the process description.
- What are the ways it might fail ***not just the ways it has failed***.

ii) The effects of failure

What happens when the failure mode occurs?

- Effects could be defined as the effects on the customer, i. e. what they may notice or experience as a result of the failure mode when considering "output".
- Alternatively for system design, effects may be just the implication on the manufacturing process itself – perhaps the first steps for CBM.

iii) Potential causes of failure

- Define how the failure mode could occur.
- List every conceivable failure cause possible for each failure mode.

iv) Current Controls

These are the controls that either:

- prevent the failure mode occurring
- detect the failure if it occurs

v) Delta

This symbol is used if a potential failure mode has **Safety Implications**.

vi) Risk Priority Number RPN

This is the crucial FMEA indicator that ranks the severity of failure for the process. It is calculated as follows:

$$\textbf{RPN} = \textbf{Severity} \times \textbf{Occurrence} \times \textbf{Detection Rank}$$

The highest RPN is most significant and indicates where action is a priority. The RPN is continually evaluated as the process operation becomes more refined and of course improved.

vii) Severity

1 Of minor nature, not detectable.
2, 3 Will probably be noticed.
4, 5, 6 Causes some dissatisfaction, degradation of further processes.
7, 8 High degree of dissatisfaction and affect on further processes.
9, 10 Very high degree of dissatisfaction and severely affects further processes, safety critical areas.

viii) Occurrence

1 Remote, failure unlikely.
2 Very low.
3 Low.
4, 5, 6 Moderate, experience shows that the process occasionally fails.

7, 8 High, experience shows that the process often fails.
9, 10 Very high, failure almost inevitable.

iv) Detection
1, 2 Very high, failure almost certainly detected.
3, 4 High, good chance of detection.
5, 6 Moderate, may detect failure.
7, 8 Low, poor chance of detecting failure.
9, 10 Very low, no detection.

Consider an example taken from an actual manufacturing plant that represents just a 27-week FMEA study during which 18.3 hours of delays were recorded for the process operating 24 hours per day and 7 days per week. Data for this study are as follows:

		Downtime (min)	**Downtime (%)**	**Occurrence**
1	Hydraulic leaks	780	70.9	7
2	Loss of control	130	11.8	2
3	Servovalve failure, unstable, vibrating	50	4.5	2
4	Failure of actuators	15	1.3	1
5	Failure of pressure transducers	40	3.6	1
6	Cooling water pump failure	25	2.3	1

Problems associated with hydraulic leaks would appear to be the obvious priority area with perhaps loss of control following. However, a more detailed FMEA approach is needed to consider occurrence, severity, and detection rank as previously outlined.

Analysis of the faults leads to the following points:

- Faults **1, 2, 3** contribute **87.2%** of the downtime recorded.
- In the case of unstable control systems, the working life of the actuators can be reduced as seals wear at a higher rate. In addition hydraulic oscillations are undesirable when product quality is considered.
- The pressure transducer's life span is reduced when continuous pressure oscillations occur, and the zero pressure calibration often suffers.
- Oscillations lead to increased wear of servovalve components. This also occurs if the oil is contaminated with particles or with water if seals fail and allow process water into the hydraulics.

Severity, Occurrence, Detection, and the **RPN** are assessed by the FMEA team as follows:

		Severity	Occurrence	Detection	RPN
1	Hydraulic leaks	8	7	8	**448**
2	Loss of control	10	2	1	20
3	Servovalve failure, unstable, vibrating	10	2	8	**160**
4	Failure of actuators	8	1	9	72
5	Failure of pressure transducers	10	1	9	90
6	Cooling water pump failure	10	1	1	10

Action on **leakages** as the **first priority**
Action on **servovalves** as the **second priority**

These key actions should be implemented by the appropriate maintenance team and the plant performance re-evaluated at the agreed operating interval. Of equal importance is the assessment of the monitoring methods and whether improvements or new installations are necessary to minimise, hopefully eliminate, future plant downtime.

1.9 Correcting the Fault – Fault Tree Analysis

Having determined the most significant fault and taken action to replace the component or subsystem, an equally important requirement is to determine the cause of the fault. This can be a complex interactive problem in fluid power systems and a systematic method of cause and effect is needed to aid the action.

Fault Tree Analysis can help here in the sense that it provides a logical approach providing that all possibilities are included.

