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Predicting solenoid valve spool displacement through current analysis

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A method of identifying solenoid valve transition events by analyzing the current through the solenoid coil is proposed. Solenoid valves experience lags and transition times which are non-trivial in the context of control methods that require precise valve timing. The proposed methodology allows a user to positively identify the beginning and end of valve transition events through identifying slope changes in the solenoid coil current traces. This methodology was shown to identify the timing of valve transition events with less than 7% error when compared to measuring the position of the valve spool with a laser displacement sensor. The proposed methodology is based upon measuring the current through the solenoid coil and requires no modification to the valve or valve housing to achieve these results.

Keywords: solenoid valve; valve transition; current measurement

Introduction

Two position on/off solenoid valves are ubiquitous in hydraulics as an effective and inexpensive way to remotely control hydraulic flow conditions. These valves are an interface between an electrical control signal and a change in fluid flow direction. In application, a valve does not transition immediately upon coil excitation and deenergization. There are time delays between electrical actuation and motion and transition times that must be characterized in order to have a precise knowledge of actual valve behavior.

The methods proposed in this paper provide a simple and easy to implement way for researchers and practitioners to characterize these time delays and transition times based upon analyzing the current through the solenoid when energized by a DC voltage source. Constant voltage excitation is simpler in execution, but more complicated in analysis when compared to constant current excitation. Constant current excitation requires an infinite voltage at excitation onset in order to generate a true step in current. This infinite voltage requirement is limited by the voltage saturation of the current driver employed. Additionally, solenoids will suffer from coil to coil shorting at voltages outside of their operating specification, which is detrimental to performance and will likely damage the coil. DC voltage excitation allows for a known valve excitation input using widely available power electronics and simple circuitry, which guarantees an operating point within the limits of the solenoid.

Energizing and deenergizing delays and valve transition times are often not specified by the manufacturer and must be determined experimentally. These delay times are functions of magnetic and electrical saturation as well as forces acting on the spool. The proposed analysis method applies to any solenoid in which an air gap in the magnetic circuit is opened or closed in the process of valve transition.

When energized by a DC voltage supply, solenoid valves depend on current passing through the coil to generate flux through the solenoid magnetic circuit. This flux passes through the yoke and across an air gap. A schematic of a simplified translating armature solenoid and magnetic equivalent circuit can be found in Figure 1. The force across the air gap is proportional to the square of the flux density in the gap (Roters, 1941). Once the flux generated force exceeds the spring preload, the solenoid plunger accelerates to close the gap. The result is an energizing time delay between the onset of coil excitation and the beginning of valve transition. Upon deenergization, the current in the solenoid and hence magnetic flux must decay to a point where the spring force can overcome the magnetic force. This decay time results in a deenergizing delay between the end of the excitation signal and the actual valve spool return motion.

A variety of hydraulic circuit architectures are being researched that put new demands on solenoid valves. Active valve control of a pump or motor, also known as digital control, requires an understanding of the actual valve transition timing in order to allow fluid flow in or out of the pump or motor at precise times in the cycle to control the effective displacement. Switch mode control is another emerging hydraulic power modulation scheme that depends on control of a duty ratio to deliver power. This methodology requires knowledge of valve energizing and deenergizing delays and transition times to understand the actual duty ratio of the valve relative to

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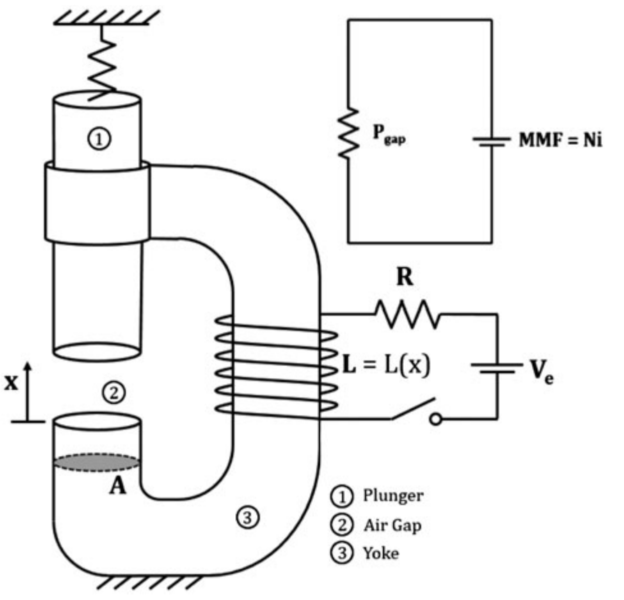

