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INSTRUMENTATION AND SIGNAL CONDITIONING FOR BARKHAUSEN NOISE MEASUREMENT

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Abstract – The aim of this work is to describe an improved Non Destructive Testing (NDT) methodology based on the analysis of Barkhausen noise (BN). A purposely designed probe has been realized, that allows the acquisition of the Barkhausen noise together with the magnetic induction flux experimented by the pick-up coil core plus the material under test. The basic idea is to support the BN analysis with information related to the hysteresis cycle; experimental results show how a multivariate approach can lead to a better resolution and repeatability.

Keywords: Sensor data processing, Barkhausen Noise, NDT

1. INTRODUCTION

In the last few years BN has been widely used as NDT for ferromagnetic materials, since it is a fast inspection technique that allows on-line quality control. BN method, also known as the magnetoelastic or the micromagnetic method, is based on the measurement of a noise-like signal, generated when an alternate external magnetic field is applied to a specimen. The microstructure of ferromagnetic materials consists of magnetic domains (MDs) that align themselves along the magnetic field **H** direction, thus minimizing the overall system energy. MDs roto-translation occur in an irreversible way, especially in the lowest portion of the magnetization cycle, i.e. at low field value. For this reason, the induction field exhibits “jumps” even when the magnetization process occur under a continuous magnetic field. These jumps can be sensed by a pick-up coil placed near the material surface (in particular, it is possible to distinguish between contact and non-contact type measurements). Two material characteristics greatly affect the BN: the presence and distribution of elastic tensile stresses and the material microstructure [1]. The former effect, called magnetoelastic interaction, increases the BN activity in presence of tensile stress in materials with positive magnetic anysotropy. In fact, the stress acts like the magnetizing field, favouring those MDs aligned along the stress direction. On the other side, microstructural defects (as dislocations, inclusions etc.) acts like pinning-site; in particular, samples characterized by higher hardness exhibit a lower BN activity. An exemplification of this process is depicted in Fig.1.

Traditionally, the energy content of the BN signal is measured (Root Mean Square – RMS – value) and correlated to the state of the specimen under analysis, even if the measurement method and the complexity of the phenomena make the results corrupted by electromagnetic noise and not repeatable. More recently, different signal analysis technique, based on signal shape and impedance measurement, has been proposed showing an improvement of the noise immunity and repeatability [2].

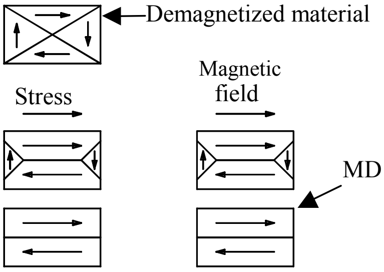


Fig. 1. Comparison between the magnetoelastic effect and the magnetization process.

Other authors have suggested to retrieve indication about the stress not only by the BN but also by the hysteresis cycle, since it can be correlated both to the microstructure and to the applied stress, according to the magnetoelastic theory [3]. In these references another coil has been added surrounding the specimen [4,5]. Obviously, this limits the stress analysis only for particular specimen shape.

In our paper, we propose to overcome these limits suggesting an alternative method to measure data correlated to the hysteresis cycle suitable to work in laboratory and industrial sites, since the analysis is done on the plain surface of the material under examination. This feature has been obtained by a modification of the traditional probe that is driven by a current or a voltage generator with a single circuit. Also the signal processing circuit has been designed to preserve the signal to noise characteristics of the Barkhausen instrumentation. Moreover the proposed instrumentation adopts a PC-based architecture, offering the powerful capability of the digital signal analysis and a flexible configuration suitable to adapt the experimental parameters according to the required measurement specifications.

In this research project, which involves also the Department of Mechanical Engineering of our University, an experimental testing will be conducted on the proposed instrumentation with the specific aim to measure several different parameters related to the BN and to separate in this way the mechanical and micro structural parameters which influences them.

In the following, the probe, the signal conditioning circuit and software algorithms are described in detail. At least, experimental results obtained with a specimen subjected to tensile stress are shown.