One approach, for example, could be to consider the observed characteristic of the deteriorating system and then work through the fault tree to determine the most probable cause of the fault. The concept of basic fault tree construction is shown in Figure 1.10, which illustrates just the beginning of a particular application.

The fault tree shown is by no means complete or definitive, but does suggest that expert input is needed to ensure that the major problems and means of correction are covered. Equipment manufacturers often provide manuals to aid this procedure prior to return for specialist analysis or repair. The systematic fault detection procedure can often be particularly advantageous in identifying not only component deficiencies but operating malpractice.

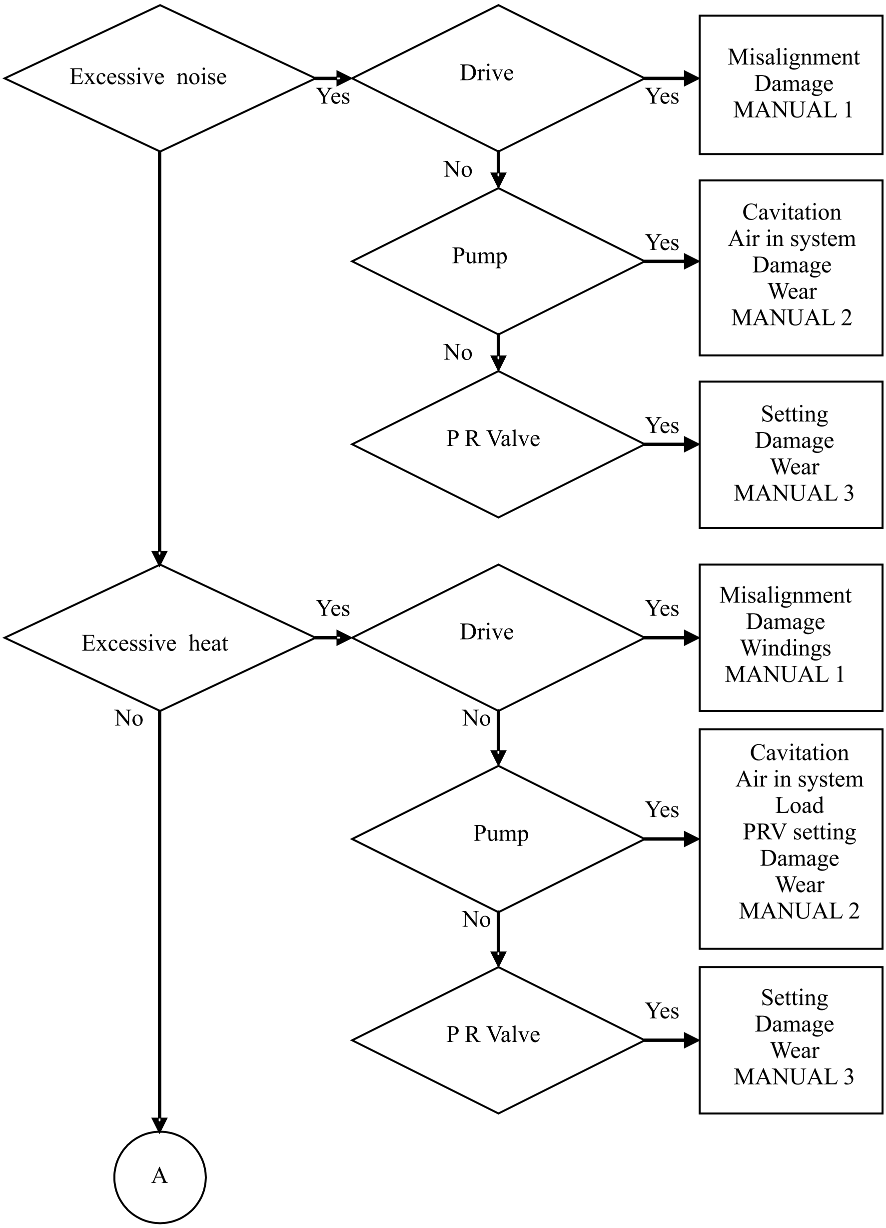


Figure 1.10. Development of a fault tree for diagnostics

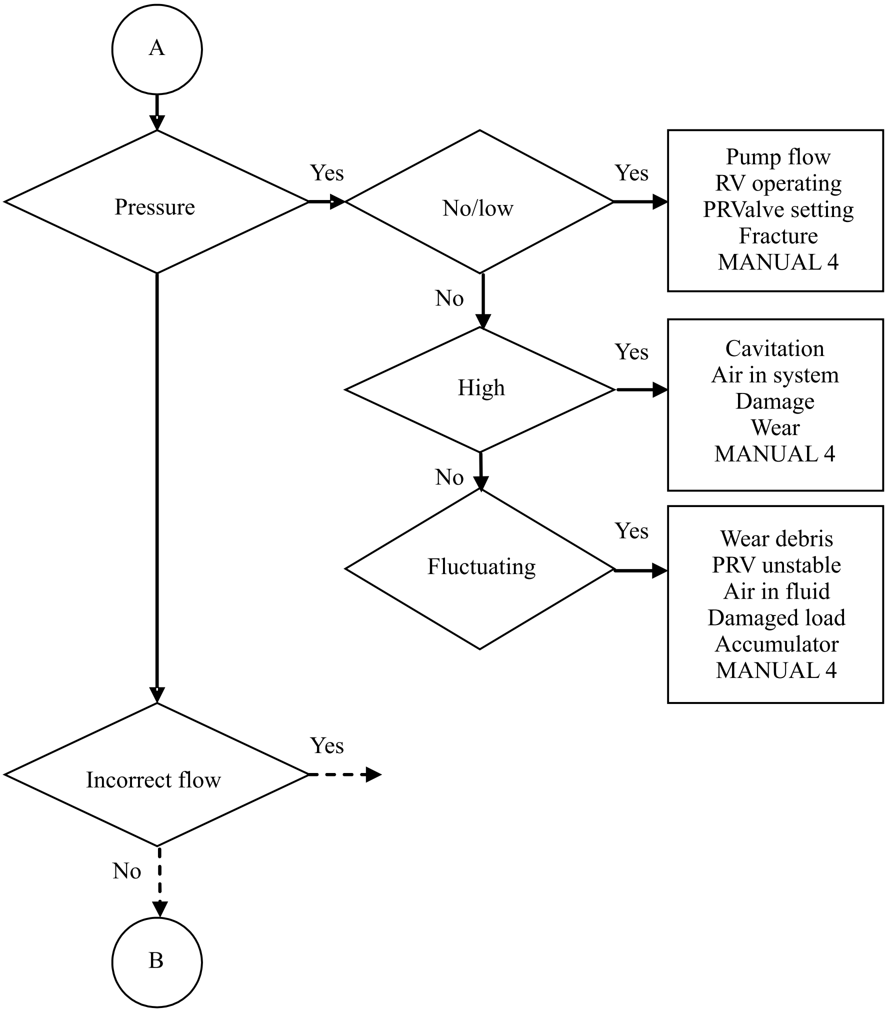


Figure 1.10. (continued)

1.10 Computer Simulation as a Fault Synthesis/Detecting Tool

The concept of a computer model-based approach to fault systhensis and/or detection is attractive but of course it does require sufficiently accurate component models. The understanding of both the steady-state and dynamic behaviour of fluid power components dramatically increased during the second half of the 20th century to date. However, one issue is simply the vast number of components on the market. A particular component, for example a pressure relief valve, has many variations of operating concept, size and slight design changes between each manufacturer. There is value in the approach for a particular industrial system that uses the same standard component replacements and where a good system model has been developed from extensive theoretical and experimental testing.

What does make the approach worth pursuing is also the ability to simulate faults and observe changes in system behaviour in a manner that simply could not be achieved in practice, for example pipe leaks. It is also particularly useful if system parameter changes, resulting from a fault, are measurable easily in practice. Some important features of a computer model-based approach are as follows:

- A fault may result in a change in steady-state pressures, flow rates, torque, speed, force at other points in the circuit.
- The steady-state energy distribution might be different at other points in the circuit and implies measurement of (force.distance), (pressure.flow rate), (torque.speed), (voltage.current).
- The dynamic performance may change, which implies the use of fast-acting transducers in practice to track such changes for a particular actuation sequence that is often used.
- A post-operation matching technique may be used whereby parameters in the computer simulation are changed in some statistical sequence such that the computer model behaviour emulates the practical system behaviour in the presence of a fault.

