MONITORING AND PROGNOSTICS OF HYDRAULICALLY OPERATED BUTTERFLY VALVES

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ABSTRACT

The development of a condition-based maintenance (CBM) system for large, hydraulically operated butterfly valves is presented here. The focus of this research project included development of physics-based models of the system components for a typical hydraulic actuated control system for dynamic simulation using MATLAB/Simulink, and evaluates the valve system performance under various flow, pressure, and forcing conditions. The simulation components include a three-stage servo-valve, double acting hydraulic cylinder, large diameter butterfly valve, a hydraulic power source, and system controls. Real-time failure-free operational data was provided to ensure that the system dynamics were captured in the model simulation results. Then, selected failure modes inherent in this type of system were introduced into the model simulation to validate model performance and to identify and extract features that are indicative of system component degradation. Some of the failure modes include gas entrainment, valve friction changes, sensor anomalies, and fluid leakage. The simulation results of the baseline and various valve operating conditions were within good agreement of actual plant operational data and the model results of the seeded failure modes showed definite deviations from normal operating conditions. Model-based features were extracted and used for the valve health monitoring architecture that employs a fuzzy logic expert module that identifies the failure modes and trends behaviors to estimate RUL. The architecture is also built into a Generic Agent for Distributed Software (GADS) module so that the valve health monitoring system is scalable, multi-platform, and distributable over different computer networks.

Key Words: butterfly valves, failure modes, prognostic features

1 INTRODUCTION

Hydraulically actuated control valves, used in process and high-pressure systems, play an important role in plant operational efficiency, safety, maintainability, and product quality. The cost of unit downtime is very high due to plant unavailability due to repair and replacement costs. Valves that do not operate efficiently may substantially affect the performance of the entire system. In light of these issues and to enhance the overall reliability of these systems, the development and implementation of a condition-based maintenance (CBM) strategy is useful in the detection and identification of impending failures. Continuous monitoring of critical equipment by trending anomaly-related signatures may be used to estimate Remaining Useful Life (RUL) of valve systems. Such information could be used for maintenance planning, and equipment repair/replacement, and thus, minimize plant downtime and loss of revenue. This project effort focused on a literature review, model development of a hydraulic actuation system for a large butterfly valve, identification and testing of various failure modes commonly found in this type of system, feature extraction and development of a valve health monitoring system that uses the extracted features to estimate the RUL of a the system. In Section 2, we discuss the valve system and components and also typical valve and valve hydraulic actuator failure modes. Section 3 will briefly describe the MATLAB/Simulink valve system model development using the physical equations of state for each component and the various system controls. In Section 4 we show the fault free simulation results compared against supplied real-time data of various operating conditions. Last, Section 5 will discuss some of the model based features and their use in the valve health monitoring system. The GADS software and model architecture is also discussed.

2 VALVE SYSTEM COMPONENTS AND COMMON FAILURE MODES

In this section, we will describe the various components for a typical hydraulically actuated control valve system and some of the common inherent failure modes found during the course of research. An open literature review was first conducted that focused on different types of valves found in industry, actuation systems for control and the failure modes found in these systems. Also, past modeling efforts for butterfly valve dynamics and systems was also investigated [8,9]. A butterfly valve is a common control valve, also termed a 2-way control valve since the valve can operate if the flow through the line is in either direction. A simple butterfly valve consists of a disc that is attached to a rod. The rod is connected to an armature called a stem which is connected to a linkage from an actuation system. This supplies the force to open or close the valve. The actuation force can be induced manually or automatically through hydraulic, pneumatic, or electric motor driven actuators. The disc and rod are contained within the valve housing which also has a seal called a seat. The seat is where the valve disc rests when in the closed position and also helps in sealing when the valve is closed. Figure 1 shows a schematic of a typical butterfly valve.

