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THE INFLUENCE OF THE LEAKAGE ON THE DYNAMIC BEHAVIOUR OF A HYDRAULIC SYSTEM AND ITS USE BY THE FAULT PREDICTION FROM AN EXPERT SYSTEM

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ABSTRACT

Dynamic modelling techniques can improve the reliability in a diagnostic methodology and add effectiveness to the diagnostic task when they are involved in the structure of a knowledge-based system. This paper presents the use of modelling and simulation of the dynamic behaviour of hydraulic systems in real time knowledge based systems. This can be achieved by developing a suitable mathematical model so that the special characteristics of hydraulic systems can be studied and used for the development of advanced diagnostic procedures for these systems.

1. INTRODUCTION

The procedure of using model information to generate additional signals for comparison with measured variables has received considerable attention as a quantitative fault detection method and many approaches have been developed for the decision making stage usually by generating error signals known as residuals [1, 2, 3].

The main advantage of involving dynamic modelling information to a diagnostic system is the ability to predict real time faults in parallel to the traditional diagnostic task.

Hydraulic systems are used for the transmission and control of forces and movement by means of fluids. In recent years hydraulic systems have taken an important place in the area of the production technology because of their ability to drive and control heavy loads in combination with high speeds.

The difficulty by the search for defective components in case of a malfunction is due to their inaccessibility and the high working pressures and has driven to some attempts to implement knowledge based systems in this domain for diagnostic purposes [4, 5, 6].

Leakage of a worn component is the main source of a fault. Leakage increases usually progressively during a long period of time until it can affect the performance of the system and produce a considerable fault but a very small amount of leakage can already change dramatically the dynamic behaviour of the system at the very beginning. The detection of this small leakage can be used for a fault prediction.

A real-time diagnostic system operates in parallel to the actual process so that the response time is a critical issue for these systems. Numerical calculations of the simulation program must be performed in a very short time in order to perform fault diagnosis in a suitable time. In addition there is a need for a mathematical model that can describe accurately the dynamic behaviour of the actual system. In consequence, a mathematical model is needed that corresponds to the real technical characteristics of the hydraulic elements without increasing unnecessarily the simulation time.

In this work, the dynamic behaviour of hydraulic systems is studied and described using non-linear differential equations of the hydraulic components and their connection pipes and the numerical solution of these equations is performed using simulation techniques.

2. MODELLING IN HYDRAULIC SYSTEMS

A hydraulic system consists of hydraulic elements connected with pipes and a hydraulic medium. As mechanical systems are a combination of three basic elements, spring, damper and inertia, hydraulic systems can also be described in similar terms. The elasticity of the oil can be considered as a spring effect and the hydraulic friction forces and the leakage of the elements as a damper.

The description of the dynamic behaviour of complicated hydraulic systems is a difficult task because, among other factors, the hydraulic components of the system are also smaller dynamic systems that have an influence on the behaviour of the whole system. More difficulties are added by the fact that the dynamic behaviour of the whole system has also an influence on the hydraulic components [7]. On the other hand most components in a hydraulic system can be regarded as quasi-steady, because the volume of the incorporated hydraulic fluid is usually very small, so it can be regarded as incompressible, and in addition their moving parts are so small that their inertia is unimportant. Hence, the dynamic state of the components can be regarded as a sequence of stationary states while the whole system is dynamic.

If the target is to model a hydraulic element, it is recommended by [7, 8] to consider the element as a small sub-system with inertia, spring and damper and describe it using detailed equations. In the case of a hydraulic system it is recommended to consider the whole system as consisting of "quasi-steady" hydraulic elements connected with pipes that contain compressible fluid [9].

A variety of modelling methods has been developed in hydraulic systems depending on the modelling target. Methodologies of modelling and estimation of the dynamic behaviour of hydraulic systems are presented, among other researchers, by [9, 10, 11].

In this work effort has gone into developing a mathematical model that takes into account the non-linear character of hydraulic systems and the incompressibility of the hydraulic fluid in the pipes as well as the special characteristics of the used hydraulic elements. For these reasons the mathematical equations that describe the behaviour of the hydraulic elements are based on their technical specifications, function curves and parameters values given by the manufacturer and tested in the laboratory and not on equations with theoretical parameter values, as some researchers in this area suggest [12, 13]. So, the model represents the behaviour of the system elements more accurately.

