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Sensitivity of Wavelet-Based Internal Leakage Detection to Fluid Bulk Modulus in Hydraulic Actuators

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Abstract- Fault detection and isolation (FDI) is a useful tool to investigate proper performance of dynamic systems. With respect to hydraulic actuators, as they are extensively used in industry, and are responsible for producing accurate displacements and high forces, FDI role is crucial. One of the phenomena that can affect the internal leakage detection is the variation in the value of fluid effective bulk modulus (EBM) originating mainly from the penetration of particles, water or air in the fluid. Hydraulic actuator internal leakage detection using wavelet transform technique is the focus of this paper. This study shows how the increase in the value of EBM affects the detection of the internal leakage using wavelet transform. Simulation results indicate that the increase in EBM value could change the sensitivity of the wavelet detailed coefficients to the internal leakage. Based on results, the level three detailed coefficient calculated from chamber one pressure signal could be an appropriate indicator to detect the internal leakage in a hydraulic actuator whose EBM is larger than normal value.

Keywords**:** Fault detection, internal leakage, effective bulk modulus of fluid, wavelet transform.

1. Introduction

Valve-controlled hydraulic actuators are extensively used to produce accurate displacements and high forces for industrial applications. Examples are flight control, robotics, and off-road machines (Cao and Dai, 2014). Detecting faults in hydraulic actuators is important to prevent malfunctions. One of the major faults is the actuator internal leakage that occurs due to wearing in piston seal. Actuator internal leakage is difficult to detect without dismantling the actuator. Thus, internal leakage should be detected by analysing the system performance using advanced diagnostic methods (Karpenko and Sepehri, 2010). Moreover, any change in the value of fluid effective bulk modulus (EBM) affects the hydraulic actuator performance. Fluctuation in the value of EBM can originate from the fluid contamination by water, air, or other particles that affects the dynamic performance of the hydraulic actuator. It may also arise from the change in the fluid operating pressure and temperature (Skormin *et al*., 1994).

As far as previous work on the actuator internal leakage is concerned, Tan and Sepehri (2002) applied the concept of Volterra nonlinear modeling to diagnose actuator leakage faults. They reported a method that requires a model of leakage to do the prediction. A reduced-order model was presented for the fault detection of an open-loop-controlled mobile hydraulic valve (Nurmi and Mattila, 2013). An observer-based actuator fault detection algorithm for an electro-hydraulic system was developed by Rezazadeh *et al.* (2010). Observer-based methods utilize different directions of faults in the state space of the model, and these methods are not capable of isolating faults whose directions are the same in the system state space (Yu, 1997). Kalman filtering (KF) method is another popular approach for states estimation of a system recursively. The feasibility of using extended Kalman filter (EKF) to detect incorrect supply pressure in a hydraulic system was also reported by An and Sepehri (2003; 2005). Recently, a scheme has been shown for fault diagnosis using the unscented Kalman filter (UKF) and a mathematical model of the hydraulic servo system (Liu *et al*., 2014). Moreover, a method was presented to generate hydraulic system fault symptoms automatically by on-line processing of raw sensor data from a real experimental setup (Sepasi and Sassani, 2010).

The above schemes are all model-based, and require an exact information and estimation of model parameters to properly detect faults. Signal processing-based FDI methods have also been used. They are easy to implement, and need only data of output signals of the hydraulic actuator. A comprehensive study has been carried out on fault detection and isolation of a leaky hydraulic actuator based on wavelet, Fourier, and Hilbert-Huang transforms (Goharrizi *et al*., 2010; 2012; 2013). Both internal and external leakages were considered as sources of faults, and fault detection and isolation were experimentally conducted regardless of the effect of variation in EBM value on leakage detection. In the wavelet-based work, authors reported that certain detailed and approximation coefficients are sensitive to internal and external leakages, respectively. Thus, both leakages could be detected and isolated by analyzing the percentage of the change of wavelet coefficients. They also investigated the effect of the change in viscous friction value on internal leakage detection and realized that the variation in viscous friction coefficient does not affect the wavelet-based internal leakage detection procedure.