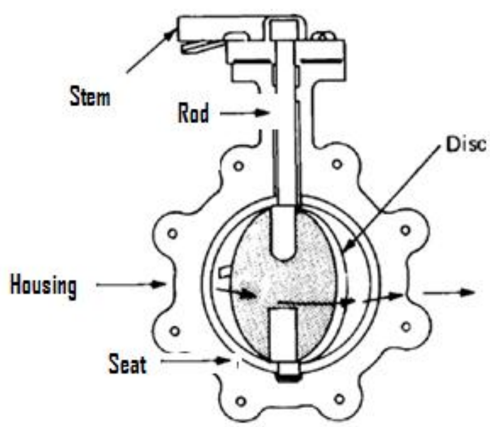

Figure 1. Schematic of Typical Butterfly Valve

The main failure modes discovered in the literature review for a butterfly valve include basic wear and aging of all components, seal and stem wear and disc warping. These are considered top-level failures, where a low-level failure such as inability to open may be due to another component failure in the hydraulic system, such as loss of line pressure. Table I lists each component of the valve and some of the main failure modes and causes of each failure [1-4].

Table I. Butterfly Valve Failure Modes

Component	Failure Modes	Cause
Disc	Warping, failure to close	Cavitation, aging, linkage failure
Rod	Warping, seizure	Wear, process accumulation, stem failure
Stem	Breakage, jamming	Actuator damage, over-pressure
Seat	Cracking, rupture	Wear, foreign body accumulation
Housing	Cracking, holes	Defect, age

The listed failures constitute the primary failure modes of the butterfly valve system. If these modes are not the cause of malfunction in the butterfly valve, then the cause can be attributed to a failure from some other part of the hydraulic system. Next, major hydraulic system components are examined. The system components include the servo-controller, displacement transducer, actuator, servo-valve, and the hydraulic power supply. The failure modes of these components are varied and a failure in one usually leads to a systemic system failure or outage. Table II lists the major components of the hydraulic system, main failure modes and the cause [1, 4 & 5].

Table II. Hydraulic System Component Failure Modes

Component	Failure Modes	Cause
Servo-Controller	Bad input/output, basic failure	Electrical issues, bad calibration, wear/aging
Displacement Transducer	Basic Failure	Electrical issues, programming malfunction
Actuator	Under/Over Pressure, leakage basic failure	Piston wear/shear/aging, over/under line pressure, contamination
Servo-valve	Torque motor inoperable, basic failure	Electrical issues, seal damage, over/under line pressure
Hydraulic Power Supply	Basic wear/aging of fluid	Dirt, over/loss of line pressure

3 MATLAB/SIMULINK MODEL OF THE VALVE SYSTEM

In this section, we describe the Simulink model developed during the research project for the hydraulically actuated butterfly system. Figure 2 outlines the basic idea layout of hydraulically controlled butterfly valve system components and their relationships.

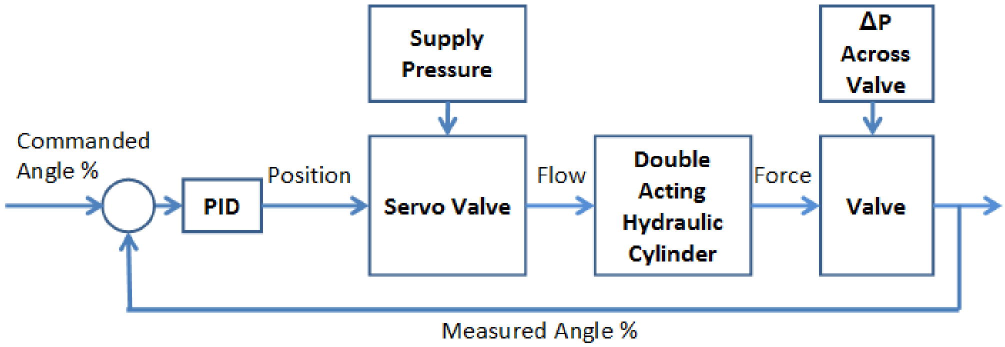

Figure 2. Basic Modeling Outline of Hydraulic System

Starting from the left of Figure 2, the operational characteristics can be explained by first the operator desiring to change the commanded opening angle of the valve. The commanded valve angle is then compared to the actual measured valve angle to produce an error. Then, this error is sent to a position controller (PID controller) which in turn controls the orifice opening of the servo-valve. The servo-valve responds by demanding hydraulic power from the hydraulic power supply and sends the flow of fluid to the double acting hydraulic cylinder actuator. The piston in the actuator responds to the fluid flow and supplies force to move the linkage that is connected to the valve stem and rod. This moves the valve disc to the desired valve opening. The measured (i.e. sensed) values of the simulation include the command angle and valve angle percentage, pressure of the hydraulic supply, the supply and return pressures in chambers A and B of the actuator, the pressure difference in chambers A and B, the cylinder length of the linkage attached to the butterfly valve and finally the spool position of the servo-valve. In an actual valve system, some of these measurements may not be available and can be estimated through relationships with other sensed measurements.

