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IFAC-PapersOnLine 48-17 (2015) 201–206

Modelling of Material Properties Using Frequency Domain Information from Barkhausen Noise Signal

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Abstract: Frequency spectrum, bispectrum and bicoherence which are computed from Barkhausen noise (BN) signal are used to model material properties. The use of frequency domain information can be a significant addition to the more common time domain data analysis of the BN signals. The frequency spectrum shows the magnitude of the spectral components present in the signal. These components can also have interaction which is revealed only by the higher-order spectra. Third order spectrum can be used to detect the quadratic phase coupling phenomenon, which is a result of nonlinearity in the signal. In this study, a special attention is paid on the segment biphase to distinguish the quadratic phase coupling from constant non-zero biphase. Partial least squares regression models are made to model the surface hardness and residual stress properties from a set of carburizing case-hardened steel samples.

Keywords: Barkhausen noise, bicoherence, biphase, bispectrum, feature extraction, ferromagnetic materials, frequency spectrum, partial least squares regression

1. INTRODUCTION

Non-destructive testing (NDT) methods are used in material testing with means that do not compromise the usefulness of the material (McMaster, 1963). Barkhausen noise (BN) measurement is an electromagnetic non-destructive testing method that is suitable for ferromagnetic materials. The Barkhausen phenomenon occurs when a sample is placed in an external varying magnetic field causing magnetic domain wall movements. These movements are stochastic leading to abrupt changes in the magnetisation of the sample and further to the BN signal (Cullity and Graham, 2009). BN has been shown to be sensitive to microstructure and different material properties such as composition, residual stress and hardness (Jiles, 2000). The physical relationship between BN and the material properties is not studied in this paper. Instead, this study focuses on the data-driven modelling of surface hardness and residual stress based on the frequency domain information extracted from the BN signals.

The second-order statistics, such as mean and variance, completely characterise the probability density function of a Gaussian signal. In the frequency domain, the information contained in the power spectrum similarly suffices for the complete statistical description of a Gaussian signal (Nikias and Mendel, 1993). Higher-order spectra have been developed as a signal processing tool for providing information about signals which are non-Gaussian and produced by nonlinear systems. Third order spectrum, named as bispectrum, particularly reveals information about quadratic nonlinearities. These nonlinearities manifest themselves through the quadratic phase coupling (QPC) phenomenon. Although this phenomenon is included in the bispectrum it is masked by the effect of the amplitudes of the involved spectral components. To remove the amplitudes, a normalised bispectrum, named as bicoherence, is used. It measures the degree of phase coupling between the spectral components (Kim and Powers, 1979). There is a frailty in the basic form of bicoherence, because it cannot distinguish QPC components from the uncoupled components (Fackrell, 1997). Therefore, a phase check procedure is applied during bispectrum and bicoherence estimation in this study.

There are many types of real signals that need higher than second order measures to be fully described. These include seismic measurements, chaotic signals and vibrational signals from rotating machine components (Rivola and White, 1998). Other fields, where higher-order spectra have been used include biomedical signal diagnosis (Chua et al., 2008) and ground penetrating radar (GPR) data analysis (Strange et al., 2005). Frequency domain analysis of BN signal is carried out for example in (Kypris et al. 2014; Sorsa et al., 2014a) but as far as the authors are aware, this is the first time higher-order spectra from BN signals have been applied in material property modelling.

In this study, partial least squares regression is used to model surface hardness and residual stress of a set of carburizing case-hardened samples. Frequency domain information from the amplitude spectrum, the bispectrum and the bicoherence and time domain information from the signal time series are used as the input data and the results are compared. Features, such as *root mean square* (*rms*), *median*, *sum*, 99*th* *percentile* and *skewness* are computed from the spectra and the time series. Altogether fifteen input variable sets are compared and

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.10.103

the results discussed. The challenges related to the frequency domain analysis of Barkhausen noise signals are considered.

2. MATERIALS AND METHODS

This section describes the measurement practice, the frequency domain techniques and the modelling approach. The detailed descriptions of the well-known methods used, such as *amplitude spectrum*, *rms*, *percentiles*, *sum* and *skewness*, are omitted. The estimation of third order spectrum is covered in detail due to its specific method of application.

2.1 Measurements

The samples studied are manufactured from 18CrNiMo7-6 (EN 10084) steel. They are carburising case-hardened followed by tempering at different temperatures to introduce changes in hardness and stress states in sample surfaces. A more detailed description of sample preparation is found in (Sorsa et al., 2012). The residual stress measurements are carried out with XStress 3000 X-ray diffractometer and surface hardness measurements with Matsuzawa NMT-X7 hardness tester. Rollscan 300 device is used for BN measurements. The magnetising frequency used is 45 Hz while sampling frequency is 2.5 MHz. The specifics of the measurement devices are found in (Sorsa et al., 2012).

