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Analysis of Barkhausen noise using wavelet-based fractal signal processing for fatigue crack detection

Krzysztof Miesowicz[a], Wieslaw J. Staszewski[a,*], Tomasz Korbiel[b]

[a] Department of Robotics and Mechatronics, AGH University of Science and Technology, Al. Mickiewicza 30, 30 059 Krakow, Poland
[b] Department of Mechanics and Vibroacoustics, AGH University of Science and Technology, Al. Mickiewicza 30, 30 059 Krakow, Poland

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ABSTRACT

The paper presents new approach to Barkhausen noise signal processing for detection of fatigue crack. Barkhausen noise signal from mild steel samples under axial fatigue is investigated using fractal signal processing, particularly wavelet variance method. Based on repeatability analysis new algorithm is developed and applied to acquired signals. The influence of fatigue on fractal characteristics of Barkhausen noise is analyzed. Signal analysis reveals significant and repeatable changes in wavelet variance, spectral parameter and estimated Hurst exponent just after crack initiation. The results demonstrate high potential of fractal analysis of Surface Barkhausen noise applied to fatigue crack initiation detection.

1. Introduction

Maintenance of many engineering structures is important to guarantee structural integrity and safety. Material fatigue is one of the major concerns when engineering structures are monitored and inspected for damage. It is well known that different types of fatigue failures occur in metals. Sequences of cyclic loads – and thus stresses and strains – lead to fatigue cracking, which is the most common mechanism of fatigue structural failure in metallic structures. Fatigue cracking exhibits different stages of fatigue damage such as [1]: sub-structural and microstructural changes, microscopic cracks formation of dominant cracks, stable propagation of dominant cracks and structural instability leading to complete fracture. Although various methods have been developed over the last few decades for fatigue crack detection [2–7], detection of crack initiation still remains a real challenge in Non-Destructive Testing (NDT). The major problem relates to the fact that the early microstructural stage of fatigue cracking is stochastic and therefore exhibits a significant degree of randomness.

The Barkhausen Noise (BN) – discovered nearly one hundred years ago – is one of the NDT approaches that rely on microstructural properties of material and involves some randomness. The BN effect is a complex phenomenon of abrupt changes in magnetization of ferromagnets under varying magnetic field [8]. The main sources of these changes are irreversible, irregular and discontinuous movements of the domain Bloch walls in a step part of hysteresis curve [9]. The BN is sensitive to various factors – such as material microstructure, dislocations, stress state or material composition [8,9] – that influence the domain structure of ferromagnets. Therefore the effect has been used for the analysis and degradation of various material properties. Previous research investigations in this area include mainly studies on material: stress states [10], residual stress estimation [11,12], plastic deformation [13], hardness analysis [14], fatigue level [15,16], grinding burn detection [17]. These investigations have led to the conclusion that tensile stress along easy axis direction increases Barkhausen noise amplitude and energy. In contrast, compressive stress decreases the level of both parameters. Similar effect is caused by changes in hardness of the material. Low hardness results in high signal amplitudes, while high hardness makes the signal amplitude lower [18].

It appears that very limited studies relate to structural damage detection. Examples in this area of research include investigations on crack [19] and volumetric flaw detection [20]. In the former, energy of BN, as well as pulse height distribution and number of events were analyzed and showed sensitivity to crack depth and variations of these indicator in crack vicinity. The latter employs innovative Continuous Magnetic Barkhausen Noise method and uses signal smoothing and time–frequency analysis to detect and locate precisely volumetric flaws in steel samples. The amplitude of BN peak at various stages of fatigue life has been analyzed in [21]. The results show that variation of BN peak voltage with

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* Corresponding author.
E-mail address: w.j.staszewski@agh.edu.pl (W.J. Staszewski).

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mechanical deformation can be correlated with changes of micro structure of material at different fatigue stages. Initial increase in peak voltage was followed by a decrease and then sharp increase till failure. The work in [22] indicates that the BN changes mild steel and high strength steel samples follow the changes observed in Acoustic Emission signals. For mild steel samples, an initial decrease in the BN amplitude has been observed. This behavior has been followed by the amplitude saturation phase and the sudden increase prior to failure. A similar behavior during low cycle fatigue in 9Cr–1Mo ferritic steel has been reported in [23]. The initial decrease of the BN peak amplitude has occurred in the early stage of the fatigue test, indicating the hardening stage. Further progressive cycling has led to the increase of BN amplitude, indicating the softening stage. After that saturation stage has occurred where the BN signal behavior has been unaltered. Crack initiation has been identified by the sharp increase of the BN peak amplitude.