3. MODELLING OF HYDRAULIC COMPONENTS

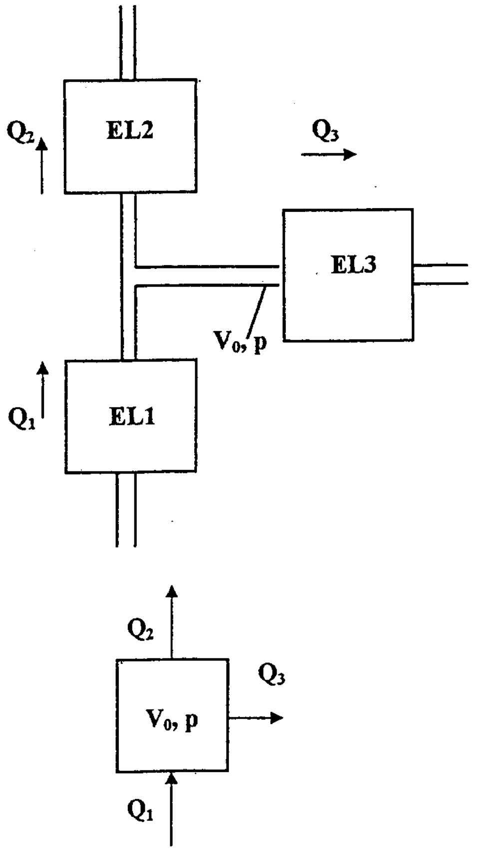


Figure 1. Junction of a hydraulic circuit

The hydraulic systems consist mainly of valves, connecting pipes, cylinders and motors. Cylinders, motors and pipes are elements normally including large oil quantities, while valves are very compact elements including a very small quantity of oil. If such small elements are connected together with pipes we can consider them as quasi-steady and the included oil volume in the pipes that connect them as a unique volume where the increase of the pressure, during a dynamic state, is proportional to the difference between the incoming and outgoing flows.

In Figure 1, the connection of three elements (EL1, EL2, EL3) is illustrated. The flow rates Q1, Q2, Q3 through these elements can be described with mathematical equations derived from their characteristics.

Vo is the included oil volume in the connection pipes and p is the pressure in this part of the system.

The lower part of Figure 1 shows the block diagram of the oil volume Vo included in the pipes with the incoming and outgoing flow rates.

The difference of the incoming and outgoing flows results in a compression of the volume Vo, Figure 2.

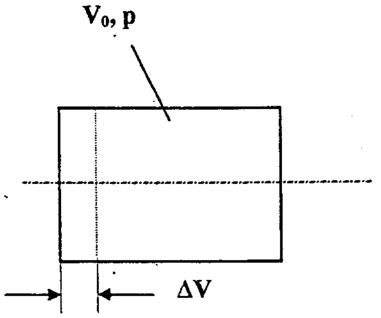


Figure 2. Oil volume compression

The basic equation for the volume compression (ΔV) as a function of pressure increase (Δp) and oil volume (Vo) is:

$\Delta V = \beta v \,.\, \Delta p \,.\, Vo$ volume compression

where $\beta v = 1 / E$ elasticity coefficient of the oil (E = modulus of oil elasticity),

Vo oil volume

Δp pressure increase

As a consequence the increase in pressure is given by:

$\Delta p = (E / Vo) \,.\, \Delta V$

This equation can be expressed as:

$$dp / dt = (E / Vo) \cdot (dV / dt) = (E / Vo) \cdot Q$$

where Q = flow (volume/time).

So, if we consider every junction of the circuit as a volume Vo, where Vo is the oil-volume of the connection pipes and the involved oil-volume of connected cylinders and hydraulic motors, we have the relation:

$$dp / dt = (E / Vo) \cdot \Sigma Q \qquad (1)$$

where ΣQ = Qin - Qout,

Qin is the incoming flow to the volume Vo,

and Qout the outgoing flow from Vo.

That means that the pressure increase in a pipe element at a junction is proportional to the algebraic sum of the incoming and outgoing flows and inverse proportional to the included oil volume.

The flow rates Qin and Qout through the elements at a junction depend on the nature of the elements.

For example, for a hydraulic motor:

$$Q_m = c_m \cdot (d\varphi / dt)$$

where $c_m = V_m / 2\pi$ is a motor constant

V_m is the displacement volume of the motor

and $d\varphi / dt = \omega$ is the angular velocity.

For a servo valve:

$$Q = c_v \cdot \sqrt{\Delta p}$$

where c_v is a valve constant that depends on the valve characteristics and the command current to the valve

The use of the relation (1) in every junction of the circuit and the equations that express the flow rates according to the kind of the element, build the mathematical model of the hydraulic system.

4. CONNECTION PIPES

When the connection pipes of a hydraulic system are of short length they can be considered as quasi-steady elements and they can be modelled as the other components. When the length of the pipes is long they should be divided in a lot of small parts that can be considered as a subset of small elements with specific characteristics whose properties can be described with differential equations. From these equations a system of differential equations can be derived that can be solved using a suitable method.

