A WAVELET-BASED APPROACH FOR DIAGNOSIS OF INTERNAL LEAKAGE IN HYDRAULIC ACTUATORS USING ON-LINE MEASUREMENTS

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Abstract

Prompt diagnosis of faults associated with hydraulic actuators is important to maintain reliability and performance and to avoid complete loss of functionality. This paper presents new development and evaluation of a wavelet-based method, intended for on-line detection of internal leakage in a valve-controlled hydraulic actuator. This work is built upon the initial study by the authors, in which actuator's internal leakage was detected using limited-duration data on one of the actuator's chamber pressures, in response to a structured input signal and under no load condition. In the present work, the more realistic case of an actuator that is driven in a closed-loop mode to track pseudorandom position references is considered. Additionally, the actuator is subject to loading. Furthermore, limited-duration pressure signals are obtained using a sliding window technique applied to the stream of on-line measurements. It is shown that the root mean square values of level two detail coefficient vectors of pressure signals collectively establish a feature index that can effectively detect internal leakage. This monitoring index is shown to decrease in magnitude and energy once the leakage occurs. Extensive validation tests are performed to demonstrate the effectiveness of the proposed technique in detecting internal leakage, given any reference step input or loading condition. The significance of the proposed method is that it does not need models of the actuator and leakage fault or any baseline information on performance of the healthy actuator. Furthermore, the method remains effective even with control systems that are tolerant to leakage fault. Finally, the method can detect low internal leakages, in the range of 0.2 to 0.25 l/min, not reported in any of the previously published work. These aspects make the method very attractive from the industrial implementation viewpoint.

Keywords: hydraulic actuators, internal leakage, on-line fault detection, wavelet analysis

1 Introduction

Fluid power systems are used in many applications including aircraft and heavy equipment due to their ability to produce high forces or torques with low inertia (Jelali and Schwarz, 1995). Reliability is crucial for proper operation in these applications. Thus, condition monitoring of fluid power systems is of great importance to both academic and industrial fields. Towards this goal, it is desirable to develop fault diagnosis (FD) schemes that can report abnormal conditions in hydraulic systems (Isermann, 1996). FD systems can also be effectively used with active fault tolerant controllers that are designed to react to the changes in the system's parameters due to faults, through adaptation or reconfiguration (Karpenko and Sepehri, 2003).

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One of the concerns regarding hydraulic actuators is the leakage of hydraulic fluid. According to its location, leakage can be classified into: (i) internal (cross-port) leakage, where the fluid leaks to another part of the circulation within the hydraulic system and (ii), external leakage where the fluid leaks out of the hydraulic circulation. Whereas external leakage can be, to a great extent, inspected visually, internal leakage caused by seal damage cannot be detected until the actuator seal is completely damaged and the actuator fails to respond to any control signal. Thus, it is critical to pay special attention to detecting this fault as part of any health monitoring strategy.

Condition monitoring of hydraulic systems can be done using off-line or on-line approaches. In an off-line approach, a structured predefined input signal is normally applied to the system under ideal (no-load) condition. Information on the system response, obtained over the entire test period, is then used for diagnosis. In on-line approach, data on the states of the system are obtained and analyzed while the system is operating through its routine work cycle. Within the context of hydraulic actuation, this implies the actuator must track reference position signals of various magnitude and duration and under various loading conditions. An example would be positioning of an aircraft control surface. As opposed to off-line approach where the diagnosis can be conducted using responses from the system under open-loop control, the on-line approach uses data from the system operating in a closed-loop position control mode. Thus, the diagnosis method should preferably function independent from the controller type or effectiveness. Furthermore, during the on-line approach, information is obtained from limited-duration segments of the continuous stream of measurements collected on-line. On-line fault detection is more interesting than the off-line one, since it provides information about the health of the system without interrupting its routine operation. It can also provide a support for active fault tolerant controllers to reconfigure their control actions in response to changing conditions due to occurrence of faults.

A comprehensive source describing methods of fault detection applied to hydraulic systems is the book by Watton (2007). As far as methods for internal leakage diagnosis is concerned, the existing literature is rather limited. Watton and Pham (1997) employed neural networks and dynamic feature extraction technique to classify leakage type and level in hydraulic actuators. Similarly, Tan and Sepehri (2002) applied the Volterra nonlinear modeling concept to implement a FD scheme in hydraulic systems. By constructing a parametric space, changes in the supply pressure, hydraulic compliance and actuator leakage were detected. Both techniques required that the hydraulic system having various fault types and levels be emulated (through simulations or via experiments) and Volterra or neural network models be developed beforehand. An and Sepehri (2005) studied the feasibility of an EKF-based FD scheme for detecting internal and external leakage faults. They further extended this work to include both friction and loading as unknown external disturbances and for actuators tracking pseudorandom reference inputs. Although the requirement of having a model for leakage was removed in the work by An and Sepehri (2005, 2008), the need for knowing the model of the hydraulic actuator still remains a challenge. In order to overcome the difficulties associated with modeling nonlinear hydraulic systems, a linearized model with an adaptive threshold (to compensate for the error due to linearization) was used by Shi et al. (2005) to detect fault due to internal and external leakages.