In this paper, the effect of change in EBM value of fluid on internal leakage detection is studied when using a discrete wavelet transform (DWT) technique. Simulation studies are carried out based on a nonlinear model of a valve-controlled hydraulic actuator to investigate the effect of EMB value on the system performance. Internal leakage detection is then performed using DWT under different faulty modes defined by the various values of EBM and internal leakage levels. Results show how sensitive the wavelet-based internal leakage detection is to variations of EBM value.

The rest of this paper is organized as follows. Section 2 presents an overview of dynamic modeling of a double-rod hydraulic actuator driven by servovalve. Section 3 shows results of internal leakage detection considering the change in EBM value using DWT. Conclusions are presented in Section 4.

2. Modeling

Figure 1 shows the schematic of a hydraulic actuator subject to internal leakage. As shown in Fig. 1, an internal leakage is produced by bypassing fluid across the piston. The input signal, u, and the piston displacement, x_P, are related using the following six sets of equations (Merrit, 1967).

a) Piston-related equations

$$\dot{x}_p = v_p \tag{1}$$

$$\dot{v}_p = \frac{1}{m}(AP_1 - AP_2 - F_f - K_{ex}x_p) \tag{2}$$

Where, x_p and v_p represent the displacement and the velocity of actuator piston, respectively. m is the combined mass of the piston and load. A denotes the piston annulus area. P_1 and P_2 are pressures of each chamber. The total friction force applied on the piston is denoted by F_f. K_{ex} is referred to as the stiffness coefficient of environment spring connected to actuator piston rod.

b) Servovalve-related equations:

$$\dot{x}_v = v_v \tag{3}$$

$$\dot{v}_v = -\omega_v^2 x_v - 2\xi\omega_v v_v + k_v\omega_v^2 u \tag{4}$$

x_v and v_v are the position and the velocity of the valve spool in servovalve, respectively. k_v is the position gain of servovalve spool. ω_v and ξ represent the servovalve-related natural frequency and damping ratio, respectively. u denotes the servovalve input signal.

c) Pressure-related equations

$$\dot{P}_1 = \frac{\beta}{V + Ax_p}(q_1 - q_{il} - q_{el1} - Av_p) \tag{5}$$

$$\dot{P}_2 = \frac{\beta}{V - Ax_p}(-q_2 + q_{il} - q_{el2} + Av_p) \tag{6}$$

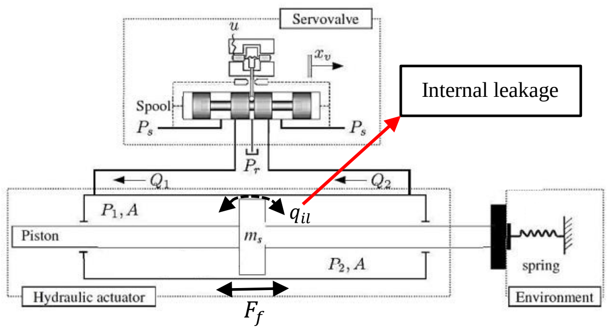


Fig. 1. Schematic of a hydraulic actuator driven by servovalve subject to internal leakage (Karpenko and Sepehri, 2010)

β is the fluid effective bulk modulus, and V denotes the volume of fluid contained in each chamber of the cylinder. q_1 and q_2 describe the servovalve control flows to chambers 1 and 2, respectively. q_{il} represents the internal leakage flow between two chambers of the cylinder. q_{el1} and q_{el2} are referred to as the actuator external leakage flows from chambers 1 and 2, respectively.

d) Flow-related equations

$$q_1 = K_v w \, x_v \sqrt{\frac{P_s - P_r}{2} + sgn(x_v)(\frac{P_s + P_r}{2} - P_1)} \tag{7}$$

$$q_2 = K_v w \, x_v \sqrt{\frac{P_s - P_r}{2} + sgn(x_v)(P_2 - \frac{P_s + P_r}{2})} \tag{8}$$

$$q_{el1} = K_e \sqrt{P_1} \tag{9}$$

$$q_{el2} = K_e \sqrt{P_2} \tag{10}$$

$$q_{il} = K_i sgn(P_1 - P_2)\sqrt{|P_1 - P_2|} \tag{11}$$

Where, K_v is the servovalve flow gain, and w represents the servovalve area gradient. P_s and P_r denote the return and supply pressures, respectively. In Eqs. (9) to (11), K_e is referred to as the coefficient of the external leakage, while K_i is that of the internal leakage.

