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Adaptive Control System for Electrohydraulic Camless Engine Gas Valve Actuator

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Abstract— **If realized, the camless internal combustion engine offers significant advantages over the engines on the market today in the areas of efficiency, fuel economy, and emissions reduction [1-5]. In previous work completed, a mathematical model of an electrohydraulic gas exchange valve actuator was created. For this system to be useful, the ability to control it must be demonstrated. Using a cosimulation approach, an adaptive controller was developed and simulated. The results from these simulations showed that the controller was able to converge on the desired output.**

I. Introduction

THE focus of this paper is the development of an adaptive control system for an electrohydraulic (EH) actuator intended for use as a gas exchange valve (GEV) in a camless internal combustion engine.

The starting point is a previously developed mathematical model of an EH GEV that was created by Donaldson [6]. The design is a single acting hydraulic actuator, or cylinder, with spring return controlled by two EH flow control valves.

The flow control valves are spool style valves with one valve controlling flow into the actuator (inlet valve) and one controlling the flow out of the actuator and back to tank (outlet valve). It is an “open center” system so that the static supply pressure during periods of no demand is limited to the summation of pressure drops resulting from the flow through the valves and back to tank. A schematic of this actuator is shown in Fig. 1.

The control system developed here is limited to the control of the engine crank angle at which the GEV opens and the height to which it opens. It is assumed that an engine control module and sensors will provide these position values of the GEV to the controller.

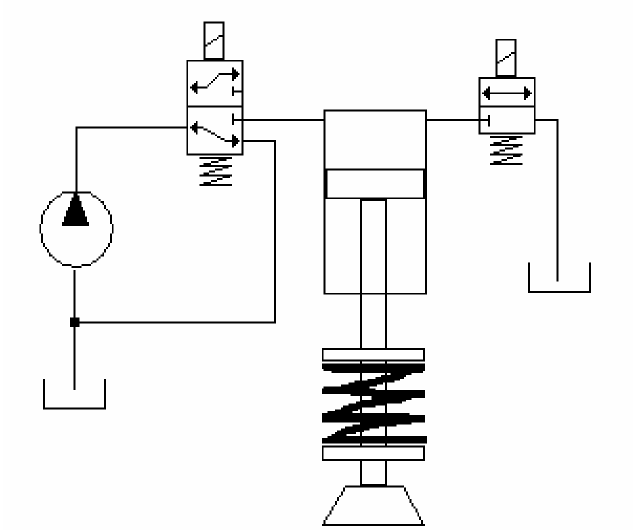

Fig. 1: EH GEV Schematic

The control system will be required to deliver this desired position over a wide range of system parameters. These include a range of engine speeds, engine operating temperatures (hydraulic oil temperatures), internal pressure effects within the combustion chamber, hydraulic fluid properties (viscosity and bulk modulus), hydraulic system flow rate, and others.

As a result of the large range of system parameters that must be accommodated, this system lends itself to an adaptive control strategy. The development and simulation of that system is detailed below.

II. Controller Development

A. Controller Outputs

The outputs of the controller, the inlet valve signal parameters of open lag time and open signal duration, are described in this section. How these outputs will be varied to achieve control is also described in this section.

1) Valve Displacement Profile

Assumptions have been made to simplify the control strategy with regard to the GEV displacement profile. These include limiting the controlled profile characteristics to the crank angle at which the GEV begins to open and the

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height to which it opens. Additionally, the controller is designed such that the GEV will travel as fast as possible between these required points. This ideal lift profile looks like the profile in Fig. 2.

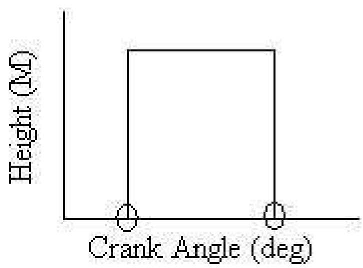

Fig. 2: Ideal Lift Profile of GEV.