Figure 1. Plunger type solenoid. Magnetic equivalent circuit inlaid in upper right.

the solenoid excitation signal duty ratio and for timing of soft switching to reduce transition losses (Rannow and Li, 2012). One approach to reduce valve delay and transition time is to apply a high voltage peak, followed by a lower holding voltage to keep the solenoid engaged and then reversing the voltage to rapidly decay the magnetic field (Breidi et al., 2014). The tuning process for peak, hold and reverse excitation would benefit from positive identification of both the onset and completion of both valve transitions.

Previous work characterizing valve transition behavior can be classified into either direct measurement of valve spool displacement or indirect measurement techniques, such as pressure monitoring. Vaughn and Gamble used an LVDT to sense spool position to validate a proposed solenoid valve control scheme (Vaughan and Gamble, 1996). Scheidl et al. used an eddy current sensor to sense spool position (Scheidl et al., 2014). In the process of validating proposed models, Kajima used a Hall effect sensor at the end of a pin that was fixed to the solenoid spool (Kajima, 1995). These methods are accurate and give a detailed profile of spool position, but do require access to the valve spool itself. Since most hydraulic valves are sealed to allow pressure balancing and prevent leaks or contamination, methods which require direct access to the valve spool require modification of the valve body.

Breidi et al. determined valve timing by monitoring the pressure drop across the valve (Breidi et al., 2014). This approach provides positive confirmation of the initiation of the opening transition and completion of the closing transition of the valve, but the completion of the opening transition and the beginning of the closing transition cannot be clearly identified. This is due to the fact that the pressure drop is coupled to the flow rate and valve orifice area through the orifice equation. At low flow rates, the pressure drop across the valve will be lower for a particular valve orifice area relative to a higher flow rate through the same orifice area. If a pressure drop is used as a threshold for determining valve transition status, the threshold must be a function of the flow rate through the valve. This necessitates additional computation and sensors to accurately determine valve transition status.

This work proposes a methodology that positively identifies the beginning and end of valve transition times relative to the excitation signal without requiring modification of the valve body. It identifies the solenoid transition timing during a step input voltage excitation based upon the effect of motional EMF on the current that flows through the valve solenoid. This idea is further detailed in Section 2, using a classical electromagnetic system model. Section 3 discusses the experimental setup used to validate the proposed approach. Next, the experimental results are presented, followed by a discussion in Section 5. Concluding remarks are made in Section 6.

Mathematical formulation of the problem

In this section, a simplified model of the solenoid actuator in Figure 1 is presented. The simplified model demonstrates that the time derivative of current is influenced by the induction of the solenoid as well as motional EMF that is generated when the valve plunger has non-zero velocity. For the purposes of this simplified mathematical model, non-linear effects such as saturation and eddy currents have been neglected which results in an assumed constant flux density throughout the plunger and yoke. Leakage flux and fringing flux at the air gap are also neglected in this analysis. While these non-linearities may change the bulk shape of the current traces, their effects are subordinate to the key terms derived in the analysis of fast acting valves.

The solenoid electrical circuit can be separated into the resistive element of the coil and the coil inductance as shown in Figure 1. Analysis begins with Kirchhoff's voltage applied to the circuit:

$$V_e = iR + i\frac{\mathrm{d}L}{\mathrm{d}t} + L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{1}$$

where V_e is the excitation voltage, i is the current through the circuit, R is the resistance of the coil, and L is the inductance of the solenoid coil.

The inductance of the coil is dependent on the number of turns in the solenoid (N) and the equivalent permeance of the magnetic circuit (P_{MEC}) (Roters, 1941). In this analysis, the yoke is assumed to have a high permeance relative to the air gap and is thus neglected. Therefore, the equivalent permeance reduces to just the permeance of the air gap (P_{gap}).

$$L = N^2 P_{\mathrm{MEC}} = N^2 P_{\mathrm{gap}} \tag{2}$$

The solenoid plunger translates in a manner which closes or opens the air gap. Assuming a uniform field in the air gap, the permeance of the gap is:

$$P_{\text{gap}} = \frac{\mu_{\text{gap}} A}{x} \tag{3}$$

where A is the cross sectional area of the air gap, and x is the length of the air gap, which is zero when closed. At an air gap length of zero, the permeance of the gap is infinite and it acts as a magnetic short circuit. The permeability of the medium in the air gap is μ_{gap}. Non-ferrous materials have a permeability that is within a percent of the permeability of free space, μ_{o}. Therefore, this permeability can be assumed to be equal to that of free space whether the air gap is filled with air or hydraulic oil.