e) Friction force equation (Armstrong, 1995)

$$F_f = \begin{cases} \left[F_c + (F_{brk} - F_c)e^{-c_v|v_p|}\right] sgn(v_p) + f v_p & if \ |v_p| \geq v_{th} \\ \frac{v_p}{v_{th}}[f v_{th} + F_c + (F_{brk} - F_c)e^{-c_v v_{th}}] & if \ |v_p| < v_{th} \end{cases} \tag{12}$$

F_c and F_{brk} symbolize the Coulomb friction and breakaway friction forces, respectively. c_v represents the transition approximation coefficient, while f is that of viscous friction. v_{th}, denotes the linear region velocity threshold.

3. Wavelet-Based Internal Leakage Detection Procedure

This study investigates the effect of increase in EBM value on internal leakage detection of a valve-controlled hydraulic actuator using DWT. Table 1 lists the values considered for normal operating mode of the hydraulic actuator. These values are taken from the combination of previous research work on the hydraulic test rig available in Fluid Power and Telerobotics Research Laboratory, University of Manitoba. To solve dynamic equations, Runge-Kutta 4th order method with the integration time of 0.001 seconds was used.

To detect the internal leakage in the presence of variation in fluid EBM value, detailed coefficients of chamber one pressure signal (P_1) were calculated by applying the combination of multiresolution signal decomposition (MSD) (Mallat, 1989; Burrus *et al.*, 1998) and quadrature mirror filter (QMF) (Strang and Nguyen, 1996) techniques on the hydraulic actuator according to the procedure used by Goharrizi *et al.* (2010). The mother wavelet function is *Daubechies-8* wavelet function (Goharrizi *et al*., 2010). Daubechies wavelets are compactly supported with external phase and the highest number of vanishing moments for a given support width (Daubechies, 1992; Ukil and Zivanovic, 2006); furthermore, associated scaling filters are minimum phase. From implementation point of view, Daubechies wavelet is a good choice for this application. A high order mother wavelet is better to avoid overlapping between two adjacent frequency bands (Cusido *et al.*, 2008); that is why the order eight has been chosen.

Table 1. Normal values of parameters used in simulations

Parameter	Value	Parameter	Value
m (kg)	12.3	w (m)	20.75×10^{-3}
A (m^2)	633×10^{-6}	k$_v$ (m/Volt)	2.79×10^{-5}
V (m^3)	275×10^{-6}	ω_v (Hz)	175
P_r (Pa)	0	ξ	0.7
P_s (Pa)	$17.2 \times 10^{+6}$	F_c (N)	200
β (Pa)	$551 \times 10^{+6}$	F_{brk} (N)	500
K (m^3/ [illegible])	0	f (Ns/m)	250
K (m^3/ [illegible])	0	c_v	40
K$_v$ (m$^{3/2}$/kg$^{1/2}$)	0.0292	v_{th} (m/sec)	10^{-3}
		K_{ex} (N/m)	125000

Detailed coefficients were obtained up to decomposition level of 5. To better investigate the effect of increase in EBM value on wavelet coefficients in an internally leaky actuator, the percentage of change of each coefficient with respect to the healthy mode (normal operating mode) was calculated according to Eq. (13). For each coefficient a root mean square (RMS) value was defined to facilitate the comparison process.

$$\delta = \frac{RMS_{healthy} - RMS_{faulty}}{RMS_{healthy}} \times 100 \quad (13)$$

Where, δ is the percentage of change of RMS value with respect to normal operating mode (healthy system). $RMS_{healthy}$ and RMS_{faulty} represent the root mean square value of each wavelet coefficient in healthy and faulty modes, respectively. By faulty mode, it means that the system is internally leaky.

