Wavelet Based Approach for Sensor Validation

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Abstract - The objective of this paper is to study the wavelet based approach for sensor validation. Earlier the sensors were viewed as simple signal generators and were also assumed that the data generated by the sensors were correct. But with the emergence of the concept of smart sensors, the sensor architecture has been changed. Recent research importance on intelligent sensor is given on assessing the quality of the sensor signal [1]. The signal generator methods are no longer acceptable. As a matter of fact there has been a trend to design sensor validation algorithm for a wide range of sensors. In spectral analysis method by tracking the amplitude and frequency distribution of measured signals and by comparing these with the characteristic of healthy system’s signals one can detect the fault(s). Spectral analysis is done with the help of mathematical tools such as Fourier transform and wavelet transform [2]. Moreover, Wavelet analysis is a rapid growing tool having many applications [3].

Keywords - Intelligent sensor, validation algorithm, spectral analysis, wavelet transform, Fourier transform, short time Fourier transform, self diagnostics, AI, ANN, FL ANN, VLSI etc.

I. INTRODUCTION

In mechatronics systems, any kind of malfunction is understood as a fault that leads to an unacceptable anomaly in the overall systems performance [4]. Attention has to be paid to this problem in order to meet the demand for safety, reliability, and availability. The qualitative and quantitative indices of reliability have been studied and reported. Reliability is defined as the probability of a system or component to perform a required function under specified conditions for a certain period of time and availability refers to accessibility of the system/component during the acceptance period. As such quantitatively, it is defined as operational use hours of the system/component minus equipment failure down time divided by the operational use hours. Faults may occur in sensors and/or actuators [5]. Such issues are more often not considered in the design and use of traditional mechatronic systems. The development of methods which contribute to the provision of fault diagnosis and fault tolerance is strongly advocated as an essential requirement.

The operator based procedures for such a system are not suitable. Intelligent or smart control systems are those in which, the processing power is incorporated at the device level and soft computing based diagnostic capabilities are built into the devices to improve the overall performance [6]. For more automated application it is thus good to have self-diagnostic devices. In fact, for total automation self-diagnostics of the device is very much essential. Self-diagnostics is a process of assessing the performance of the device with regard to any abnormal situation such as unscheduled shutdowns. Thus, the plant efficiency and the availability of the plant improve and for the same a versatile automatic self diagnostics scheme is needed. Soft computing method uses Artificial Intelligence (AI) tools and techniques such as Artificial Neural Network (ANN) [7], Fuzzy logic (FL) [8], evolutionary algorithms like GA (Genetic Algorithm) [9], and AIN (Artificial Immune Network) [10]. In mechatronics, mainly two types of devices are used. They are sensors and actuators.

The diagnostics has become a fundamental requirement within the machine control systems due to the need for high productivity and less down-time. The theoretical base for FDI has long been discussed in technical journals and conferences [11-15]. The faults must be isolated in a predefined time. As machinery becomes more complex and more costly to build and maintain, preventive maintenance measures become increasingly important. There is currently a great need
for equipment to automatically predict, detect, and diagnose faults in even smaller machine systems including MEMS (Microelectromechanical Systems) devices [16]. Devices such as sensors, actuators, valves, and switches are considered as the integral parts of the mechatronic systems. It is important to note that these devices can be considered as intelligent if and only if they accommodate diagnostic features along with the required control functions [17].

Let us take an example of a sensor used as a feedback device in a mechatronic system. In this context, until recent time, the only continuous contact between the sensor measurement and the control system has been the unidirectional flow of measurement data [18]. It is understandable that a sensor employed in such a system has been viewed, from the control point of view, as a simple signal producer and that its value is assumed to be ‘ideal’. However, this conservative approach may not be acceptable because the control (in assumed to be ‘ideal’. However, this conservative view, as a simple signal producer and that its value is a system has been viewed, from the control point of context, until recent time, the only continuous contact feedback device in a mechatronic system. In this

II. SPECTRAL ANALYSIS METHOD

Arguably, spectral analysis is considered to be a model-free technique. The scheme is employed in systems where process measurands have a typical frequency spectrum in normal operating modes. In many cases, the spectrum changes when faults occur. An abnormality on the spectrum would indicate failure symptoms (Fig.2). The characteristic signature in the spectrum is used for failure isolation. System spectra of both normal and that of faulty one are compared and abnormality is recognized. Ying et al. proposed a method to analyse the noise using spectral technique. The noise power at various frequency bands present in the sensor output are calculated using power spectral density estimation and then compared with the historically established noise pattern to identify the faults [20]. Spectrum analysis schemes have been employed based on Fourier Transforms (FT) and STFT (Short Time Fourier Transform). The expression for Fourier transform is stated below.