All the major valve system components were modeled in Simulink. Next, we will list some of the equations used to develop each of the component sub-systems for the simulation which are the hydraulic power supply, servo-valve, hydraulic double-acting cylinder and the butterfly valve. The torque motor block dynamics are governed by a simple first order transfer function that may be modeled as a series L-R circuit [6]. The transfer function used is:

$$\frac{V(s)}{L(s)} = \frac{1}{Ls + R} \tag{1}$$

where L is the inductance of the motor coil and R is the resistance of the motor coil. Values for L and R are taken from servo-valve manufacturer data sheets. The voltage supplied V, is from the user input and this voltage induces a current which is then used to drive the spool valve. The spool dynamics are represented by a second order transfer function [6 7]:

$$\frac{X(s)}{I(s)} = \frac{A\omega^2}{s^2 + 2\varphi\omega s + \omega^2} \tag{2}$$

where ω is the natural frequency of the servo-valve model, φ is the damping ratio for the servo-valve model and A is a constant. Values for Equation 2 can also be found from the manufacturer data sheets. The output of the spool movement block is the spool position x and a dead zone block is also added to this value to model a dead zone in the spool chamber of an actual system. The flow across the servo valve orifices can be calculated as follows [6 7]:

$$q = C_o x_s \sqrt{\Delta P} \tag{3}$$

where C_o is a discharge coefficient defined as:

$$C_o = \frac{Q_n}{x_{s,\max}\sqrt{\frac{\Delta P_n}{2}}} \tag{4}$$

where Q_n is the rated flow of the servo valve, P_n is the nominal pressure drop and $x_{s,\max}$ is the ratio of the spool position and the maximum displacement of the spool displacement. The spool positions are used in place of usual flow equations that use the ratio of the actual and rated current values when computing servo-valve flow. The flow through the servo-valve can be found from [7]:

$$Q_{1,2} = \operatorname{sgn}(P_1 - P_2) Q_N \sqrt{\frac{\Delta P_N}{2}} \left| \frac{x}{x_{\max}} \right| \sqrt{|P_1 - P_2|} \tag{5}$$

Here only turbulent flows are considered (laminar flows were ignored) and the final flows through each of that valve orifices, Q_A and Q_B, can be found from the following expressions when x_S (spool position) is greater (Eq. 6-7) or less than zero (Eq. 8-9) [6,7]:

$$Q_A = C_0 x_s \operatorname{sgn}(P_S - P_A)\sqrt{|P_S - P_A|} \tag{6}$$

$$Q_B = C_o x_s \operatorname{sgn}(P_B - P_o)\sqrt{|P_B - P_o|}, \text{ for } x_s > 0 \tag{7}$$

$$Q_A = C_o x_s \operatorname{sgn}(P_A - P_o)\sqrt{|P_A - P_o|} \tag{8}$$

$$Q_B = C_0 x_s \operatorname{sgn}(P_S - P_B)\sqrt{|P_S - P_B|}, \text{ for } x_s < 0 \tag{9}$$

where P_S and P_O are the supply and return pressures of the system, respectively. These flows are used to determine the hydraulic power supply, which is modeled as a pump system with a constant volume tank [6]:

$$P_S = \int \frac{\beta}{V}(Q_{in} - Q_{out})dt \tag{10}$$

The flows in Equation 10 are the flows from the servo valve and are compared with the valve spool to determine which valve orifice is connected to the pump system and thus the flow out of the tank. These flows provide a force that drives the piston in the actuator chamber. The hydraulic force is converted to a mechanical force that is used to open and close the butterfly valve. In order to calculate the mechanical force generated by the piston in the actuator chamber, we use:

$$F = (P_A - P_B)A_P \tag{11}$$

where P_A and P_B are the chamber pressures and A_P is the area of the piston [7]. The pressure in either of the actuator chambers may be modeled as follows:

$$dP = \frac{\beta}{V}\left(Q - \frac{dV}{dt}\right)dt \tag{12}$$

where V is the volume of the chamber, β is the bulk modulus of the hydraulic fluid and Q is the flow into the actuator chamber.