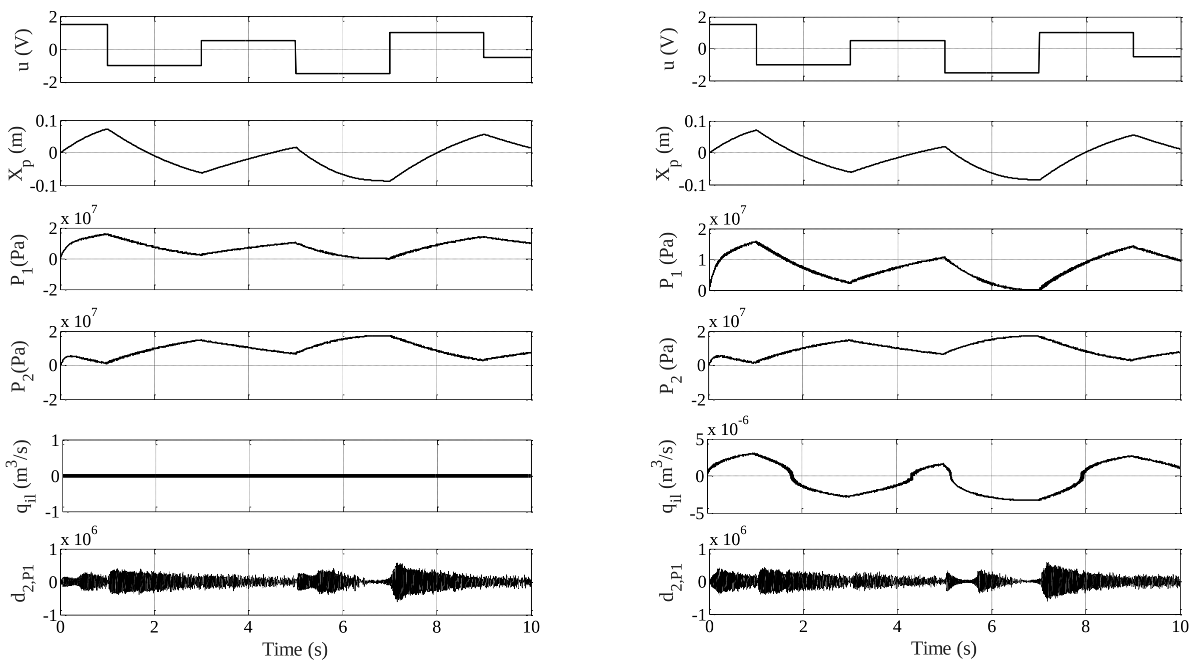
3. 1. Typical Simulation Results

To study the effect of increase in EBM value on internal leakage detection, different simulations were performed including combinations of different values for EBM and the internal leakage. Results of 9 simulation modes (listed in Table 3) are reported to observe how EBM can affect the detection process of the internal leakage in hydraulic actuators. To maintain the compactness of the paper, typical results of the simulation for a set of faulty mode are presented, and for other faulty modes, results are only summarized.

In the first set of simulation studies, detailed coefficients of P_1 were obtained in normal operating mode and in a set of faulty mode comprising a small internal leakage of 0.122 lit/min in average and three different values for EBM of fluid. In this study, there is no external leakage within the hydraulic circuit.

Figures 2-a and 2-b show piston displacement and pressure signals in the hydraulic actuator under normal operating mode (no leakage and EBM=551 MPa) and a faulty mode with small internal leakage of 0.122 lit/min in average and EBM of 551 MPa, respectively. With reference to Figs. 2-a and 2-b, the same input signal was applied on the servovalve in different modes. It was also shown that how the second level detailed coefficient of P_1 (d_{2,P_1}) changes when the hydraulic actuator becomes internally leaky. This change is also shown as RMS values in Table 2. This is in line with the study performed by Goharrizi *et al.* (2010) showing that d_{2,P_1} is the most sensitive coefficient to the internal leakage when the fluid EBM is equal to the normal value. Goharrizi *et al.* proved that the coefficient d_2 has the largest percentage of change among all detailed coefficients when the hydraulic actuator becomes leaky.

