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Simulation Analysis of Wiener and Low-Pass Filtration in EHS

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***Abstract*— In electro-hydraulic systems (EHS), when using tach generator feedback, we have high-frequency noise due to various sources. Precise control of the speed of the actuator is necessary because the tachometer signal is crucial for closed-loop control. Therefore, accurate measurements are essential. In this paper, an analysis of Wiener filter and low-pass filters used in an electro-hydraulic system with feedback from the speed of the actuator (hydraulic motor) is made.**

Keywords— Electro-hydraulic systems, Wiener filter, low-pass filters.

I. INTRODUCTION

Electro-hydraulic systems are used in numerous applications and industries due to their efficiency and power. Electro-hydraulic systems provide precision and speed in production in automated assembly lines, aircraft control, robotic surgical systems, wind turbine control systems such as hydraulic blade adjustment mechanisms and many other areas of application [1, 5, 6, 7, 8, 9].

White noise in sensor feedback can cause various problems in the control and regulation of the electro-hydraulic system, and can blur the actual speed values, leading to inaccurate measurements and less precision in system control [2, 3, 4, 20, 23, 24, 25].

Unwanted fluctuations in the control signal may occur, which can lead to system instability and uneven operation. Due to noise, the controller may react incorrectly to changes in feedback, resulting in a delay in response or over-regulation [15, 16, 17].

In systems with adaptive control [10, 11, 12, 22], noise can make it difficult for the controller to learn, resulting in inefficient adaptation to changes in operating conditions. Instability and fluctuations caused by noise can lead to increased wear on hydraulic components, which reduces their lifespan. The overall efficiency of the system may decrease because the controller cannot optimize operation due to incorrect measurements. Finally, poor system regulation caused by noise can lead to an increase in energy consumption, which is economically inefficient.

In conclusion, this can significantly affect the performance and reliability of an electro-hydraulic system [18, 19, 21], highlighting the importance of filtering and signal processing.

II. MATERIALS AND METHODS

A. Description of the electro-hydraulic system

Fig. 1 shows an electro-hydraulic system with hydraulic motor speed control via a pulse width modulator (PWM), consisting of: 1 – PWM, 2 – DC Motor, 3 – Pump, 4 – tach generator, 5 – hydraulic motor and 6 – PID Regulator.

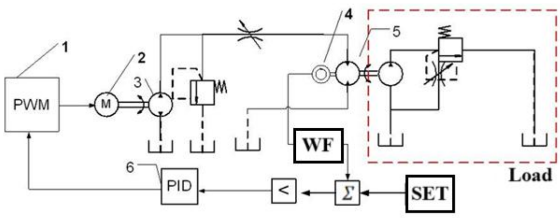

Fig. 1. Frequency response of the Butterworth filter for different filter orders.

The speed of the hydraulic motor is adjusted by PWM via the signal received from the feedback sensor /tach generator/, where the signals from the developed control optimization filter are transmitted and enters the summing device. Then is compared with the signal from the setting device and is processed by the PID regulator.

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B. Filter comparision

A Wiener filter (WF) is a complex statistical filter that aims to optimally reconstruct a signal from noisy data, while a low-pass filter (L-PF) is a simpler filter that removes high-pass components, often used to smooth out or reduce noise.

TABLE 1 FILTER COMPARISION

Feature	Wiener Filter	Low-Pass Filter
Goal	To optimally estimate an unknown signal from noisy observations.	To attenuate high-frequency components in a signal
Approach	Based on statistical principles, minimizing the mean square error between the estimated and desired signals.	Based on frequency response, attenuating frequencies above a cutoff frequency.
Design	Requires knowledge of the signal and noise power spectra	Primarily determined by the cutoff frequency
Adaptivity	Can adapt to changes in signal and noise characteristics	Fixed unless the cutoff frequency is adjusted
Performance	Can achieve optimal performance in the mean square error sense	Performance depends on the choice of cutoff frequency and the nature of the signal and noise.

It would be good to use WF when optimal signal estimation is crucial, and knowledge of signal and noise statistics is available.

On the other hand, when a simpler approach is sufficient and the main goal is to eliminate high-frequency noise, L-PF are recommended.

In an electro-hydraulic tachometer feedback system, we have high-frequency noise that can come from various sources such as:

a) Tachometer noise: Electronic noise, mechanical vibrations, etc.

b) Hydraulic system noise: Pressure fluctuations, valve switching noise, etc.

c) Environmental noise: Electromagnetic interference, etc.