The air gap length, x, is a function of time if the valve spool and plunger are permitted to translate. Combining Equations (2) and (3) yields:

$$L = N^2 \frac{\mu_o A}{x(t)} \tag{4}$$

Equation 4 shows that the dL/dt term from Equation (1) has a non-zero value during valve motion and should be included in the electrical circuit analysis. Vaughn and Gamble make a 'slow valve' assumption in their analysis of a proportional valve, which allows them to drop this term (Vaughan and Gamble, 1996). Solenoid on/off valves are characterized by rapid movement, and this motional term can be utilized to identify valve transition.

Taking the derivative of the coil inductance, Equation (4), with respect to time:

$$\frac{\mathrm{d}L}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t} N^2 \frac{\mu_o A}{x} = -N^2 \frac{\mu_o A}{x^2} \frac{\mathrm{d}x}{\mathrm{d}t} \tag{5}$$

$$\frac{\mathrm{d}L}{\mathrm{d}t} = -\frac{L}{x} \frac{\mathrm{d}x}{\mathrm{d}t} \tag{6}$$

Combining Equations (1) and (6):

$$V_e = iR - i\frac{L}{x}\frac{\mathrm{d}x}{\mathrm{d}t} + L\frac{\mathrm{d}i}{\mathrm{d}t} \tag{7}$$

Solving for the time derivative of current:

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{V_e - iR}{L} + \frac{i}{x}\frac{\mathrm{d}x}{\mathrm{d}t} \tag{8}$$

Equation 8 shows that the time derivative of current is dependent upon both an inductive and a motional term. This indicates that current will change slope when the plunger, and thus spool, goes from a zero to non-zero velocity or vice versa. The foundation of our approach lies in identifying when the motional term is activated. First, control cases are established by generating current traces for the solenoid when the spool and plunger are held in the air gap open (AGO) and air gap closed (AGC) positions. As motion is prevented in these cases, the motional term of Equation (8) is zero. Then, the current trace through a valve that is allowed to transition can be compared to these control cases. Any deviation from the control current signal indicates that the motional term is non-zero and the plunger and spool are in motion.

Experimental procedure

The valve used to verify the proposed current analysis methodology is a HydraForce SV08-30 two position, three way spool valve. This valve is solenoid operated, with the axially translating spool slotted into to the solenoid plunger as shown in Figure 2. A coil spring in the air gap provides the valve resetting force. This valve is pressure balanced via a port that runs through the spool and plunger and terminates at the air gap.

To experimentally verify the proposed current analysis method, the spool position was measured optically using an MTI Microtrak 3 model 120-20 laser displacement sensor. The Microtrak 3 is a non-contact laser sensor that uses triangulation to determine position. In order measure position during operation of a hydraulic power circuit, a housing for the SV08 valve was built with a sight glass that allows line of sight on the end of the valve spool as shown in Figure 3. The sight glass was made from 25 mm thick acrylic and was designed to withstand 21 MPa.

The laser light refracts at the surfaces of the acrylic sight glass and the hydraulic fluid. Snell's law calculations were carried out to understand the effects of light refraction as it passed across those surfaces. Acrylic has a refractive index of 1.49 and mineral oil has a refractive index of 1.48 (Budwig, 1994). The results yielded 0.4% non-linearity error that was caused by introduction of trigonometric terms in the refraction calculations. The non-linearities were considered minor enough to neglect. Valve spool displacement was measured with a dial indicator and a linear scaling operation was applied to align the laser sensor output with the measured spool travel.

The valve was driven by the DC solenoid driver shown in Figure 4. The current passing through the circuit was measured by calculating the voltage drop across R_{sense}, which is a 0.5 ohm resistor with a 1% tolerance specification. The drop across the sensing resistor and the laser sensor output were sampled at 20 kS/s.