Motivated by developing a method that does not rely on a model of the system or fault, the authors initiated a research directed at employing the wavelet transform to detect internal leakage in valve-controlled hydraulic actuators. The wavelet transform is a signal processing tool that decomposes a source signal into time and frequency domains simultaneously focusing on short time intervals for high-frequency components and long time intervals for low-frequency components (Daubechies, 1992). The time-frequency localization property of wavelet transform has recently drawn wide-spread attention as a promising tool to deal with fault detection. To name a few, Zhang and Yan (2001) developed a wavelet-based method for detecting sensor faults. Gao and Zhang (2006) employed wavelet transform for on-line hydraulic pump health diagnosis. The pulsation pressure signal was used and faults contributing to pump malfunctioning were isolated based on the detail wavelet coefficients. Additionally, wavelet transform method was shown to be more sensitive and more robust than the fast Fourier transform approach, in detecting faults associated with hydraulic pumps (Gao et al. 2005). Recently, Goharrizi et al. (2009) used wavelet transform for off-line detection of internal leakage in hydraulic actuators. The method analyzed system's pressure at one side of the actuator, given a structured periodic step input control signal and under no-load condition. It was shown that the detailed version of decomposed pressure signal, using discrete wavelet transform and multiresolution signal decomposing method (Mallat, 1989; Mallat and Zhong, 1992), can effectively detect internal leakage and its severity. The significance of the proposed approach is that the method does not require a model of the system and/or the leakage. The proposed scheme, however, required a baseline (threshold) value, predetermined first, by analyzing pressure signal of the healthy actuator. Also, periodic evaluation must be conducted under the same loading condition and structured input signal for diagnosis.

This paper is built upon the work reported earlier (Goharrizi, Sepehri and Wu, 2009) to establish a framework for detecting internal leakage on-line. In the earlier work, the authors showed that level two detail coefficients, obtained from the measured actuator pressure signal, are sensitive to internal leakage fault, and its amplitude and energy change with the severity of leakage. The work reported here represents a more realistic case of an actuator under load that is controlled to follow arbitrary reference position signals. To make the approach applicable to on-line applications, a sliding window technique is applied. Segments of measured pressure signal from one side of the actuator are collected, and the root mean square (RMS) value of the level two detail wavelet coefficient vector obtained from each window is calculated as an index during the run time. It is shown that once internal leakage happens, the subsequent RMS values decrease in magnitude. Thus, by monitoring these values, the faulty operating condition can be detected.

The effectiveness of the proposed approach is validated through extensive experiments, designed for a hydraulic actuator that tracks pseudorandom reference signals against a load which is emulated by a spring. Detecting small leakages is the focus of this paper since they are most interesting in early detection of fault. The proposed approach is shown to detect low leakages in the range of 0.2 to 0.25 l/min, regardless of the reference input and loading condition. Additionally, the results are shown to be independent of the feedback position controller type. To prove the latter claim, two QFT controllers, developed previously (Karpenko, 2008), are used in the experiments. The first controller has been designed to be only robust against typical uncertainties inherent to hydraulic actuators. The second controller has been designed to also be robust to the internal leakage fault.

The rest of this paper is organized as follows. Section 2 describes the test rig on which all the experiments are performed and the manner in which the internal leakage is created. Section 3 provides a brief description of signal decomposition via wavelet transform. Section 4 provides detailed experimental results describing how the approach is used to detect the internal leakage. Note that similar results have been obtained through simulation studies. Here only the experimental results are reported, since simulation results are consistent with experimental observations. Conclusions are provided in Section 5.

2 Description of Experimental Test Rig

The photograph of the test-rig, on which the validation tests are carried out, is shown in Fig. 1. The actuator is a double rod type having a 610 mm (24 in) stroke, 38.1 mm (1.5 in) bore diameter, and 25.4 mm (1 in) rod diameter. It is controlled by a Moog D765 servovalve. The actuator is powered by a pump operating at a nominal pressure of 17.2 MPa (2500 psi). The position of the actuator is measured using a cable-driven optical rotary encoder and is monitored by a PC via a Keithley M5312 quadrature incremental encoder card. The PC is also equipped with a DAS-16F input/output board that is used to send the input signal generated by the software to the valve. The DAS-16F board is also used to monitor the outputs of all other instruments, including pressure transducers, a load cell and several flowmeters. As illustrated in Fig. 1, the piston seal leakage is emulated by opening a ball valve that connects the two chambers of the actuator. This allows hydraulic fluid to be bypassed across the piston. The severity of leakage is controlled through adjustment of a needle valve. A positive displacement flowmeter (JVA-20KL by AW) having a range from 0.08 to 7.6 l/min (0.02 - 2.0 gpm) with ± 0.5 % accuracy is used to measure the leakage flow rate. Also, a force sensor is mounted at the end of the actuator to measure the environmental resistance emulated by a spring (see the inset of Fig. 1).

It has been documented by Karpenko and Sepehri (2005) that internal leakage adds damping to the system dynamics and this effect is intensified as the size of the leakage grows. Thus, using dynamic information on the pressure signal is important to detect internal leakage, a conclusion that was also cited by Watton and Pham (1997).