2. THE PROBE AND THE MEASURING INSTRUMENTATION

Up to now, we have spoken about “probe” rather than “sensor” since the transducer employed in BN analysis is a whole system, not a single sensing element. The basic structure of conventional probe is made up of an exciting coil (S1), whose aim is to apply an alternate field to the specimen, and a pick-up coil (S2), that senses the stray induction field. This kind of probe is able to retrieve information about the BN signal (S2) and the overall impedance of the system electromagnet and material under test (S1). In fact, if we ensure a low reluctance path for magnetic field (depending on the coupling condition), the specimen plus the exciting core can be considered as a whole. In order to acquire the hysteresis cycle, we must know both the magnetic **H** and the induction field **B**. The former can be easily obtained starting from the current flowing in the magnetizing coil (S1). The latter can be derived from the induced voltage in an added coil (S3), wounded over the exciting coil core, as depicted in Fig.2. In fact, the induced voltage in S3 is proportional to the magnetic flux Φ and the induction field **B** can be retrieved with a numerical integration.

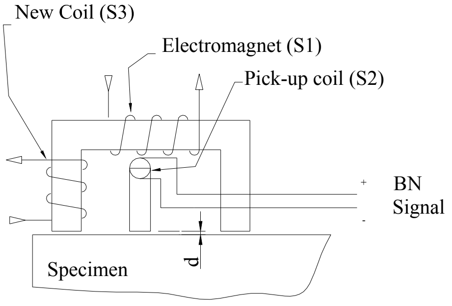


Fig. 2. Block diagram of the proposed probe.

Dimensions have been chosen to realize a probe for manual inspection of plane samples. Fig.3 shows the final probe outline; to ensure high durability and stability, the probe is cast with epoxy into a stainless steel case.

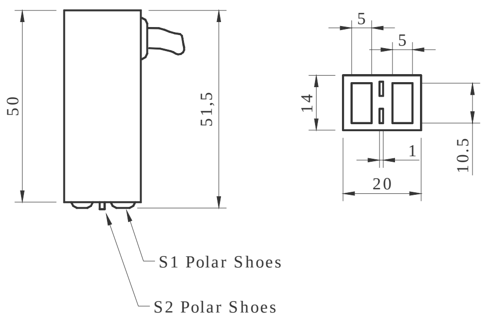


Fig. 3. Outline of the proposed probe (dimensions in mm).

Great attention has been devoted to the driver circuit. Usually, the specimen is excited with a sinusoidal voltage signal, since traditional instrumentations simply calculate the RMS-value of BN signal. However, to acquire the hysteresis cycle, the excitation cycle should be performed with a constant rate, i.e. with a triangular current waveform. For this reason, the driver can be a voltage or a current imposed circuit. A logic signal is used to switch between the two control modalities.

If the probe is current driven it is possible to acquire the voltage signal (voltage sensing) and vice versa (current sensing). In fact, the voltage drop across S1 is buffered through U3 and filtered, while the difference amplifier U2 is used to sense the current flowing in the electromagnet as the voltage across R6. The availability of both the exciting current and voltage makes possible to estimate the impedance of the core together with the sample. It has been proven that impedance can be used to supervise coupling conditions. A simplified schematic is sketched in Fig.4. When the circuit is current driven switches K1 e K2 are in the ‘1’ position; in this way, a positive feedback path is realized by U3 and R6.

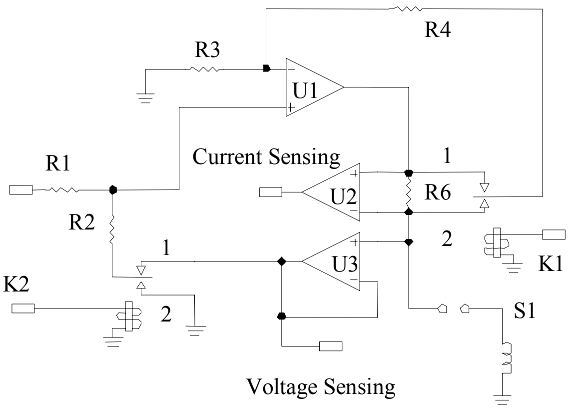


Fig. 4. Simplified driving circuit schematic.

In this configuration the circuit realizes a Howland generator. The operational amplifier U1 is a monolithic integrated circuit able to deliver a continuous output current up to 5A. In this manner a quite strong magnetic field can be applied to the specimen under test.

When the circuit is voltage driven, switches K1 and K2 are on the ‘2’ position and the whole stage acts like a non inverting amplifier.