The valve angle dynamics are represented by a second order differential equation and were derived from the geometry of the actual valve system:

$$J\ddot{\alpha} + F(\dot{\alpha},\alpha) = T(\alpha) + AF\cos(\sin^{-1}(\frac{A\sin(C)}{B+x}) - \frac{\pi}{2} + C \tag{13}$$

The left hand side of Equation 13 contains an inertia term along with a function dependent of valve angle which represents any friction (Coulomb and/or viscous) and/or spring forces. The right hand side contains various angle dependent and independent torque values acting on the butterfly valve including the torque contribution from the actuator (with force, *F*), hydrodynamic torque, bearing torque, seating torque, etc. The right hand side also contains constants A, B and C that are dependent on the geometry of the system. The simulation also takes into account the valve disc thickness, area and mass so any size valve may be modeled with the simulation.

4 FAULT-FREE SIMULATION RESULTS

In this section we show some of the results for the simulation compared against supplied real-time plant data. The model outputs were first compared with several operating conditions of the valve in order to determine that the simulation behaved as the actual system. The supplied data contained different opening/closing responses of the valve and the hydraulic system behavior when subjected to different step inputs and a ramp response. Figure 3 shows the actual system output (left) compared with the simulation output for a step response to the system. The measured responses shown in the figure are for the percentage the shaft angle changes and percentage that the actuator piston position changes.

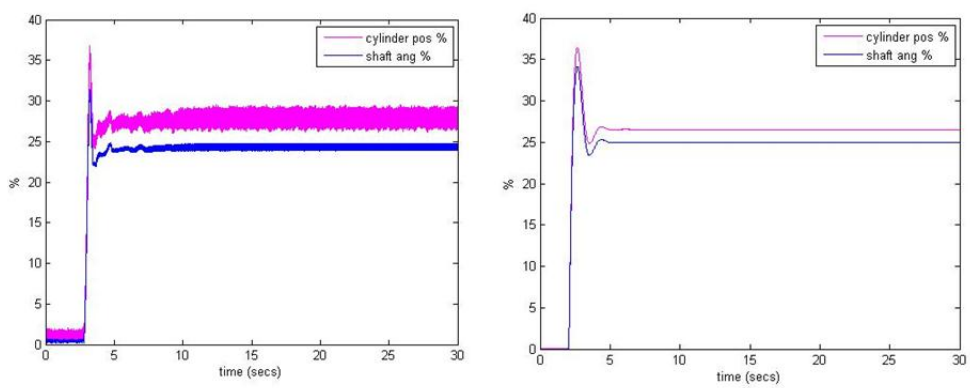

Figure 3. Step Response 0-25% Butterfly Valve Comparison

Looking at Figure 3, it is seen that the simulation output resembles the response of the actual system. The system pressures for this type of step response are shown in Figure 4.

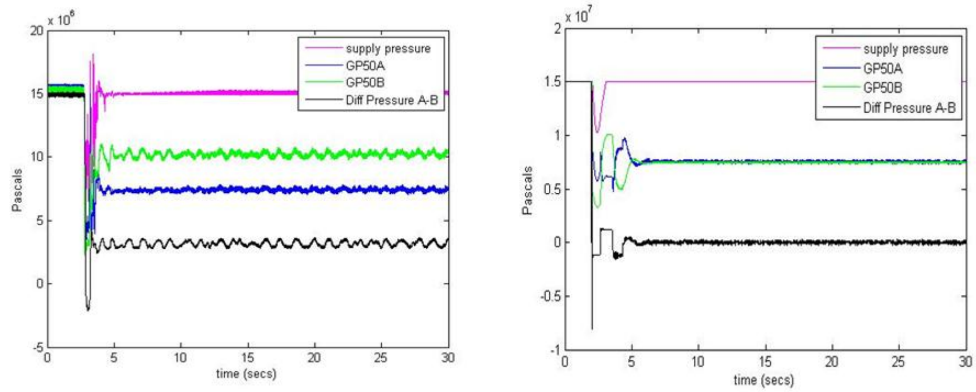

Figure 4. System Pressure Comparison for Step Response of 0-25%

The simulation results for the system pressures shown in Figure 4 also closely follow the behavior of the real system.

