Design and Steady-state Analysis of Hydraulic Control systems

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Abstract: *Modern hydraulic power and control systems must meet increased user expectations of high quality system performance, reliability and long life. To meet these expectations engineers involved in design and manufacturing these components and systems, as well as users, should have a good knowledge and appreciation of hydraulic technology. This book fills the gap in fluid power literature by providing both theoretical and practical information on how to carry out steady-state analysis of hydraulic control and power systems. Although it is primarily aimed at final year students in mechanical engineering courses and postgraduate student working in the area of fluid power, it will also be useful to practising engineers as it contains over 70 solved examples of typical hydraulic systems used in industry. The first chapter deals with the general topic of system design. Each of the following chapters provide a short introduction to steady-state characteristics of basic hydraulic components e.g. pumps/motors, valves, and then illustrate application of steady-state analysis to hydraulic systems which incorporate these components. The last chapter provides general guidance, again illustrated by examples, to selection of system components, calculation of pressure losses and thermal conditions in a system. The book consist of 280 pages and contains 152 illustrations.*

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Preface

Modern hydraulic power and control systems must meet increased user expectations of high quality system performance, reliability and long life. However, experience with many industrial and mobile systems shows that in many cases hydraulic systems do not meet these expectations. This is not surprising as in many such cases the design process is manual and intuitive and thus it is very much dependent on the level of design competence, knowledge of hardware, and thorough understanding of the physical laws governing the operation of the system. Experience of the designer also plays a large part in the success of the design, although the advantage of previous experience is lost when a new application is radically different or operates under different operating conditions. Thus, in many cases the design of a new system based on accumulated experience with similar systems will result in a system which will operate satisfactorily but not necessarily in an optimal way.

As is true for any design, the design of a hydraulic system should be an iterative process involving synthesis (concept development), analysis (check of system steady-state and dynamic characteristics) and physical testing. In practice, with the exception of complex e.g. aeronautics, military applications, system synthesis is seldom followed by a steady-state and dynamic analysis of the complete system. Relative and often deceiving ease with which a hydraulic system can be assembled from components selected from available manufacturers' catalogues often lead designers to indiscriminate decisions. It is often forgotten by the designers that a system build of "perfect" components will not necessarily perform perfectly! Thus many industrial and mobile systems, some in critical applications, are designed, built and commissioned without a deep understanding of how the system operates and with disregard, based on ignorance, of dangers involved.

The above problems are mirrored in an academic environment where fluid power technology is considered as a subset of mechanical engineering rather than a technology in its own right and thus not require specialised training. Low access to education in the field of fluid power (a fluid power course usually represents only a very small fraction of mechanical engineering curriculum), and a widespread belief that fluid power technology is easy and thus does not require educational background and experience to apply it. Teaching of fluid power in Universities and Colleges is often limited to a description of the operating principles of fluid power components e.g. pumps, motors, valves and ignores system design and analysis. We may contrast this with the availability of specialised education for engineers involved in the electronic, electrical or mechanical fields.

Books in the fluid power area fall into two categories: technician level books which describing operation of system components without any depth and give only very basic information about fluid power systems. Books in this category do not have much hard data which could be used by the reader and as such they are not suitable for mechanical engineering courses neither undergraduate nor postgraduate and are useless for engineers involved in the design of hydraulic control systems. Some of these books include problems to be solved by a reader - usually no answers are provided. The second category of books, very useful to researchers and postgraduate students but less to industrial engineers and undergraduates usually ignore hardware description and steady-state design of hydraulic systems and deal mainly with the dynamic characteristics of hydraulic components and circuits.

This book differs radically from other books in the fluid power area It is concerned with the design of hydraulic systems and the intention of the authors was to provide engineering students and industrial engineers with a text which would help them to gain insight into the design and steady-state analysis of modern hydraulic systems. It is aimed at final year students in mechanical engineering courses and postgraduate students working in the area of fluid power. The book can also be used as a handbook by fluid power engineers as it contains numerous solved examples of typical hydraulic systems used in industry.

The book consists of chapters dealing with different groups of hydraulic components (pumps, motors, valves, hydrostatic drives etc.) and their typical applications. Each chapter has a brief, hardware independent, introduction to the characteristics of such components followed by a score of solved problems. Chapter 1 provides general introduction to the design process. Chapter 2 deals with hydraulic pumps and motors. Chapter 3 deals with linear actuators, Chapter 4 with control valves and Chapter 5 with hydrostatic drives. Chapter 6 is concerned with the synthesis of hydraulic systems, calculation of pressure losses in a system and thermal analysis, again solved examples of design problems are given. Although metric units are used throughout this book, SI units are purposefully used along with units used in general engineering practice to give the reader experience in using these units.

The authors would like to express their thanks to colleagues who contributed examples presented in the book. Special thanks to Monika M. Stecki who assisted in the preparation of this book and Andrew Stecki who produced all the drawings.

Jacek Stecki and Andrzej Garbacik
Melbourne 2001

Table of Contents

List of Figures

List of Tables

CHAPTER 1
Design of Hydraulic Systems

Hydraulic power and control systems due to their favourable characteristics in performing primary functions, i.e. power transmission and conversion, ease of interfacing with electronic/computer controls are used across many industries to provide motion and force control. If such systems are under advanced, intelligent control they will be classified as mechatronic/neuromechanic systems, [16],.[21]. The intelligence level of a control system in mechatronics/neuromechanic systems will range from adaptive controls to advanced knowledge processing systems based on fuzzy logic, neural nets, genetic algorithms [15], [17].

Hydraulic power drives offer advantages over electrical or mechanical drives in performing of power functions, some of them are:

- the ease of speed and force control
- smooth stopping
- quick reversal
- inherent capability to prevent shocks during load reversal or stoppage
- wide controllability range
- flexibility in design layout
- soft failure modes etc.

These characteristics are specially advantageous in applications demanding transmission and delivery of large powers. On the other hand, however, the necessity of performing secondary functions like contamination temperature and leakage control will impose additional initial installation and continuing maintenance costs. It must be noted that this necessity to perform secondary functions which are technology specific applies to any system using a specific technology be it electrical, mechanical or hydraulic for the delivery of primary functions.

Proper design of components and system play a great part in reliability of hydraulic systems. The hydraulic technology is now matured to a degree that most problems associated with design of components are eliminated or minimized. Unfortunately system design is in many cases well below the acceptable standard and as a result there are many systems which have operational, performance and safety problems.

1.1 Concept of a System

Whenever an engineering problem is investigated, a designer can either investigate the system by direct experimentation on the real system or carry out the investigation on the basis of some type of model. One may argue that even when working directly with a real system, the system can be considered to be a "model" of itself as any experimentation is necessarily limited only to some aspects of behavioural or structural characteristics of the real system. The instant the designer conceptualises the real system, he/she is thinking about a system's model. Thus, modelling activity is basic to the design process and a prerequisite to any design activity, fig. 1. The full investigation of a system includes both its structural and behavioural characteristics.

