On-Line Fault Detection and Compensation of Hydraulic Driven Machines Using Modelling Techniques

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Abstract

The development of on line model-based fault detection systems in machinery improves the operational reliability of industrial systems and reduces the operational and maintenance costs. In this direction, this paper presents the use of modelling information to determine changes in characteristics from measured data for the fault detection purpose of hydraulic driven machines as well as for the compensation of incipient faults where applicable. For this purpose a suitable implementation environment was developed that allows the on line interaction of real time data and simulation results and makes possible their direct effect to the actual system.

Keywords: Modelling, Simulation, Hydraulic motors, Fault detection, Fault Compensation

1. Introduction

Model-based fault detection is typically realized using a process model together with on-line measurements to estimate some of the process states and parameters and to test these estimates against confidence limits in order to examine various diagnosis hypotheses. Several survey papers have been published for the implementation of model-based procedures in automated industrial processes as (Patton et al. 2000, Chen and Patton 1999, Frank 1996, Isermann and Balle 1996, Mangoubi and Edelmayer 2000)

Electro-hydraulic drives and systems are used in wide variety of applications throughout the entire field of automation technology from robotics and aerospace to heavy industrial systems. Electro-hydraulic drive systems are related to the basic operation of a hydraulic system and their performance affect the reliability of the total system. Hence, the development of on-line diagnostic procedures for these components is very significant for the industrial maintenance processes. Hydraulic motors are subject to a fault in a system that is often recognised by a small insipient leakage. The development of a suitable system that is able to detect and compensate the consequences of the leakage until the defective component is repaired offers higher degree of reliability and operational efficiency of the total systems. Fault diagnosis and monitoring for rotating machines has been reported in a number of papers such as (Edwards et al. 1998, Nandi. and Toliyat 1999, Randall 2002). Recent research work on developing diagnostic methods for hydraulic systems is published by (Angeli and Atherton 2001, Mundy and Stammen 2002, Muenchof et al 2003, Kwan et al. 2003).

In this paper, a model based fault detection method is presented that is successfully applied to a hydraulic driven machine. The hydraulic motor-mass-pipes system of the machine was modelled using mathematical equations. Real-time data are acquired from the actual system and compared with the relevant variable values of the simulation process referring to pressure signals and to the angular velocity signal. The DASYLab data acquisition and control software was used for the data acquisition process as well as for the implementation of the fault compensation function to the actual system.

2. Modelling of the Drive System

The hydraulic system of a hydraulic driven machine typically consists of one or more hydraulic motors or cylinders, a power unit and a control block. The task of the hydraulic system is to move the hydraulic actuators and the attached loads. The hydraulic motor used, shown in Figure 1, is a fixed displacement motor.

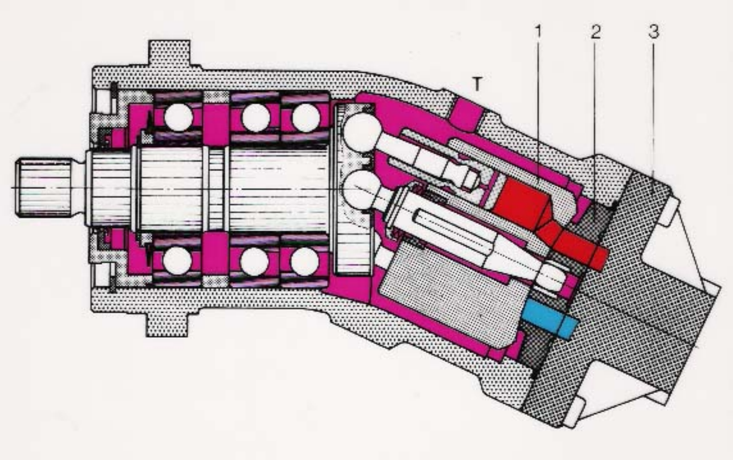

Figure 1 Hydraulic motor (Rexroth-Hydromatik)

The function diagram is given by the manufacturer. The diagram represents the operating curves of the motor for different values of the pressure drop Δp. From these curves the pressure drop in bar for a given load in kW as well as the actual flow in l/min for a demanded rotation speed in r/min can be found. The flow curves can be used for the estimation of the volumetric efficiency of the hydraulic motor.