The positioning of the actuator against the spring load is achieved according to the two-degree-of-freedom feedback system configuration shown in Fig. 2. The controller, $G(s)$, and the prefilter, $F(s)$, are designed to satisfy the desired closed-loop performance specifications. Two controllers are used here to examine the efficacy of the fault detection technique developed here. The first controller has been designed using quantitative feedback theory (QFT). It is a fixed gain controller that is robust against typical uncertainties inherent to hydraulic actuators. The elements of this controller, which is hereafter referred to as 'basic controller,' are:

$$G(s) = \frac{2.76\times10^6(s+25)}{(s+16)(s^2+108s+120^2)} \tag{1}$$

$$F(s) = \frac{100}{s+100} \tag{2}$$

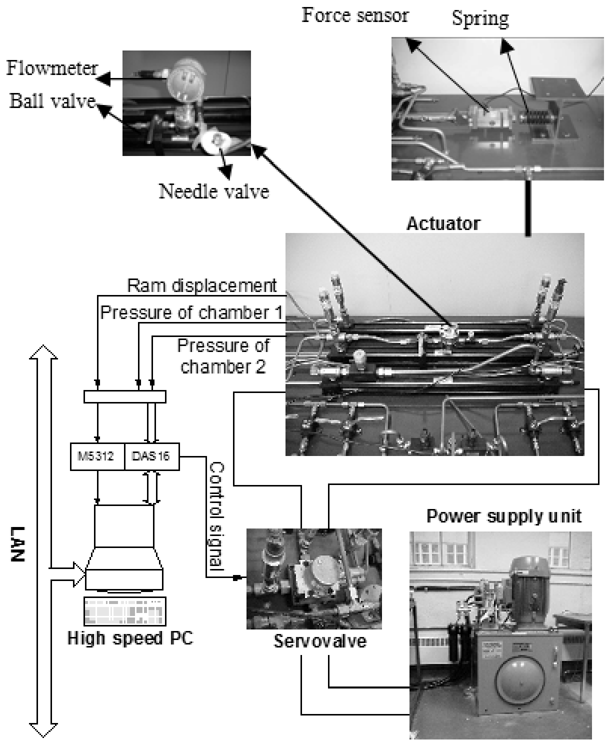

Fig. 1: *Test rig upon which all experiments are carried out*

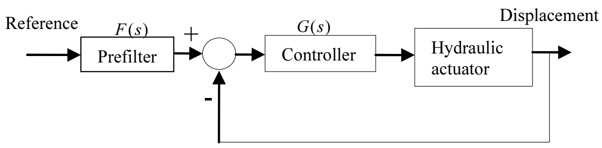

Fig. 2: *Block diagram showing controller and prefilter*

The second controller is also a QFT-based controller with an additional characteristic of holding a desirable performance even in the presence of an internal leakage fault up to 40 % of the rated servovalve flow across the actuator piston. The structure of this controller, hereafter called 'fault tolerant controller,' is shown below:

$$G(s) = \frac{246.59s^3 + 7.18\times10^3 s^2 + 4.78\times10^7 s + 5.49\times10^8}{s^3 + 420s^2 + 9\times10^4 s} \tag{3}$$

$$F(s) = \frac{22.04s + 297.5}{s^2 + 43.5s + 297.5} \tag{4}$$

The detailed derivation of the QFT controllers has been reported elsewhere (Karpenko and Sepehri, 2005; Karpenko, 2008).

3 Wavelet Transform

The wavelet transform (WT) is a powerful signal processing tool that decomposes a nonstationary signal into scales (also known as levels) with different time and frequency resolution. A wavelet is an oscillatory waveform of effectively limited duration and has an average value of zero. As opposed to Fourier analysis that breaks up a signal into sine waves of different frequencies, wavelet analysis breaks up a signal into shifted and scaled versions of the original (mother) wavelet. Fig. 3 shows a typical mother wavelet.

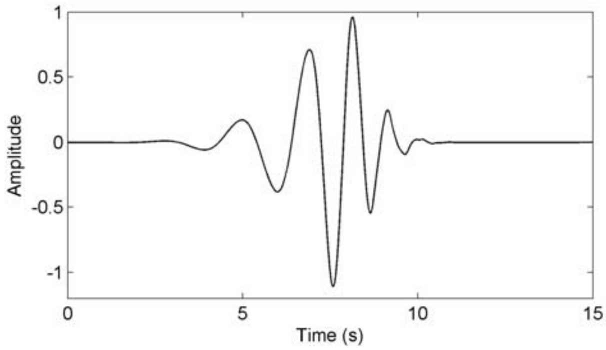

Fig. 3: *Daubechies mother wavelet*

For nonstationary signals, the Fourier analysis transforms the signal into the frequency domain and the time information gets lost. This deficiency of the Fourier analysis can be removed to some extent by analyzing a small section of the signal at a time — a technique called windowing. It, however, has the drawback in that the size of the time-window is the same for all frequencies. Wavelet analysis, on the other hand, allows a time-windowing technique with variable-sized regions, i.e., using long time intervals when more precise low-frequency information are required, and shorter regions when high-frequency information are required. The detailed descriptions of wavelet transform can be found in references (Daubechies, 1992; Vetterli and Herley, 1992). A brief overview of wavelet transform is provided here.

