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Simulation-Based Fault Detection For Hydraulic Elements

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***Abstract* -The purpose of performance monitoring and fault diagnostics are to detect and distinguish faults occurring in machinery in order to increase the level of maintenance and improve safety conditions. In fluid power systems, it is necessary for safety reasons to detect faults in an early phase by establishing a suitable diagnostic system. The diagnostic system presented in this paper compares simulation results and data acquired from an actual system in a suitable environment and the residuals are evaluated for the fault detection process. The final fault diagnosis process is achieved by interaction of modelling information, on-line measured values of the system variables and stored knowledge.**

***Keywords* - Modelling, Simulation, Fluid power systems, Fault detection**

I. Introduction

Components, sensors and actuators in physical systems are often subjected to unexpected and unpermitted deviations from acceptable conditions for many reasons that can cause loss of the overall performance of the system and may lead to unacceptable economic loss. The objective of fault detection is not only to determine if a fault is present in the system but also to predict faulty conditions and try to maintain the normal operation of the system until the faulty component is repair depending on the size and time varying behaviour of the fault.

The development of an appropriate diagnostic tool has the potential to produce a reduction in life cycle costs of the system. Most of fault detection schemes consist of two levels, a symptom generation part and a diagnostic part. In the first level symptoms are generated that indicate the state of the process and in the second level the relation between symptoms and faults is established. Model-based fault diagnosis is a well established approach and gives the opportunity of developing diagnostic functions able to cover a more wide area of the diagnostic activities such as [1], [2], [3], [4].

In fluid power systems a possible failure can have catastrophic results if for example a containment failure of hydraulic fluid at high pressure occurs. In these systems faults are often caused by a small incipient leakage that has as effect an increased temperature, a decreased performance or both. The development of a system able to monitor, detect and compensate the consequences of an incipient fault until the defective component is repaired is very useful for the entire system that improves the level of the maintenance process. Recent research work on developing diagnostic and monitoring methods for hydraulic actuators includes [5], [6], [7] where a detailed causes of malfunction of the overall conditions in the system is concluded.

In this paper an approach for effective interaction of real-time data and modelling information for the detection and diagnosis of incipient faults in online performance of electro-hydraulic systems is presented. The detection of incipient faults is realised taking into consideration specific parallel deviation of pressure signals with or without relevant deviations of angular velocity signals.

The paper is organized as follows: Section 2 presents the actual system used for the experimentation part of this work as well as the modelling process. Section 3 focuses on fault detection and compensation process, while Section 4 presents the justification of the results. Finally, Section 5 includes concluding remarks. Recent research work in diagnostic procedures for hydraulic systems or hydraulic components includes [8], [9], [10], [11], [12], [13].

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II. Modelling of the system

The hydraulic system used in this work, Figure 1, consists, besides the power unit, mainly of a proportional 4/3-way proportional valve and a hydraulic displacement motor with an attached rotating mass J_m.

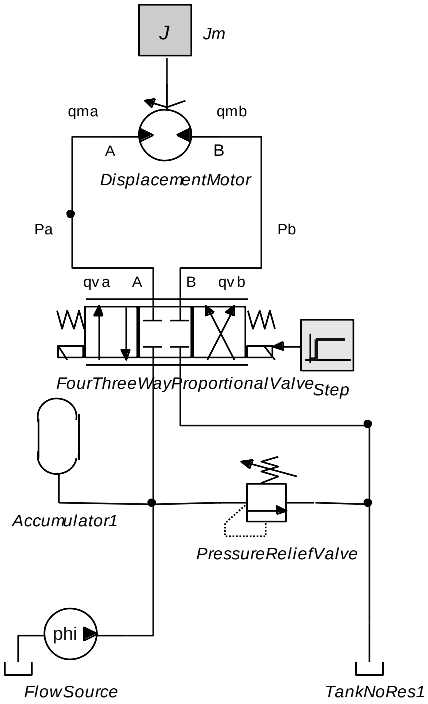

Figure 1. The actual system

Figure 2 shows the hydraulic motor. The function diagram, Figure 3, represents the operating curves of the motor for various values of the operating pressure. From these curves the actual flow in l/min for a demanded rotation speed in min^{-1} can be found. The flow curves can be used for the estimation or validation of the volumetric efficiency of the hydraulic motor