Perhaps the most obvious approach is to consider the steady-state behaviour of a system in its normal operating mode and with various faults. Changes in performance parameters may be deduced either by experience or from a well-developed and sufficiently accurate simulation model. For example consider the valve-controlled hydrostatic transmission shown in Figure 1.11 which was studied by Bull et al. (1997). In this study bond graph concepts were used to determine the particular parameter that best defines the energy fluctuation within the bond graph. An algorithm was developed to deal with qualitative behaviour and the associated energy storage and resistive elements representing losses due to leakage, friction, etc were included in the bond graph for steady state conditions. The outcome is a failure mode identifier such as “supply pressure up”, “supply pressure down” etc. The first stage of this analysis method is to identify the potential failure modes and this can be done using the bond graph dynamic model. By considering faults, the power fluctuation is propagated around the circuit and the rules developed result in, for example, the concern for the motor which identifies a drop in speed.

In this way a failure mode table can be generated such as that shown in Table 1.1. Such a table depends upon the choice of a sufficiently significants failure level injection and it may well evolve that different faults create the same failure modes as evident from similar parameter changes. It was noted that fault simulation times were typically of the order of 1 second. The result of such an analysis may then require a more detailed investigation, for example via a complete dynamic simulation.

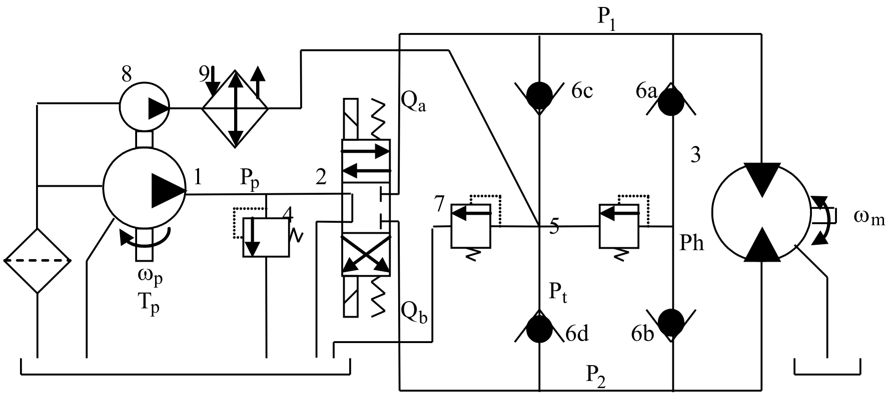


Figure 1.11. Valve-controlled hydrostatic drive [Bull, Stecki, Edge and Burrows, 1997]

Table 1.1. Failure modes and effects on the hydrostatic transmission

	Effect					
Failure Mode	T_p	ω_p	P_p	Q_a	Q_b	ω_m
Pump shaft slows down	up	down	down	down	down	down
Pump pressure falls	down	up	down	down	down	down
Pump pressure increases	up	down	up	up	up	up
Directional valve partially open	up	down	up	down	down	down
Increased friction in motor	down	up	down	up	down	down
Reduced line pressure	down	up	down	up	down	down
Reduced flow in RV 4	down	up	down	up	down	down
Increased flow in RV 4	up	down	up	down	up	up
Higher pressure in RV5	up	down	up	down	up	up
Lower pressure in RV5	down	up	down	up	down	down
Higher pressure in RV7	up	down	up	down	up	up
Lower pressure in RV7	down	up	down	up	down	down
Reduced flow in check valve 6a	down	up	down	up	down	down
Reduced flow in check valve 6b	down	up	down	up	down	down
Reduced flow in check valve 6c	down	up	down	up	down	down
Reduced flow in check valve 6d	down	up	down	up	down	down

The complexity of the dynamic modelling approach can be appreciated, for example, by considering the hydraulic circuit of a forging press control system similar to that shown as Figure 1.1. Consider one press concept shown schematically in Figure 1.12. Such a press usually has retracting cylinders in addition to the

