PERGAMON

Engineering Applications of Artificial Intelligence 14 (2001) 655–666

Engineering Applications of
ARTIFICIAL INTELLIGENCE

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Intelligent on-line quality control of washing machines using discrete wavelet analysis features and likelihood classification

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Received 1 November 1999; received in revised form 1 November 2000; accepted 1 October 2001

Abstract

This paper presents a method for extracting features in the wavelet domain from the vibration velocity signals of washing machines, focusing on the transient (non-stationary) part of the signal. These features are then used for classification of the state (acceptable-faulty) of the machine. The performance of this feature set is compared to features obtained through standard Fourier analysis of the steady-state (stationary) part of the vibration signal. Minimum distance Bayes classifiers are used for classification purposes. Measurements from a variety of defective/non-defective washing machines taken in the laboratory as well as from the production line are used to illustrate the applicability of the proposed method. © 2002 Published by Elsevier Science Ltd.

Keywords: Quality control; Wavelets; Classification; Intelligent systems

1. Introduction

Conventional Fourier analysis provides averaged spectral coefficients which are independent of time (Ambardar, 1995). They represent the frequency composition of a random process which is assumed to be stationary. However, many random processes are essentially non-stationary (Sólnes, 1997). For example, the sound pressure recorded from speech and music is non-stationary (Qian and Chen, 1996); in vibration monitoring, the occurrence of transient impulses makes the recorded signal non-stationary (Newland, 1994a, b; Tamaki et al., 1994; Wang and McFadden, 1994; Wilkinson and Cox, 1996); vibration during the start-up of an engine is non-stationary (Kim et al., 1995), and so on.

The basis functions used in Fourier analysis, sine waves and cosine waves, are precisely located in frequency, but their duration spans the entire time axis. The frequency information of a signal calculated by the classical Fourier transform is an average over the entire duration of the signal. Thus, if there exists a local transient over some small interval of time in the lifetime of the signal, the transient will contribute to the Fourier transform but its location on the time axis will be lost (Saito, 1994). Although the short-time Fourier transform (Qian and Chen, 1996) overcomes the time location problem to a large extent, it does not provide multiple resolution in time and frequency, which is an important characteristic for analyzing transient signals containing both high- and low-frequency components (Lee and Schwartz, 1995; Qian and Chen, 1996).

Wavelet analysis overcomes the limitations of Fourier methods by employing analysis functions that are local both in time and in frequency (Galli et al., 1996; Vetterli and Kovacevic, 1995). These wavelet functions are generated in the form of translations and dilations of a fixed function, the so-called mother wavelet. The focus of this paper is to present the basic ideas of discrete wavelet analysis and to demonstrate the application of wavelet analysis for feature extraction, in conjunction with statistical digital signal processing techniques (Hayes, 1996; Krauss et al., 1994), to the problem of classification of the state of washing machines based on vibration velocity transient signals.

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0952-1976/01/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S0952-1976(01)00028-8

2. Basic ideas of wavelet analysis

2.1. Wavelet analysis

Wavelet analysis breaks up a signal into shifted and scaled versions of the original (or *mother*) wavelet (Saito, 1994). The analyzing (mother) wavelet determines the shape of the components of the decomposed signal. Wavelets must be oscillatory, must decay quickly to zero, and must have an average value of zero. In addition, for the discrete wavelet transform considered here, the wavelets must be orthogonal to each other.

There are several families of wavelets such as Haar wavelets, Daubechies wavelets, biorthogonal, Coifflets, etc. (Misity et al., 1996; Strang and Nguyen, 1996). The Daubechies family is often represented by DN, where N is the order, or the size of the mother wavelet, and D stands for the "family" of wavelets. This family has been used extensively, since the maximum of the signal energy is contained in a limited number of coefficients in Daubechies wavelets. In this work the D4 wavelet is used, which captures well the characteristics of the vibration velocity signal.