2) Cycle To Cycle Operation

To actuate the GEV, there are a number of events that must take place. These include energizing the solenoid on the inlet valve, displacing the inlet valve, and then building sufficient pressure to develop the force required to accelerate the GEV. The first operation, energizing and opening the inlet valve, can require up to one-half millisecond. The second operation, building sufficient pressure to develop the force required to displace the GEV, requires up to 1 millisecond. Combining these two values shows that there can be a lag of 1.5 milliseconds between when a signal is applied to the inlet valve and when the GEV begins to move.

For acceptable performance, this lag must be taken into account. This implies applying the valve signals prior to the time at which the GEV will need to be opened. For this reason, the controller parameters are updated on a per cycle basis instead of real-time control. In this method, a set of system gains is applied to an input signal and a single cycle is executed. Following completion of the cycle, the results of the cycle are compared to the desired results and adjustments are made to the system gains before the new outputs are calculated and output for the next cycle.

3) Signal Variation

To achieve the desired opening crank angle and height, the controller will dictate the opening and closing of the inlet valve of the system. The control of this valve will be limited to a “digital” or on and off control. This means that the controller will only be able to vary the time, relative to the engine crank angle, at which the power will be applied to the inlet valve and the duration of time the power is applied.

Using only these two controller outputs to match the desired valve profile will require modifying the signals in the following ways.

a) Open time lag

As mentioned previously, there is delay between when the GEV begins to move and when a signal is applied to the inlet valve in the range of 1-2 milliseconds. This time delay will be called the open time delay. To accurately control the crank angle at which the GEV opens, this time delay must be accounted for and the crank angle at which the signal to the inlet valve is originally applied leads the desired open angle. If the GEV opens too late, the opening time lag is too long and must be shortened. If the GEV opens too early, the opening time lag is too short and must be extended.

b) Open time duration

To control the displacement height of the GEV, the duration of the signal to the inlet valve, or open time duration, is varied. If the height is not high enough, the open time duration is extended. If the height is too high, the open time duration is shortened.

4) Signal Duration Variance

To control the opening height by varying only the inlet valve signal duration, the relationship between this parameter and opening height was examined. It was learned that for opening heights greater than 4 millimeters, the relationship between signal duration and opening height was nearly linear. The relationship for a single set of system parameters is shown in Fig. 3.

This same relationship was investigated for a range of system parameters including flow rate, oil temperature (the model included viscosity and bulk modulus effects with temperature), and the residual cylinder pressure. For an extreme case of each parameter, the corresponding coefficients of the linear relationship were developed. They are summarized in Table I.

It is noted here that the relationship between signal duration and GEV displacement does not vary significantly over the wide range of operating conditions. The significance of this is that a slope and intercept can be assumed as an initial guess to calculate the signal duration required to achieve a certain displacement. During the error correction, the value of the slope is held constant and a correction is made to the intercept.

Table I: Curve Fit Slope and Intercept for Signal Duration versus Displacement

Factor	Spec	Slope (s/M)	Intercept (s)
Ideal	--	0.3585	0.0018
Flow Rate	9 L/min	0.3548	0.0021
	11 L/min	0.3084	0.0018
Oil	-18C	0.3039	0.0016

Temp	98C	0.3327	0.0018
Res Psi	8 bar	0.3433	0.0017
	12 bar	0.3194	0.0022

III. Control Algorithms

Three steps are required to achieve control of the actuator. The first step is to be able to analyze the feedback signal to determine the response of the system to the previous set of inputs. This includes identifying the key valve position characteristics that took place: crank angle at which the GEV opened and height to which the GEV opened. Engine speed when the GEV opened, crank angle when the opening height was reached, and engine speed when opening height was reached are also needed for the controller. The algorithms for generating this information are not covered in this paper as they will be completely dependent upon the method used to attain them. (For the simulation and results presented below, this information was attained from a position feedback on the GEV as well as a crank angle and crank speed signal.)

The second step is to compare these values to the desired values supplied by the engine control module, apply an algorithm to modify the system settings, and then pass this new signal through to the system. These algorithms are presented below.

The third step is to apply the controller outputs to the system. This includes switching the inlet and outlet valve signals on and off according to the opening time lag and signal duration relative to the controller inputs of opening crank angle and opening height.