Figure 2. Hydraulic motor

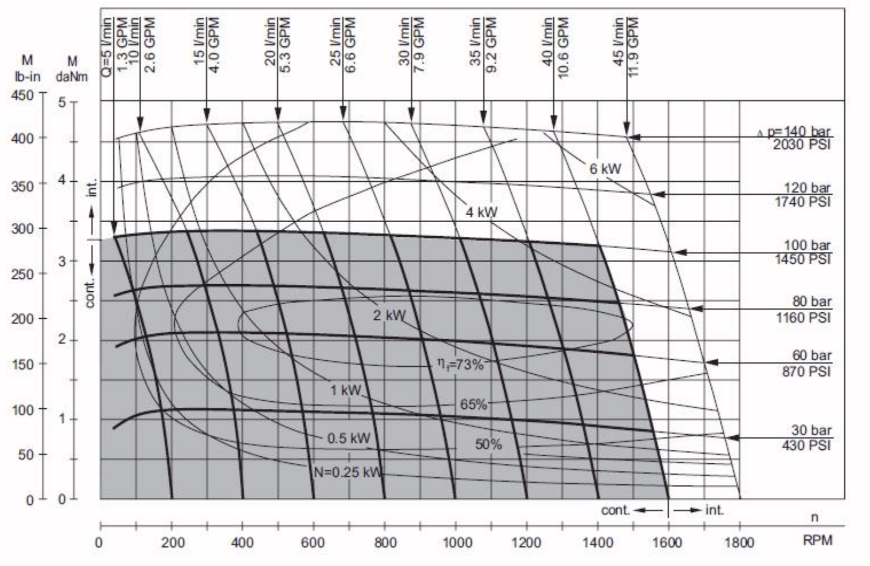

Figure 3. Motor performance as a function of operating speed

Assuming that the working pressure is constant, the variables of the system are following: The pressure p_a at the port A of the hydraulic motor, the pressure p_b at the port B of the hydraulic motor, the rotation angle of the motor shaft φ, the angular velocity ω, the flows q_{va} and q_{vb} through the A and B ports of the proportional 4-way valve, the flows q_{ma} and q_{mb} through the ports A and B of the hydraulic motor, the input current to the proportional valve I_2 or the corresponding voltage to the amplifier of the proportional valve U_2.

The main considerations for the description of the dynamic behaviour of hydraulic systems referred to the fact that the 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.

For those components which contain large quantities of oil as pipes and hydraulic actuators it may be assumed that the change in pressure in the dynamic state is proportional to the net inflow of oil, that is:

$dp / dt = (E / V_o) . \Sigma Q$ where

E is the elasticity module of the oil plus the included air,

V_o is the Volume of the pipe plus a part of the volume of the attached actuator,

$\Sigma Q = Q_{in} - Q_{out}$,

Q_{in} is the incoming flow to the volume V_o of a connecting pipe and

Q_{out} is the outgoing flow from V_o.

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 variable displacement pump is controlled by a proportional valve according to the relation:

$V = V_{max} \cdot U_2/U_{max}$ where

V is the displacement (flow per revolution) of the pump

V_{max} is the maximal displacement

U_2 is the voltage to the amplifier of the proportional control valve and

U_{max} is the maximum voltage (10 V)

The pump flow to the hydraulic motor is given by:

$Q = V \cdot n \cdot \eta_v$ where

n is the number of the revolutions per minute of the pump shaft and

η_v is the volumetric efficiency of the pump

The description of the dynamic behaviour takes also into account the non-linear character of hydraulic systems as well as the special characteristics of the hydraulic elements used. In consequence the model represents the behaviour of the system elements more accurately. The modelling of the hydraulic elements with the coupled moving masses leads to a non-linear system of equations.

III. Fault Detection and Compensation Using Modelling Data

A generalized structure of model-based fault detection schemes consists of two stages of residual generation and residual evaluation. The main measurable variables of the hydraulic system are the angular velocity of the hydraulic motor and the pressures between the components of the system.

The structure of the fault detection is presented in Figure 4. The input to the actual system is the voltage signal U_2 from the control system and the outputs which are fed to the expert system are the angular velocity ω, the pressures p_a, p_b, and the state signals from the devices of the power unit.

