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FAULT DIAGNOSIS OF ELECTROHYDRAULIC SYSTEMS

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ABSTRACT

Reliability is essential for electro-hydraulic systems due to the high energy densities associated with their operation. A failure can have catastrophic results, for example, if a contamination failure of hydraulic fluid at high pressure occurs. A novel approach for fault diagnosis of hydraulic systems has been proposed, using genetic algorithms as the parameter optimization method, and model based simulation. Performance tracking of critical parameters within the hydraulic system assesses subtle state changes and attempts to identify failure modes associated with these state changes. The proposed approach, which requires analysis of each component of the hydraulic system under normal operation and with specific, induced failure modes, has been successfully applied to a hydraulic system incorporating a servovalve and linear actuator. The results of this study provide a basis for future studies of more complex hydraulic components and systems.

KEY WORDS

electro-hydraulic systems, fault diagnosis, modeling, performance tracking, genetic algorithms

INTRODUCTION

Mechanical systems in general can be expected to develop faults if operated for any length of time. These faults need to be detected and identified, preferably at an early stage before they become compounded. There would be clear advantages if an automated system were used to monitor the performance of a complex mechanical system, providing early warning fault conditions. A monitoring sysem would need to recognize faults in specific components in particular those that are central to the best and safe operation of the mechanical system.

This paper reports on the performance of fault diagnosis tasks by applying model-based and optimization techniques, which aims to detect potential and on-going failures in electro-hydraulic systems, by looking at small changes at the state of the hydraulic system that could be associated with typical or expected failure modes. Reliability is essential for electro-hydraulic systems due to the high energy densities associated with their operation. A failure can have catastrophic results, for example, if a containment failure of hydraulic fluid at high pressure occurs.

A novel approach for fault diagnosis of hydraulic systems has been proposed, using Genetic Algorithms (GA) techniques as part of the optimization method used, and parametric model-based simulation. Performance tracking of critical state parameters within the hydraulic system assesses subtle state changes and attempts to identify failure modes associated with these state changes. The proposed approach requires the

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analysis of each component of the hydraulic system under normal operation and with specific, induced failure modes. A detailed study has been completed on one sub-system: a servovalve and linear actuator configuration. This study provides a template for future studies of other hydraulic components.

While GA toolbox used was developed by [1] and MatLab/Simulink used as the simulation software, the combination of GA and a parametric simulation model is an innovative contribution to the filed of fault diagnosis in hydraulic systems.

Experimental results show that the developed diagnosis algorithm can detect and classify small changes in state parameters of the hydraulic system due to controlled and induced failures [2]. However, when sudden step changes are induced to the hydraulic system, the developed diagnosis algorithm has only been able to detect the abnormal behavior of the hydraulic system.

An advantage of the developed technique is the reusability of the knowledge introduced in the monitoring system. This benefit provides a good flexibility of the software that could be fitted into other application, in which the basic engineering rules may only be changed.

HEALTH MONITORING OF MECHANICAL SYSTEMS

Health monitoring systems perform two basic tasks: diagnosis and prognosis of failures. Fault diagnosis assesses the state of a mechanical system and performs an automated diagnosis to evaluate potential failures. Fault diagnosis may be subdivided into fault detection and fault classification stages, where the former triggers the latter by detecting possible failures in the system. After detection, the monitoring system classifies the fault into its most probable failure mode. Features of the classification algorithm usually are part of the monitoring system's requirements and can be addressed towards the end user. Some examples of this final classification: Clogged filter / Critical failure, *"stop the machine"*; Electronic controller failure / Abnormal system event, *"call service personnel"*; Pressure sensor communications lost / System abuse, *"change mode of operation"*.

Fault prognosis is concerned with the estimation of potential future failures and the associated implication to the mechanical system, for example [3, 4; 5]. For example, prognosis aims to enhance maintenance planning and scheduling of expected failures [6].

EXPERIMENT SETUP AND TEST RIGS

This section outlines the test rig development. When setting up the experiment, it was necessary to accommodate possible variables that, if overlooked, may adversely impact upon the results. The number of uncertainties is minimized in the experimental test rig by eliminating erroneous inputs that may affect the desired output, maximizing the certainty of experimental repeatability.

An accumulator was used at the inlet pressure port of the servovalve. It was found that a sudden change in spool speed direction, associated with the change of movement of the actuator, causes high ripples that the input line cannot compensate. This ripple caused undesired pressure spikes in the resulting outputs. The pressure at the inlet pressure port rises sharply when the actuator starts changing direction.