Figure 2 shows a typical scheme of a close circuit system, consisting of a constant hydraulic motor and a variable pump, controlled by a proportional 4-way valve. The hydraulic motor must be able to accelerate and rotate a mass with a given speed. The rotation speed of the hydraulic motor depends on the actual flow rate through the motor and on its displacement volume.

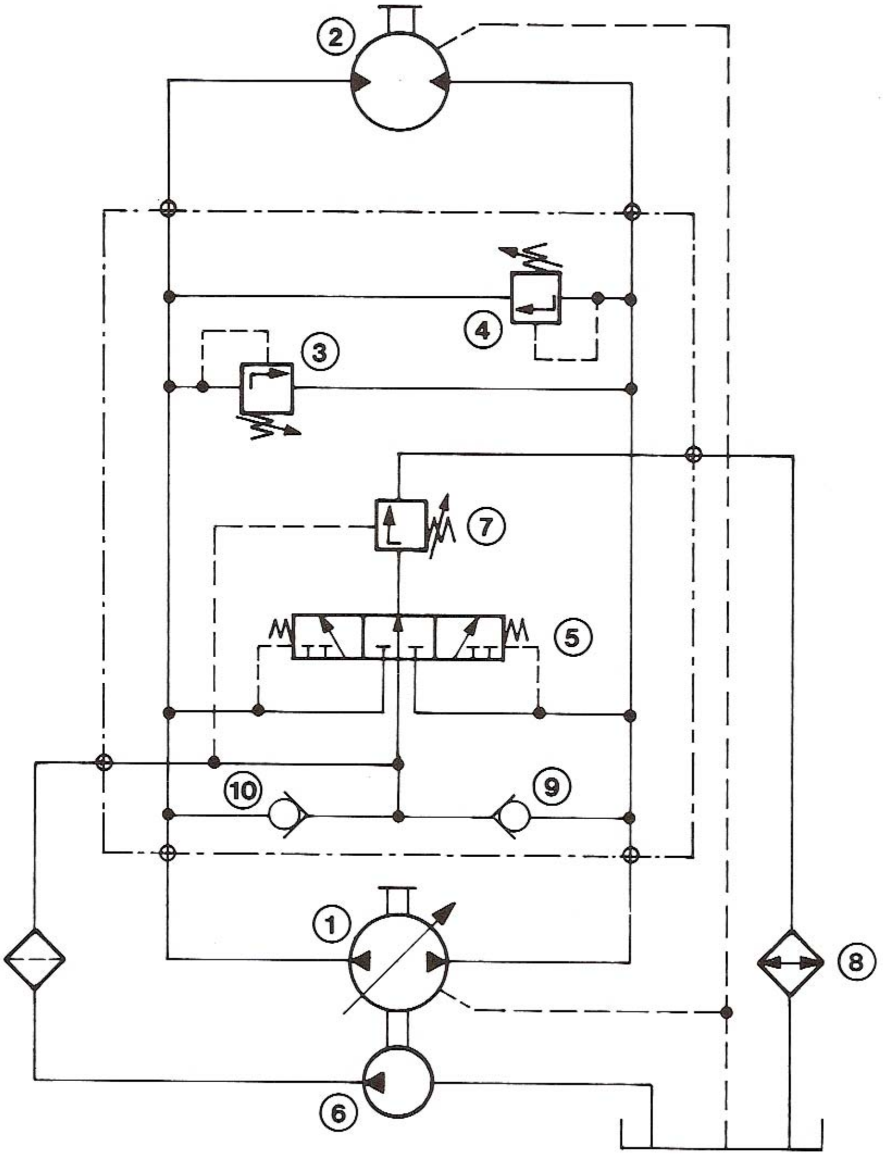

Figure 2. The Hydraulic motor in the hydraulic system.

For the purpose of fault detection an accurate model of the hydraulic motor was developed and validated in comparison to the real process measurements. In this model physical relations as well as relations derived from the technical specifications given by the manufacturer were used.