A 29.3 V, 0.07 s duration square pulse was used as the excitation signal for all results. After voltage drops across the driving circuitry and transmission cabling, this signal resulted in a 24 V drop across the solenoid which is the rated voltage of the coil. This pulse was long enough to ensure magnetization of the solenoid but short enough to prevent significant resistive heating of the coil, which allows for characterization of the solenoid valve at ambient temperature. The control curves should be collected at the operating temperature at which the solenoid valve is to be characterized due to changes in coil resistance with temperature.

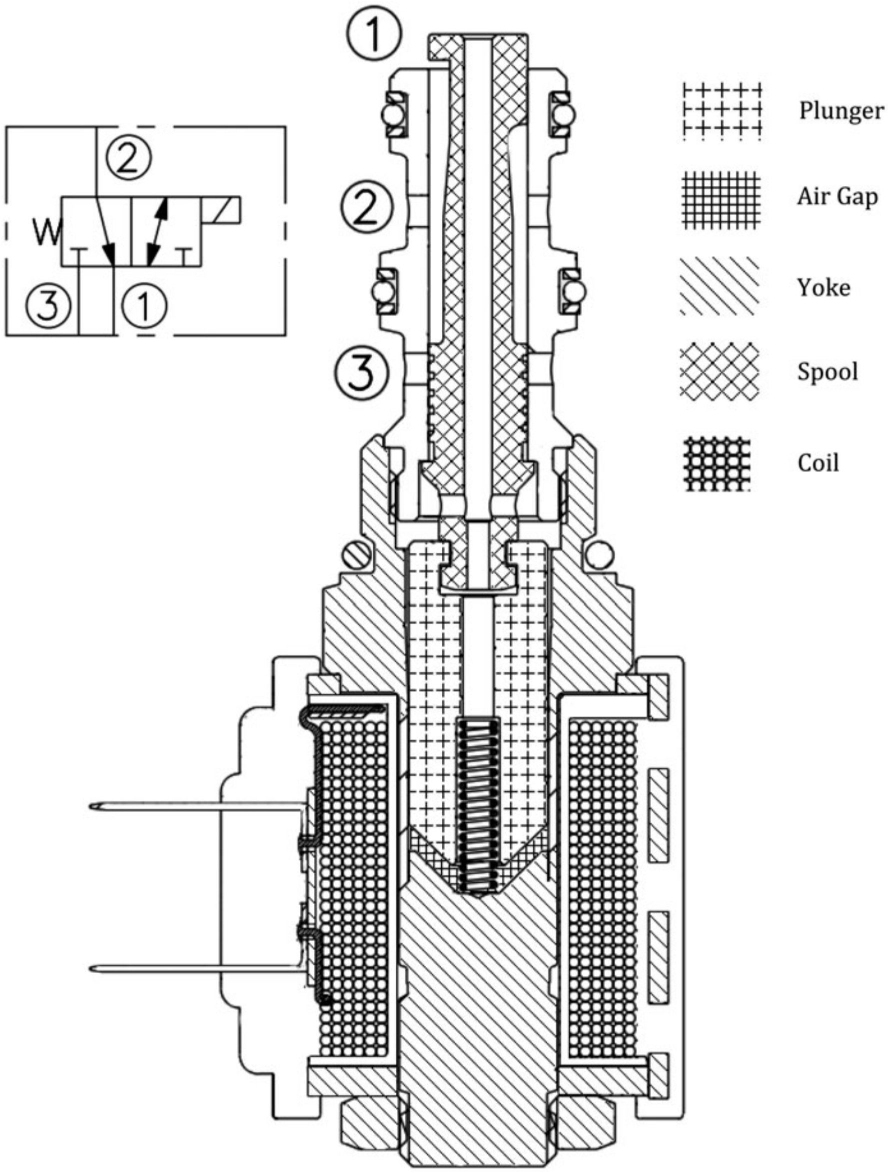

Figure 2. Cross section and schematic of the HydraForce SV08-30 valve (xxx, 2014).

As a first step of the procedure, the current passing through the solenoid was recorded while a DC voltage excitation signal was applied to the two control cases: the valve held in the AGO and AGC positions. To hold the solenoid in the AGO position, paper tissue was loaded into the air gap to prevent motion. Lack of valve spool and plunger motion was verified with the laser sensor. Similarly, to hold the plunger in AGC position, the air gap was held closed by squeezing the spool and plunger to the downward position in a vise with a non-ferrous jaw.