Pressure transducers were used in both chambers of the linear actuator. The analog signal from the pressure transducers is proportional to the measured pressure, and a conversion chart was generated to determine pressure from the analog voltage value. The actuator drive command signal was acquired from the test rig. This signal drives the servo-valve's torque motor.

FAILURE MODES CONSIDERED

The scope of the completed study focused on functional failures, which occur when one or more of the target functions are lost. In addition, degradation failures are sought in this work, which are difficult to detect and if so, the standard procedure involves manual troubleshooting that is time consuming and sometimes low in accuracy of its results.

Clogged filter: This failure mode considers a clogged filter in the servovalve's pilot line. In order to reassemble the blockage condition, a restrictive nozzle (orifice) was used to throttle the oil flow going to spool end chambers. An adapter was manufactured to hold the orifice in position and replace the original filter. The new orifice does not filter pilot oil, but decreases pilot pressure to values that can be adjusted by changing the size of the orifice.

The original filter adapter was machined and modified to hold the new orifice adapter. Pilot pressure was measured at both spool end chambers using custom manufactured end plates, with integrated pressure ports, installed on both sides of the valve body.

Pressure gauges on an existing hydraulic test rig were used to measure the reduced pilot pressure. Pressure gauges measured pilot pressures at both sides of the spool, and supply pressure.

The function of the flapper-nozzle valve is to create an unbalanced pressure differential between both chambers at spool ends. The spool moves from one side to the other within the bushing according to this pressure differential. Merritt [7] argues that the optimal pilot pressure for flapper-nozzle servovalves occurs at a value of half of the supply pressure. This optimal value gives the maximum pressure sensitivity and is considered as a design criterion. Two thirds of supply pressure is the nominal design value for pilot pressure in

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two stage servovalves. Experimental results in this work produced a pilot pressure between half and two thirds of supply pressure.

Broken feedback wire: The ball at the end of the feedback wire was removed to reproduce this type of failure. The backlash between the broken end of the feedback wire and the hole in the spool increases dramatically with this failure mode. Two torque motors were used in these tests (i.e. one with a normal feedback wire and the other with a broken feedback wire).

Sticky spool: Guillon and Griffiths [8] analyzed valve sticking in a generic spool. They argue that the most common method to reduce spool sticking on the bushing is to groove the spool in order to reduce pressure that creates unbalanced radial forces, which may push the spool against the bushing. The unbalanced pressure may induce high forces between the spool and bushing creating large amounts of heat.

Another cause of valve sticking is the presence of contaminants such as lacquers that would produce a physical contact between the spool and the bushing. This failure mode increases the friction between the latter elements by the addition of foreign material. Given that this study focused on failure modes induced by oil contamination, the second failure mode for spool sticking was selected.

In order to reassemble the increased spool-sticking force, two grooves were machined at both side ends in the spool. Pairs of rings were then fitted onto each spool end: one o-ring and one friction ring. The o-rings provide the spring effect that pushes the friction ring against the bushing.

SIMULATION MODEL

The development of a theoretical model for the hydraulic arrangement (figure 1) implemented theory developed by other researchers, in particular, [9, 10, 11, 12, 13], and the authors, to generate the appropriate simulation equations.

The simulation includes input signals that come from the test rig, such as fluid pressure, valve drive and piston position. Initial position conditions are recorded at the particular sampling data file that is being assessed for failures, such as initial pressures and positions. The two active components under investigation are the servovalve and associated actuator.

Hydraulic model development. The servovalve simulation "block" design is a third order equation model that contains two additional blocks that correspond to each of the servovalve's stages. The actuator simulation design incorporates the position transducer, which is a Linear Variable Differential Transformer (LVDT) that is located inside the cylinder rod, and three cylinder chambers. Including additional sub-systems, such as line pressure drop and hose expansion, increases the accuracy in the simulation output plot. The implication of these sub-systems in the simulation was assessed.

Servovalve simulation design. A third order model, used for the servovalve design, located in the armature-flapper valve block. The model structure was developed with a "tune-up" phase using specifications from the manufacturer.