Precise speed control is required in closed-loop driving, so accurate measurements are essential.

Low pass filter advantages are: Simple, computationally inexpensive, effective in silencing high-frequency noise.

Disadvantages: It can lead to phase shift and slowdown, potentially affecting the stability or performance of the system.

Wiener filter advantages is: Optimally minimizes the mean square error, can adapt to changing noise characteristics.

Disadvantages: Requires knowledge of signal and noise statistics, can be computationally more complex.

For most practical electro-hydraulic systems, a well-designed low-pass filter is often sufficient for easier implementation and adjustment.

It can effectively reduce noise while maintaining reasonable system response. The reduced computational burden has fewer requirements on the control system.

let us look at the following factors in which the Wiener Filter is preferable:

a) Noise characteristics: If the noise is strongly connected or stationary, the Wiener filter can offer better performance.

b) System complexity: If computing resources are plentiful and noise is a significant problem.

C. Principle of operation of the Low-pass filters

a)Butterworth filter

A Butterworth filter is a type of signal processing filter designed to have the flattest frequency response in the passband. It is also known as a maximum amplitude flat filter. It was invented in 1930 by British engineer and physicist Stephen Butterworth in his paper "On the Theory of Filter Amplifiers".

The main characteristic of a Butterworth filter is that it provides a flat frequency response up to a cutoff frequency, after which this response begins to decline. The cutoff frequency is the point at which the signal amplitude decreases by 3 dB. Butterworth filters can be designed with different orders, with higher orders providing a steeper decrease in the frequency response after the cutoff frequency.

Butterworth filters are preferred when it is necessary to provide a smooth frequency response without ripples in the passband.

In design, we aim for a response close to the ideal filter. Finding the exact ideal characteristics is a challenge that requires complex higher-order filters.

If we increase the order of the filter, the number of cascaded stages with the filter also increases. But in practice, we cannot achieve the ideal Butterworth frequency response. Because it produces excessive ripples in the passband.

The Butterworth filter provides a mathematically flat frequency response up to the -3dB cutoff frequency without any ripples. Frequencies above this limit will roll off at a rate of -20 dB in a first-order filter.

If you increase the order of the filter, the rate of roll-off period also increases. And for the second order it is -40 dB. The quality factor for the Butterworth filter is 0.707.

The fig.2 below shows the frequency response of the Butterworth filter for different filter orders.

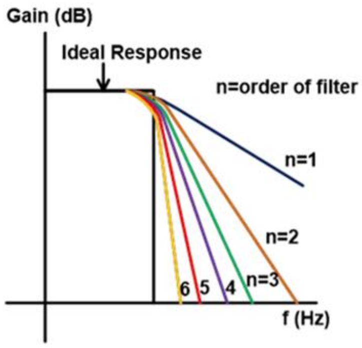

Fig. 2. Frequency response of the Butterworth filter for different filter orders.

The generalized form of frequency response for nth-order Butterworth low-pass filter is:

$$H(j\omega) = \frac{1}{\sqrt{1+\varepsilon^2\left(\frac{\omega}{\omega_C}\right)^{2n}}}, \quad (1)$$

where: n- order of the filter, ω- operating frequency (passband frequency) of circuit,
ω_C- cut-off frequency, ε- maximum passband gain = A_{max}.

The below equation is used to find the value of ε.

$$H_1 = \frac{H_0}{\sqrt{1+\varepsilon^2}}, \quad (2)$$

where: H_1 – minimum passband gains and H_0 – maximum passband gain.

b) Savitzky-Golay filter

The Savitzky-Golay filter (S-GF) is a digital filter used to smooth data while preserving important signal features, such as peaks and valleys. It was developed by Abraham Savitzky and Marcel Golay in 1964 and is also known as the polynomial smoothing filter.

The basic idea of the S-GF is to apply a polynomial fit to subsets of adjacent data points using the linear least squares method. This is achieved by convolution, using convolution coefficients that are applied to all subsets of the data to obtain estimates of the smoothed signal.

The S-GF is particularly useful in data processing where it is important to preserve the high-frequency components of the signal while reducing noise. It is used where it is necessary to smooth data without significant loss of information.