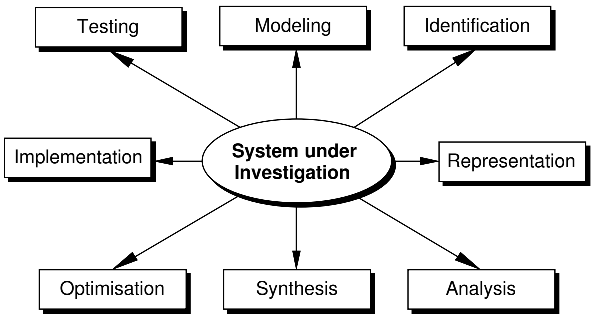


Fig. 1. Investigation of a system

The starting point for the following discussion is the definition of a system and of generalised information. A dictionary definition of a *system* is "a set or assemblage of things connected, associated or interdependent so as to form a complex unity". Implied in this definition is the purpose of such a set which, in engineering terms, is the transmission of generalised information that can be in a form of energy, mass or control information. We are interested in systems whose primary objective is to transmit energy and to convert it into useful work. The system has a boundary that encloses the system and a number of points that are common with other systems or the environment. These points are information transfer terminals, and the information passing through these points will define the character of interaction with other systems and the environment. After the boundary and its transfer points are defined the system can be investigated in isolation from other systems and its environment. Although selection of a system's boundary is arbitrary, the choice of boundary is influenced by the objective of the investigation. The objective of modelling is to construct a system, a model, which is a subset of the real, physical system. Investigation of the model will yield information about behavioural and structural properties of the real system under consideration.

Let us assume that we only have a description of the need, that is a statement of the system's objective and our task is to design the product or system to satisfy this need. A typical example could be an end effector (a mechanical hand) which allows handling of fragile, irregular shape components. The end effector is attached to the manipulator arm that positions the workpiece according to some required program. The first step in considering such a problem would be to identify a boundary that will separate the effector from its environment and to identify its attributes (information transferred to and from the system to the environment). The process of delineation of a system boundary and identification of its attributes is called modelling. The real object has a great number of these attributes and the investigation of the system would be difficult if all are considered, thus a skilful designer will select only these attributes that are relevant to the subject of investigation. To simplify the investigative task some attributes are totally ignored while others are idealised, on the basis of a certain set of criteria and assumptions accepted by the designer. The correct choice of modelling assumptions is the one factor that will usually seriously affect the quality of the system investigation and the magnitude of modelling and simulation tasks. The model of a real system, developed on the basis of such a set of assumptions, should in all important dynamic and steady-state characteristics be equivalent to the original real system.

The subset of selected variable attributes of the system that represent information transfer between the environment and the system can be separated into two sets. These variable attributes that represent information transfer from the environment to the system and which can be controlled or manipulated are assigned as inputs to the system. Variable attributes that represent information transfer from the system to the environment and can be measured or observed are assigned as outputs. Other attributes that represent the physical or geometric attributes of a system, for example kinematic viscosity of fluid, or which cannot be or were chosen not to be controlled and/or manipulated are designated as parameters. Parameters do not have to have constant value, e.g. viscosity of fluid will vary with system temperature. The system model can be represented by a "black box", - its structure can be unknown at this time - which is subjected to known inputs and produces measurable outputs, fig. 2. The model of the system can be constructed on various levels of abstraction. A physical "bread-board" model of the system (an empirical, physical model) of the system may be built or a model may be represented in the form of mathematical equations (an analytical, mathematical model). Information obtained from both empirical and analytical approaches may also be combined and a semi-empirical model developed.

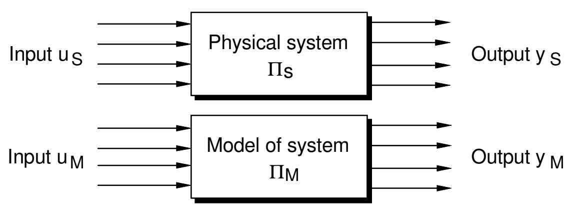


Fig. 2. Black box representation of a system

The complexity of a particular model will be dictated by its purpose, the nature and complexity of the original system and available solution procedures. The objective of the investigation will, to some extent, influence the selection of the boundary of the system and selection of the input/output attributes. The modelling process is shown in fig. 3.

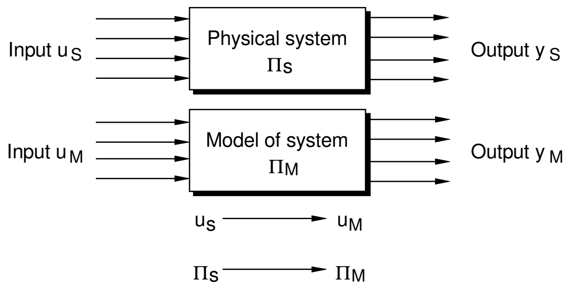


Fig. 3. Modelling process

1.2 Hydraulic Control System

A hydraulic system can be defined as a system which converts, transmits and controls energy flow between two or more points spaced apart, using a pressurized liquid as a working medium. The three functions which must be performed by a hydraulic system: energy conversion, energy transmission and control, are not always explicitly defined.

The primary objective of a hydraulic system is to convert and transmit power, to accept the mechanical power input at a given point and, after conversion into hydraulic power, transmit it to some other point (or points) where it is re-converted back into mechanical power.

1.2.1 Design process

A simplified flow chart of the design process is shown in fig. 4. We may notice that the design process is iterative by nature.

1.2.2 Problem recognition

The starting point for any design process is to review the requirements, and having reviewed the requirements, then to develop a specification against which the performance of the completed system will be evaluated.

The system under consideration is visualized as a "black box" whose structure is still unknown and the important system attributes are being defined. The variable attributes - input and output variables - define functional interaction of the system with its environment, other attributes define the system constraints. Defining the system requirements is of great importance as the solution will have to meet functional requirements within the constrains imposed by factors (quantitative constraints, e.g. cost, length of machine cycle, loads, speeds) and effects (qualitative constraints, e.g. noise).

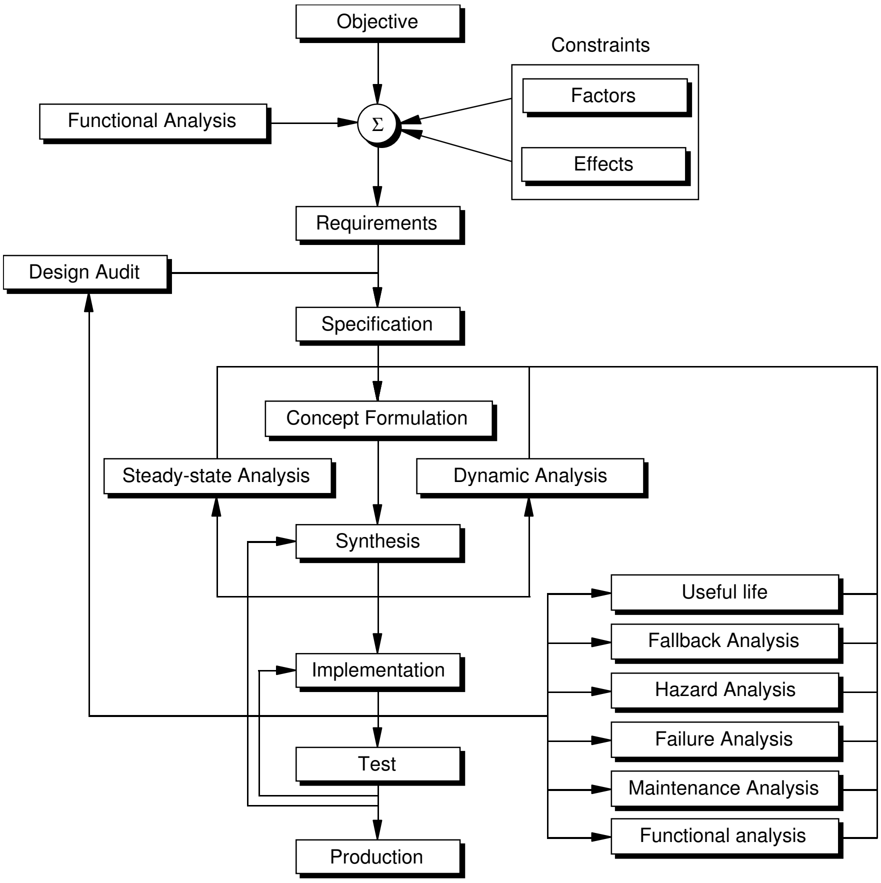


Fig. 4. Design process

The action of the system in meeting the system's objective is described in terms of functions that the model (system) must perform to process input information into output information. Identification of functions is rather difficult task but the effort may be greatly reduced by using some of the value analysis techniques like FAST (Function Analysis System Technique), [24].