5. SIMULATION OF THE SYSTEM

The modelling of the hydraulic elements with the coupled moved masses leads to a non-linear system of equations.

This system can be usually written in the following state vector form:

$$\dot{\bar{x}} = f(\bar{x}) \qquad \text{where} \qquad \bar{x} = \begin{bmatrix} p_a \\ p_b \\ \dot{\varphi} \\ \varphi \end{bmatrix}$$

Thus:

$$\begin{bmatrix} \dot{p}_a \\ \dot{p}_b \\ \ddot{\varphi} \\ \dot{\varphi} \end{bmatrix} = f \begin{bmatrix} p_a \\ p_b \\ \dot{\varphi} \\ \varphi \end{bmatrix}$$

As method of integration for the simulation of the dynamic behaviour of the hydraulic system can be used the standard fourth-order Runge-Kutta method.

Runge-Kutta methods are generally considered well suited to non-linear systems given in state space representation and can generate accurate results. The accuracy is achieved by increasing the number of function evaluations that must be computed for every time step. Another characteristic of this method is that the size of the stability region increases when the order of accuracy increases. The computation time due to the multiple function evaluations that must be computed per time step is a little increased in relation to other methods but by using a modern personal computer this is no more a problem.

Typical programming languages for writing the actual code of the simulation program are Fortran, C, Pascal or Basic. In this work, a program written in C performed the simulation.

The parameter values for this program are derived by the manufacturer's data after laboratory testing.

6. IMPLEMENTATION OF MODELLING INFORMATION FOR THE PREDICTION OF FAULTS

Every hydraulic system consists of two kinds of components. Components that are related to the dynamic behaviour of the system such as cylinders, hydraulic motors, valves and the pipe connections between them and components that do not affect the dynamic behaviour of the system, such as the power pack and the different accessories.

For experimentation purposes and evaluation of the proposed methodology a typical hydraulic system was used. This system consists mainly of a hydraulic motor that rotates a mass with a moment of inertia Jm. Figure 3 presents this part of the hydraulic system.

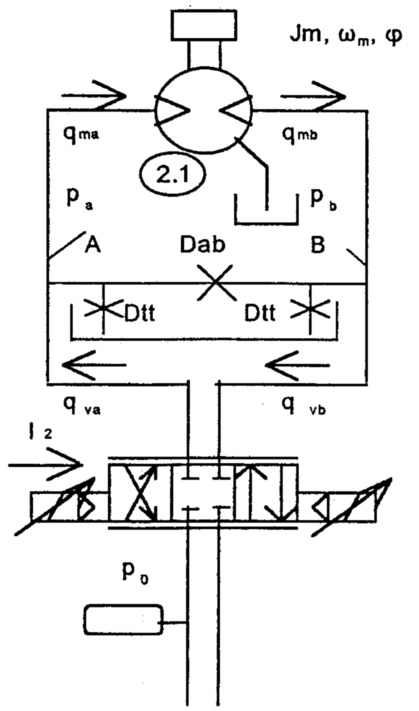
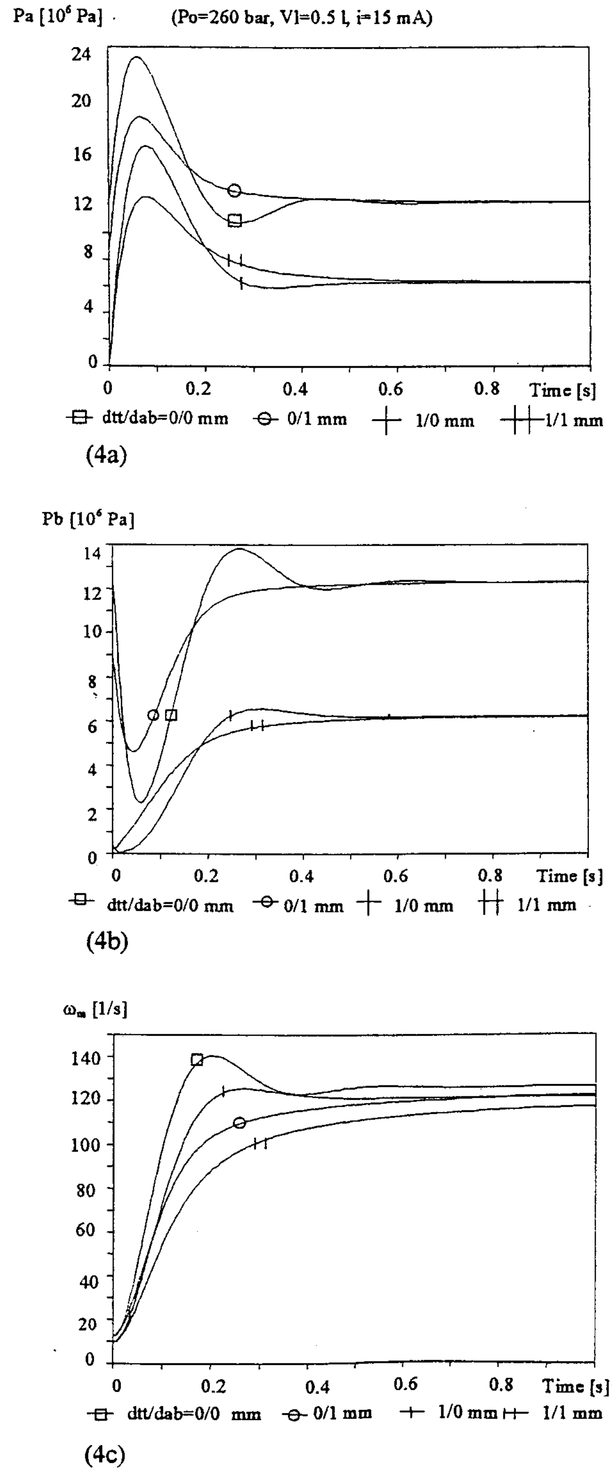