A typical BN signal is shown in Fig. 1. The signal has an almost stationary mean and nonstationary standard deviation. The FFT size is the length of BN signals (277777 points) in the presented amplitude spectrum. The characteristics of the signal are discussed later.

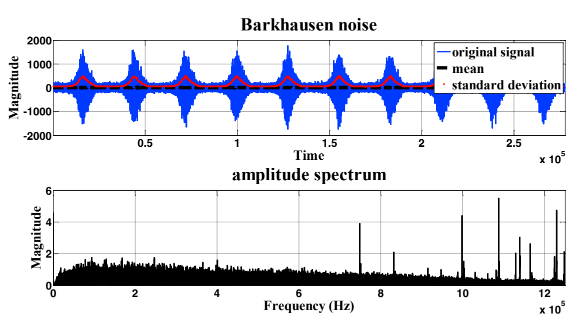

Fig. 1. Barkhausen noise signal with its means and standard deviations from one thousand consecutive time blocks and the amplitude spectrum.

2.2 Estimation of Third Order Spectrum

Third order spectrum can be estimated using either the direct method or the indirect method (Kim and Powers, 1979). The direct approach, which is used in this study, is based on the segment averaging approach and it is an extension of Welch's periodogram averaging technique for spectral estimation. Data is divided into M number of segments of length N. Discrete Fourier transform (DFT) is used on each segment. The appropriate terms are multiplied and then averaged over the M segments. Before using DFT on a segment, the segment is multiplied with a window function, such as Hanning window. The segments have a specific amount of overlap in order to reduce the variance of the estimates. The bispectrum (1) is estimated as a direct average of the triple products of the Fourier transforms over i segments

$$B(k,l) = E[X(k)X(l)X^*(k+l)], \qquad (1)$$

where $X(k)$, $X(l)$ and $X(k+l)$ denote the Fourier coefficients of the segment at frequencies k, l and $k+l$, respectively. The asterisk, *, stands for the complex conjugate. The term E refers to the expectation. The bispectrum has an amplitude and a phase. The spectral components are calculated over the triangular region $0 \le l \le k$, $k + l \le f_N$, where f_N is the Nyquist frequency. All of the significant information is contained in this principal domain (Fig. 2) if the sampling frequency is at least twice the highest frequency of the spectrum.

The bicoherence $b^2(k,l)$ is a normalised bispectrum which measures QPC on an absolute scale between 0 and 1 at any frequency pair k, l. QPC occurs if the phases $\theta(k)$, $\theta(l)$, $\theta(k+l)$ at frequencies k, l, and $k+l$, respectively, have the relation $\theta(k+l) = \theta(k) + \theta(l)$.The bicoherence can be defined as

$$b^2(k,l) = \frac{\left|\frac{1}{M}\sum_{i=1}^{M} X_i(k)X_i(l)X_i^*(k+l)\right|^2}{\frac{1}{M}\sum_{i=1}^{M}\left|X_i(k)X_i(l)\right|^2 \frac{1}{M}\sum_{i=1}^{M}\left|X_i(k+l)\right|^2}. \qquad (2)$$

The idea of Fourier transform is to represent any function with a set of sinusoids. In the estimation of higher-order spectra, it is assumed that the sinusoid phases are random variables over $[0\ 2\pi]$ (or $\pm\pi$). This means that the component phases should be randomised at the start of each i segment. The mechanism that leads to the ability to distinguish between uncoupled and quadratically phase coupled signals, relies on this assumption. If this phase randomization assumption does not hold, then the bicoherence (and bispectrum) can peak even without QPC (Fackrell, 1997; Sáez et al., 2014). The bicoherence is unable to distinguish between zero biphase (which indicates QPC) and constant biphase (which does not indicate QPC). Therefore, biphase has to be checked during each i segment. Biphase can be written as

$$\angle B(k,l) = \theta(k) + \theta(l) - \theta(k+l). \qquad (3)$$

In this study, the bispectrum and the bicoherence are multiplied by a coefficient based on the biphase. The coefficient is a percentage of QPC from all the M segments. An acceptance region is considered around zero biphase. In the present study, an acceptance region of ±0.2 rad is applied to indicate QPC. The number of segments from all the segments inside the acceptance region for each $\angle B(k,l)$ is checked. This proportion is used as the coefficient to multiply the bispectrum and the bicoherence. For the most part similar approach was presented in (Sáez et al. 2014). Fig. 3 illustrates the used method schematically. Segment size $N = 10000$ with 75% overlap and Hanning window are used in this study. The zero hertz component is removed from the bicoherence.