3.1 Continuous Wavelet Transform

The continuous wavelet transform (CWT) of signal $x(t)$ is defined as:

$$CWT(a,b) = \int_{-\infty}^{+\infty} x(t)\psi_{\mathrm{a,b}}(t)dt \tag{5}$$

where

$$\psi_{\mathrm{a,b}}(t) = |a|^{-1/2}\psi\left(\frac{t-b}{a}\right) \tag{6}$$

The mother wavelet $\psi(t) \in L_2(R)$ can be a complex-valued function. The parameters $a,b \in R$ are the 'scaling' and 'shifting' parameters, respectively. $|a|^{-1/2}$ is the normalized value of $\psi_{\mathrm{a,b}}(t)$ that ensures $\|\psi_{\mathrm{a,b}}(t)\| = \|\psi(t)\|$. The Fourier transform of $\psi(t)$, $\Psi(\omega)$, satisfies the admissibility condition $\int_{-\infty}^{+\infty}\frac{|\Psi(\omega)|^2}{|\omega|}d\omega < \infty$, which implies that the mean value of $\psi(t)$ is zero and $\Psi(0) = 0$. Since the spectrum of $\psi(t)$ decays at high frequencies, the wavelet exhibits a bandpass behavior.

3.2 Discrete Wavelet Transform

Instead of continuous scaling and shifting, the mother wavelet may be scaled and shifted discretely by choosing $a = a_0^{\mathrm{m}}$ and $b = na_0^{\mathrm{m}}b_0$ in Eq. 5 and 6 where $a_0 > 1$, $b_0 > 1$ and $m, n \in Z$. The discrete wavelet transform (DWT) is then defined as:

$$DWT(m,n) = \int_{-\infty}^{+\infty} x(t)\psi_{\mathrm{m,n}}(t)dt \tag{7}$$

where $\psi_{n,m}(t) = a_0^{-m/2}\psi(a_0^{-m}t - nb_0)$. By choosing $a_0 = 2$ and $b_0 = 1$, the family of scaled and shifted mother wavelets constitutes a dyadic orthonormal transformation. The implication of this transformation is that, due to the orthonormal properties, there will be no information redundancy among the decomposed signals. Also, with this choice of a_0 and b_0, there exists a well-known algorithm, known as 'multiresolution signal decomposition technique' (Mallat, 1989), which decomposes a signal into scales (levels) with different time and frequency resolutions.

3.3 Multiresolution Signal Decomposition and Quadrature Mirror Filter

Given a discrete-time original signal, $x[n]$, multiresolution signal decomposition (MSD) technique decomposes the signal in the form of WT coefficients at scale 1 into $a_1[n]$ and $d_1[n]$, where $a_1[n]$ is the approximate version of the original signal, and $d_1[n]$ is the detailed version of the original signal:

$$a_1[n] = \sum_{k=-\infty}^{+\infty} h[2n-k]x[k] \tag{8}$$

$$d_1[n] = \sum_{k=-\infty}^{+\infty} g[2n-k]x[k] \tag{9}$$

$h[..]$ and $g[..]$ are the impulse responses of low-pass and high-pass filters that decompose $x[n]$ into $a_1[n]$ and $d_1[n]$, respectively. Down-sampling is done in the process of decomposition so that the resulting $a_1[n]$ and $d_1[n]$ each has $n/2$ points. The next higher scale decomposition will be based on $a_1[n]$:

$$a_2[n] = \sum_{k=-\infty}^{+\infty} h[2n-k]a_1[k] \tag{10}$$

$$d_2[n] = \sum_{k=-\infty}^{+\infty} g[2n-k]a_1[k] \tag{11}$$

Thus, the decomposition process can be continued, with successive approximations being decomposed in turn, so that the original signal is broken down into many lower resolution components. This is called the wavelet decomposition tree (Mallat, 1998).

MSD is realized with the cascaded quadrature mirror filter (QMF) banks (Strang and Nguyen, 1996). A QMF pair consists of two finite impulse response filters, one being a low-pass filter (LPF) and the other a high-pass filter (HPF). The QMF pair divides the original signal into low-frequency and high-frequency components at the dividing point of halfway between 0 Hz and half the data sampling frequency. The output of the LPF is the approximation version of the input signal and is used as the next QMF pair's input. The output of the HPF is the detailed version of the original signal.

Figure 4 shows the wavelet decomposition tree using MSD technique and QMF pairs. After transforming the original signal into smoothed and detailed versions, wavelet transform approximate and detail coefficients, a_i and d_i (i being the scale or level) are obtained, in a general form, as:

$$a_i[n] = \sum_{k=-\infty}^{+\infty} h[2n-k]a_{i-1}[k] \tag{12}$$

$$d_i[n] = \sum_{k=-\infty}^{+\infty} g[2n-k]a_{i-1}[k] \tag{13}$$

where $i = 1, 2, \ldots, j$ and $a_0[k] = x[k]$.

4 On-Line Internal Leakage Detection

4.1 Preliminary Observation

The present work is built upon our initial study on applying wavelet transform to detect internal leakage for a hydraulic actuator (Goharrizi et al., 2009). In that work, a periodic step input signal was applied directly to the control valve to move the actuator back and forth for a certain period of time. The test was a simple off-line experiment; the control signal was applied to the actuator in an open-loop fashion; the actuator operated under no-load condition. The analysis was performed after all data were collected. Using a multiresolution signal decomposition technique, the pressure signal in one of the actuator's chamber was decomposed into detail wavelet coefficients. The level of decomposition needed is application specific, and is determined by the frequency bands that carry the signature signal (Gao and Zhang, 2006). Given a sampling rate of 500 Hz, level two detail wavelet coefficient of system's pressure was found to be adequate to observe the effect of internal leakage on pressure signal. Daubechies 8 wavelet (Daubechies, 1992) was found to be a good choice as the mother wavelet. The analysis was done on a program developed using MATLAB wavelet toolbox.