5 MODEL-BASED FEATURES AND GADS SYSTEM OVERVIEW

In order to analyze how valve system sensor readings may be affected by failure modes, failure data must be collected. Often, it is not feasible to introduce failures into the actual system because of high costs and existing failure data from the system may not exist. This is the case for large valve systems. However, some valve failures can be introduced into the model developed in Section 3 and simulated data can be obtained.

Four common failure modes were introduced into the model by the following methods.

- **Hydraulic Fluid Gas Entrainment**, modeled by modulating the magnitude of the hydraulic fluid bulk modulus
- **Valve Friction Effects**, modeled by changing the values of Coulomb and viscous friction constants
- **Valve Actuator Hydraulic Leakage**, modeled as internal and external leaks in the hydraulic and servo-valve components
- **Valve Angle Sensor Failure**, modeled as a bias of the cylinder piston and valve angle sensor signals

Other types of valve and valve actuator failure modes could be introduced into the model such as stuck valve, valve seal leak, etc. Simulated sensor readings of pressures, positions, and volumes were recorded when each of these failure modes were introduced. Data generated for different magnitudes of failure effects and failure growth with respect to time was also collected.

Once a good set of simulated failure and baseline data had been collected for the various failure modes, methods to detect, identify, and predict failure modes can be hypothesized. Sensor data is often processed and transformed into what are called signal features or condition indicators to aid in diagnostics and prognostics. Common feature calculations include taking FFT or Wavelet coefficients at specific frequencies of sensor signals, calculating statistical measures (time averaging, kurtosis, etc.), and taking advantage of mathematical/physical relationships. We have primarily taken the latter approach to create a single feature for each of the failure modes described above.

Hydraulic Cylinder External Leak Failure Mode Features

A hydraulic cylinder leak is implemented by associating an orifice flow in a chamber of the hydraulic cylinder to the external environment. A leak in chamber A can be represented by the equations:

$$\frac{dP_A}{dt} = \frac{\beta}{V_A}(Q - C_o x\sqrt{P_A} - \frac{dV_A}{dt}) \tag{14}$$

Where the leak manifests itself as a flow equal to $-C_o x\sqrt{P_A}$ (assuming pressure external to cylinder = 0 Pa) and x controls the size of the leaking orifice.

A leak size measure can then be estimated as:

$$C_o x = \frac{C_o x_S^* \sqrt{\Delta P} - \frac{V_A^* dP_A^*}{\beta dt} - \frac{dV_A^*}{dt}}{\sqrt{P_A}} \tag{15}$$

The "*" notation represents estimates from the available sensors (i.e. valve actuator chamber pressures and piston position). The values produced by this feature measure can be tracked over time as a prognostic measure for leak size growth.

Hydraulic Cylinder Piston Position / Valve Angle Sensors Failure Features

The valve angle and cylinder piston position is related through the equation.

$$x = \frac{-a + \sqrt{b + c\cos(\alpha + c))}}{2} \tag{16}$$

This equation was developed from the geometric relationships between the actuator, linkage, and the valve. For a measured valve angle, Equation 16 can be calculated and then compared with the measured cylinder position. If the two measurements exceed a set tolerance value, then either of the sensors may be considered to be in a faulty state. Unfortunately, using this single feature, one cannot determine which of the two sensors is faulty, only that one of the sensors is faulty. Also, if both sensors fail at the same time, then the feature still could be in agreement with the measured cylinder position. Of course, there may be a mechanical reason that these two values may not be in agreement. Thus, other features could be developed to help isolate the failure mode.

Valve Friction Failure Mode Features

Valve friction increase failure mode is introduced into the model by increasing the Coulomb friction value of the Hydraulic Cylinder. The forces/torques applied on the valve is primarily affected by this change.

Keeping track of the amount of energy required to turn the valve is one way to monitor this feature. For example, one could integrate the differential pressure across the hydraulic cylinder piston. A test feature was created:

$$F = \int \left| \dot{\alpha} \right| (P_A - P_B) dt \tag{17}$$

Gas Entrainment Failure Mode Features

The Gas Entrainment fault was generated by reducing the bulk modulus by a constant value. Features that can track bulk modulus for each hydraulic actuator cylinder chamber separately can be derived from Equations 6-9 and 12 as:

$$\beta_A^* = \frac{\dfrac{dP_A}{dt}^* V_A^*}{(C_0 x_s^* \sqrt{\Delta P} - A \dfrac{dx_P}{dt}^*)} \tag{18}$$

Next, the feature values for the gas entrainment fault are shown. Typical values of the bulk modulus are on the order of 1×10^9 Pascal. Figure 5 shows the response of the system for a fast open/close case after the magnitude of the bulk modulus had been reduced by two orders of magnitude.