The majority of the BN signal investigations have involved simple time-domain parameters such as the peak amplitude or the Root Means Square (RMS) level. The avalanche-like, irreversible process of domain movements in material leads to the hierarchical structure of the BN signals. The fractal nature of the BN has been observed in the 1980s (e.g. [24]). Fractals are usually associated with self-similar structures or patterns. However, when signals are analyzed statistical self-similarity is often observed and revealed by statistical parameters – such as the mean or variance – that remain similar within certain ranges of scales [25–28]. These parameters can be described using the so-called power law since scales are inversely proportional to frequency [26]. Scaling properties of the BN for various magnetically soft materials have been analyzed in [29], revealing avalanche-like, scaling processes of irreversible nature. Chaotic attractors reconstructed from the BN after the bending stress tests have been analyzed in [30]. Changes in attractor trajectories and increased fractal dimension have been observed for increased stress. However, differences observed have been not significant.

Recent years have shown a growing interest in the fractal signal processing of the BN because of two major reasons. Firstly, the BN is one of the best examples of dynamically disordered systems exhibiting the crackling noise [31]. The crackling noise is a scaling phenomenon that represents the avalanche-dynamics important in physics, seismology, economy and many other areas. Secondly, recent research studies in [32,33] indicate that the fractal nature of the BN is a key element that could be used for damage characterization of magnetic materials. This work shows that fractal dimensions – based on the correlation analysis – change with fatigue cycling of material. Small oscillations and decrease of the values of fractal dimensions give an opportunity to determine the stage of material damage due to fatigue or plastic deformation. Although, no clear indication of crack initiation has been given.

The work presented in the current paper demonstrates that fractal parameters change suddenly after crack initiation, allowing for reliable crack detection. In contrast to previous investigations, the wavelet analysis is used for the estimation of fractal parameters. The structure of the paper is as follows. The fatigue experimental tests – used to obtain the BN data from the undamaged and damaged specimens – are described in Section 2. Fractal signal processing that involves the wavelet analysis is described in Section 3. Crack detection results based on fractal signal processing of the BN data are given in Section 4. Finally, the paper is concluded in Section 5.

2. Experimental fatigue tests

A series of fatigue tests was performed to analyze the effect of fatigue crack initiation on the BN fractal characteristics. Three rectangular 80 × 250 mm specimens were laser-cut from a 1 mm thick sheet of DC01/1.0330 mild steel. The geometry of the specimens is given in Fig. 1. The chemical composition of the material used is given in Table 1. Two small notches were introduced centrally to both vertical edges of the specimens, as indicated in Fig. 1.

The steel specimens were clamped in the INSTRON 8872 testing machine – as shown in Fig. 2 – and fatigue cycled. The cyclic tensile load (the mean force equal 4.5 kN and the amplitude of sinusoidal load equal to 3.5 kN, as shown in Fig. 3) was applied to all specimens. The specimens were fatigued for 25,000 cycles. This resulted in the maximum 2.62, 3.81 and 4.28 mm cracks for the three specimens investigated. Fig. 4 gives the crack propagation curves. The notch zones were monitored under a microscope to observe crack initiation and propagation. Fig. 5a and b give the photographs displaying 0.15 and 3.1 mm fatigue cracks after 6000 and 23,000 cycles, respectively.

Once the fatigue test were performed the BN signals were acquired after each 1000 of cycles using a typical surface-type BN sensing head – with an electromagnet for alternating magnetic field excitation and a pick-up coil for detection – together with the *Thomas*™ device and the *Agilent*™ *DSO-X 3204* digital microscope for data acquisition. Measurements were performed in three locations (A – middle of the specimen; C,D – notch areas) indicated in Fig. 1. Sensing head was aligned in the direction of tensile force. The BN data acquisition was performed when the specimens were exposed to the 1 kN force level of tension. The sampling frequency was equal to 2 MHz.

3. Fractal signal processing

This section introduces briefly the fractal signal processing concept used to analyze the BN data. After a short introduction

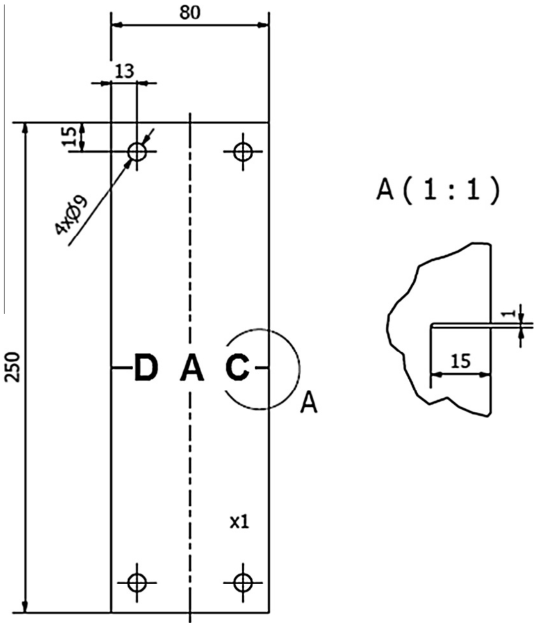

Fig. 1. The geometry of fatigue specimens with the D, A, C points indicating measurement locations.

Table 1
Chemical composition of the DC01/1.0330 mild steel material used in the fatigue tests.

	C	P	S	Mn	Ti
DC01/1.0330	0.12	0.045	0.045	0.60	–