The present paper extends the previous study to include the more realistic case of the actuator following a pseudorandom reference positioning signal and under a load emulated by a spring. The pseudorandom signal is characterized with a series of desired step inputs having amplitudes between 0.025 m to 0.05 m and duration between 0.5 s to 4 s. This type of signal resembles activities of flaps for typical in-flight maneuvers (Nguyen, 1979), and thus allows us to investigate on-line fault detection ability of our method. All experiments are conducted with QFT-based controllers described by Eq. (1) to (4) and for very small leakages, since they are most interesting for early detection of faults.

The first experiment relates to the case, where a healthy actuator undergoes a set of positioning tasks against a spring having stiffness of 80 kN/m. The basic controller described by Eq. 1 and 2 is used for the control purpose. After 15 seconds of operation, an internal leakage having a mean value of ≈ 0.21 l/min is introduced. Assuming linear pressure dependence, this flow represents ≈ 0.12 l/min/MPa. The actuator displacement response is plotted in Fig. 5. Fig. 6 shows the plot of internal leakage.

With reference to Fig. 5, it is clearly seen that there is an error in system response after the occurrence of internal leakage since the controller, although designed to be robust to uncertainty of the parameters of the system, was not robust to the internal leakage. The cylinder pressures are plotted in Fig. 7. As was mentioned earlier, our approach for on-line internal leakage detection is based on studying level two detail coefficient, d_2, derived from the chamber one pressure signal, P_1 as shown in Fig. 8. Note that, one may equally choose the pressure signal in chamber two, P_2, for the analysis.

With reference to Fig. 7 and 8, internal leakage adds damping to the system which in turn, suppresses the transient pressure response. This in turn decreases the amplitude as well as the energy of the detail wavelet coefficient d_2 (defined as $\sum_{k=1}^{N} |d_2(k)|^2$, where N is the number of data samples), which is clearly seen from Fig. 8. Following this observation, design of the on-line leakage detection method is described.

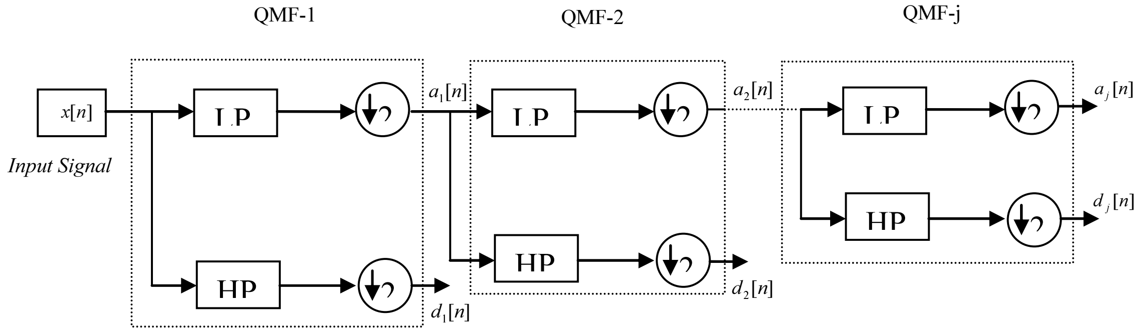

Fig. 4: *Multiresolution signal decomposition scheme*

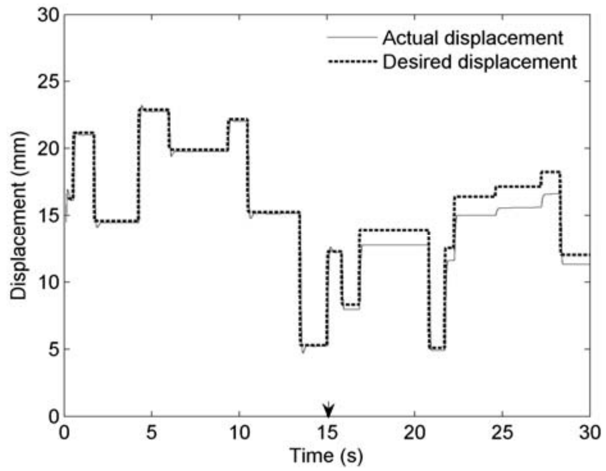

Fig. 5: *Desired and actual displacements of hydraulic actuator with internal leakage introduced at t ≈ 15 s*