Savitzky-Golay smoothing filters tend to filter out less of the signal's high-frequency content than standard averaging FIR filters. However, they are less successful at rejecting noise when noise levels are particularly high.

In general, filtering consists of replacing each point of a signal by some combination of the signal values contained in a moving window centered at the point, on the assumption that nearby points measure the same underlying value. For example, moving average filters replace each data point with the local average of the surrounding data points. If a given data point has k points to the left and k points to the right, for a total window length of L = 2k + 1, the moving average filter makes the replacement

$$x_s \rightarrow \hat{x_s} = \frac{1}{L}\sum_{r=-k}^{k} x_s + r, \quad (3)$$

S-GF generalize this idea by least-squares fitting an nth-order polynomial through the signal values in the window and taking the calculated crucial point of the fitted polynomial curve as the new smoothed data point. For a given point, x_s

$$\begin{bmatrix} x_{s-k} \\ \vdots \\ x_{s-1} \\ x_s \\ x_{s+1} \\ \vdots \\ x_{s+k} \end{bmatrix} =$$

$$\begin{bmatrix} b_0 + b_1(t_s - k\Delta t) + b_2(t_s - k\Delta t)^2 + \cdots + b_n(t_s - k\Delta t)^n \\ \vdots \\ b_0 + b_1(t_s - 1\Delta t) + b_2(t_s - 1\Delta t)^2 + \cdots + b_n(t_s - 1\Delta t)^n \\ b_0 + b_1(t_s - 0\Delta t) + b_2(t_s - 0\Delta t)^2 + \cdots + b_n(t_s - 0\Delta t)^n \\ b_0 + b_1(t_s + 1\Delta t) + b_2(t_s + 1\Delta t)^2 + \cdots + b_n(t_s + 1\Delta t)^n \\ \vdots \\ b_0 + b_1(t_s + k\Delta t) + b_2(t_s + k\Delta t)^2 + \cdots + b_n(t_s + k\Delta t)^n \end{bmatrix}$$

$$= \begin{bmatrix} a_0 + a_1(-k) + a_2(-k)^2 + \cdots + a_n(-k)^n \\ \vdots \\ a_0 + a_1(-1) + a_2(-1)^2 + \cdots + a_n(-1)^n \\ a_0 + a_1(-0) + a_2(-0)^2 + \cdots + a_n(-0)^n \\ a_0 + a_1(1) + a_2(1)^2 + \cdots + a_n(1)^n \\ \vdots \\ a_0 + a_1(k) + a_2(k)^2 + \cdots + a_n(k)^n \end{bmatrix}, \quad (4)$$

or, in terms of matrices,

$$x = \begin{bmatrix} 1 & -k & (-k)^2 & \cdots & (-k)^n \\ \vdots & \vdots & \vdots & ⋰ & \vdots \\ 1 & -2 & (-2)^2 & \cdots & (-2)^n \\ 1 & -1 & (-1)^2 & \cdots & (-1)^n \\ 1 & 0 & 0 & \cdots & 0 \\ 1 & 1 & 1^2 & \cdots & 1^n \\ 1 & 2 & 2^2 & \cdots & 2^n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & k & k^2 & \cdots & k^n \end{bmatrix} \begin{bmatrix} a_0 \\ \vdots \\ a_n \end{bmatrix} \equiv H_a. \quad (5)$$

To find the Savitzky-Golay estimates, use the pseudoinverse of H to compute a and then premultiply by H:

$$\hat{x} = H(H^T H)^{-1} H^T x = Bx. \quad (6)$$

To avoid ill-conditioning, “sgolay” uses the “qr” function to compute an economy-size decomposition of H as H = QR, in terms of which $B = QQ^T$.

It is necessary to compute B only once. The Savitzky-Golay estimates for most signal points result from convolving the signal with the center row of B. The result is the steady-state portion of the filtered signal. The first k rows of B yield the initial transient, and the final k rows of B yield the final transient.

c) Median filter

The main idea of the median filter (MF) is to run through the signal entry by entry, replacing each entry with the median of the entry and its neighboring entries. The idea is like a moving average filter, which replaces each entry with the arithmetic mean of the entry and its neighbors. The pattern of neighbors is called the "window", which slides, entry by entry, over the entire signal. For one-dimensional signals, the most obvious window is just the first few preceding and following entries, whereas for two-dimensional (or higher-dimensional) data, the window must include all entries within a given radius or ellipsoidal or rectangular region (i.e., the MF is not a separable filter).