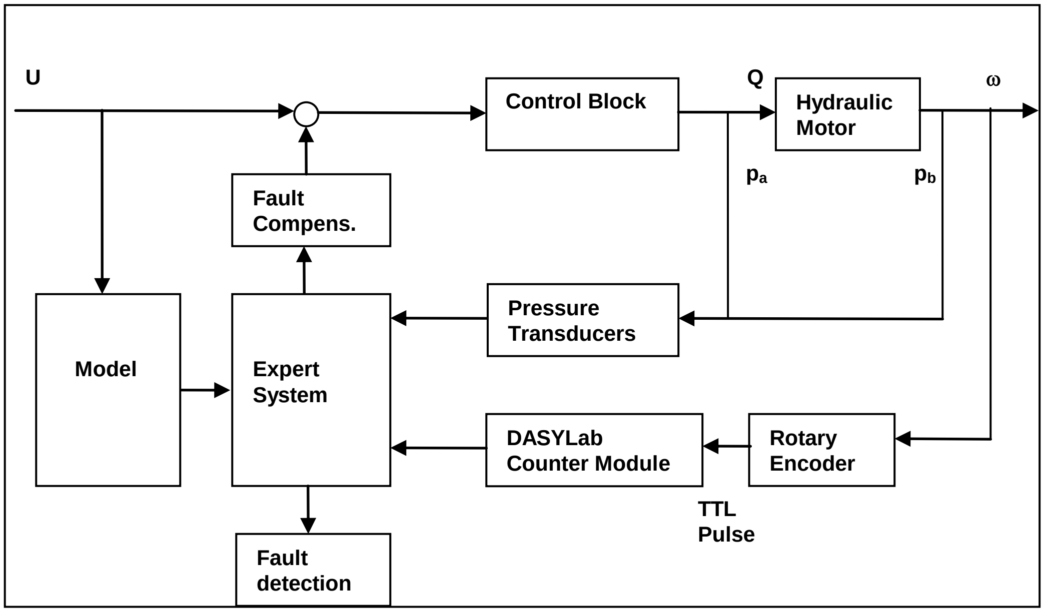

Figure 4. Fault detection and compensation process structure

The simulation program calculates the values of the angular velocity and the pressures for the same period of time. The comparison of the measured and the calculated values is then performed and the difference is written to output files.

This information can interact with the knowledge base of the system for the final diagnostic process. Reasoning about equipment faults is based on variable changes and related experimental knowledge suitably formatted.

The decreased speed of a worn hydraulic motor can be compensated by adding a correction voltage value ΔU_2 to the command value U_2 of the proportional valve that controls the motor speed. This voltage value can be calculated using a mathematical relation between command voltage and speed. The relation for the correction voltage is obtained from the equations (1) and (2) assuming a stationary state in order to achieve a fast on-line compensation. The stationary state was taken into consideration because the target is to maintain the given motor speed in the stationary state.

Decrease of the motor speed in the stationary state means decrease of the efficiency of the machine. In the case of the stationary state it is:

$q_{va} = q_{ma}$ where: q_{va} = flow coming from the proportional valve and $\Delta U_2 = U_2 \cdot (\Delta \omega / \omega_m)$, where $\Delta \omega$ is the reduction of the motor speed and ω_m is the motor speed that corresponds to the voltage U_2 calculated from the model. This is the relation for the correction voltage ΔU_2 that must be added to U_2 in order to compensate the reduced motor speed.

This relation is valid for a leakage free system. In order to show that the relation between $\Delta\omega$ and ΔU_2 is linear and also valid for different motor leakage values, a relation between ω, U_2 and an artificial produced motor leakage ql is determined.

The control of the hydraulic motor and the fault compensation process are implemented using the DASYLab software. The correction value $\Delta\omega/\omega_m$ is transferred to the worksheet through a connection file transformed to a correction voltage and added to the command voltage.

When the fault compensation process is activated a relevant warning message appears on the screen because although the fault is compensated for a short period of time it still exists.

IV. Evaluation of the diagnostic results

The system was tested for various cases of malfunction using simulated faulty conditions. The parameters, as the friction torque M_r, the moment of inertia J_m and the oil elasticity E were varied. For a variation of ± 5 %, and ± 10 % of these parameters affect the effectiveness of the fault detection process is not affected.

V. Conclusion

In this paper a model-based approach for the detection and isolation of faults in hydraulic motors was presented.

The final model, used by the fault detection system, is able to simulate quite precisely the actual behaviour of the physical system. The developed system is also able to compensate the consequences of faults without the need of additional devices by calculating a suitable control signal.

The main benefit of using fault compensation functions in a diagnostic system is the higher degree of reliability of the operation of the system by preventing a low performance, small faults or unexpected shutdowns. The experimentation results are promising and the method is applicable to real world situations.

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