\[ V(f) \Leftrightarrow \int_{-\infty}^{\infty} v(t)e^{-2\pi ift} dt \]  \[1\]

Where, \(v(t)\) is the time domain signal. \(V(f)\) is its Fourier Transform, a signal in frequency domain. Note that \(V(f)\) is a complex signal. The symbol \(\Leftrightarrow\) implies, there exist inverse Fourier Transform of \(V(f)\) which is simply \(v(t)\). Mathematically, the STFT of the time domain signal, \(v(t)\) is expressed as in Eq.2.4.

\[ STFT(t, f) = \int_{-\infty}^{\infty} v(t)w^{*}(t-t')e^{-j2\pi ft} dt \]  \[2\]

Where, \(v(t)\) is the time domain signal, \(w^{*}\) is the conjugate of the fixed window function.

Especially, in rotating machinery the vibrations are considered to be harmonics of the rotation frequency. FT and STFT can provide a fast estimate of the spectrum. Parametric spectral analysis techniques are also used for estimation of spectrum. As reported, the problems in frequency domain analysis of fault detection, on the other hand, are to distinguish sensor failure from the legitimate sensor output, which is composed of the unknown signal and the stochastic measurement noise. The scheme is also costly as the signal processing is always in frequency domain.

Haloui et al. have presented research work on the fault diagnosis of a gear reducter made up of two-toothed wheels operating at constant condition. They
have showed that the fault diagnosis of the gear system can be performed by observing the evolution of the power spectrum of the vibration signal during the observation days of the gear system [21].

The problem with FT and STFT is that they use a single analysis window. On the other hand, the Wavelet Transform (WT) uses scale parameters (s), in order to have short windows at high frequencies and long windows at low frequencies. For this reason, WT based signal analysis is referred to as multiresolution decomposition technique. The existence of scaling parameter in WT enables to achieve constant relative bandwidth frequency. The STFT is a linear process and the WT is logarithmic in nature. Signals with sharp changes might be better analysed with an irregular wavelet than with a smooth sinusoid. In wavelet analysis, signals are represented by using a set of basic functions. These are derived from a single prototype function called the mother wavelet. This can also be stated that basic functions are formed by shifting and scaling the mother wavelet in time. So wavelet transform is viewed as a decomposition of signal in time frequency (scale) plane. In other words, the wavelet transform indicates the degree of similarity between the signal and a basic function (i.e., mother wavelet) and is achieved by dilating the mother wavelet and translating it over the signal. Thus, wavelet transform maps one dimension time domain signal to a 2-dimensional function of time and frequency (scale). The scale is related to frequency. The 3-dimensional plot gives an indication as to which frequency components are present at what times. The timescale diagram is called Scalogram [22]. If there is any fault in the signal then it will affect the scalogram plot and there will be a change in magnitude in the Scalogram. Therefore, by observing the change in magnitude in the scalogram plot the fault can be detected.

III. MULTiresolution SIGNAL DECOMPOSITION

Much research is going on wavelet decomposition techniques for signal processing and analysis and interest in this area is increasing steadily for a wide range of applications [23-28]. The multiresolution signal decomposition technique consists of two stages i.e the analysis and synthesis operations, which are shown in Fig.3.

The analysis process is used to decompose the signal. Here we concerned with the sensor signal which is random and non stationary. The synthesis or reconstruction process is used to enable the decomposed components to be assembled back into the original signal without loss of information. The analysis process involves filtering and down sampling. The reconstruction process consists of up sampling and filtering. The low pass (LPF) and high pass (HPF) decomposition filters together with their associated reconstruction filters form a system of quadrature mirror filters. In wavelet analysis when we decompose a signal, we will get approximations and details. The approximations are the high scale, low frequency components of the signal. The details are the low scale, high frequency components of the signal.
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The companion function of the wavelet function \( \Psi(t) \), satisfies the dilation equation given by [24]:

\[
\Phi(t) = \sqrt{2} \sum_k h_k \Phi(2t - k) \tag{3}
\]

Where, \( h_k \) is a called scaling function coefficient.

The scaling function coefficient \( h_k \) is given by

\[
h_k = \sqrt{2} \int_{-\infty}^{\infty} \Phi(t) \cdot \Phi(2t - k) dt \tag{4}
\]

The wavelets may be computed from the respective scaling functions by using the wavelet equation given by [25]

\[
\Psi(t) = \sqrt{2} \sum_k g_k \Phi(2t - k) \tag{5}
\]

The coefficient \( g_k \) is given by

\[
g_k = \sqrt{2} \int_{-\infty}^{\infty} \Psi(t) \cdot \Phi(2t - k) dt \tag{6}
\]

The scaling function \( \Phi(t) \) generates all the basis functions of the approximation space. The orthonormal basis is given by the equation

\[
\Phi_{j,k}(t) = 2^{j/2} \Phi(2^j t - k) \tag{7}
\]

For multiresolution analysis, the detail space has an orthonormal basis \( \Psi_{j,k}(t) \) given by the equation

\[
\Psi_{j,k}(t) = 2^{j/2} \Psi(2^j t - k) \tag{8}
\]

The orthonormal basis \( \Psi_{j,k}(t) \) is called the wavelet basis.