With the assumed completion of step one, the critical points of the GEV response to the previous controller outputs are known and the algorithms for adjusting the controller outputs of open time lag and open time duration are calculated.

The algorithm used to adjust the open time lag is a proportional type with a unity gain. In other words, the controller alters the open time lag the same amount as the error signal. A single calculation of the algorithm is shown below:

$$\theta_{open\_err}(\deg) = \theta_{open\_sig}(\deg) - \theta_{open\_act}(\deg)\ , (1)$$

$$t_{open\_err}(s) = \frac{\theta_{open\_err}(\deg)}{\varpi(\deg/s)}\ , (2)$$

and

$$t_{open\_lag\_time}(s) = t_{open\_lag\_time}(s) + t_{open\_err}(s)\ , (3)$$

where θ_{open_sig} is the controller input for the desired open crank angle, θ_{open_act} is the detected opening crank angle from the previous run, and ω is the measured engine speed at the time when the opening angle was detected.

Before continuing, (2) should be discussed in more detail as it is converting the open lag error from degrees of crank angle rotation to the time domain. This transformation becomes necessary as the engine control module signal will be in the engine crank angle domain and the valve signals will need to be in real time. This change is achieved with the measured engine speed in degrees per second. Using the engine speed at a single point assumes that the engine speed during the time span of the open lag time is constant. This is not exactly the case, but errors in lag time are on the order of less than 1 millisecond and engine speed does not change fast enough to create significant error using this approximation.

The algorithm used to adjust the open time signal duration is also proportional with a gain of the assumed slope of the relationship between the signal duration and the GEV displacement as shown in Fig. 4. In this figure, one line represents the assumed relationship between signal duration and opening height that was used for the previous cycle. The other is the calculated relationship from the detected output of the cycle. Since the slope of the relationship is assumed, the difference in intercepts between these two can be calculated and the relationship adjusted. The equations (4-8) below show a calculation of the adjustment:

$$m(s/m) = \frac{db(s)}{dh(m)}\ , (4)$$

$$db(s) = m(s/m) * dh(m)\ , (5)$$

$$db(s) = m * (h_{input\_disp} - h_{measured\_disp})(s)\ , (6)$$

$$b(s) = b(s) + db(s)\ , (7)$$

and

$$t_{sig}(s) = m(s/m) * h_{input\_disp}(m) + b(s)\ . (8)$$

In the relationships above, *m* is the assumed slope of the signal duration and displacement relationship, *b* is the intercept that is being adjusted, *h* is the input and measured displacement, and t_{sig} is the output signal duration.

Adjustments to the signal duration occur by means of another algorithm for cycles that reach the maximum displacement. This secondary algorithm is needed with the saturation that occurs with the displacement and signal duration relationship. Fig. 5 shows an example of this relationship.

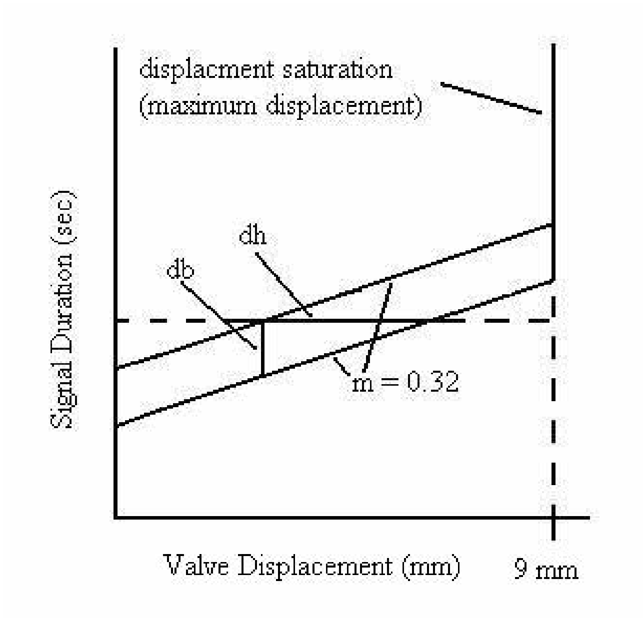

Fig. 4. Signal Duration Adjustment.