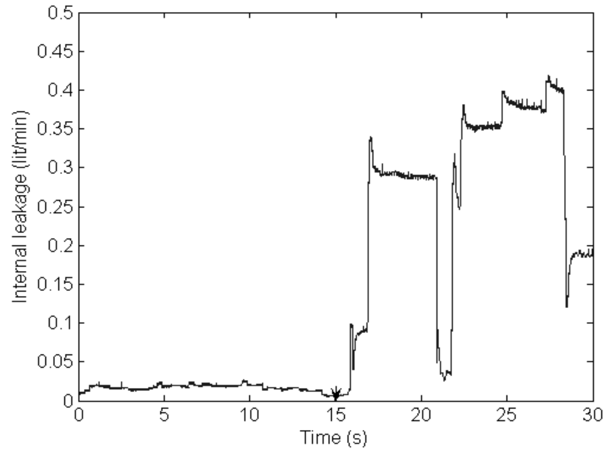

Fig. 6: *Internal leakage fault representing ≈ 0.12 l/min/MPa*

4.2 Design of On-line Detection

In an on-line equipment health monitoring, signals are monitored and gathered during the operation. The wavelet analysis breaks each limited-duration data sequence into packets containing only the signal components within certain frequency bands. Here, the sliding window technique by Zhao and Xu (2004) is adopted to form data segments.

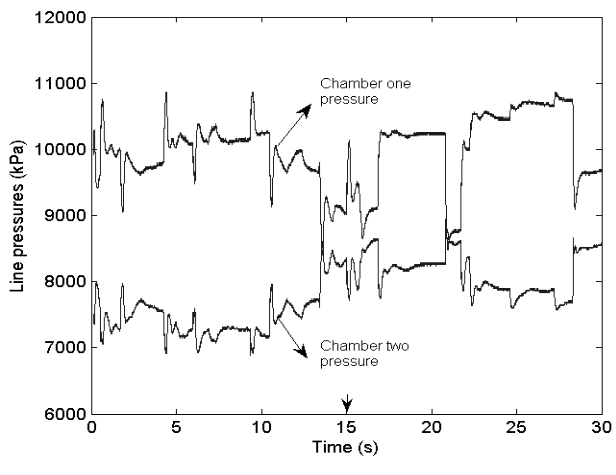

Fig. 7: *Pressures in chambers one and two with internal leakage introduced at t≈15 s*

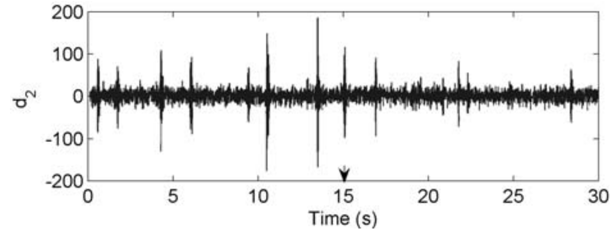

Fig. 8: *Level two wavelet coefficient of chamber one pressure with internal leakage introduced at t≈15 s*

With reference to Fig. 9, the data window has a length l_1. The past window contains data collected in the past and the current window which is the shift of the past window with a fixed step size l_2, contains data collected in recent time. Wavelet coefficients are repeatedly recalculated for intervals of l_2 samples, each based on the most recent l_1 samples of the signals. The root mean square (RMS) of the elements of vector of coefficients d_2 obtained from each window is then calculated as an index. Note that in order to extract reliable and complete information from the decomposed signals, each window should carry a sufficient length of data (Gao and Zhang, 2006). The length of the step size with respect to the window size should also be selected carefully. A small step size increases the computational cost and the nature of the windowed signal may not be sufficiently affected by the new data zone. A very large step size increases the detection delay as one needs to wait longer to update the relevant index. In this work, window size of l_1 = 400 samples and step size of l_2 = 20 samples were found to be appropriate. The measurement sampling rate was 500 Hz.

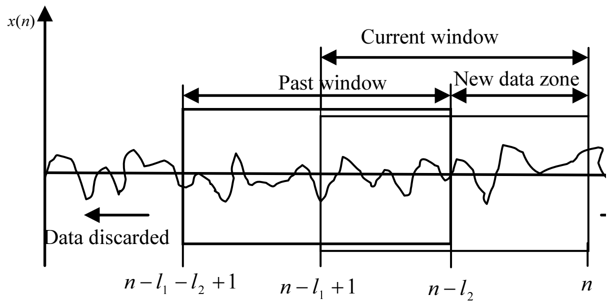

Fig. 9: *Sliding window technique*

The sliding window concept is now applied to the results of the case study reported earlier in this paper. The RMS values obtained from each updated window are plotted in Fig. 10. As is seen, the RMS decreases once the internal leakage is introduced to the system at t ≈ 15 s. Whereas d_2 in Fig. 8 was obtained using the entire data (gathered over 30 seconds), the plot shown in Fig. 10, is the result of information being processed online.

In order to show the robustness of this method to the type of controller, two more tests are conducted with a small internal leakage. For each test, the reference position signal is generated randomly, and the system runs for 600 s. A small internal leakage is then manually introduced at t ≈ 300 s. The test employs the basic control scheme described by Eq. 1 and 2.