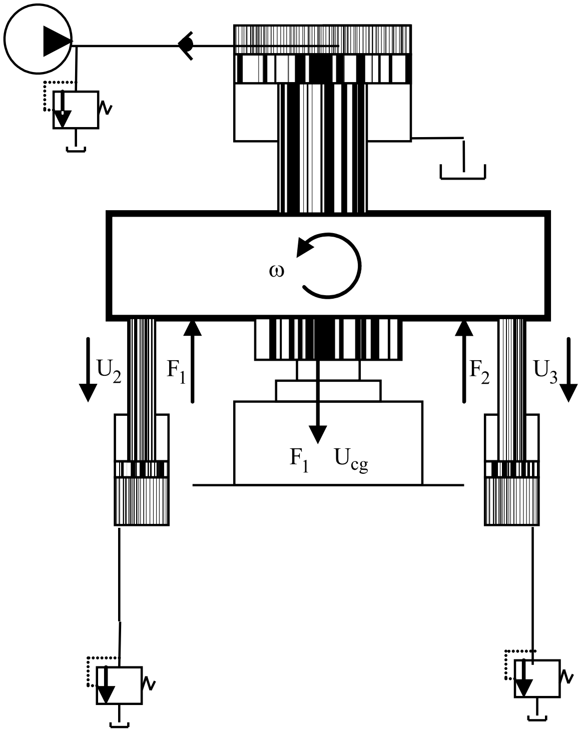


Figure 1.12. Press system schematic in its ready-to-press mode

main press cylinder/s. Also the multiple-pump units are often positioned some distance away from the press with distances that can be more than 100 m.

Such systems have a complex sequence of actions and safety procedures and in the mode shown in the schematic Figure 1.12, the two retracting cylinders are holding the press moving mass at rest via the pressure relief valves. The main pump sets are then switched in to initiate pressing.

For the pressing mode shown, long lines significantly contribute to the system dynamic behaviour and are reflected as the dominant frequency component in the measured press cylinder pressure. Therefore in this application transmission line modelling is a crucial aspect with three lines being in operation.

Press position is usually a smooth characteristic as a consequence of the filtering effect of the large press cylinder volumes. System damping is provided by the pressure relief valves and the large-diameter lines, often with turbulent flow conditions, but the main pressure can have fluctuations during pressing compared with the retracting cylinder pressures, and due to transmission line effects. The main lines do not always have pressure relief valves in operation but the retracting cylinders do have pressure relief valves in operation during pressing. Note that a check valve is often placed in the main press line and this can be designed to improve damping at the cost of a small pressure drop. However, this is not the normal procedure for check valve operation. Any frequency modes from lines and/or fluid volume/moving mass contributions are expected to be low for this type of system.

Computer modelling issues that then have to be addressed are:

- pump flow and controller characteristics
- transmission line dynamics and for large-diameter lines probably with turbulent flow
- very large compressibility flows have to be accommodated
- pressure relief valve, servovalve, directional control valve dynamics and nonlinear flow characteristics, often at very high flow rates where experimental validation is difficult and expensive
- material forging force/displacement properties
- press motion and deformation, force and moment equations
- press control techniques, for example to minimise rotation if off-centre forging is to be done
- cylinder friction forces are difficult to assess for very large cylinders, but they must be included for pressing modes where pressure relief valves are not in operation

The use of dynamic data may be difficult for condition monitoring of such large force systems, but a comparison of pressures, positions, angles, etc. can prove useful when oscillations have decayed and the press is still moving.

Consider, for example a computer model using modelling concepts previously discussed. In this application a pressing force of 22.5 MN is being generated and with rotation angle (Proportional + Integral) control using flow bleed control valves. It is useful to first construct a simulation flow chart to link and thus organise each modelling aspect, and in this example, Figure 1.13 illustrates such a flow chart. Figure 1.14 shows the press performance under normal operation and with a fault at the P + I controller. In this particular example, for this case of controller failure, the dynamic element of performance has not significantly changed. The frequency component is unchanged and there is negligible variation in the press tool position characteristic. However a drift in angle is evident indicating a suspected fault at the controller.

Other fault conditions must of course be studied so that the correct fault prognosis is made. Rapid progress is being made in such computer modelling approaches but more effort is needed to compare simulation models with practical results particularly for very large systems. The next chapter aims to briefly present some of the underlying background theory for modelling components.