The coefficients \( \{ g_k \} \) in the wavelet equation are related to the coefficients \( \{ h_k \} \) in the dilation equation by

\[
g_k = (-1)^k h_{-k} \tag{9}
\]

In the wavelet analysis \( \{ h_k \} \) behaves as low pass filter and \( \{ g_k \} \) behaves as high pass filters. In the above we have briefly discussed the orthonormal compactly supported wavelet bases. The detail description is given in [25]. Once the coefficients are computed they can be plotted in 3D space: scale (time), frequency, and amplitude [26-28].

Without loss of generality, the term VA and FDI algorithm will be used interchangeably. One can note that the current research activities in smart sensor design use the term sensor validation rather than FDI. In order to observe Validation Modes (SVM) following attempt were made. For the observation of: SVM-1 mode, a step signal was superimposed with the output of the sensor; SVM-2 mode, the sensor output was held constant for a time which is greater than T; SVM-3 mode, a signal of significant value as compared to sensor signal was superimposed with the output of the sensor; SVM-4 mode, the sensor signals were changed so as to enable output of the sensor signal to reach above and below the threshold values cyclically; SVM-5 mode, a continuously increasing signal was superimposed with the sensor signal.

IV. RESULTS

Fig.4 (a) shows the output of the sensor signal, which is random and non-stationary in nature. The signal was generated by a temperature sensor. The sensor is interfaced with the DSP input/output board. The above signal seems to be free from faults. It may be noted that we have not considered the effect of noise. It was assumed that the power spectral density (usually it is expressed in terms of \( \eta^2 \)). More detail analysis on white noise can be found in any standard book on Principles of communication) of noise is white. Fig.4 (b) presents the scalogram plot of the sensor signal. MATLAB code was developed in order to compute the Wavelet Transform and to plot the scalogram. Scalogram is taken to mean as a plot having three dimensions: here in this particular case they are amplitude, scale (frequency) and time. Second derivative of Gaussian function was selected as a mother Wavelet. The Gaussian function is expressed in . The Fig.4(c) shows the sensor output with abrupt fault. A spike is introduced in the sensor output signal at \( t = 0.15 \) sec. Fig.4(d) shows the scalogram of the sensor output with spike fault. It can be seen from the scalogram that there is a sharp increase in magnitude of the frequency components. This would not have been possible by the use of Fourier Transform as it does not provide the time of occurrence of the frequency components. In the Fig.4 (e) a constant fault is introduced in the sensor output signal. It can be seen from the Fig.4 (e) that the amplitude of the sensor output is almost constant for the entire duration of operation. In the Fig.4 (f) the scalogram of the sensor output with constant fault is plotted. As shown in the Fig.4 (f) the amplitude of the frequency components are almost constant. In the Fig.4 (g) a significant fault is introduced in the output of the sensor signal. As shown in the Fig.4 (g) at \( t=0.30 \) sec, there is an increase in the amplitude of the sensor output signal. Fig.4 (h) shows the scalogram.
plot of the sensor output signal with significant fault. It can be seen from the Fig. 4(h) that at that instant there is a gradual increase in amplitude of the frequency components. It can be observed from all the above cases that, whenever a fault occurs in the sensor output, the scalogram of the original sensor output changes.

Fig. 4(a): Output of the sensor signal (random in nature)

Fig. 4(b): Scalogram of the sensor signal (without fault)

Fig. 4(c): Sensor output incorporated with abrupt fault

Fig. 4(d): Scalogram of Sensor output with abrupt fault

FIG. 4(e): Sensor output incorporated with constant fault at the input

Fig. 4(f): Scalogram of Sensor output with constant fault;

Fig. 4(g): Sensor output incorporated with significant fault at the input
Fig. 4(h) Scalogram of Sensor output with significant fault at the input

V. CONCLUSION

Total automation demands quality signal from the sensor. For this the sensor should have self diagnostic features. With the rapid development of VLSI and embedded technology it is possible to fabricate the sensor and the validation algorithm on a single chip which makes the sensor smaller and compact. Wavelet transform can be used to write the validation algorithm. Wavelet transform is preferred over Fourier transform because of its several advantages such as time-frequency representation of the signal. It is also possible to localize the faults with the help of wavelet transform and signals with sharp changes can be better analysed with wavelet transform.

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