PREDICTION OF ROTARY HYDROSTATIC DRIVE'S VOLUMETRIC LOSSES

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ABSTRACT

This paper presents a diagnostic method of a hydrostatic drive. The diagnostic method is applied to a rotational hydrostatic drive. The basis of the method used is the design of a mathematical model of the dynamic behaviour of the hydrostatic drive in C-code, and adapted in MATLAB/Simulink® as S-functions. After completing the simulation model, real states of the system can be simulated. To have an accurate and verified model, the torque and volumetric losses have been determined by comparing the simulation model behaviour with real system output. This procedure is repeated with real system outputs from the other measurements using different conditions of the drive's wear. There have been discrepancies between previous simulation data and real system behaviour, when handling the same input values. To achieve the best accuracy of the model, torque and volumetric losses have to be changed. These changes of losses relate to the amount of wear of a component.

The values of volumetric losses at monitored time intervals are inputs into the training process of the artificial neural network. These neural networks are able to make prognoses without defining the mathematical function between input variables. The values of volumetric losses over time, the number of failures per year and the operating life recommended by the producer were used to train the 2D neural networks. The outputs from the 2D neural networks were used as inputs to the 3D neural network. The networks predict the trend of the volumetric losses.

Keywords: hydrostatic drive, prediction, artificial neural network, condition monitoring

INTRODUCTION

This paper presents a diagnostic method for a hydrostatic drive, and the mathematical model of dynamic behaviour of that hydrostatic drive. Results from the model were compared with output parameters from real hydraulic systems. Models of volumetric and torque losses were fitted to the values of losses acquired through measurement. Some output parameters of the mathematical model and outputs from artificial neural networks are presented in this paper. Figure 1 shows the block diagram of the hydrostatic drive with inputs, outputs and the flow of signals.

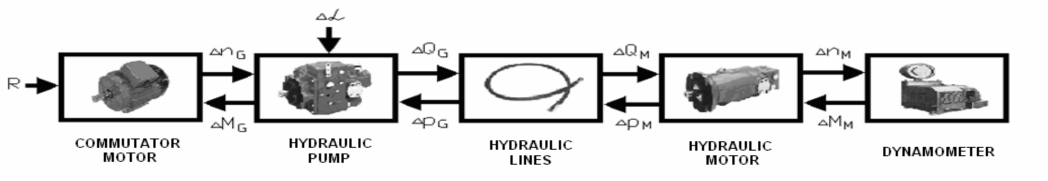


Fig. 1 Block diagram of hydrostatic drive with the flow of signals.

MATHEMATICAL MODEL OF COMMUTATOR MOTOR

The rotary mechanical system is defined by the torque equation:

$$M_E - M_G = 2 \cdot \pi \cdot I_E \cdot \frac{dn_G}{dt}, \tag{1}$$

where M_E – represents the driving torque of the electric motor,
M_G – represents the torque of the hydraulic generator,
n_G – represents the speed of the hydraulic generator,
I_E – represents the moment of inertia of the electric motor.

The torque of commutator motor M_E was calculated as a function of speed n_G and control parameter R based on approximation:

$$M_E = E_1 + E_2 \cdot n_G + E_3 \cdot n_G^2 + E_4 \cdot R + E_5 \cdot n_G \cdot R + E_6 \cdot n_G^2 \cdot R + \\ + E_7 \cdot R^2 + E_8 \cdot n_G \cdot R^2 + E_9 \cdot n_G^2 \cdot R^2 \tag{2}$$

where R represents the control parameter of the electric motor.
The coefficients E_1 - E_9 were calculated from measured data with least squares method.

MATHEMATICAL MODEL OF PUMP

The generator is defined by flow equation and moment equation. The flow equation of the generator:

$$Q_G = \alpha_G \cdot V_{0G} \cdot n_G - C_G \cdot \frac{dp_G}{dt} - Q_{LG}, \tag{3}$$

where α_G represents the control parameter (displacement ratio),
V_{0G} represents the geometrical volume of the hydraulic generator,
C_G represents the hydraulic capacity of the hydraulic generator,
p_G represents the pressure drop of the hydraulic generator,
Q_{LG} represents the volumetric losses of the hydraulic generator.

Assuming a fixed bond between electric motor and generator $M_G = M_E$. Then torque M_G was given by:

$$M_G = \frac{\alpha_G \cdot V_{0G} \cdot p_G}{2 \cdot \pi} + 2 \cdot \pi \cdot I_G \cdot \frac{dn_G}{dt} + M_{LG}, \tag{4}$$

where I_G represents the moment of inertia of the hydraulic generator,
M_{LG} represents the hydraulic-mechanical losses of the generator.