For the hydraulic motor with a volumetric efficiency η_v the inflow and outflow are given by:

$$q_{ma} = \left(\frac{C_m}{\eta_v} \right) \cdot \dot{\varphi}$$

$$q_{mb} = C_m \cdot \dot{\varphi}$$

where:

$$C_m = \frac{V_m}{2 \cdot \pi}$$

The hydraulic motor rotates the mass of the rotating ports of the machine and the application of the Newton low gives the following relationship:

$$\frac{d^2\varphi}{dt^2}=\left[\left[\frac{V_m\cdot(p_a-p_b)}{2\cdot\pi}\right]-M_r\right]\cdot\frac{1}{J_m}$$

where:	V_m	Displacement volume of the hydraulic motor
	M_r	Mechanical friction torque
	J_m	Moment of inertia of the rotating parts
	p_a, p_b	Pressure at the motor ports

3. Fault Detection

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 and fault compensation process is presented in Figure 3. The input to the actual system is the voltage signal U 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.

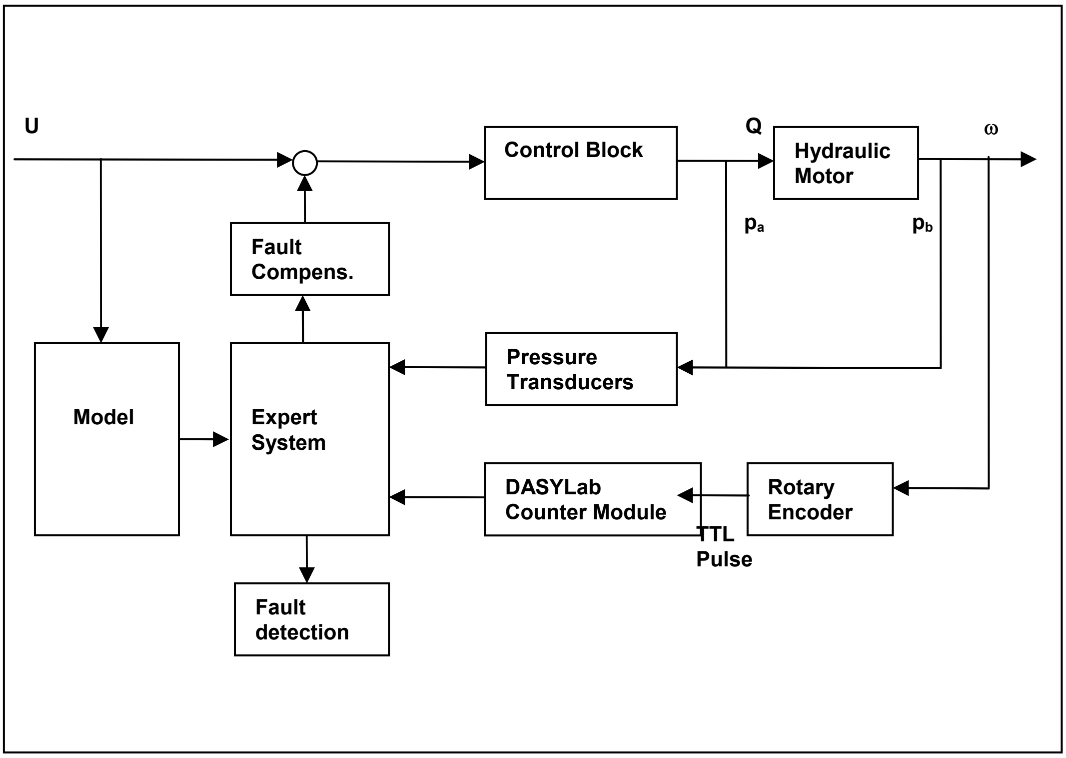

Figure 3. Fault detection and compensation process structure

For the data acquisition and fault compensation process the DASYLab software was used. The data acquisition system runs in parallel to the actual system and acquires data for the angular velocity and the pressures while the speed is changing.

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..

3. Fault Compensation Using Modelling Data

The decreased speed of a hydraulic drive due to a slightly 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 variable pump of the close circuit system and thus 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:

$$\Delta U_2 = U_2 \cdot (\Delta \omega / \omega_m)$$

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.