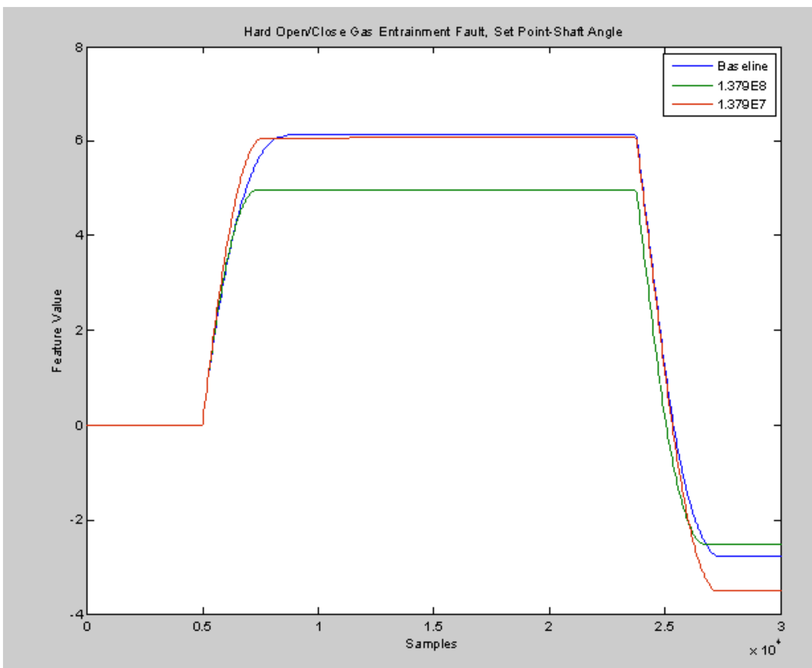

Figure 5. Gas Entrainment Fault for Hard Open/Close Case

Looking at Figure 5, it is seen that from baseline (blue), the feature showed a noticeable change after the bulk modulus value had been reduced by one order of magnitude (green). The red plot in the figure shows the response of the system after the bulk modulus had been reduced by two orders of magnitude. In this case the feature behaved nearly the same as the original bulk modulus value, though some small changes from baseline were noticed. We now move onto a description of the GADS framework and how this tool was used with the extracted features from the model to estimate RUL.

Generic Agent for Distributed Software (GADS) Framework

A Generic Agent for Distributed Software (GADS) framework was developed to support the retrieval of valve sensor data and the execution of diagnostic/prognostic algorithms (Figure 6). A GADS agent has the capability to communicate with external databases and data acquisition devices; to process and log data through scripts (Python scripting language); and to convey results to a graphical user interface. It also has the ability to share data and data processing tasks with other GADS agents over a communications network. Therefore, it is distributable among several processors/computers and is scalable for large systems with many valves to be monitored. GADS agents were implemented in C# .NET. Since Windows, MAC OS, Linux and other operating systems support both C# and Python, GADS agents are also multi-platform.

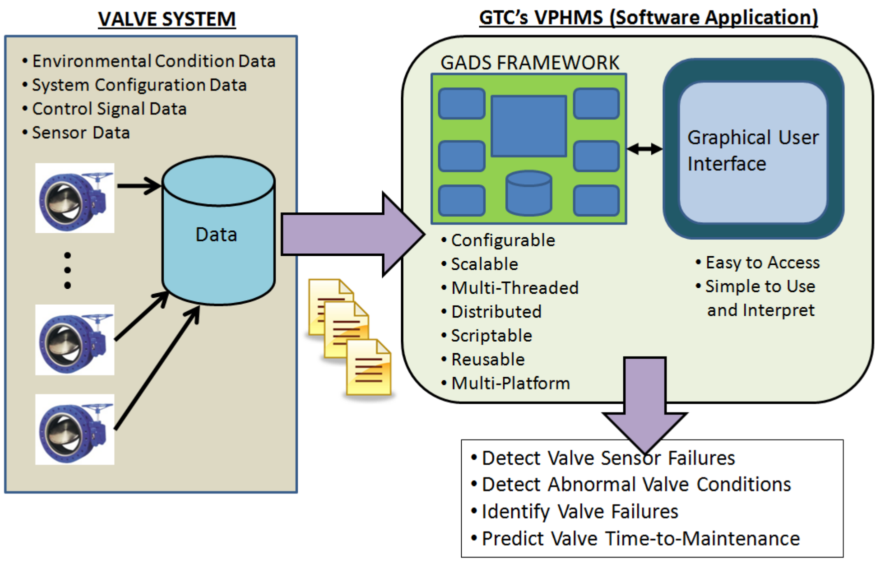

Figure 6. GADS Agent used to support valve health monitoring.