The data on efficiency obtained by measurements was transformed into the behaviour of volumetric losses and hydraulic-mechanical losses. After some simplification, the volumetric losses $Q_{LG} = f(n_G, p_G, \alpha_G)$ and hydraulic-mechanical losses of the generator

$M_{LG} = f\left(n_G, p_G, \alpha_G\right)$ were calculated as a function of speed n_G, pressure drop p_G and control parameter α_G based on approximation.

MATHEMATICAL MODEL OF HYDRAULIC LINES

The mathematical model of hydraulic lines was defined by flow and pressure equations:

$$Q_M = Q_G - C_P . \frac{dp_G}{dt}, \tag{5}$$

where Q_M represents the flow of the hydraulic motor,
Q_G represents the flow of the hydraulic generator,
C_P represents the hydraulic capacity of the hydraulic lines.

$$p_G = p_M + R_P . Q_M^n + H_P . \frac{dQ_M}{dt}, \tag{6}$$

where R_P represents the resistance against motion of liquid,
H_P represents the resistance against acceleration of liquid,
p_M represents the pressure drop of the hydraulic motor,
p_G represents the pressure drop of the hydraulic generator.

MATHEMATICAL MODEL OF HYDRAULIC MOTOR

The basic equations for the motor were torque equations and flow equations. The equation of flow for a motor:

$$Q_M = V_{0M} \cdot n_M - C_M \cdot \frac{dp_M}{dt} - Q_{LM}, \tag{7}$$

where n_G represents the speed of the hydraulic motor,
p_M represents the pressure drop of the hydraulic motor,
V_{0M} represents the geometrical volume of the hydraulic motor,
Q_{LM} represents the volumetric losses of the hydraulic motor,
C_M represents the hydraulic capacity of the hydraulic motor.

The output moment of the motor was calculated as a function of speed n_M, geometrical volume V_{0M}, moment of inertia I_M and hydraulic-mechanical losses M_{LM} :

$$M_M = \frac{V_{0M} \cdot p_M}{2 \cdot \pi} + 2 \cdot \pi \cdot I_M \cdot \frac{dn_M}{dt} + M_{LM}, \tag{8}$$

where I_M represents the moment of inertia of the hydraulic motor,
M_{LM} represents the hydraulic-mechanical losses of the hydraulic motor.

After some simplification the volumetric and hydraulic-mechanical losses of the motor were calculated as a function of speed n_M and pressure drop p_M based on approximation.

MATHEMATICAL MODEL OF DYNAMOMETER

The dynamometer was used as the ballast of the hydrostatic drive. The torque of the dynamometer had a constant value. The dynamometer was defined by this differential equation:

$$M_D = 2 \cdot \pi \cdot I_D \cdot \frac{dn_M}{dt}, \tag{9}$$

where M_D represents the torque of the dynamometer,
I_M represents the moment of inertia of the dynamometer.

ASSEMBLY OF FINAL MATHEMATICAL MODEL OF HYDROSTATIC DRIVE´S DYNAMIC BEHAVIOUR

A reduction in the number of differential equations was needed in the process of assembly. The simplification did not cause a reduction in the exactitude of the model. The previous number of differential equations was ten but after reduction became five.

EQUATIONS OF HYDROSTATIC DRIVE´S FINAL SIMULATION

After some mathematical operations the equations for the final simulation model of the hydrostatic drive were deduced. After modification for the generator we get:

$$\frac{dn_G}{dt} = NG1 \cdot n_G + NG2 + NG3 \cdot \alpha_G + NG4 \cdot p_G + NG5 \cdot p_G \cdot \alpha_G, \tag{10}$$

where NG represents the constants.

$$\frac{dp_G}{dt} = PG1 \cdot Q_M + PG2 \cdot \alpha_G + PG3 \cdot n_G + PG4 \cdot p_G + PG5 + PG6 \cdot \alpha_G \cdot p_G \tag{11}$$

where PG represents the constants.

For the motor we get:

$$\frac{dQ_M}{dt} = QM1 \cdot Q_M + QM2 \cdot p_G + QM3 \cdot p_M, \tag{12}$$

where QM represents the constants.

$$\frac{dp_M}{dt} = PM1 \cdot Q_M + PM2 \cdot n_M + PM3 \cdot p_M + PM4, \tag{13}$$

where PM represents the constants.

The final equation for the torque of the generator M_G was deduced from the moment equation of the generator (4) and the moment equation of the commutator motor (1). After mathematical modification:

$$M_G = \frac{\alpha_G \cdot V_{0G} \cdot p_G}{2 \cdot \pi} + \frac{I_G}{I_E} \cdot \left(M_E - M_G \right) + M_{LG}, \qquad (14)$$

SIMULATION

The mathematical models were created in C-code and adapted for Matlab-Simulink as S-functions. The numerical simulation was realised by equations of states. Equations of states were transformed from linearized differential equations. Figure 2 shows the model built in Matlab-Simulink and Figure 3 shows the mask of the model built in Matlab-Simulink.