The armature-flapper valve model tune-up procedure included: *Frequency response tune-up:* Preliminary sensitivity trials showed that hydraulic gain parameter has the most significant influence in model design performance); and, *Step response tune-up:* A 50mA step signal was used as the input signal to the proposed simulation design. The chosen hydraulic gain most precisely models both frequency response and step response specifications of the chosen servovalve in the experimental test rig.

Additional simulation blocks were incorporated in the simulation design to include potential non-linearities caused by failures in the servovalve: *Saturation block:* Limits the maximum electrical current that can be applied to the torque motor; *Threshold block:* Models the minimum pressure required to overcome the coulomb friction between the spool and the bushing from rest; *Supply and Return pressure compensation block*; *Filter and orifices restriction block*.

Spool flow dynamics model. A novel representation of the pressure-flow fluid in the spool was developed, incorporating the overlap and leakage flow at null, which was assessed in the overall diagnosis algorithm.

Actuator simulation design: The simulation is first adjusted to match published specifications from the manufacturer. Adjustments are associated with frequency and step response. Geometric and functional parameters associated with actuator function were measured and grouped as either model or state parameters, 7 and 6 parameters, respectively.

System issues (adjunct components): The simulation accommodates the effect of the compressibility of oil at each of chambers; describes the relationship between flows and pressures in chambers; applies Newton's second law to the piston to define its dynamic behavior; and, models the non-linear performance of the hoses associated with the test rig (pressure drop and expansion). Hydraulic flow resistance is caused by irregularities on the internal hose walls and capillarity, which are converted into a temperature increase in the fluid and is often associated with power losses [7]. Loss coefficient values for hydraulic fittings, manifolds, lines and valves were used [14].

MODEL PARAMETERIZATION

The simulation model developed contained 41 model parameters. A two dimensional array was used to

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represent parameter information: nominal parameter values that best describes a fault-free condition of the servovalve-actuator hydraulic system; the minimum and maximum boundary values of the associated parameter (the useful operational range within the simulation); whether the parameter will be considered in the optimization algorithm or not (*0* not included, *1* included); and, a description of the parameter and its associated units. The parameters are grouped in the array in accordance with the simulation block to which they correspond: Group 1: First stage of the servovalve; Group 2: Second stage of servovalve; Group 3: Linear actuator model; and, Group 4: Adjunct components.

Sources for quantitative data associated with the parameters: measured from the existing laboratory equipment; test rig experiments; data from [7, 14, 15] and manufacturer specifications; calculations using the servovalve's specification; and, comparing simulation data recorded from the test rig with simulation outcomes.

FAULT DIAGNOSIS ALGORITHM

The diagnosis algorithm contains both automated and manual features to process sample data from the test rig, and using the simulation model, to assess their similarities, which are expressed in terms of the simulation error. An increased simulation error corresponds to a reduced similarity. The algorithm aims to detect subtle changes in the sampled data coming from the test rig by performing a continuous on-line evaluation of the simulation error and attempts to classify the detected failure by optimizing model parameters that best match faulty data. Two types of data are used by the diagnosis algorithm: *sample data* acquired from the test rig by the data acquisition hardware; and, *simulation data* calculated by the simulation model. Genetic Algorithms (GA) were found to be the most appropriate optimization method to find the new set of model parameters that would reduce the simulation error below the required threshold. The following paragraphs outline features of the fault diagnosis algorithm.

Objective function: Reflects relevant, targeted functions of the hydraulic system, sub-systems or components and assesses their associated performance.

Filtering: A low pass analog filter was used between the test rig and the data acquisition hardware. Another two filters were used in the diagnosis system to process the sampled data acquired from the test rig: the moving average filter to smooth sample data coming from the test rig; and, a conventional notch digital filter design was used to remove 50Hz noise digitally.

Parameter tune up: The diagnosis algorithm has a self-tuning feature that takes sampled data that is free of failures, to tune-up nominal model parameters. The algorithm evaluates the effectiveness of each parameter in the sampled data string, by changing its value to the minimum and then to its maximum.

Fault detection threshold determination: A small value of threshold error would trigger the diagnosis system too early and may introduce false alarms.

Simulation step time: Preliminary analyses were carried out with a fixed simulation step time of 1e-5 seconds, which was found to provide enough resolution to identify all significant features within the input data.

Parameter finding approach: GA methods are used when multiple model parameters are being optimized simultaneously. An advantage of GA is that a group of model parameters can be divided in sub-groups, whereas each group can include a different Failure Mode Identifier (FMI) to initiate the model.