FAST technique allows identification of primary (basic) functions that must be performed to meet the objective of the system and secondary (supporting) functions that, although sometime necessary, do not add to functionality of the system. Each function should be described using a verb broad enough as not to limit the way the function is performed (produce a hole rather than drill a hole), and a noun making it a measurable parameter (store energy rather than provide accumulator). Any product consisting of more than just a single part will have a number of basic functions. The linked tree structure of basic and secondary functions shows the hierarchy of functions and dependency of each function on lower and higher level functions. The higher the function the more abstract it is and the design of a system that performs

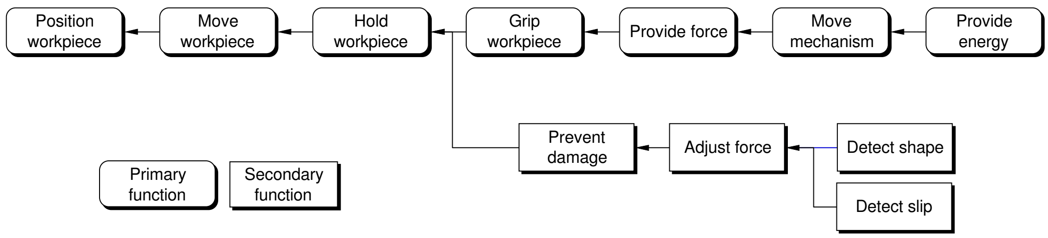


Fig. 5. FAST diagram of a gripper hand

such function will require a more broadly based and more experienced design team. An example of functional diagram is shown in fig. 5.

The FAST diagram shows a hierarchy of primary functions and we will be able to identify the highest level of function necessary to meet the objective of the system. During synthesis step we design system structure that will perform this and all lower order functions. The decision to develop a system concept using a function at a higher level than the one corresponding to the product objective will require reassessment (enlarging) of the system boundary and expanding the sets of system attributes thus increasing the complexity of the system, thus the solution space will grow as we move up in the function hierarchy. On the other hand, entry at a lower functional level will reduce the design task, and in the case of low level functions the design task may be reduced to detailed design.

Identification of constraints on system's functions is a necessary intermediate task in order to develop system specification. Identification of factors (quantitative constraints) and effects (qualitative constraints) leads to a set of requirements, fig. 6.

The effects are defined as qualitative constraints, for example aesthetics, noise, smell. The specification of the system, which is used as a yardstick used to measure the success or failure of design effort, is derived by imposing numerical values on the requirements.

The task of extracting information from the customer and formulating the system's specification is difficult as often customer's requirements are only vaguely defined. Whether the system will eventually perform to the customer's satisfaction will be heavily affected by the engineer's knowledge of the capabilities and limitations of the fluid power equipment, his past experience with similar applications of fluid power, and his understanding of what are the real needs of the customer.

1.2.3 Synthesis

The synthesis of the system is based on the identification of the system's model and functions that the system must perform. The concept of the system and later its implementation must be contained in a solution space defined by systems's functions and constraints imposed on the system, with each function defining a co-ordinate in a solution space. Synthesis is the process of developing a concept of the system

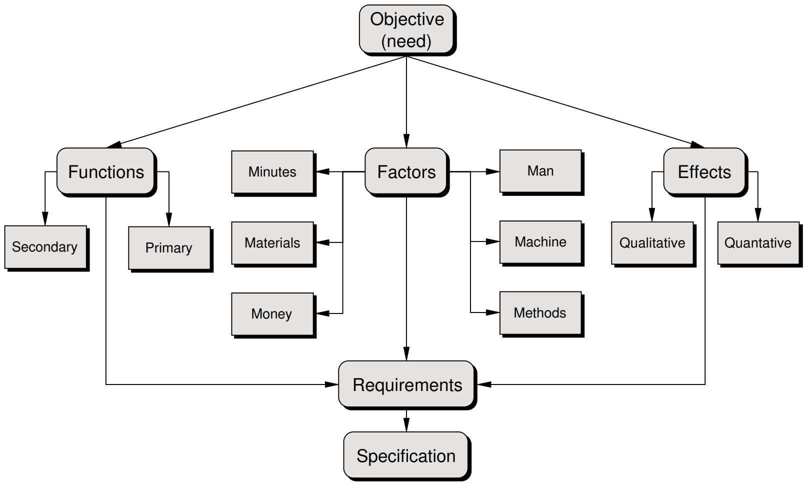


Fig. 6. Derivation of specification

and creating a structure of a "black box" model of the system - which will exhibit the specified input/output behaviour and satisfy the functional requirements within constraints defined in the problem recognition step, fig. 7. The concept of the power system is developed by using a combination of techniques like brainstorming, synetics, etc. and it is concerned only with power functions of the system. For each primary function in turn we are seeking a mechanical, hydraulic, pneumatic or electrical solution. The proposed solutions are noted on the functional diagram by linking them to the appropriate function(s). The selection of a particular technology will inevitably cause the appearance of some, additional, supporting functions. For example, the selection of hydraulic technology will be accompanied by supporting functions like pressure compensation, flow force's compensation, leakage control and will also require a supply of a hydraulic power with associated temperature control, contamination control, etc.

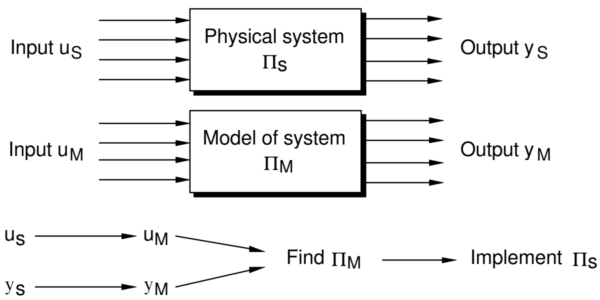


Fig. 7. Synthesis (design) process

The synthesized system must be represented in a form easily understood by other people, usually by a set of engineering documents (technical drawings, circuit diagrams, etc.). The circuit synthesis process starts when the designer taking into consideration the functional requirements which the system must satisfy decides on a topographic structure of the system. A structure of a hydraulic system is represented by a system circuit diagram which comprises of symbolic representations of the system components (standard hydraulic symbols are defined in ISO Standard 1239). The circuit diagram is then used as the basis for selection of components, calculations of flows and pressures and system steady-state and dynamic analysis. The synthesis of a hydraulic system is usually carried out manually as there are no algorithmic approaches, lending itself to computerization, available. The expertise required to synthesize fluid power system will of course depend on the magnitude and complexity of the design problem. Most hydraulic systems fall into one of the following categories:

- high performance, complex systems used in aerospace, robotics, machine tools. The performance requirements for these systems usually demand correct dynamic characteristics, stability, and smoothness of operation.
- Industrial and mobile applications which are not as critical as those above, but nevertheless often must operate adequately under varying dynamic loads.