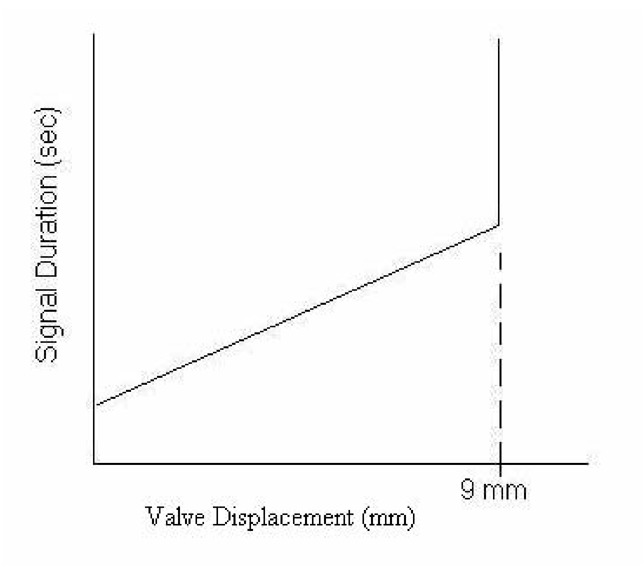

Fig. 5. Saturation of Signal Duration versus GEV Displacement.

For these instances, the controller identifies the signal duration time for which the displacement reached the maximum displacement. Using the assumed slope, the value for the intercept can be determined. A calculation is shown below:

$$t_{sig}(s) = t_{lag\_time}(s) + \frac{\theta_{max} - \theta_{start}(\deg)}{0.5*(\varpi_{max} + \varpi_{start})(\deg/s)} + 0.0005(s),$$

(9)

and

$$b(s) = t_{sig}(s) - h_{max}(m) * m(s/m). \quad (10)$$

In the relationship above, t_{lag_time} is the calculated open lag time from (3), θ_{max} and ω_{max} are the crank angle and engine speed when the maximum displacement was detected, θ_{start} and ω_{start} are the crank angle and engine speed when the valve started to move. The new intercept is b and h_{max} is the maximum displacement of the GEV. The controller output of signal duration, $t_{sig,}$ is then calculated as in (8) using b calculated in (10).

Similar to the algorithms for the adjustment of the open lag time, the engine speed is again used in (9) to transfer from the crank angle domain to the time domain. This approach differs from the open lag time algorithm as the average engine speed over the duration is used instead of the instantaneous engine speed. The engine speed change in this time frame is also negligible but the engine speed when the GEV began to open is already needed for the open time lag algorithm and might as well be used here.

IV. Simulation Method

As stated previously, the starting point of the controller development was a mathematical model of the GEV that was generated in AMESim modeling software. The control system was developed in Simulink; a controls development package available from Mathworks. The block diagram of the Simulink model used in the simulation can be found in Fig. 6.

Using a cosimulation approach, the states of the mechanical system, solved in AMESim, are fed into the Simulink controller. The control signals from the controller are then fed back into the AMESim mechanical model and the new states solved.

This method was validated by comparing the GEV response to a simulation handled entirely in AMESim with a Simulink and AMESim cosimulation. When the results for the exact same system inputs were attained, the method was validated.

V. Simulation Results

The results for the cosimulation are below. The two sets of results presented are for a disturbance signal to the hydraulic oil temperature (viscosity and bulk modulus) and system flow rate.

In each case, the open time lag and signal duration and displacement relationship start at values that are tuned for the mean operating point of the system. Then, in each case, the mechanical system model is set to a maximum value for the parameter being tested to simulate a system disturbance. It is expected that the controller will be able to compensate for the change and return the system to an opening crank angle of 90 degrees and an opening height of 8 millimeters.

In Fig. 7 (hydraulic oil temperature disturbance) and Fig. 8 (system flow rate disturbance), the lower plot represents the engine crank angle with time and the upper plot is the GEV displacement over time. The vertical lines represent the crank angle of 90 degrees and are there to reference the point at which the GEV should be opening.

In both Fig. 7-8, it is seen that the controller is able to adjust to the system disturbance and have the GEV opening at 90 degrees crank angle and displacing to 8 millimeters in three cycles.