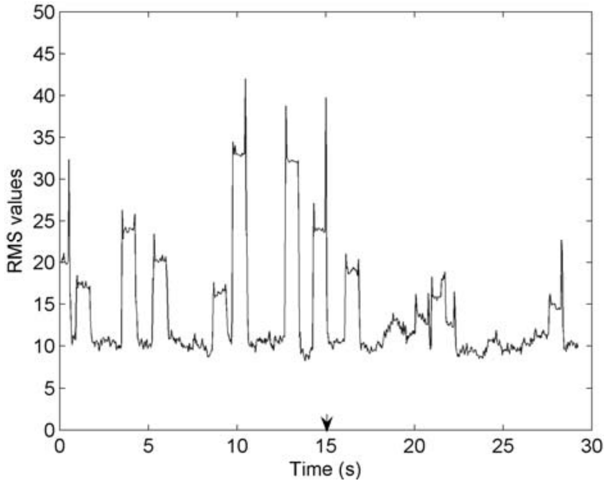

Fig. 10: *RMS of wavelet coefficient d_2 obtained from chamber one pressure with internal leakage occurred at $t \approx 15$ s*

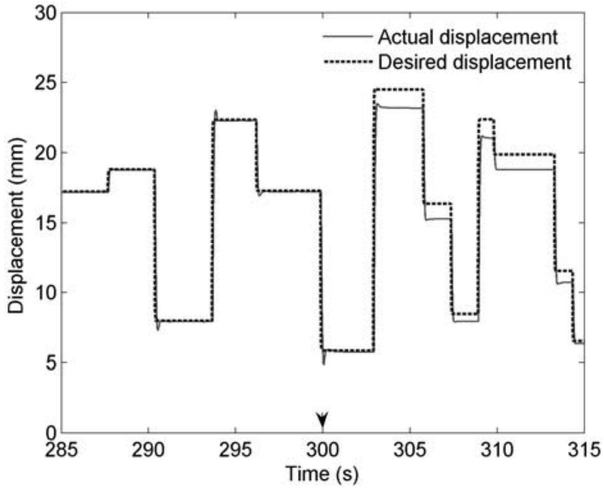

Fig. 11: *Close-up response of actuator with internal leakage introduced after t≈300 s. The 'basic control scheme' is used and the total test time is 600 s*

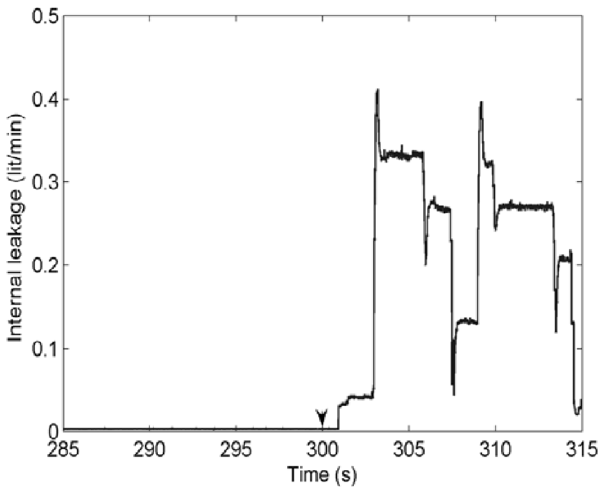

Fig. 12: *Close-up of internal leakage fault (mean value 0.25 l/min representing ≈ 0.13 l/min/MPa)*

Figures 11 and 12 show the close-up plots of displacement response of the control system and the leakage, respectively. Fig. 13 shows the RMS values of level two detail coefficients of chamber one pressure signal obtained using the sliding window technique. As one can see, the RMS values decrease after the introduction of internal leakage. To facilitate the comparison between healthy and faulty zones, a baseline value of 30 is chosen for the RMS values. It is seen that with the introduction of internal leakage the RMS values stay below the baseline close to 90 % of the time.

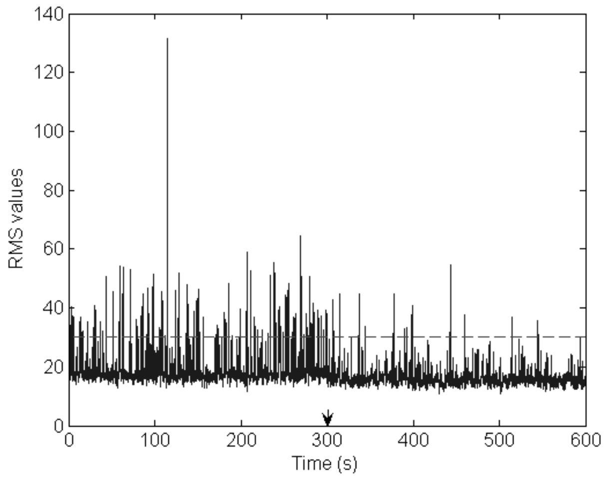

Fig. 13: *RMS values of wavelet coefficient d_2 pertaining to the experiment shown in Fig. 11 and 12*

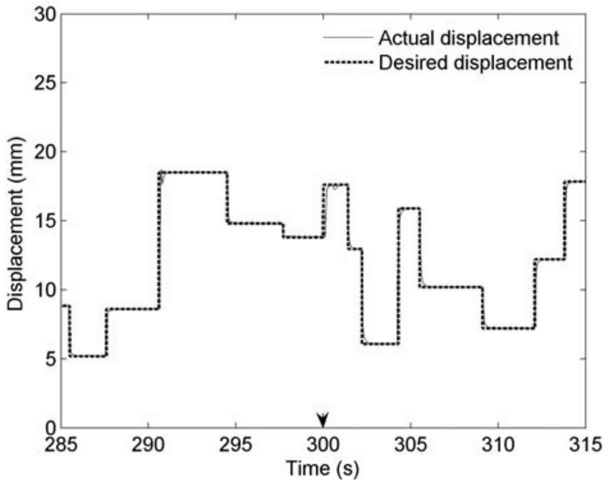

Fig. 14: *Close-up response of actuator with internal leakage introduced after t ≈ 300 s. The 'fault tolerant control scheme' is used and the total test time is 600 s*