To investigate the effect of increase in EBM value on the internal leakage detection, all detailed coefficients of P_1 were obtained under different EBM values. As observed in Fig. 3, the change in EBM value affects the values of d_{2,P_1} whose RMS values are also reported in Table 2.



(a)
Normal operating mode
(No leakage; EBM=551 MPa)

(b)
Faulty mode
(Mean Int. leakage: 0.122 lit/min; EBM=551 MPa)

Fig. 2. System parameters behavior under normal operating mode (a) and an internally leaky mode (b). Sampling frequency is equal to 500 Hz.

Table 2. Effect of increase in EBM value on detailed coefficients of P_1 in an actuator with small internal leakage of 0.122 lit/min in average.

Detailed coefficients	**Normal operating (no leakage)**	**Small internal leakage ($\overline{q_{il}} = 0.122\ ^{lit}/_{min}$)**					
	$\boldsymbol{EBM = 551MPa}$	$\boldsymbol{EBM = 551MPa}$		$\boldsymbol{EBM = 689MPa}$		$\boldsymbol{EBM = 827MPa}$	
	RMS Value	RMS Value	δ (%)	RMS Value	δ (%)	RMS Value	δ (%)
d_1	9983	10124	-1.4	14687	-47.1	17935	-79.6
d_2	164736	162939	1.1	229918	-39.5	239884	-45.6
d_3	364368	361002	0.93	306369	16	222044	39.1
d_4	314401	317001	-0.8	354323	-12.6	396761	-26.1
d_5	290618	294410	-1.3	335510	-15.4	377387	-29.8

According to Table 2, given an internal leakage flow rate, as EBM value increases, the percentage of change of d_2 with respect to its normal RMS value (δd_2) decreases, and other coefficients (*e.g.* δd_1 *and* δd_3) show better sensitivity to the internal leakage. For example, δd_3 is the only coefficient which reports positive values when EBM is larger than the normal value. As observed in Table 3, for other levels of internal leakage, other coefficients (*e.g.* $\delta d_i\, ; i = 1,2,4,5$) could not show a clear representation in sensitivity to different levels of the internal leakage.

As compared to the previous study by Goharrizi *et al.* (2010), when EBM is larger than the normal value in an actuator experiencing the internal leakage, there will be a shift in the wavelet frequency band indicating the most positive sensitivity to the internal leakage. Positive sensitivity means that the percentage of change of a coefficient (δ) is positive. As a result, to properly detect the internal leakage in the hydraulic actuator whose fluid EBM is larger than the normal value, the coefficient d_3 should be studied. Then, if δd_3 has the largest positive value, the system is experiencing the internal leakage. Figure 4 shows how the value of the detailed coefficient d_3 changes with EBM value in an internally leaky hydraulic actuator. To better understand this change, RMS values of coefficient d_3 are calculated in Table 2 for the corresponding EBM values and for a small internal leakage with the flow rate of 0.122 lit/min in average.

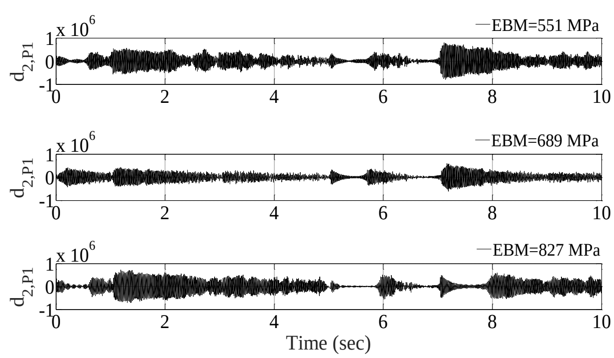


Fig. 3. Effect of increase in EBM value on level two detailed coefficient of P_1 in the actuator with small internal leakage of 0.122 lit/min in average.