The quality of manual, intuitive, synthesis is very much dependent on the level of design competence, knowledge of hardware, and a thorough understanding of the physical laws governing the operation of the system. In many cases the synthesis of a new system is based on an accumulated experience with similar systems, and the new system will operate satisfactory but not necessarily in the optimum fashion. The advantage of previous experience is lost when a new application is radically different or operates under different operating conditions.

1.2.3.1 Concept of Hydraulic Machine

A machine is defined as a physical system whose primary objective is to transmit energy and convert it into useful work. A machine may utilize various forms of energy, for example, mechanical, hydraulic, electrical or pneumatic. A machine which utilizes a hydraulic system as the main means of power transmission is a hydraulic machine. The energy transfer is controlled by changing the level of energy and changing the rate or direction of the energy flow, fig. 8.

The fluid power system must perform a number of functions - these, as discussed above, can be grouped into a set of primary functions which are critical to machine operation if the machine is to satisfy its stated objectives, and a set of secondary functions which, although not essential in meeting machine requirements, must be performed in support of the primary functions (but do not directly contribute to the "value" of the machine). Often the existence of such functions is caused by the chosen design solution. For example, filtering of hydraulic fluid is a secondary function in the hydraulic system; however, it will not exist if an electric rather than a hydraulic system is selected to provide some primary functions.

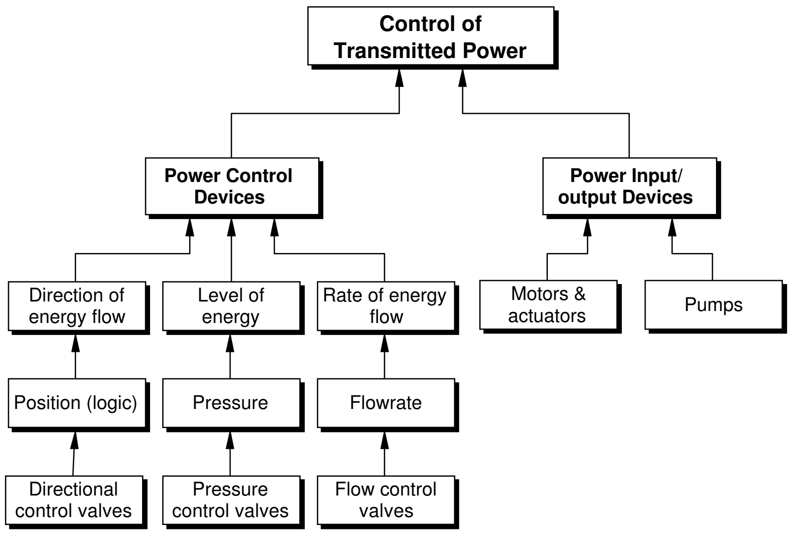


Fig. 8. Control of hydraulic power

The designer of hydraulically operated machines usually uses the concept of a machine which consists of two systems - a hydraulic system providing the power functions of the machine and a control system which provides the control functions, fig. 9.

The power-control approach is based on hardware rather than on functional considerations. In the case of systems where a number of different functions must be performed in some sequence or simultaneously, the circuit design becomes complicated. As functions, other than those specified for a hydraulic system, are not explicitly included in the control problem statement, a control system designed on the basis of the statements describing a hydraulic system must be subsequently modified to include these functions. Thus, partition of the machine design problem which is based on hardware rather than functional considerations may lead to complicated control problems. Most of these problems can be eliminated by using a functional approach, [20], in which the machine is thought to consist of three systems (without regard for the kind of hardware), fig. 10:

- The power system which provides primary power functions. The power system consists of power devices which accept a command signal from a control system and respond in a prescribed manner, fig. 11. The power system can be, in turn, partitioned on a technological basis; for example, hydraulic, mechanical and electrical/electronic systems can be identified. Although the following nomenclature can be applied to all of these systems, it refers specifically to hydraulic power systems.
  A power device is defined as an energy transmitting element. The level and path of energy flow from a power source to the power device is controlled by signals from a control system.

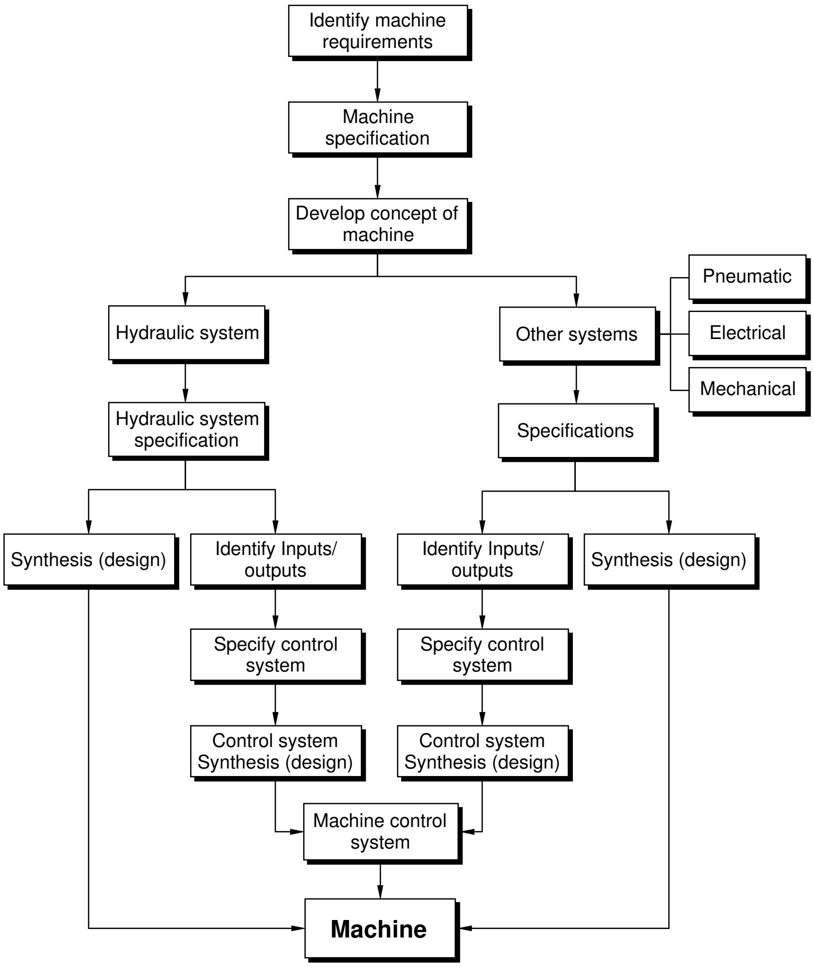


Fig. 9. Design based on a convenional concept of a hydraulic machine

Power devices consist of power output devices (linear/rotary actuators and motors) and power control elements (for example, directional control valves) which provide control of the energy level (pressure), its transfer rate (flow), and direction. Power devices may be and, in general are capable of transmitting control signals back to the control system, indicating position, force or other parameters of interest, and thus influencing the behaviour of the machine. The signals from power devices to the control system are termed "primary inputs", and the signals transmitted from the control system to power devices "primary outputs". Power devices are classified by their mode of control and their output functions.
A typical power device consists of a directional-control valve supplying a hydraulic cylinder. An input signal (from the control system) controls, via the directional-control valve, the position of the cylinder. The position of the cylinder is indicated by position sensors.