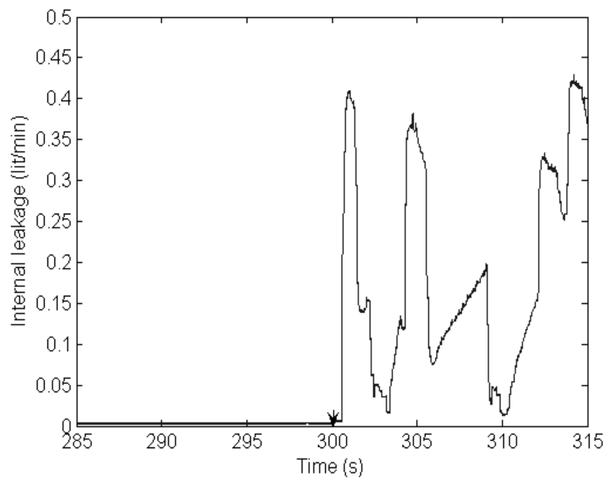

Fig. 15: *Close-up of internal leakage fault (mean value 0.23 l/min, representing ≈ 0.149 l/min/MPa)*

The final test shows that this method is sensitive to detect small amount of internal leakage even when the controller is capable to fulfill the commands. The 'fault tolerant controller' described by Eq. 3 and 4 is implemented. The close-up plots of displacement and the leakage fault are shown in Fig. 14 and 15, respectively. As one can see the controller works well even after the introduction of internal leakage after t ≈ 300 s, and there is no apparent steady-state error in the position response. This is due to the fact that the controller was designed to be robust to internal leakage.

By studying the pattern of changes in the RMS of the detail coefficients, d_2 (see Fig. 16) one can recognize the occurrence of an internal leakage after t ≈ 300 s. Given the same baseline value as in Fig. 13, one can see substantial decrease in RMS values after the occurrence of internal leakage. Thus, it is concluded that the method remains effective even with a fault tolerant controller, which maintains the positioning of the leaky actuator.

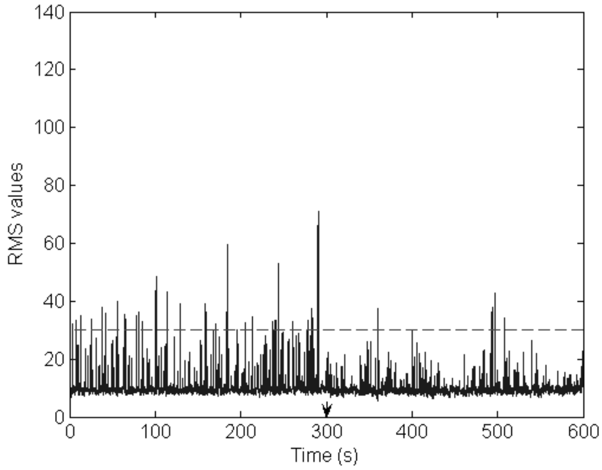

Fig. 16: *RMS values of wavelet coefficient, d_2, pertaining to experiment shown in Fig. 14 and 15*

5 Conclusions

An approach based on wavelet transform technique was developed for detecting internal leakage in hydraulic actuators. The proposed scheme is the extension of the previously developed method by the authors to make it implementable for on-line diagnosis. Whereas in the earlier work, the actuator was to be tested under no-load condition and given a predefined input signal, the present method allows information to be gathered while the actuator is controlled to perform arbitrary tracking, and under loading condition. Measurement of pressure signal at one side of the actuator is the only requirement in this method. Using a sliding window technique, limited-duration segments of measured pressure signal are collected. Each segment is then decomposed via a wavelet transform. RMS values of level two detail coefficients of the decomposed signals pertaining to each segment are analyzed to detect the occurrence of fault. It was shown that the RMS values of level two detail coefficients obtained in this manner, are sensitive to the internal leakage and can be used to distinguish between healthy and faulty conditions. When a leakage happens, the RMS values decrease in both magnitude and energy. Experimental results demonstrated the efficacy of the proposed technique. In the experimental setup, the actuator was set to track pseudorandom reference positions over a long period of time and against a load emulated by a spring. Using this technique, internal leakages in the range of 0.2 to 0.25 l/min, were detected regardless of the type of feedback controller used, reference input and loading condition.

Nomenclature

$x(t)$	Signal at time t	
$\psi(t)$	Mother wavelet	
$h[..]$	Impulse response of low-pass filter	
$g[..]$	Impulse response of high-pass filter	
a_i	Approximate wavelet coefficient at level i	
d_i	Detail wavelet coefficient at level i	
l_1	Window size	
l_2	Step size	
P_1, P_2	Pressures in chamber one and two	kPa

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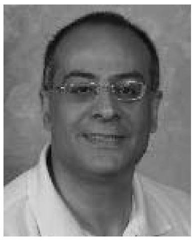

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