Typically, by far most of the computational effort and time is spent on calculating the median of each window. Because the filter must process every entry in the signal, for large signals, the efficiency of this median calculation is a critical factor in determining how fast the algorithm can run. Furthermore, some types of signals use whole number representations: in these cases, histogram medians can be far more efficient because it is simple to update the histogram from window to window, and finding the median of a histogram is not particularly onerous.

D. Principle of operation of the Wiener filter

A Wiener filter is a signal processing method that is used to smooth out superimposed noise data and to optimally recover the original signal. It is suitable for stationary systems where noise and signal have certain statistical characteristics (average value and dispersion). The main purpose of the filter is to minimize the RMS error between the restored signal and the original one.

The formula for the Wiener filter depends on the noise covariance matrix and the signal covariance matrix. Assuming that σ^2 is the dispersion of noise and that R is the autocovariance matrix of the signal, it follows that.

$$W = R(R + \sigma^2 I)^{-1} \tag{7}$$

This matrix can be calculated if the exact statistical characteristics of the noise and signal are known. In practical terms, the calculation of W may require measurements or experimental data to accurately determine parameters. In case we want to include the specific noise from the sensors to measure the parameters of the electro-hydraulic system, we need to model these influences in the specific dynamic conditions of the measurement mode. The autocovariance matrix R It usually represents the internal dynamics of the signal, including the interactions between the different states of the system.

The Disturbance Matrix (noise) σ^2 defines the input noise uncertainty, which, in the case of optimization of electro-hydraulic systems, determines how noise affects the spectral components of the signal and how they are processed to minimize the rms error. This matrix is usually diagonal, with each diagonal field representing the dispersion of the corresponding noise signal. Estimates of states are calculated according to the formula:

$$\hat{x} = Wy \tag{8}$$

where $\hat{x}$ is the vector of the evaluated states.

E. Development of the Wiener filter design

Implementing a Wiener filter alongside a PID controller can effectively enhance signal processing and control system performance by reducing noise and improving signal estimation.

It was developed linear filter used in signal processing to minimize the mean square error between an estimated random process and the desired process. A control loop feedback mechanism that computes an error value based on the difference between a desired setpoint and a measured process variable.

To define the system model let assume we have a desired signal $s(t)$ that is corrupted by noise $n(t)$.
Then the observed signal $x(t)$ is:

$$x(t) = s(t) + n(t) \tag{9}$$

The purpose of the Wiener filter is to obtain an estimate of $s(t)$ from $x(t)$. The estimated value $\hat{s}(t)$ is.

$$\hat{s}(t) = H(f).x(t) \tag{10}$$

Here $H(f)$ is the transmission function of the Wiener filter, which is determined by the spectral properties of the signal and noise.

The Wiener filter minimizes the following function:

$$J = E\{(s(t) - \hat{s}(t))^2\} \tag{11}$$

where $E\{.\}$ is the operator of the mathematical expectation.

The goal is to design a filter $H(f)$ that minimizes the mean square error. The transmission function of the Wiener filter in the frequency space is given by:

$$H(f) = \frac{S_s(f)}{S_s(f)+S_n(f)} \tag{12}$$

where $S_s(f)$ is the spectral density of the signal and $S_n(f)$ is the spectral density of noise.

In the simulation, the Wiener filter is implemented by an FIR (Finite Impulse Response) filter that approximates the desired transmission function $H(f)$. In the MATLAB the fir1 function generates an FIR filter that can be set to a certain frequency limit (in this simulation, 0.3 is set).

After filtration (fig.3), the output of the Wiener filter (the filtered signal) is fed to the PID regulator, which controls the system based on the values obtained. The mathematical model of the PID regulator is:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (13)$$

where $e(t)$ is the error between the set value and the actual value, $u(t)$ is the output of the PID regulator.

III. Results and Discussion

To simulate the ongoing processes in the system, the software product Matlab Simulink, Sim hydraulic, Sim Electronic is used.

In Fig.3. shows the signal from the tach generator and the transients of the change in the speed of the hydraulic motor at different through sections of the load throttle valve. The red curve shows the signal filtered by the Wiener filter.