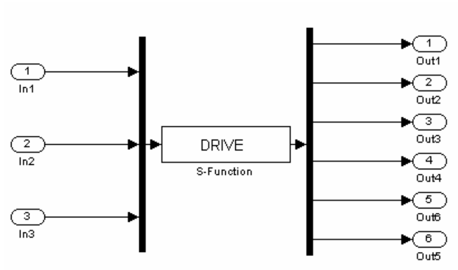


Fig. 2 Model built in Matlab-Simulink.

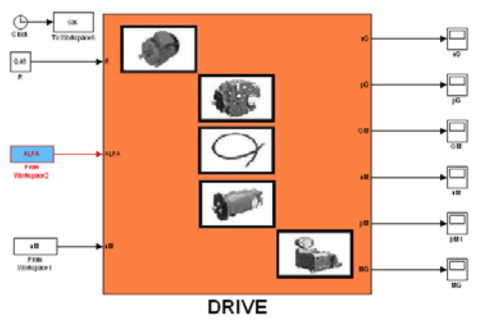


Fig. 3 Mask of the model built in Matlab-Simulink.

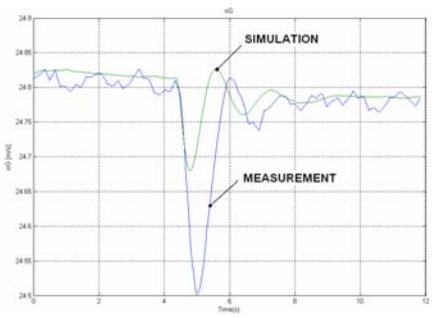


Fig. 4 Comparison of simulated and measured revolution of pump.

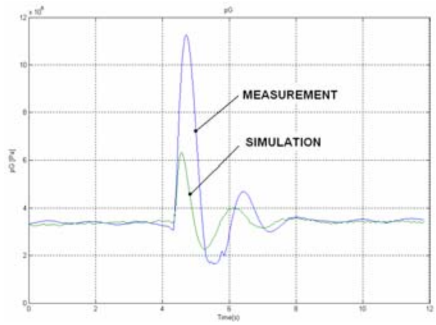


Fig. 5 Comparison of simulated and measured pressure of pump.

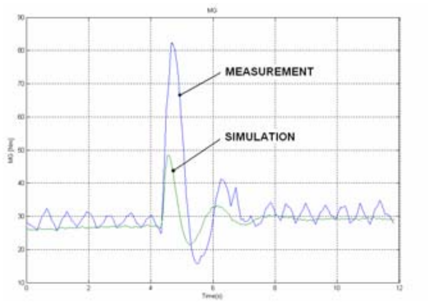


Fig. 6 Comparison of simulated and measured torque of pump.

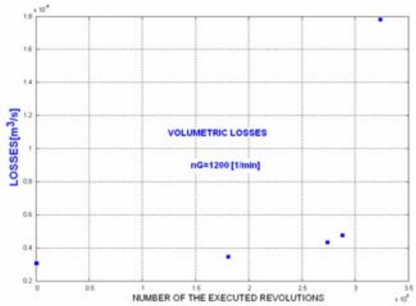


Fig. 7 Volumetric losses of pump for separate different wears of the hydrostatic drive in the first operating point.

The output signals of the simulation model were compared with measured values. Possible errors in accuracy between simulations and measured values, reflected changes in the system behaviour during operation. The changes in properties were quantified using the component's model parameters block, where the parameters of the volumetric and torque losses were defined. Figure 4 shows the time behaviour of revolution, Figure 5, the time behaviour of pressure and Figure 6 the time behaviour of torque.

PROGNOSIS

Comparing the output signals of the simulation model and measured values produced a set of data which characterized the wear of the hydrostatic drive. This data showed the values of volumetric and torque losses. Figure 7 shows the volumetric losses of the pump for different wear conditions of the hydrostatic drive in the first operating point, and Figure 8 in the second operating point. These values at monitored time periods were the inputs into the training process of the artificial neural network. The goal of this project is to create a forecasting method able to make an accurate estimation of the future trend in degradation.