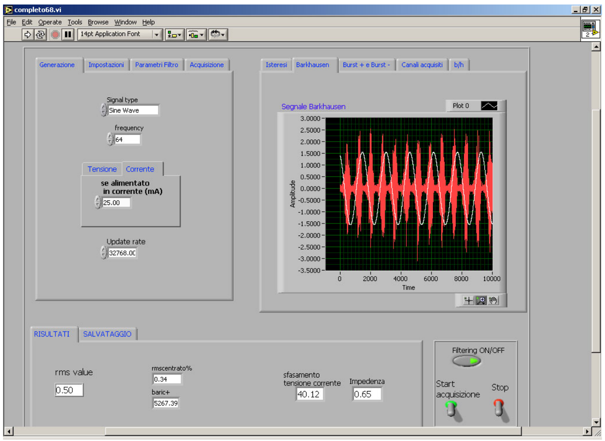
Signal coming from coil S3 is amplified and low pass filtered (10 kHz cut off frequency): it has a good S/N ratio, since S1 and S3 roughly act like the primary and secondary windings of a transformer.

On the contrary, BN is a low amplitude signal (in the order of 100μV) and thus is subjected to a very high gain amplification. Moreover, BN extends from the fundamental exciting frequency up to few MHz, therefore a high gain-bandwidth product must be provided. To satisfy these constrains, a multi stage low-noise amplifier has been designed by using a precision operational amplifier. To have a large output voltage swing, the overall gain can be changed from 500 up to 10000.

The entire system is operated under Personal Computer control that it is equipped with a National Instruments NI-PCI6110. This high performance data acquisition card has been chosen since it allows the simultaneous sampling of up to 4 channels with a nominal resolution of 12bits and a maximum sampling rate of 5MSa/s. In this way, there is no phase lag between the BN and other acquired signals, that are the current and voltage sensing and the one coming from S3. One of the output channel is used to realize an AWG (Arbitrary Waveform Generator) that feeds the driver circuit. An adequate smoothing filter has been provided to preserve spectral purity of sinusoidal and triangular waveforms.

3. INSTRUMENT SOFTWARE

The key feature of the whole system is the control and data analysis software. It has been written using the National Instruments LabVIEW environment running under Windows 2000 (a grabbed image is depicted in Fig.5).



Signal type: Sine Wave
frequency: 64
se alimentato in corrente (mA): 25.00
Update rate: 32768.00
rms value: 0.50
rmscentrato%: 0.34
baric+: 5267.39
sfasamento tensione corrente: 40.12
Impedenza: 0.65

Fig. 5. LabVIEW Application.

The waveform generation module allows the user to choose the waveform shape (sinusoidal, triangular, etc.), the amplitude (from 0 to 12Vpp or 0 to 500mA), the frequency (32/64/128/256 Hz) and the excitation type (voltage or current controlled). The data acquisition module let to set AD converters parameters, such as the sampling frequency, normally set to 1MSa/s, or the observation time, usually set to 0.5s to include at least 16 consecutive excitation periods. A numerical filtering stage allows to select the band of interest: it implements an IIR band-pass filter whose band and order are user selectable (generally a 4th order filter with a [10÷350] kHz band). It has been shown [6] that it is possible to relate the inspection depth with respect to the analysis band, since BN emission is an electro-magnetic wave that propagates through a conductor. For example, a 100kHz wave halves within 50μm in a material with a conductivity of $5\cdot10^6[\Omega^{-1}\mathrm{m}]$ and a relative permeability of about 10^4.

Acquired signals are then processed to extract significant features to be viewed for operators.

Traditionally, the most used feature extracted from BN signal is its energy content: it is evaluated as the RMS-value of the filtered signal. On the contrary, the proposed instrument has a multi-feature approach, so we call E0 this parameter to distinguish it from others.

Since the BN has a cyclostationary behaviour, ensemble averages are computed to achieve a better SNR. Current waveform is used as the trigger signal: its minimum to maximum portion identifies what we call the “positive bursts”, while the vice versa holds for “negative bursts”. Rather than use the Fourier transform, that some authors consider useless [7], we have treated the absolute signal value (i.e. rectified) as a Probability Density Function (PDF): the shape parameter module computes the generalized first order moment M1 (see Eq. 1, where N is the burst length, depending on sampling and exciting frequency, and BNi is the BN signal ith sample).

This parameter gives an indication of where the signal is concentrated with respect to the current waveform, i.e. where is the maximum BN activity with respect to the magnetizing field.

$$M1 = \left(\sum_{i=1}^{N} i \cdot BN_i \right) \cdot \left(\sum_{i=1}^{N} BN_i \right)^{-1} \tag{1}$$

Once we have obtained M1, we can calculate the RMS-value of an isolated portion around M1, characterized by a higher SNR [2]. We call this parameter E1.