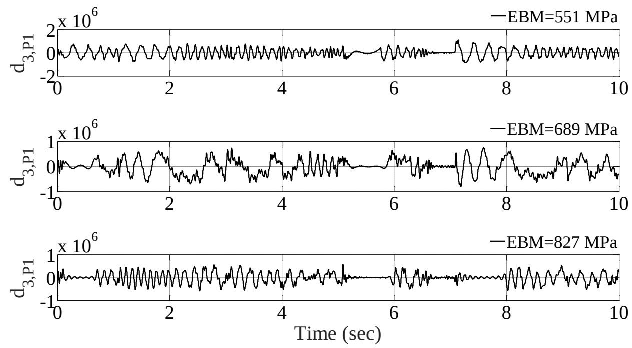


Fig. 4. Effect of increase in EBM value on level three detailed coefficient of P_1 in the actuator with small internal leakage of 0.122 lit/min in average

3. 2. Sensitivity Study

Results of simulation studies are summarized in Table 3. As seen, percentages of changes of detailed coefficients are reported in three levels of internal leakage modes (small, medium and large internal leakages). With reference to Table 3, when the fluid EBM is equal to normal value and the internal leakage flow rate grows, δd_2 increases subsequently, and d_2 is still the best indicator to detect the internal leakage within the hydraulic circuit (see *highlighted* cells in Table 3). However, in a certain level of internal leakage, as the value of EBM increases, the coefficient d_2 is affected by the change in EBM value, and its percentage of change decreases, while the coefficient d_3 reports the most positive sensitivity to the internal leakage (see *ovals* and *circles* in Table 3).

In addition, if the absolute values of percentage of changes ($|\delta d_i|$) are considered to detect the internal leakage, no specific conclusion can be arrived at from investigating the values of $|\delta d_i|$. This is because $|\delta d_1|$ does not have the largest value in all levels of the internal leakage and various values of EBM. Therefore, the coefficient d_3 seems to be a better indicator to detect the internal leakage with different flow rates in the hydraulic actuator whose EBM is larger than the normal value.

Table 3. Percentage of change of detailed coefficients in different leaky modes with different EBM values

Leaky mode	**Small int. leakage** $\overline{q_{il}} = 0.122\ {lit}/{min}$			**Medium int. leakage** $\overline{q_{il}} = 0.829\ {lit}/{min}$			**Large int. leakage** $\overline{q_{il}} = 1.547\ {lit}/{min}$		
EBM value	**551 MPa**	**689 MPa**	**827 MPa**	**551 MPa**	**689 MPa**	**827 MPa**	**551 MPa**	**689 MPa**	**827 MPa**
$\boldsymbol{\delta d_1}$	-1.4	-47.1	-79.6	6.5	-22.1	-54.3	31.8	6	-24.4
$\boldsymbol{\delta d_2}$	1.1	-39.5	-45.6	18.7	7.3	-12.3	50.3	33.5	22.8
$\boldsymbol{\delta d_3}$	0.93	16	39.1	15.3	35.7	47.6	46.1	49.9	57.4
$\boldsymbol{\delta d_4}$	-0.8	-12.6	-26.1	-2.5	-14.2	-27.4	-5.5	-14.4	-27
$\boldsymbol{\delta d_5}$	-1.3	-15.4	-29.8	-0.9	-15.6	-31.6	-0.6	-15	-29

4. Conclusions

The nonlinear model of valve-controlled hydraulic actuators was simulated to investigate the effect of increase in the fluid EBM value on wavelet-based internal leakage detection. Based on previous research work, coefficient d_2 was the best indicator to detect the internal leakage in a hydraulic actuator with normal EBM. Results of this study, however, indicated that when the EBM is larger than the normal value, the coefficient d_3 shows a better sensitivity to different levels of the internal leakage as compared to coefficient d_2. Therefore, to properly detect the internal leakage in a valve-controlled hydraulic actuator whose EBM is larger than normal value, the coefficient d_3 could be a better indicator. Future work will focus on validating simulation results using the experimental setup and comparing them with those of other FDI methods. The effect of the change in dry friction value on the detection of the internal leakage will also be examined.

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