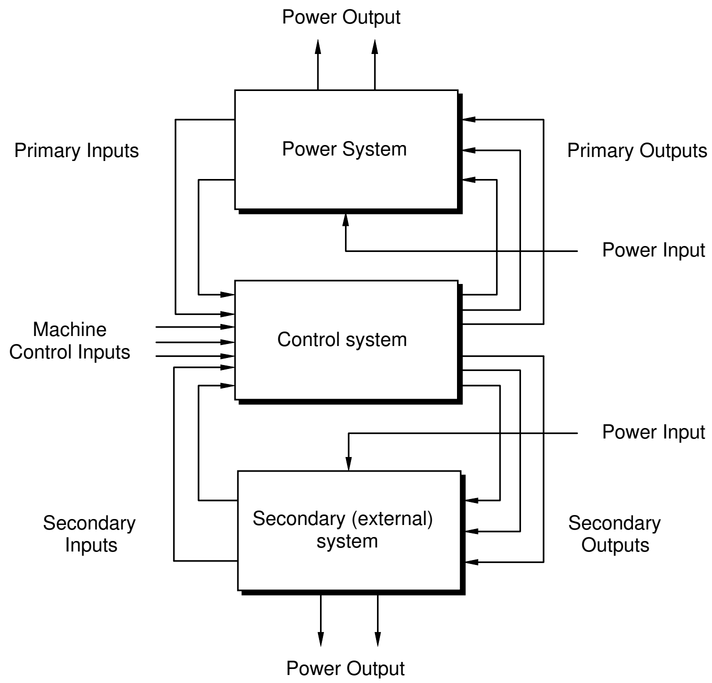


Fig. 10. Three-system representation of a machine

- The external system which provides secondary power and control functions. An external system consists of the assemblage of all elements of the machine which are not included in the power system or the control system but are, nevertheless, necessary to machine operation. The external system, in itself, may be a machine (for example, a forging manipulator or feeder conveyor) or a control system (for

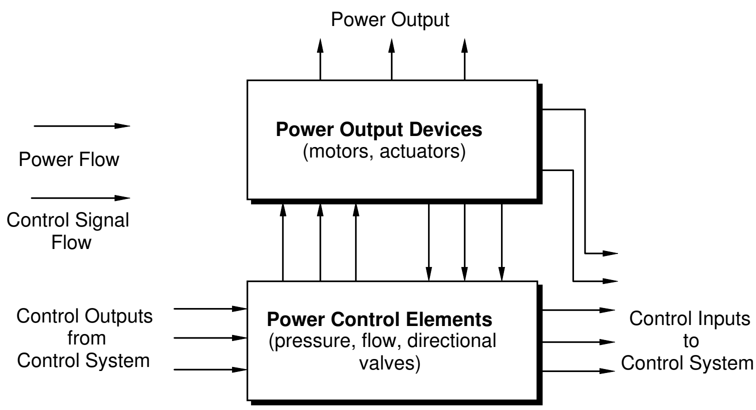


Fig. 11. Representation of a power system

example, a programmable controller). The external system is interfaced with the power system via a control system; that is, it provides input signals (secondary) to the control system and receives (secondary) output signals from the control system.

- The control system which provides primary control and interfacing between power and external systems. The control system is an information processing system which accepts a string of input information and through the use of a control algorithm produces a string of output information. The control system is defined as that aggregate of components which will accept primary (from power system) and secondary (from external system) inputs, interpret them in conjunction with any information stored in its memory, and make a decision. The control decisions are communicated to the power and external systems by primary and secondary output signals.

The functional concept of a machine is shown in fig. 12.

Further simplification of a design problem can be obtained by considering the machine as a hierarchical structure, fig. 13. The designer may arbitrarily designate some part or a function of the machine as external system, thus simplifying specifications of the power and control systems, and still be able to explicitly describe all machine functions. The hierarchy of machine functions identified during the preparation of specifications provides an additional guide to the partitioning of the machine.

Many machines have a major operating cycle which repeatedly invokes a number of sub-cycles. Usually the control system may be simplified by considering each sub-cycle independently, and then specifying the appropriate interfacing between them. The hierarchical structure of the operating cycle will, in turn, lead to identification of power and external systems for each hierarchy level. Looking at the hierarchy of control functions we may observe that a lower level function will probably use traditional control techniques, for example a PID controller, and as we are moving up in control functions hierarchy the level of system intelligence will increase.

For example, a designer of a hydraulic crane may designate each hydraulic actuator and its hydraulic control valve as a power system, electronic control of the hydraulic valve as a control system and valve contamination control as an external system. If the control system is integrated physically with the power system and the operation of the power system is controlled with only rudimentary interaction with system I/O we refer to such an implementation as an embedded system. The functional structure of the crane will then consist of the main power system controlled by the control system that also interfaces with actuator subsystems (distributed control) and any additional external systems (e.g. power supply), [12].

From the above we may see that the power-control-external concept of the machine allows explicit identification and description of the control functions and in combination with hierarchical partitioning of the system will result in small scale design problems which can be individually solved.

Using the "power-control-external" concept of a machine, all the functions of the machine can be explicitly described, and the combination of the three-system ap-

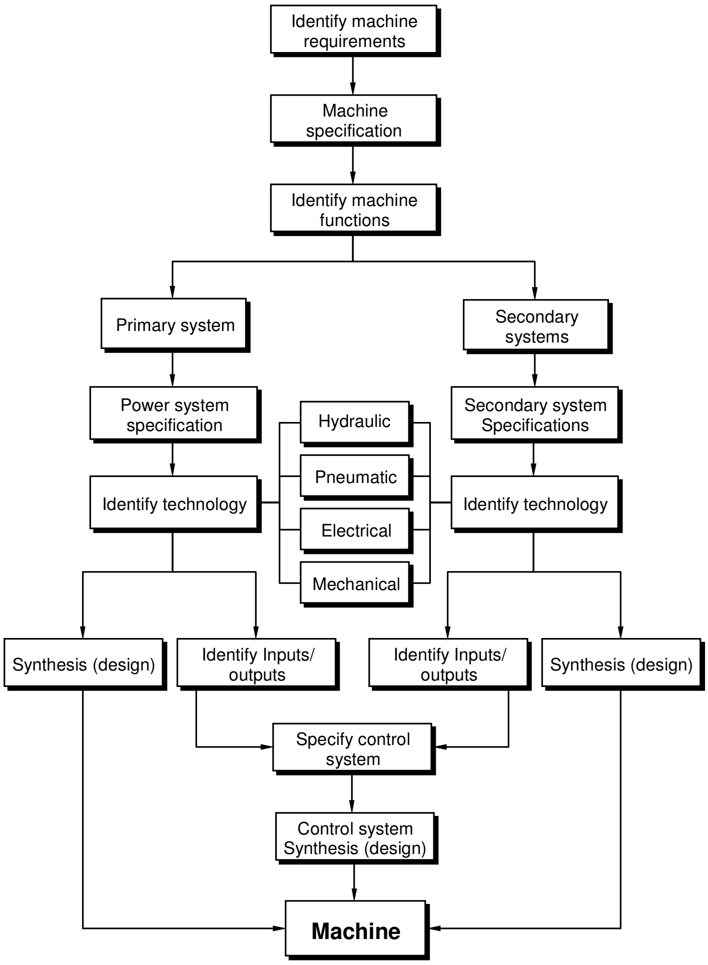


Fig. 12. Functional concept of a machine

proach with hierarchical partitioning of the machine will result in "small scale" design problems, which can be individually solved. The above discussion should lead to the realization that the majority of hydraulic machines are, in fact, "small scale" even though a whole machine can be, at first sight, large and complex. The synthesis of hydraulic systems is discussed further in the last chapter of this book.