Once the control curves were established, the valve was placed in the sight glass housing and flooded with oil. The valve was switched several times with oil flowing in order to evacuate air pockets in the valve and housing. The presence of air bubbles would generate error in the optical displacement measurement. The absence of air bubbles was confirmed visually through the sight glass.

The valve displacement tests were performed with the solenoid free to move and the valve and housing flooded with oil. Tests were conducted across a pressure range of 0–10.3 MPa and flow rates of 0–7.57 L/min. The maximum variation in the valve transition time was 10%, compared with zero flow and ambient pressure. To illustrate the proposed methodology, the results of the zero flow and ambient pressure tests will be presented in the following section.

Results

Experimental current and position data for five consecutive transition events is presented in Figure 5. The overlay of the results indicate good repeatability. Minor

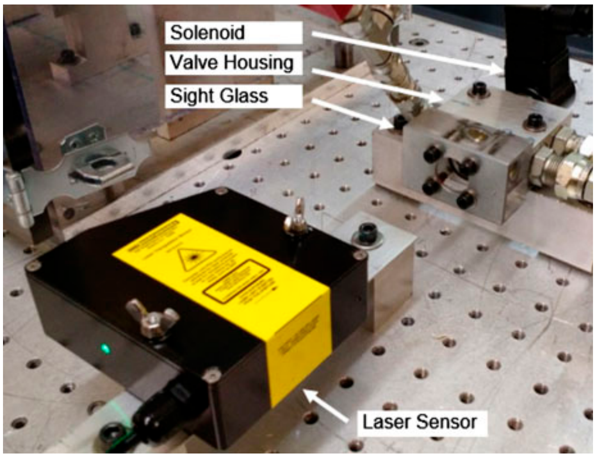

Figure 3. Experimental setup including the Microtrak 3 laser displacement sensor and sight glass valve housing.

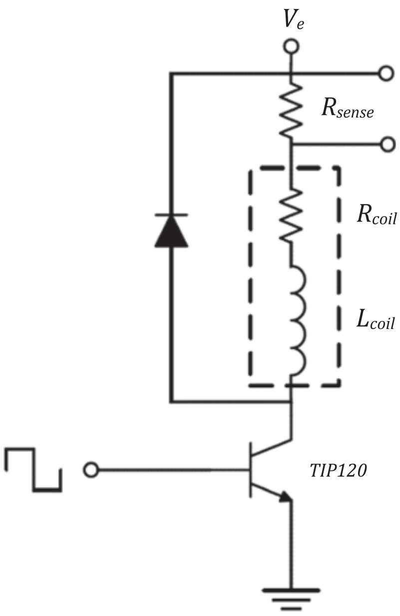

Figure 4. DC solenoid driver used to drive the SV08 valve.

inconsistencies in position data were attributed to tolerances in valve manufacturing. The time delays and transition times referenced in the paper are labeled in Figure 5. A slope change in the current trace occurs at the onset and completion of each of the time delay and transition events.

Figure 6 shows the current through the solenoid of the control cases for the valve held in AGO and AGC positions. It is evident that the time constant of the current rise and current fall for each cases are different, which is a result of magnetic saturation effects. By collecting these control curves experimentally, the non-ideal saturation effects are captured. The proposed methodology hinges on time shifting and matching portions of the control current traces to the trace of the current passing through the solenoid of the transitioning valve. To match