Python scripts were created for both on-line and off-line feature extraction, diagnostics, and prognostics. A Takagi-Sugeno type fuzzy logic inference engine using diagnostic rules based on examined feature inputs were created. As found through simulation with the valve model, the aformentioned features increased/decreased monotonically with increasing failure magnitude. A linear extrapolator on the feature values was used for prognostics. A remaining useful life measure was determined when the predicted feature values reached a certain threshold level over time,

The failure detection/identification process can be automated by using the diagnostic rules to determine the most likely cause of the failure as Figure 7 shows below. Fuzzy logic rules are evaluated with input features to produce belief output values (a number in the interval, [0,1]) for different failure modes. Some failure modes have an effect on multiple features, thus, fuzzy logic rules help correlate the connection between multiple features to specific failure modes.

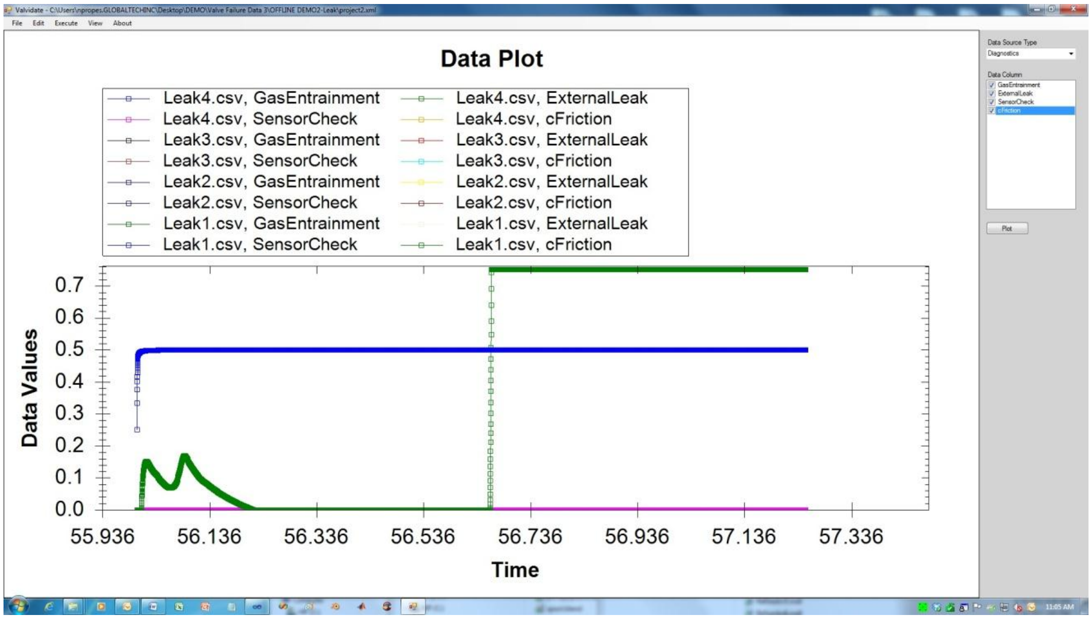

Figure 7. Diagnostic output.

For each day, all the features are averaged for a specific failure mode to produce a trendable prognostic value. As shown in Figure 8, over several days, these prognostic values can be extrapolated into the future to project the rate of failure growth and can predict a time to perform maintenance.