Figure 3. Hydraulic motor with simulated leakage

The hydraulic motor is controlled by a hydraulic servo valve. Two bypass orifices Dtt are placed at both sides of the hydraulic motor (A, B) and produce a small leakage from the ports A and B to the tank. Another bypass orifice Dab is placed between the two motor ports (A, B) and produces a small leakage from A to B. The servo valve is energised with various command values and the response of the hydraulic motor with the coupled mass is studied for various operating conditions and various bypass orifice combinations. The results of simulation for the pressures p_a and p_b and the angular velocity ω_m of the hydraulic motor for a given operational parameter set are presented in Figures 4a, 4b and 4c respectively. In these figures the parameter dtt is the diameter in mm of the two orifices Dtt and the parameter dab is the diameter in mm of the orifice Dab.

The curves in Figure 4a represent the pressure p_a of the dynamic response of the system by a system pressure p_0 = 260 bar, a pipe volume between motor and servo valve V_l = 0,5 l, a command value to the servo valve i = 15 A and various leakage orifice combinations dtt and dab. In this Figure the influence of the leakage on the pressure p_a can be observed. The two higher curves represent the pressure p_a in case that the leakage is zero (dtt = 0, dab = 0) and in case of a small leakage between A and B (dtt = 0 and dab = 1 mm).



(4a)

(4b)

(4c)

Figure 4. a. Pressure p_a for various orifice combinations, b. Pressure p_a, c. Angular velocity of the hydraulic motor

It is obvious that the dynamic response changes dramatically in comparison to the static behaviour in case of a small leakage. The change on the dynamic behaviour due to a small additional leakage from A and B to the tank is similar as shown by the two lower curves.

Similar observations can be made for the pressure p_b, Figure 4b and the angular velocity ω_m, Figure 4c.

7. FAULT PREDICTION

The above observations are useful for the implementation of the fault prediction by a diagnostic expert system. The simulation program runs in parallel with the real system. Sensors for the measurement of the variables and operational parameters of the hydraulic system are placed at suitable positions. The signals that correspond to the sensor measurements are sent to the computer through an incorporated I/O card. The values of the measured variables can be compared with the calculated values from the simulation program using a suitable diagnostic expert system [6]. The deviation of the curves from model and system in the dynamic range is the guide for the prediction of a fault.

In our system a measurable leakage of the hydraulic motor has as result a decrease of the speed ω. The difference $|\Delta\omega|$ between measurement and calculation (model) is a criterion for that decrease and can be used by the expert system for leakage detection. If the leakage is very small it is not yet measurable but it has a considerable influence on the pressure curves p_a (t) and p_b (t) in the acceleration phase of the hydraulic motor. By comparing the measured curves with the results of the simulation this small leakage can be visible and evaluated.

The differences Δp_a and Δp_b between measured and calculated curves can be measured and by exceeding of a given threshold a beginning motor leakage can be detected that otherwise could not be measured at this early phase.

8. CONCLUSION

In this work, the use of modelling procedures for diagnostic purposes of an expert system is presented. The method is developed using a real hydraulic system and the corresponding mathematical model was validated using measurements of the actual system. The simulation results are accurate and the method is applicable to real world situations with a sensitive dynamic behaviour.

The main advantage of this method is that the simulation model is realistic, reasonably accurate and can respond to the requirements for real-time performance. The model is developed using instead of detailed theoretical modelling methods the manufacturer's data after their validation so that the simulation of the actual system is more precise. This method can be used for improving the performance of intelligent systems for a more accurate control and fault diagnosis.

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