2.2. Scaling functions and wavelet functions

The *dilation equations* may be used to generate orthogonal wavelets. The *scaling function* $\varphi(t)$ is a dilated (horizontally expanded) version of $\varphi(2t)$. The dilation equation in general has the form:

$$\varphi(t) = c_0\varphi(2t) + c_1\varphi(2t-1) + c_2\varphi(2t-2) + c_3\varphi(2t-3). \tag{1}$$

For the Daubechies D4 wavelet its coefficients have values:

$$c_0 = (1+\sqrt{3})/4\sqrt{2}, \tag{2}$$

$$c_1 = (3+\sqrt{3})/4\sqrt{2}, \tag{3}$$

$$c_2 = (3-\sqrt{3})/4\sqrt{2}, \tag{4}$$

$$c_3 = -(\sqrt{3}-1)/4\sqrt{2}, \tag{5}$$

Thus, a particular family of wavelets is specified by a particular set of numbers, called the *wavelet filter coefficients*. The above set of numbers c_0, c_1, c_2, c_3 is called the D4 *wavelet filter coefficients*.

It is not possible in general to solve directly for $\varphi(t)$; the obvious approach is to solve for $\varphi(t)$ iteratively so that $\varphi_j(t)$ approaches $\varphi_{j-1}(t)$, where,

$$\phi_j(t) = c_0\phi_{j-1}(2t) + c_1\phi_{j-1}(2t-1) + c_2\phi_{j-1}(2t-2) + c_3\phi_{j-1}(2t-3). \tag{6}$$

Fig. 1 shows the scaling function for the D4 wavelet that is obtained from this iteration process, assuming the initial scaling function $\varphi_0(t)$ equals 1 for $0 \leqslant t < 1$ and 0 elsewhere.

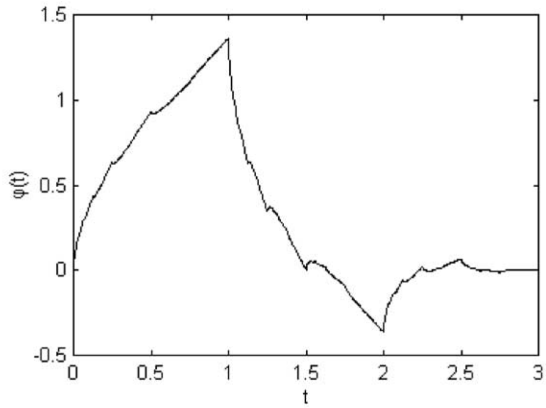

Fig. 1. Scaling function $\varphi(t)$ for the D4 wavelet after 8 iterations.

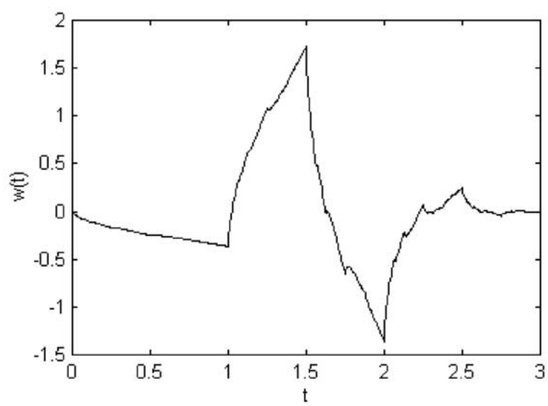

Fig. 2. D4 wavelet function after 8 iterations.

The D4 wavelet function $w(t)$ for the four-coefficient scaling function defined in (1) can be computed as

$$w(t) = -c_3\phi(2t) + c_2\phi(2t-1) - c_1\phi(2t-2) + c_0\phi(2t-3) \tag{7}$$

and is shown in Fig. 2.

In general, for an even number M of wavelet filter coefficients $c_k, k = 1, \ldots, M-1$, the scaling function is defined by

$$\phi(t) = \sum_{k=1}^{M-1} c_k\phi(2t-k) \tag{8}$$

and the corresponding wavelet is derived as

$$w(t) = \sum_{k=1}^{M-1} (-1)^k c_k\phi(2t+k-M+1). \tag{9}$$

It is observed that the scaling function, viewed as a filter's impulse response, has a low-pass form, whereas the wavelet function has a high-pass form. Thus, the wavelet function is essentially responsible for extracting

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