1.2.3.2 System behaviour

An important characteristic of fluid power systems is their operation both in continuous and discrete modes. The input signals from the control system will cause discrete changes in the state of the power control elements, e.g. directional control valves will switch their position, pump servoactuators will change displacement of pumps. The behaviour of the power output devices, e.g.. hydraulic actuator, will however depend on the rate of change in the state of the power control element, and

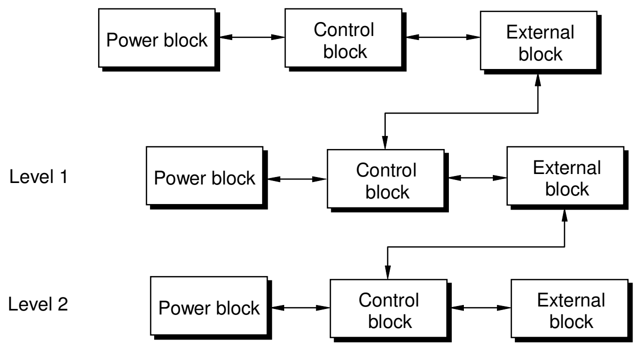


Fig. 13. Hierarchical structure of a complex machine

the characteristics of the power source, power output device and the loads. The rate of change in the state of the power control elements will depend on the level of the input signal and the dynamic characteristics of the power control elements. Thus the overall dynamic characteristics of the power system are important for satisfactory operation of the system, although the importance varies with the application.

The non-linear character of the behaviour of hydraulic systems, which operate in both discrete and continuous modes, has prevented development of an algorithmic approach to system synthesis. Thus systems are derived more in the hope that they may prove to be adequate rather than in the knowledge of how they will actually perform. The attempts to develop a computer aided synthesis programs, based on design algorithms, were not very successful and resulted in programs which will analyse the proposed system's behaviour only after the designer has specified the configuration of the system. Design techniques based on AI technology (expert system, fuzzy and neural technology) may however provide a computer based tool for the synthesis of hydraulic systems.

1.2.4 Analysis

The system analysis step, i.e. the investigation of the behaviour and properties of the system, is based on the knowledge of the inputs and the internal structure of the system, fig. 14. As the operating requirements and complexity of hydraulic systems increase, the analysis of steady-state and dynamic characteristics of the system are becoming increasingly important, [10].

The design process increasingly takes advantage of computing tools both in synthesis and analysis tasks. As there are no tools available which will allow computer-aided synthesis of fluid power systems, so the synthesis step is usually carried out manually and is based on the previous experience of a designer with earlier systems. This makes analysis, performed in an iterative loop with synthesis and hardware implementation tasks, an important step in design of fluid power systems. The results of analysis, both steady-state and dynamic, will show how the system will perform and will provide guidance to any necessary design modifications.

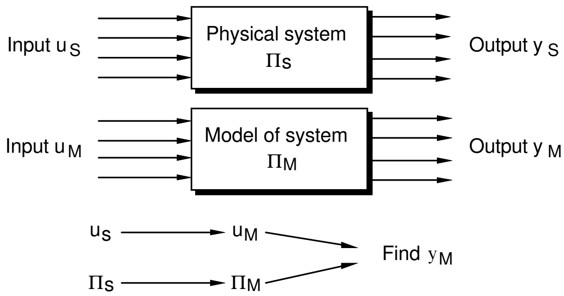


Fig. 14. Analysis process

Dynamic analysis should be used as a design tool - various variants of design can be investigated to provide a workable solution, techniques like 'hardware-in-loop' simulation may drastically reduce development costs and simulation applied in diagnostic mode may be a very useful tool in the maintenance of a system. Cost of experimentation on computer in developing various variants of system design is only a fraction of tests on hardware - with the additional advantage of the ability to establish limits of system performance without experiencing catastrophic in-field failures. The other use of simulation, it appears not recognised by fluid power companies, is its application as a marketing tool. When confronted with various solutions, the solution which is supported by simulation results will give a customer more confidence in its correctness. The success of a dynamic analysis task essentially depends on three sub-tasks:

- modelling,
- data acquisition, and
- simulation.

All approaches to modelling require an insight into the physical laws and relations which govern the behaviour of various elements of the system, an appreciation of the interaction between system components and the knowledge of the structure of the system. The success of analysis is based on extensive knowledge of the modelling techniques, knowledge of mathematical methods of solution and availability of data. The results of analysis show if the system will perform as intended and will provide guidance for optimization of the system. The modelling task is in itself is relatively small, no more than 10% of total modelling and simulation time is spent on developing of the model. Most of the time is directed towards the task of getting correct parameter data and running numerical solvers. There are many good simulation tools which could be used in design, analysis and diagnostics of hydraulic systems. Some of them are specific to fluid power technology, e.g. Bathfp, Imagine or Easy5, are general purpose programs. Software like ACSL, Matlab or Vissim [11], are examples of general simulation packages which easily adaptable to fluid power application. Some of these packages have also the capacity to simulate operation of artificial AI controls like fuzzy logic, neural nets, etc., and can be used in hardware-in-loop applications. An important feature of some of these packages, e.g. Vissim, is that we can develop a control system with a help of simulation, and after translating the code into C++ language embed it on a chip.

In engineering practice various graphical and symbolic forms of models can be used to derive a set of system equations e.g. transfer function, vector-matrix model, block diagram, signal flow diagram, terminal graphs and the bond graphs [22], these modelling approaches and available software tools are shown in fig. 15.

Simulation software is often "opaque" to the user - the models of individual components are represented in the program in numerical form and the user has not or has very little control over their structure and the data which describes each component. Such packages are very valuable design tools, but it must be understood that, to apply such packages effectively, the designer must still have a sound understanding of system dynamics so that he can understand the importance of various system characteristics, the validity of input data and finally so he can evaluate the results and their implications.

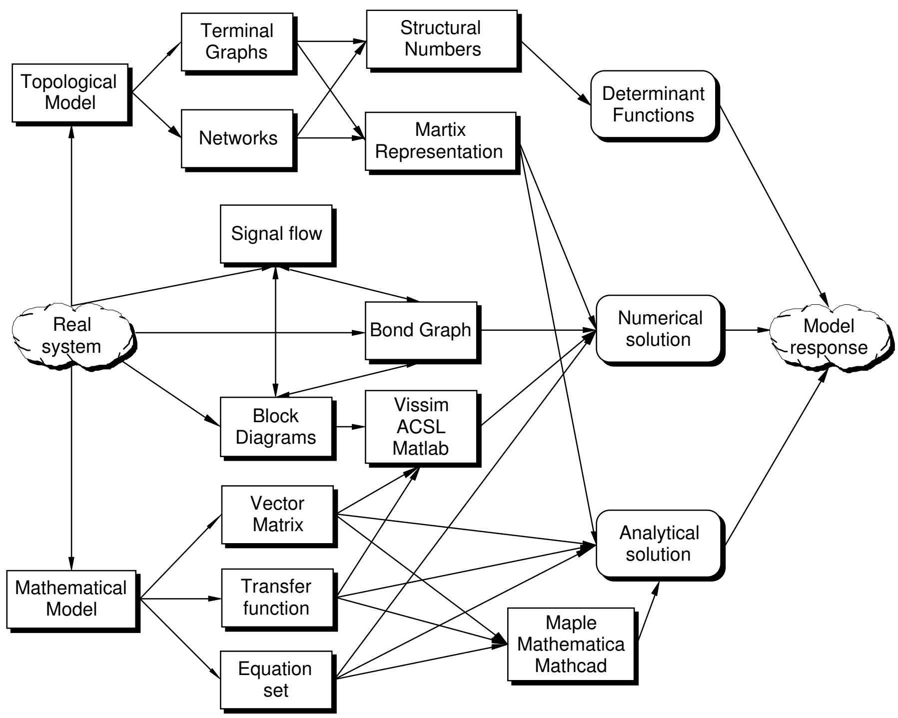


Fig. 15. Modelling approaches

1.2.5 Implementation

In the implementation step of the design process the system hardware is selected and/or manufactured and assembled to make a physical system. The selection of hardware is based on the knowledge of system variables and parameters, e.g. flow rates, pressures, temperatures; obtained on the basis of steady-state and dynamic analysis of the system. The task of selecting hardware does require an sound knowledge of the range of available hardware, its limitation and applicability in a given environment is still required.