VI. CONCLUSION

The paper covers the development and simulation of an adaptive control system for controlling the opening crank angle and opening height for an EH GEV. In the simulation, it was found that the controller developed was able to adjust to a disturbance in the system within three cycles.

It is realized that this is only half of the control needed as the GEV will need to be closed as well. It is noted here that the same concepts used to control the opening of the GEV can be applied to the development of algorithms for the closing of the GEV.

The adaptive control approach to this problem for the adjustment of the relationship between the signal duration and GEV displacement suits the need of the system to be able to adapt to a wide range of system operating conditions. Its capabilities could be expanded with the addition of a second algorithm to alter the assumed parameter of slope, a map of parameters with respect to system condition to increase initial guesses, or a higher order approximation for the relationship.

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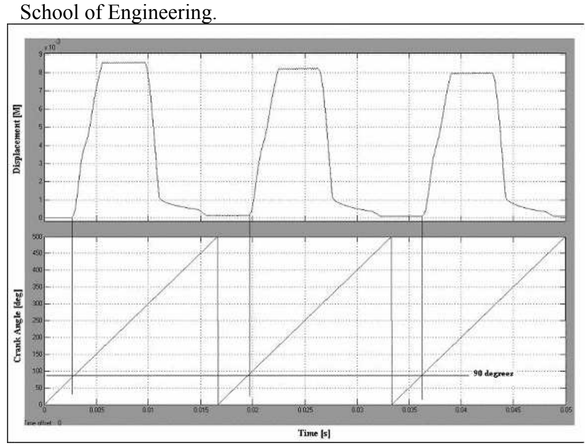

Fig. 7. Displacement and Crank Angle versus Time for Hydraulic Oil Temperature Disturbance.

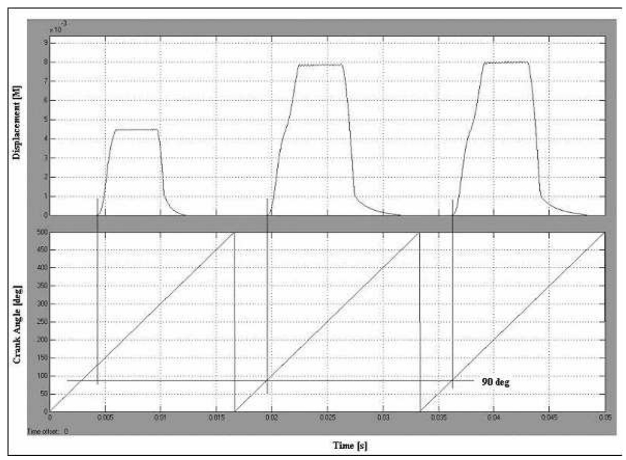

Fig. 8: Displacement and Crank Angle versus Time for System Flow Disturbance.