If the value of the flow q_{mb} through the hydraulic motor is determined then the angular velocity ω and the pressures p_a and p_b in relation to q_{mb} can be calculated:

From the above equations we have: $\omega = d\varphi/dt = 2.\ \pi.\ q_{mb} / V_m$

and $q_{mb} = \eta_v\ .q_{ma} = q_{ma} - ql$

The angular velocity ω is a function of U_2 and ql

$$\omega = f(U_2, ql)$$

The calculation of the angular velocity ω for various command voltage values and the ql values 0,00, 0,40, 0,80, 1,20, 1,60 and 2,00 l/min is plotted in Figure 4.

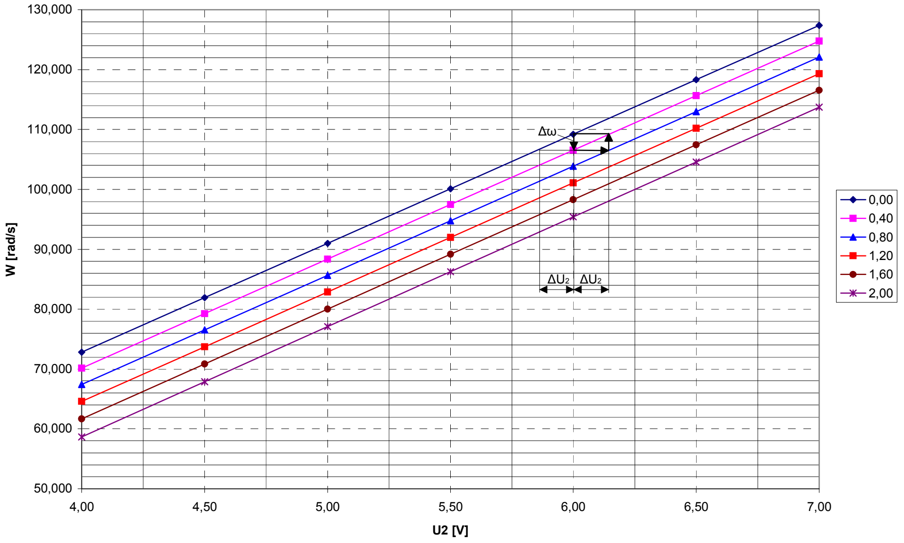

Figure 4 Relation of angular velocity ω , voltage U_2 and leakage ql values

From Figure 4 it can be observed that the relation between the angular velocity ω and the voltage U_2 for various bypass flow values ql is approximately linear. The curve 0,00 corresponds to a fault free system. The curves for the other ql values are approximately parallel.

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. The control of the hydraulic motor and the compensation process is shown in Figure 5.