1.2.6 Monitoring of hydraulic systems

In the past, monitoring of hydraulic systems was limited to the monitoring of pressure (and occasionally flow rate measurement) in various parts of the circuit and to visual monitoring of the system for leakages, fluid aeration, water contamination, reservoir temperature, etc. The pressure measurements allowed the identification of excessive pressure losses, leakages etc. Although monitoring of pressure and visual observation of the system condition are still valid techniques of condition monitoring, the development of a wide range of sensors for monitoring of vibration, noise, flow, contamination, water content and other parameters of interest and better understanding of phenomena affecting operation of hydraulic systems e.g. contamination, aeration, flow forces led to the development of advanced monitoring techniques which are able to detect early stages of failures. Some, more important, techniques are shown in fig. 16.

1.2.7 Testing and troubleshooting

Testing is an activity which require a fair amount of expertise. The objective of testing is to verify by observations and measurements that the system meets design specification. The troubleshooting during testing and commissioning of the system require a thorough knowledge of the system and its behaviour, experience in the identification of signs which indicate malfunction and knowledge of the dynamic characteristics of fluid power components. The complexity of a modern fluid power system increasingly requires a level of troubleshooting expertise which is outside the capability of technicians who acquired their expertise only via "practical experience".

1.2.8 Failure Modes and Effects Analysis (FMEA)

Faults or failures critical to the operation of the machine should be investigated in order to establish their origins and thus provide a set of symptoms which would identify these faults/errors. The purpose of failure analysis is to identify failure/faults in a system which may result in material/production losses and/or human injuries during their regular or occasional use. Failure analysis requires a clear understanding of the system's operation, details of system components and their interaction, knowledge of the functions which the system and its various parts must perform and knowledge of interfaces with external systems. As a system may operate in various modes (e.g. emergency mode, start-up mode, test mode) the analysis should be carried out for all the modes of a system's operation.

In engineering practice there is a number of available techniques for failure analysis, some of them are :

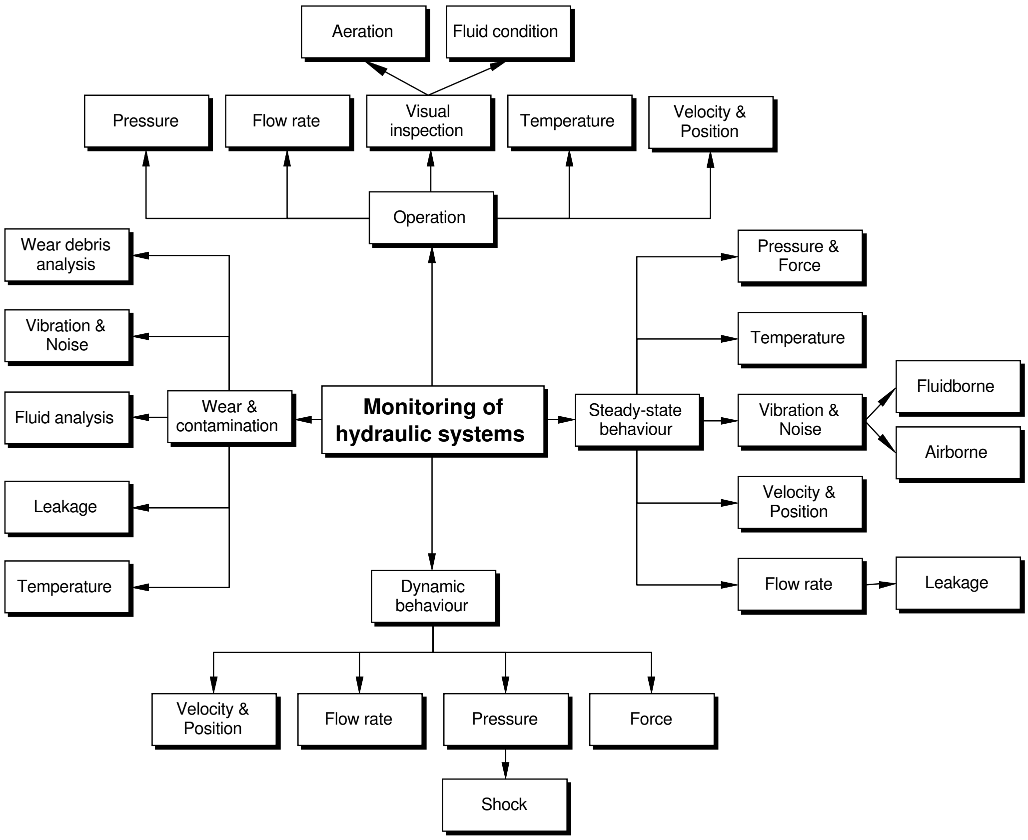


Fig. 16. Monitoring of hydraulic systems

- Failure modes analysis (FMA) - identification of unwanted conditions of the system.
- Failure modes and effects analysis (FMEA) - identification of effects of component failure on the system operation and safety, [23].
- Hazard analysis (HA) - identification of potential hazards during system operation.
- Failure modes, effects and criticallity analysis (FMECA) - identification of effects of component failure on the system operation and safety, probabilities of occurrence and their criticallity.

The Failure Modes and Effects Analysis (F.M.E.A) is the usual method of failure analysis, other techniques can be considered variations of this technique, it is a tool for a systematic analysis of failures and malfunctions which can occur in the system, fig. 17.

The F.M.E.A analysis is concerned with hardware failures and malfunctions, it does not include hazards due to errors caused by human operators, effects of the environment and other operating and hazardous conditions outside the scope of design

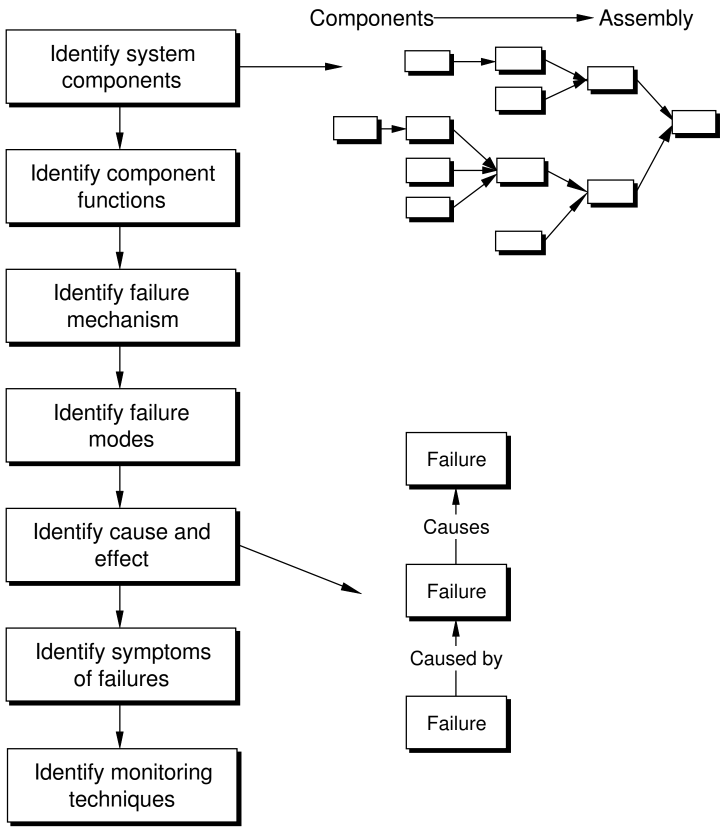


Fig. 17. Failure Modes and Effects Analysis

limits of the components. The other information sought during analysis is what are the manifestations of failures and if there are any redundancies, backup components or sensors which safeguard components against failures.