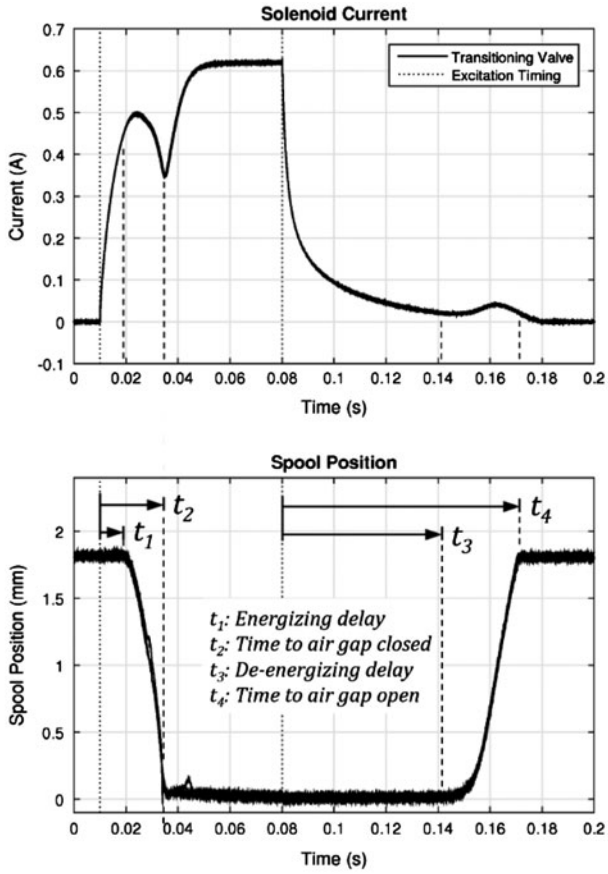

Figure 5. Experimental data collected for five consecutive valve transitions.

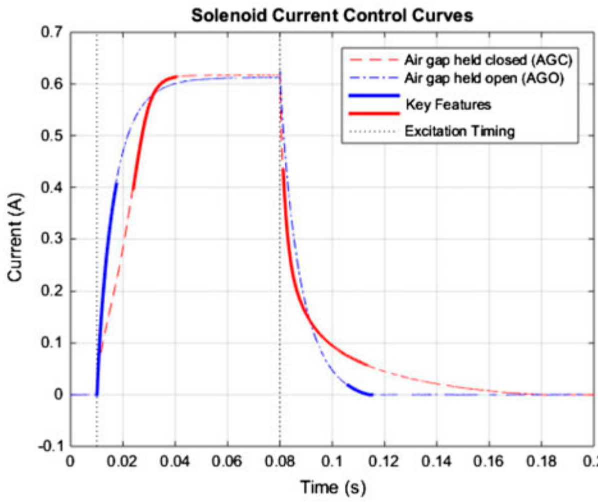

Figure 6. Experimentally collected current through the solenoid for two cases in which spool motion is prevented. These are the 'control' curves. The key features used to align the control curves with the transitioning valve are shown with a wider line.

these curves, key features of the control current traces were isolated, shown as solid lines in Figure 6. The key feature segments of the control current data were time shifted incrementally along the current data for the transitioning valve. At each time increment, the sum of the squared residuals between the key feature segments and the transitioning valve data were calculated and the time shift resulting in the minimum error was selected.

In order to identify the transition events, a threshold deviation of 0.25% of the maximum current was used. When the transitioning valve plot deviates from the overlaid control current curve by this threshold amount, a transition event is recorded. In the following results and discussion, a lowpass filter with a 7500 Hz cutoff frequency has been applied to the data. The lowpass filter attenuates signal noise and allows precise determination of current curve deviation. Figure 7 shows the filtered transitioning valve data with the control plots overlaid for a single valve cycle. All transition events were detected in post processing.

The initial transition event is a motion from an open air gap to a closed air gap. While the air gap is open, the current through the solenoid will follow the current plot of the solenoid held in the AGO position. The onset of motion is seen in Figure 8 where the current deviates from the control current by 0.25% of the maximum current at 0.0187 s. The laser sensor indicates that motion