Model parameter selection criteria: There are always redundant model parameters (attributes), that must be set to their constant nominal value (i.e. discarded) before the model parameters are incorporated in the GA loop. Otherwise they would provide redundant solutions to the optimization process, and hence, there is no unique arrangement of model parameters that satisfy the optimization routine.

Null adjustment: There are some state variables in hydraulic systems that do not produce a system failure when they are not working at their nominal operational condition (i.e. out of calibration). It was experimentally found that a state variable associated with this event is an uncalibrated servovalve null.

ANALYSIS OF DIAGNOSIS ALGORITHM PERFORMANCE

Two types of experiments were performed using the diagnosis algorithm: *type-1* using the diagnosis algorithm alone (three sets of experiments – these experiments analyse the performance of the features included in the diagnosis algorithm prior to the analysis of real data from the test rig); and, *type-2* using actual sampled data from the test rig in the diagnosis algorithm (three sets of experiments). A total of 35 trials of the type-1 experiments were performed, and a total of 116 trials of the type-2 were completed using the data from the test rig.

Self diagnosis analysis: Experiments sought to determine the performance of: parameter tune-up; automated model parameter selection; and, self diagnosis simulation. The diagnosis algorithm was not able to determine any combination of simulation parameters that reduced the simulation error below the threshold, although parameters 1 (i.e. valve filter blockage ratio: positive speed) and 2 (valve filter blockage ratio: negative speed) are able to represent a high clogged condition of the servovalve filter. A summary of some of the conclusions reached following these experiments: **1.** Only small variations in model parameters values can lead to a successful classification

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of failures. Large changes in the sample data caused by failures in the hydraulic system may lead to erratic solutions associated with different combinations of model parameters. **2.** A population of 50 GA "individuals" provides classification results similar to 100 individuals. Simulation cycle times are dramatically reduced by using the 50 individual population size. **3.** Low classification performance in some model parameters results in the number of model parameters that can be used simultaneously being reduced considerably.

Experimental analysis: Clogged filter A clogged filter fault has an associated condition where the pilot pressure at the servovalve is reduced. A series of different pilot pressure values were manually measured in test rig. A pilot pressure greater than 50% of supply pressure was found in all the experiments using a fault free servovalve. When the restrictive orifice was used to replicate a clogged filter condition, the pilot pressure dropped significantly. Simulation results obtained for this failure mode are in accordance with observations and show that the diagnosis algorithm can successfully recognize the introduced clogged filter condition in the servovalve.

Experimental analysis: Broken feedback wire There are two failure modes found in the experiments that can develop when the feedback wire is broken: *increased backlash* (i.e. the feedback wire is still located in the spool hole, but the backlash between the feedback wire and spool hole is high due to the absence of the feedback ball) and *loss of feedback* (i.e. occurs when the feedback wire is too short and cannot reach the spool hole). When the drive command signal is disabled, the final null position is affected by the force from the feedback wire pressing against the spool. This results in an erratic null position when the servovalve is at idle, that may exceed normal operational limits. In addition, spool position feedback is lost and the valve acts as a proportional valve, only.

The servovalve was observed to behave differently during experimental trials, depending on which sub-failure mode is in effect. Pilot pressure considerably increased when the loss of feedback failure mode occurred, reflected as an increased hydraulic gain. Simulation model parameters associated with this failure mode are: hydraulic amplifier gain (parameter 6); valve glitch (parameter 9); and, servovalve null (parameter 41). The variation in the three model parameters can be matched with the induced failure modes, because when there are no failures introduced in the test rig, the diagnosis algorithm selects the nominal model parameter values (i.e. no failure condition) as a result of the classification. When the model parameters 6, 9 and 41 are compared against their nominal values in this set of experiments, broken feedback wire sub-failure modes can be qualitatively identified.

Experimental analysis: Sticky spool This failure mode is caused by the blockage of spool travel by contaminants between the spool and the bushing. The maximum unbalanced force for the servovalve under investigation can be calculated [7].

The sticky spool failure mode was introduced through the use of o-rings located at both ends of the spool. The o-ring specifications used, and the squeeze factor on each o-ring between spool and bushing, were used to calculate the radial diameter variation in the o-rings after being mounted. The o-rings modified the servovalve's performance, but performance remained within acceptable specification limits.