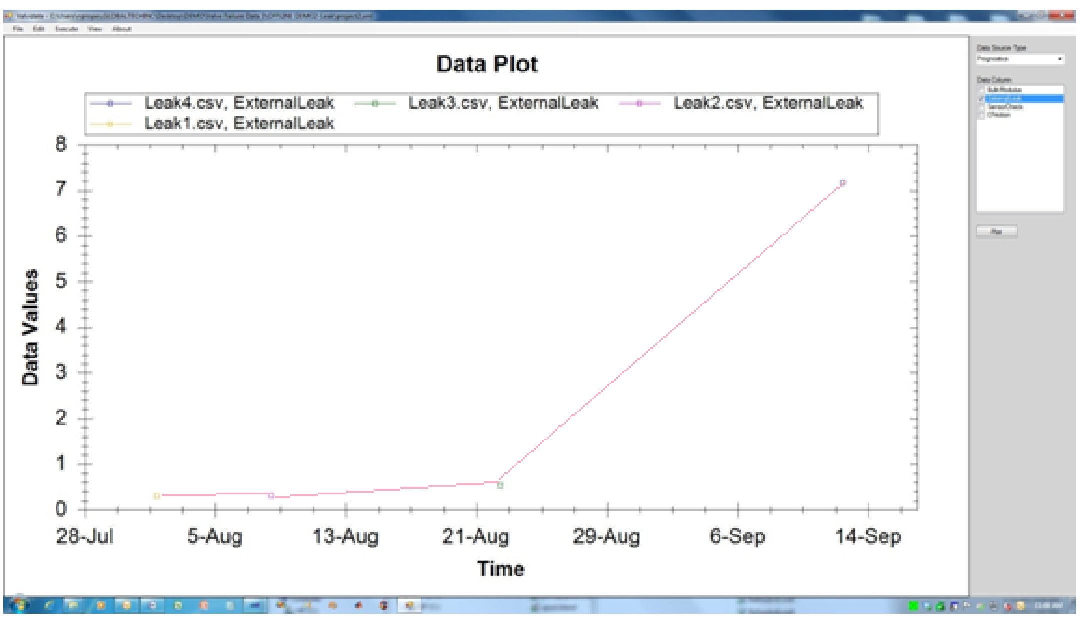

Figure 8. Prognostic trending.

6 CONCLUSIONS

In conclusion, we have shown that a valve system model can provide means to develop a diagnostic and prognostic system for various failure modes. The model was first developed with known physical relationships and then tested against several operational modes of real world data. The model outputs were seen to closely resemble actual data. Next, valve system failure modes were seeded into the model and failure data was simulated. The failure modes induced in the model were gas entrainment, hydraulic fluid leakage, valve friction increase and sensor failures. The baseline and failure data were used to generate model based features. The GADS diagnostic/prognostic system was configured with these features to detect and predict hydraulically actuated butterfly valve failure modes in offline and online modes.

7 ACKNOWLEDGMENTS

This project was funded by a SBIR contract AF102-220 with United States Air Force. We would like to thank Arnold Air Force Base for their support in this effort.

8 REFERENCES

1. Patton, R., "A benchmark study approach to fault diagnosis of industrial process control systems", IEEE Seminar on Control Loop Assessment and Diagnosis, pp. 61-79, 2005.
2. Riyaz, A., "Predicting Health of Final Control Element of Safety Instrumented System by Digital Valve Controller" ISA, 2004.
3. Cristina, H. "Reliability Analysis of Butterfly Valve (BV) Using the Failure and Events Trees", Annals of Oradea University, Fascicle of Management and Technological Engineering, vol. 11, pp. 1-6, 2007.
4. Kreuser, A., Schulze, V., and Tirira, J., "ICDE Project Report: Collection and Analysis of Common-Cause Failures of Motor Operated Valves", NEA/CSNI, 2001.
5. Rozali, S., *et al.*, "PID Controller Design for an Industrial Hydraulic Actuator with Servo System", IEEE Student Conference, 2010.
6. Poley, R., *DSP Control of Electro-Hydraulic Servo Actuators*, Texas Instruments, Application Report SPRAA76, January 2005.
7. Heinze, A., *Modeling, Simulation, and Control of a Hydraulic Crane*, MS thesis, Munich University of Applied Sciences, September 2007.
8. Naseradinmousavi, P. and Nataraj, C., "Nonlinear Mathematical Modeling of Butterfly Valves Driven by Solenoid Actuators", Applied Mathematical Modeling, vol. 35, pp. 2324-2335, 2010.
9. Wojtkowiak, J. and Popiel, C., "Investigations of Butterfly Control Valve Flow Characteristics", Foundations of Civil and Environmental Engineering, vol. 7, 2006.