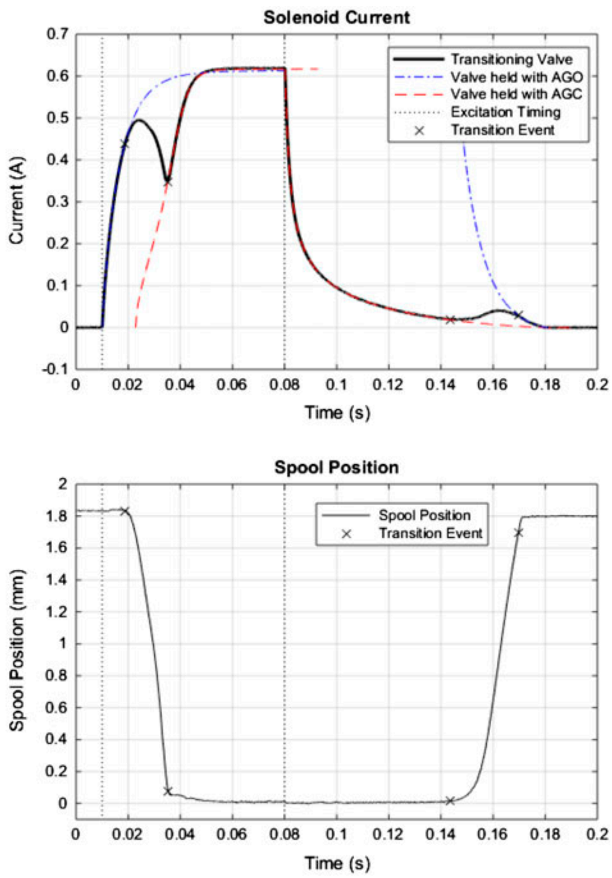

Figure 7. Comparison of valve current and spool position data. Transitioning valve current and position data was collected experimentally. Transition event timing shown was determined through current analysis.

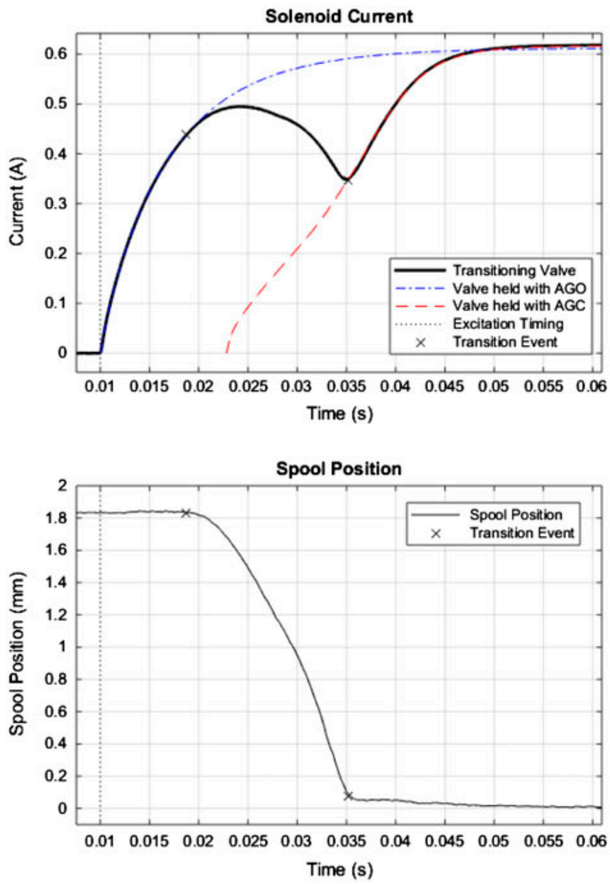

Figure 8. Detail on the air gap closing transition event of Figure 7. Transition event timing is determined through current analysis.

occurs at 0.0193 s. The valve spool then travels downwards as the air gap transitions to a closed position. With the valve now in the AGC position, the current curve of the transitioning valve will follow the AGC control current curve. Current analysis data shows that this event occurs at 0.0351 s, while optical position measurement indicates that the air gap fully closes at 0.0358 s.

After the excitation period, there is a delay while the coil current decays. During this time, the air gap is closed, and the current through the solenoid follows the current trace of the solenoid held in AGC position. In Figure 9, at 0.1435 s, the current through the motive solenoid departs from this trace. The position measurement data indicates that this transition event occurs at 0.1426 s.

To identify the point at which the spool is fully transitioned to the AGO position, the current decay plot from the experiment in which the valve was held open (AGO) was referenced. This fixed position current plot was matched to the transitioning valve data. When the transitioning valve current begins tracking this plot, the motional term is equal to zero and the valve has stopped moving. This occurs at 0.1696 s by the current analysis method. Position measurement identified this transition occurring at 0.1711 s.

Table 1. Absolute and relative error values for analysis of five valve cycles.

		Absolute error		Relative error	
	Mean process time (ms, per optical displacement sensor)	Mean (ms)	Std dev (ms)	Mean (%)	Std dev (%)
Energizing delay	10.23	0.65	0.75	6.35	7.54
Time to AGC	25.89	0.29	0.37	1.12	1.45
Deenergizing delay	63.19	1.15	0.45	1.82	0.72
Time to AGO	91.51	1.51	0.63	1.65	0.33