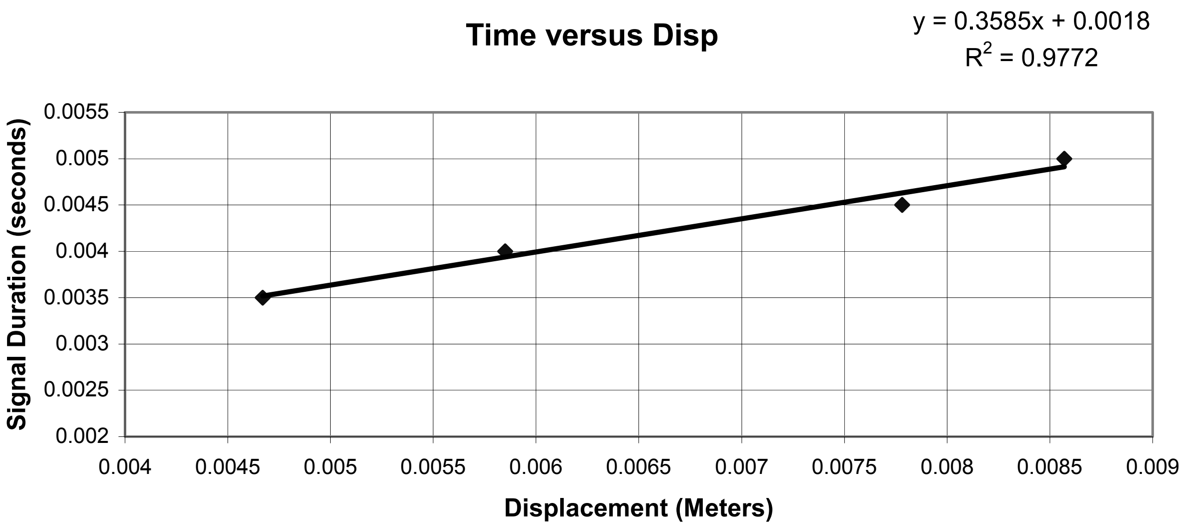

Fig. 3: Linear Curve Fit to Signal Duration versus Displacement.

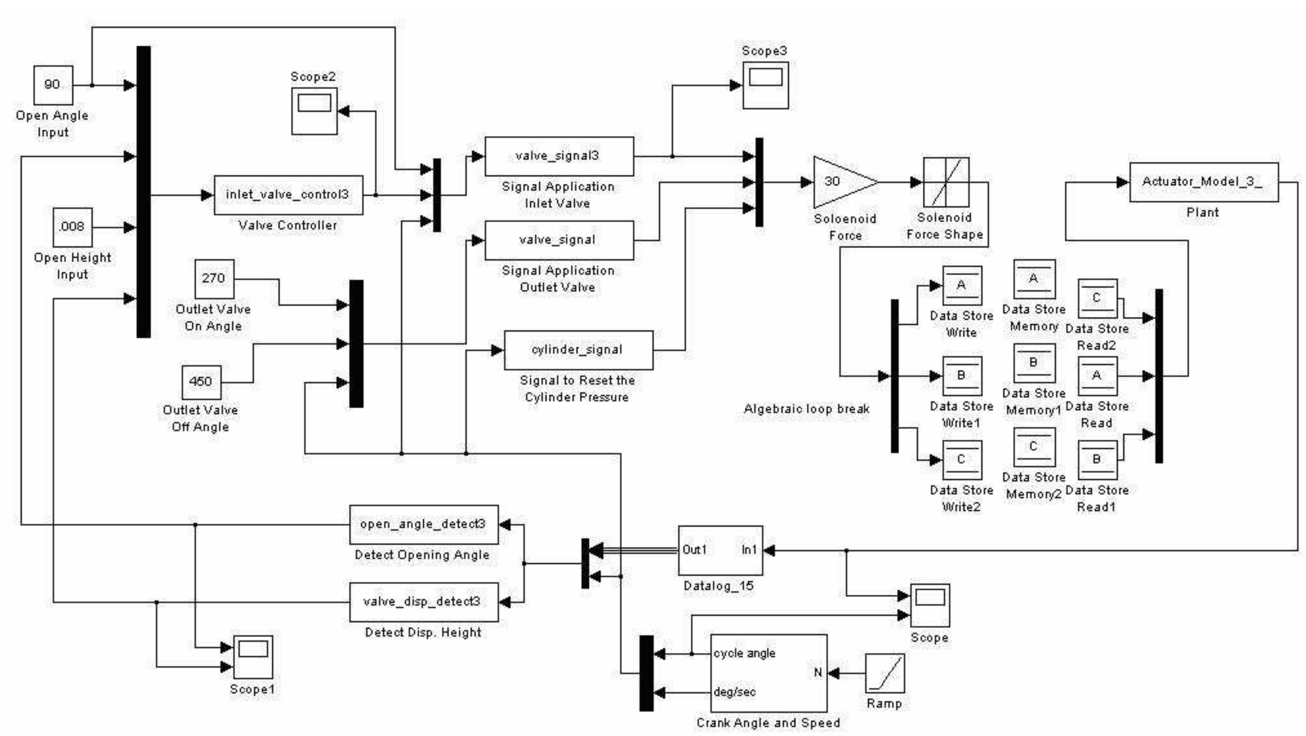

Figure 6: Simulink Block Diagram.