O-ring influenced servovalve performance results were introduced into the diagnosis algorithm. The increase in the sliding friction force introduced by the o-rings produced a close correlation between the simulation output and the actual hydraulic test rig output, even though no failure was apparent. As the experimental servovalve was not available for testing to destruction, more significant friction inducing components could not be introduced to a modified spool. This will be the subject of future study.

Sticky spools are a significant problem in hydraulic systems, but the underlined cause is not well understood [8].

CONCLUSIONS

This paper describes research that demonstrates that model-based simulation and optimization techniques can be used to diagnose failures in electro-hydraulic systems. The research identifies new opportunities to further develop automated tasks that can dramatically increase the availability and reliability of electro-hydraulic systems. The following specific tasks has been completed: development of a simulation model that replicates in detail the electro-hydraulic system used in the test rig; validation of the simulation model with real sampled data; parameterization of the simulation model with real sampled data: creation of model parameters; development of the diagnosis algorithm to optimize model parameters and match real sampled data; and, analysis of the diagnosis algorithm performance. The diagnosis algorithm facilitates the analysis of subtle changes in the state parameters of electro-hydraulic systems. The simulation experiments have shown successful results when diagnosing some subtle failure modes (i.e. clogged filter and broken feedback wire) introduced in the servovalve, but not in other experiments associated with almost imperceptible failure modes (i.e. sticky spool). However, the simulation of the servovalve performance close matches observed servovalve behavior.

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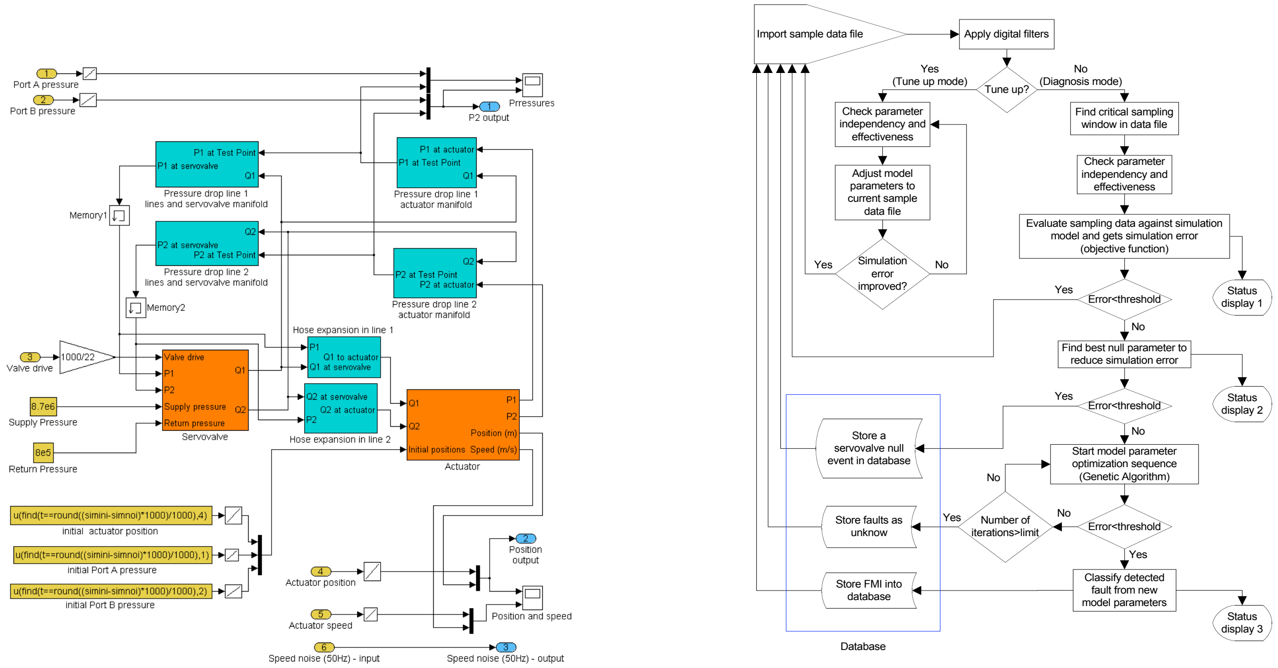

Figure 1. Left: Simulation Model layout (yellow blocks = inputs, blue = outputs, orange = two active components under investigation, i.e. servovalve and linear actuator), and green = adjunct components
Right: Fault diagnosis and tune-up flow diagram.

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