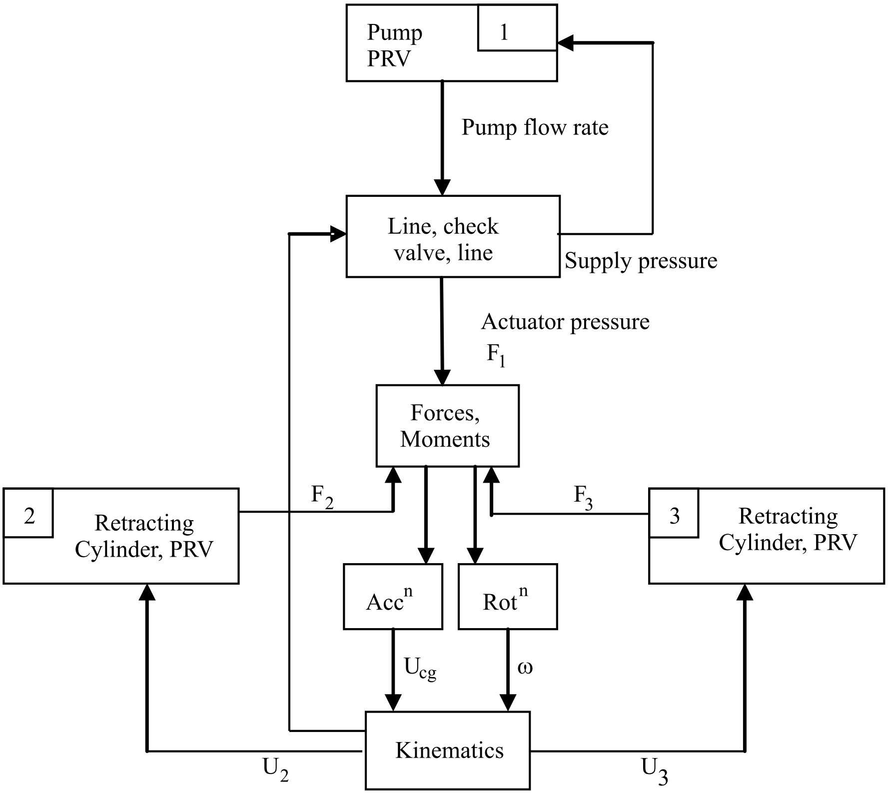
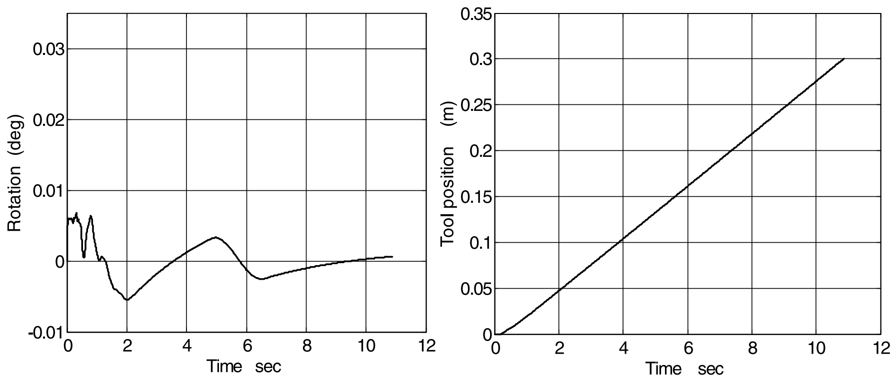
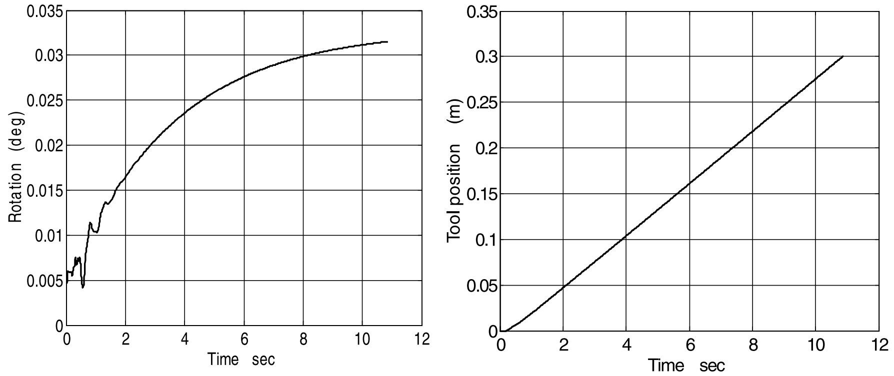


Figure 1.13. Computer modelling flow chart



a) Normal operation



b) Fault at the P + I angle controller

Figure 1.14. Press performance under normal and one fault condition

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