MULTILAYERED PRECEPTRON USED FOR PROGNOSIS

The role of the artificial neural network is to find the relationship between the vector of volumetric losses over time, the number of failures per year and the operating life recommended by the producer. In the training phase the Levenberg–Marquardt algorithm was used because this algorithm is able to obtain lower squared errors. Demuth and Beale consider that the Levenberg – Marquardt algorithm is an algorithm with the fastest convergence. The collected data is used to train the network with the aim of producing future values of the volumetric losses. The first step of prediction was the comparing of the measured values and the outputs from the simulation for four separate different instances of wear of the hydrostatic drive at two different operating points. Then the values of the volumetric losses over time, the quantity of failures per year and the operating life recommended by the producer were used to train the 2D neural networks. Figure 9 shows prediction of volumetric losses in the first operating point and Figure 10 shows prediction of volumetric losses at the second operating point. The outputs from the 2D neural networks were used as inputs to the 3D neural network. The networks predict the trend of the volumetric losses. Figures 9 and 10 display the 2D outputs from double layered neural networks with two neurons in the hidden layer and one in the outer layer. Figure 11 depicts the outer of the three layers multilayered feed forward neural network with two and two neurons in the hidden layers and one neuron in the outer layer.

CONCLUSIONS

The hydrostatic drive's simulation model is a diagnostic element. There are differences between outputs and real system behaviour, for the same inputs. To achieve the best accuracy of the model, torque and volumetric losses have to be changed. These changes of losses reflect the wear of the component. The values of volumetric and torque losses define the wear of the hydrostatic drive. These values at monitored times were inputs to the training process of the artificial neural networks. These neural networks are able to make prognoses without defining the mathematic function between input variables. Target values during the training process will be set to volumetric loses obtained from simulation and measured value comparisons. Figure 12 shows 3D neural network prediction in hours 3D view and Figure 13 shows the 2D view.

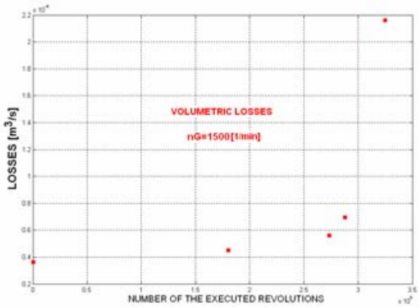


Fig. 8 Volumetric losses of pump for separate different instances of wear of the hydrostatic drive at the second operating point.

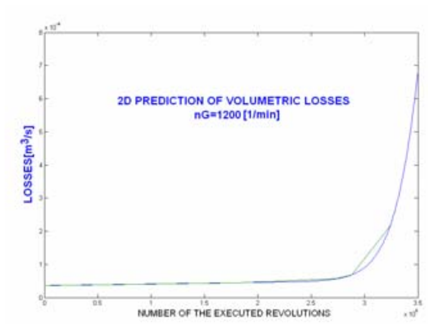


Fig. 9 Prediction of volumetric losses at the first operating point.

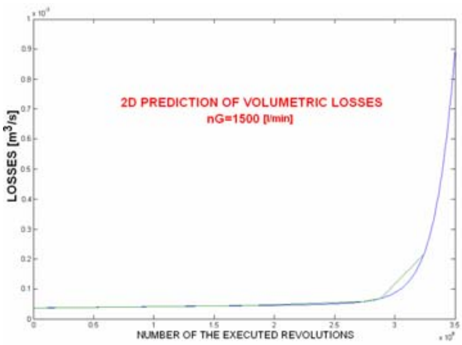


Fig. 10 Prediction of volumetric losses at the second operating point.

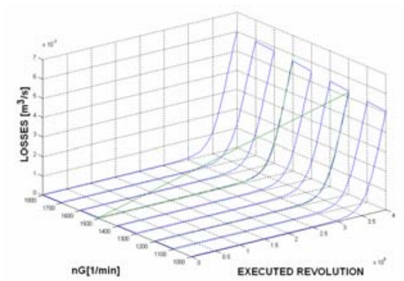
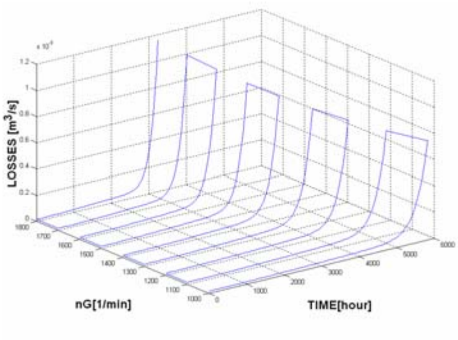


Fig. 11 3D Neural network prediction 3D view.



Fig, 12 3D Neural network prediction in hours 3D view.

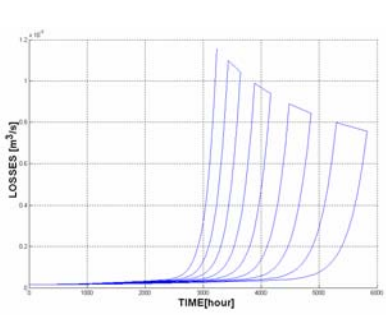


Fig. 13 3D Neural network prediction in hours 2D view.

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