1.2.9 Tribological analysis (Wear and contamination)

A function of a mechanical system can be represented as in fig. 18, the system is subjected to energy input and as a result of system's action useful energy outputs (i.e. work) and some losses will be produced.

We may differentiate between energy losses which result in heat and noise generation and material losses which lead to changes in machine geometry as well as to production of wear debris. Both energy and material losses lead to changes in lubricating regime of the system (viscosity, lubricity, contamination) as well as to misalignment, vibration, surface condition etc. We may thus consider each of these as some symptoms of machine state and propose techniques capable of detection of changes in these system variables and parameters. Fig. 19 shows wear, leakage and contamination entry points in a typical hydraulic system.

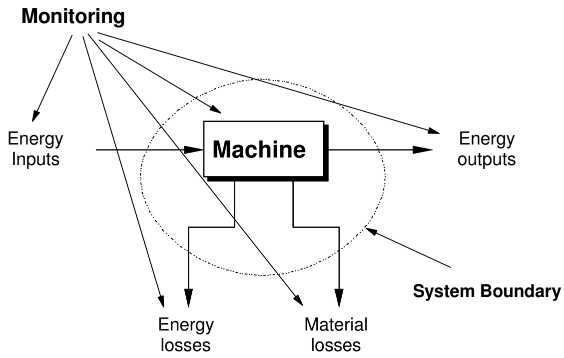


Fig. 18. Engineering system

Some design, operational and performance characteristics of hydraulic drive systems and hydraulic power control are shown in table 1. Tribological pairs in typical hydraulic components are shown in table. 2.

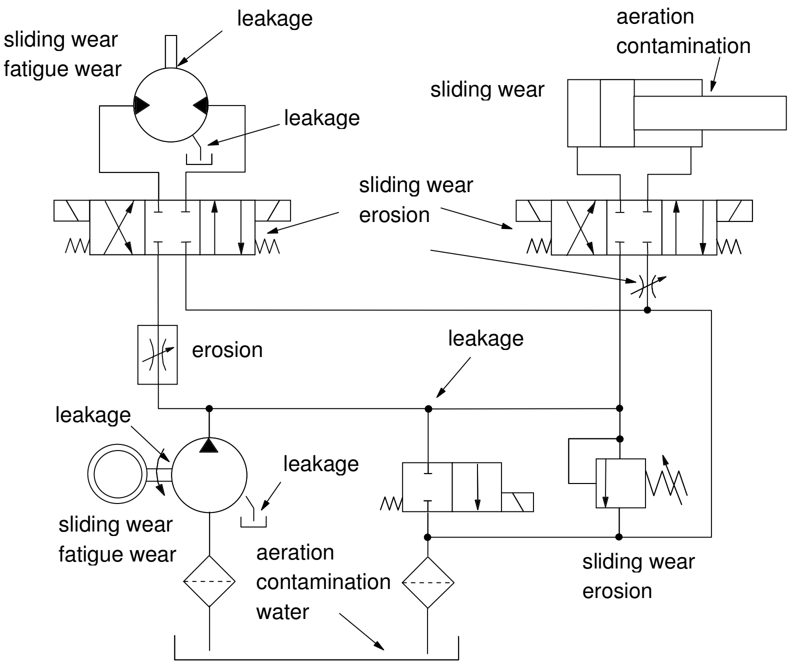
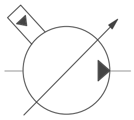
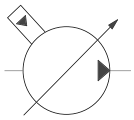
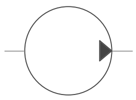
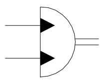
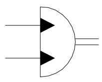
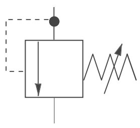
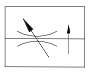
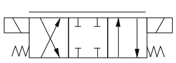
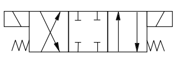
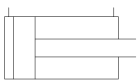
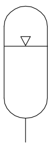


Fig. 19. Wear in a hydraulic system

Table 1. Characteristics of hydraulic systems

Characteristic	**Result in**	**Preventive measure**
High power density (ratio of weight/ transmitted power)	High operating stresses	choice of material, design
High speed operation	noise, vibrations	proper design of system
High contact stresses (valve plate/cylinder block, gears, etc)	fatigue wear	choice of material, design
High temperature operation	fluid oxidation, distortion, poor lubrication	temperature control (heat exchange, reservoir design)
Shock loading	high operating stresses	pressure control, design
Leakage	entry of contaminant, increased temperature	seals, close tolerances, contamination control
Predominance of sliding tribological pairs (pistons, spools, poppets, vanes etc)	damage due to scoring, sliding wear. Production of wear debris	selection of materials, contamination control
High precision of equipment (servovalves, pumps, etc), small clearances	very high sensitivity to contamination and wear , silting (valves)	seals design, contamination control
Low cycle fatigue (high start-up loads)	high stress level	design, pressure control
Fluid as transmission medium	sensitivity to temperature, contamination, aeration	reservoir design, temperature control, aeration control, contamination control
Flow throttling as means of control	erosion, aeration	design of components, choice of materials
Pressures/flow pulsation	noise, vibrations	noise/vibration control, design
Need to seal pressure volumes	close tolerances, seals, leakage	seal design, contamination control
Unskilled operators	overloading, incorrect operation	design, pressure control
Poor maintenance practices	contamination, sealing problems	contamination control, aeration control
Improper system design procedures	operational, maintenance, safety problems	education, training, quality control (design audits)

Table 2. Hydraulic components - mechanisms of wear

Hydraulic component	**Symbol**	**Tribological pair**	**Wear mechanism**
Vane pumps and motors		bearings vane/cam ring vane/rotor vabe/casing	fatigue, sliding sliding sliding sliding
Piston pumps and motors		bearings piston/block block/valve plate slipper/thrust plate	fatigue, sliding sliding sliding sliding
Gear pumps and motors		bearings gear pair gear/thrust plate	fatigue, sliding sliding sliding
Rotary actuators (vane)		bearings vane/body vane/rotor	fatigue, sliding sliding sliding
Rotary actuators (rack & pinion)		bearings rack/pinion seal/cylinder	fatigue, sliding fatigue, sliding sliding
Pressure control valves		poppet/body seat/poppet seat & poppet metering orifices	sliding impact flow erosion flow erosion
Flow control valves		poppet/body seat/poppet seat & poppet metering orifices	sliding impact flow erosion flow erosion
Servovalves		spool/body metering orifices	sliding flow erosion
Directional control valves		spool/body jet nozzle metering orifices	sliding flow erosion flow erosion
Actuators		piston seal/body rod seal/body	sliding sliding
Accumulator (piston)		piston seal/body	sliding