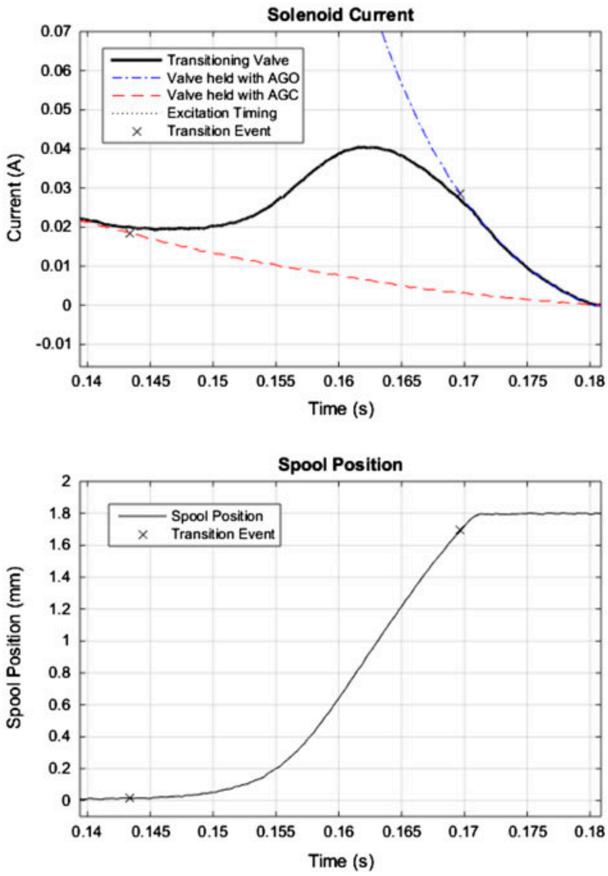

Figure 9. Detail on the AGO transition event of Figure 7.

Discussion

Figure 6 demonstrates the expected result that inductance of the solenoid is lower when the air gap is held open versus when it is held closed. In these tests, the valve was prevented from transitioning, so $dL/dt = 0$. Since the same voltage pulse is applied in both of these experiments, greater current slope indicates a lower inductance, as described in Equation (8).

As a comparison for the current-based valve transition events, the transition events were identified from the optical position measurement data, using a threshold of 0.5% of the overall valve travel. The absolute error between the transition event time determined from the position measurement and the current analysis is defined as:

$$e_{\text{absolute}} = \left| t_{\text{optical}} - t_{\text{current analysis}} \right| \quad (9)$$

where t_{optical} is the event timing determined by the optical position measurement and $t_{\text{currentanalysis}}$ is the event timing determined by the current analysis method. Both of these times are measured relative to the start of the voltage energization or deenergization. The relative percent error is defined for each trial as:

$$e_{1,\text{relative}} = \frac{e_{1,\text{absolute}}}{t_{1,\text{optical}}} \times 100 \quad (10)$$

Both the absolute and relative error were calculated for each of the four transition events. The mean and standard deviation of the error across five trials are presented in Table 1. The timing events listed are defined in Figure 5.

The valve duty ratio is a key metric in the context of switch-mode hydraulics. As seen in Figure 5, the energizing and deenergizing delays are of different duration, which means that the duty ratio of the valve will not be equal to the duty ratio of the excitation signal. The valve duty ratio is a function of the entire valve transition event, from departure to return to deenergized state.

The error values reported in Table 1 could be further reduced by applying a smaller current deviation threshold. For the purpose of consistency, a 0.25% of maximum current deviation was applied to identify all transition events through current analysis in this paper. More sophisticated filtering or data collection techniques may result in smoother current traces, which would allow for the application of a tighter threshold, and thus more accurate results. Manual inspection and time shifting of the current traces also yields low error and might be the best option if few analyses are required.

Conclusion

In this paper, a method of identifying valve transition timing through current analysis is supported by an elementary electromagnetic model and demonstrated experimentally. This valve timing characterization methodology allows researchers to identify solenoid valve energizing and deenergizing delays and transition times without physical access to the valve spool itself. In most cases accessing the spool would require modification to the valve housing which leads to increased failure probability and system contamination risks. Determining valve timing through solenoid current analysis is easy to implement and has been shown to identify the length of time delays and transition events with less than 7% mean error, which could be further reduced with additional improvements on current trace deviation detection. Transition event timing is of special interest to those working in switch mode hydraulics, active valve control, peak and hold tuning as well as for monitoring valve health. The proposed methodology allows researchers and practitioners to simply and reliably identify valve transition events.

Disclosure statement

No potential conflict of interest was reported by the authors.

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