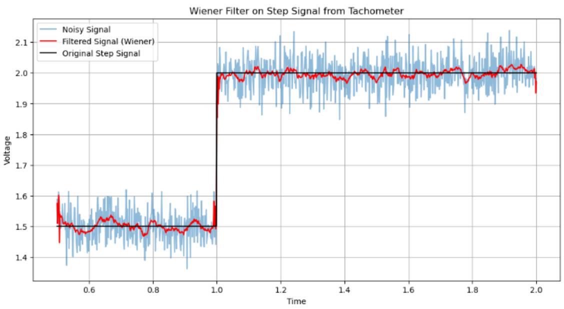

Fig. 3. Signal from the tach generator and the transients of the change in the speed of the hydraulic motor at different through sections of the load throttle valve.

The developed simulation model makes it possible to study the dynamic characteristics of an electro-hydraulic drive system with rotary movement of the actuator. Transients obtained under different loads and input signals allow to analyze the behavior of the system and evaluate the influence of different parameters of setting the analyzed types of filters.

When using a Wiener (see fig.4) filter with an appropriate setting, a significant reduction in the identified error in the system is achieved and the quality of the transient process is improved.

The use of hydraulic and electro-hydraulic systems to drive several machines and assemblies in the industry places different demands on the quality of work and the accuracy of work in static and dynamic modes.

As a result of the simulations and analysis of the electro-hydraulic speed control system of a hydro motor, it can be concluded that the error is greater between the set value and the actual value of the signal from the speed sensor in the low-pass filters compared to the Wiener filter under the same conditions. As can be seen in Fig.4. With the reduction of the load (opening the load throttle) in the first minute of the simulation, the speed response from the tach generator changes ramp wise.

DC motors can be used in a variety of applications in a wide range of prices and sizes. Therefore, the PWM control system of the DC motor driving an unregulated pump is energy efficient and cheaper to implement.

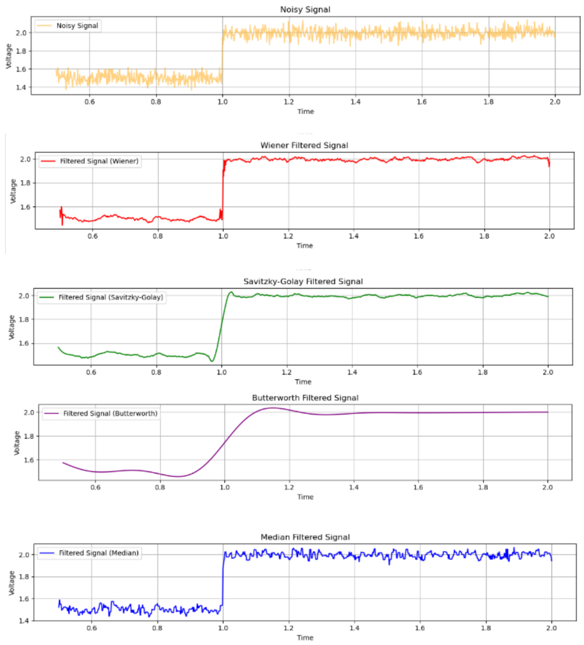

Fig. 4. Comparative presentation of simulated filter results.

The main reason for using pulse width modulation in DC motor regulation is to avoid excessive heat dissipation in linear amplifiers. The problem of dissipation often leads to high heat absorption, because of which forced cooling. PWM amplifiers can significantly reduce this problem because they have much higher power conversion efficiency. In addition, the input signal can be directly received from any digital system without the need for digital-to-analog converters.

IV. Conclusions

Evaluating the selected filter in a simulation environment can evaluate its performance under various conditions. Evaluating the filter on the actual system and fine-tuning the parameters based on observed performance reduces the time required to implement the system, as potential problems can be identified and resolved.

Simulation and analysis of several types of filters for processing signals with sensor noise in electro-hydraulic systems provide significant benefits, including system optimization, increased reliability, improved signal quality, flexibility, and ease of implementation. These benefits lead to more efficient and reliable systems that can meet the specific requirements of different applications.

The main advantage of the Wiener filter over low-pass filters is its ability to optimize the signal-to-noise ratio (SNR). While low-pass filters reduce the high-frequency components of a signal, they can also reduce useful information and introduce distortion. The Wiener filter, on the other hand, uses the statistical properties of the signal and noise to minimize the mean square error between the filtered and the original signal.

In this way, the Wiener filter can better restore the original signal and preserve the useful information, while reducing noise. This makes it more effective in situations where preserving signal quality is important.

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