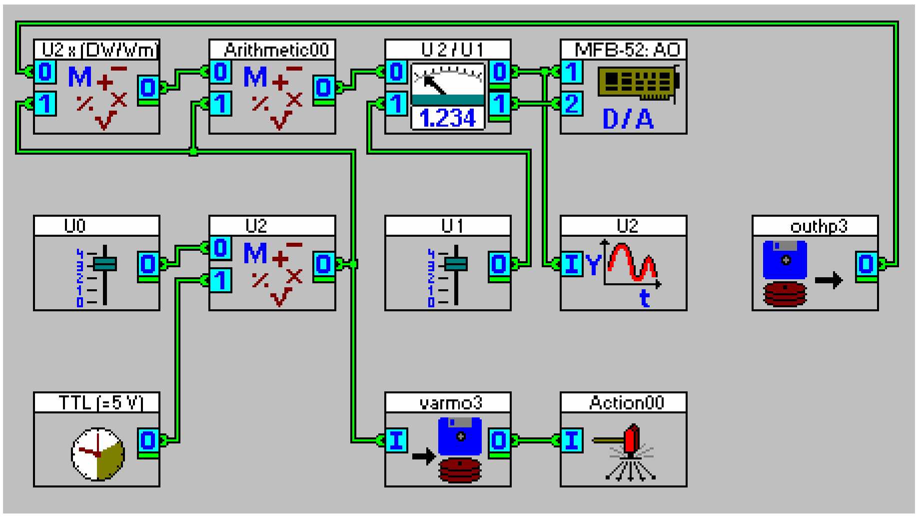

Figure 5. Control and fault compensation of the hydraulic motor

In this worksheet the measured speed of the hydraulic motor is compared with the theoretical value that comes from the simulation. The deviation between these values is calculated and written to the file “outhp3”. The combination of the modules "U0", "TTL(=5V)" and "U2" produce a periodical square-wave form voltage signal that takes the values $U_0 = 1$ V and $U_2 = 6$ V, corresponding to the low and high speed of the hydraulic motor.The correction voltage that compensates the reduction of the motor speed is calculated by the module "U2x(DW/Wm)" and added to the command voltage U_2. The "MFB-52:AO" module corresponds to two analogue outputs of an I/O card transfers the command voltage signals to the amplifier of the proportional valve for the regulation of the flow to the hydraulic motor and the amplifier of a proportional pressure valve for the regulation of the system pressure.

The "varmo3" module is used to store the value of the voltage U_2 that is needed by the simulation program, so that the simulation runs every time with the updated command value.

When the fault compensation process is activated a message appears on the screen "Compensation process. Please repair the hydraulic motor!". This is a useful message for the operator because after the application of the correction voltage the fault will be compensated and no more detected for a period of time, although it still exists.

4. Conclusion

The development of on-line model based fault detection and compensation procedures for technical systems offers a higher degree of reliability of the operation of the system by preventing a low performance, small faults and/or unexpected shutdowns of the production procedure. In this paper, modelling information was used in comparison with on line measurements referring to the pressure signals as well as to the angular velocity signal for the detection of abnormal behaviour of a hydraulic driven machine and for the calculation of the suitable control and fault compensation signal. The experimentation results show that the control of the hydraulic motor and the fault compensation system are reliable and the method is applicable to real world systems.

5. References

Angeli, C. and D. Atherton 2001, "A model-based method for an online diagnostic knowledge-based Systems". *Expert Systems* Vol. 18, Nr. 3, pp. 150-158.

Chen, J. and R. Patton 1999, "*Robust Model Based Fault Diagnosis For Dynamic Systems*", Kluwer Academic Publishers.

Edwards, S. A. Less and M. Friswell 1998, "*Fault diagnosis of rotating machinery, Shock and Vibration*" Digest, 30, 4-13.

Frank, P.M. 1996, "Analytical and qualitative model-based fault diagnosis: A survey and some new results". *European Journal of control*, Vol. 2, 6-28.

Isermann, R. and P. Balle 1996, "Trends in the Application of Model Based Fault Detection and Diagnosis of Technical Processes". *IFAC World Congress 1996*, San Francisco.

Kwan, C. R.Xu and X. Zhang 2003, "Fault detection and Identification in Aircraft Hydraulic Pumps Using MCA", *In Proceedings Safeprocess 03*, Washington, U.S.A. pp. 1137-1143.

Mangoubi, R.S. and A. M. Edelmayer 2000, "Model based fault detection: the optimal past, the robust present and a few thoughts on the on the future", *In Proceedings Safeprocess 00,* Budapest.

Muenchof, M. H Straky and R. Isermann 2003, "Model-based fault detection and diagnosis for hydraulic braking systems", *SAFEPROSESS 2003*, Washington, USA, pp.307-312.

Mundy, S. and C. Stammen 2002, "Condition Monitoring for fluid technology", *o+p Oelhydraulic and Pneumatic* Vol. 46, Nr.2.

Nandi, S. and H. Toliyat 1999, "Condition Monitoring and Fault Diagnosis of Electrical Machines – A Review", *In Proceedings IEEE-IEMDC Conference*, Seattle, WA, pp. 352-358.

Patton, R., P Frank and R. Clark 2000 "*Issues in Fault Diagnosis For Dynamic Systems*", Springer-Verlag.

Randall, R. 2002, "State of the art in monitoring rotating machinery", *In Proceedings ISMA 2002*, 4, pp. 1457-1477.