One parameter has been chosen to resume characteristics of the hysteresis cycle; as previously stated, we use the current signal as an indication of the magnetizing field, while we perform a numerical integration to obtain an indication of the induction flux Φ. To avoid offsetting of the integrated signal, the dc-component of each period is estimated through a linear interpolation among consecutive signal maxima or minima and consequently subtracted. A linear fitting has been estimated when Φ=0, a position that we assume correlated to the coercive force Hc. The slope Mu has been considered as an indication of the incremental permeability $\left.\frac{\partial\mu}{\partial H}\right|_{Hc}$ of the electromagnet core plus the material under test. Obviously, variations in its value should be imputed only to the specimen. From the magnetoelastic theory we know that, in the simplest case, a linear relationship exists between the magnetic permeability μ and the applied stress σ (see Eq. 2). The proportionality coefficient K is called magnetoelastic coupling factor and describes the ratio of the stored elastic stress energy to the total stored energy.

$$\mu(\sigma)=\mu(0)+\mathrm{K}\cdot\sigma \tag{2}$$

In addition, signals coming from coil S1 have been used to estimate the equivalent impedance of the system made up of the excitation magnet (S1) core and the specimen. In particular, modulus Z and phase shift ϕ of the ratio of the voltage developed across S1 and the injected current have been evaluated.

In conclusion, the proposed instrument outputs six features:

- E0, the overall BN RMS value
- E1, the centred BN RMS value
- M1, the first order moment of the rectified BN signal
- Mu, the incremental permeability in proximity of Hc
- Z, the excitation impedance modulus
- ϕ, the excitation impedance phase shift

Finally, there are software modules that allow to plot and save both raw data (sampled waveforms) and numerical readouts for further analysis or multivariate processing techniques (e.g. neural networks).

4. EXPERIMENTAL RESULTS

Numerous tests have been conducted, with the collaboration of the Prof. G. Donzella research group (Department of Mechanical Engineering of our University), in order to verify the effect of tensile stress with respect to BN emission. A ferrous specimen has undergone several tensile stress (from 0MPa to 260MPa by step of 20MPa, thus remaining within the elastic limit) applied by an universal testing machine Instron 8501.

Since a good contact is essential to ensure measurements correctness, an adequate support has been realized and a rubber band is used to impress a constant normal force and to prevent a varying air gap.

Some authors [5] have highlighted how BN is strongly affected by magnetizing parameters, that must be carefully chosen. When BN is used as a tool for NDT, the magnetizing frequency is usually set in the order of 1-100Hz: thus, MD roto-translations occur in non-stationary condition, i.e. when the external field is changing. This is a point that is still under investigation by several research groups [8].

Though the proposed instrument is versatile and can impose several excitation signal, we have preferred the most common form of magnetic stimulation, that has been widely treated in literature. For each of our experiments we have selected a sinusoidal voltage signal with an exciting frequency of 128Hz and an amplitude of 1.2V. It is to say that a current controlled experiment has been conducted with an exciting current of 25mA, corresponding to about 1.2V of drop across S1, leading to very similar outcome. Numerical results shown in Fig.6 have been obtained as the average of 20 consecutive instrument readouts. Each of them is the result of features computation taken over 0.5s long signals acquisition with a sampling frequency of 1MSa/s. All data refer only to positive bursts. Experiments have highlighted an asymmetry between positive and negative bursts that is still under investigation. M1 has been expressed in degrees with respect to the excitation current signal, starting from minima (one period equal to 360°).

To resume selected parameters performances we have adopted some indexes, as shown in Table 1: Lin_{LMS} is simply the linearity error in Least Mean Squares (LMS) sense; S and D are defined in Eq.3, where P is the considered parameter mean value, and σ is the related standard deviation. Subscripts X and Y refer to the applied stress.

$$\begin{aligned} S_{\text{X-Y}} &= \frac{P_{\text{Y}}-P_{\text{X}}}{\sigma_{\text{Y}}+\sigma_{\text{X}}} \\ D_{\text{X-Y}} &= 100\cdot\frac{P_{\text{Y}}-P_{\text{X}}}{P_{\text{Y}}+P_{\text{X}}} \end{aligned} \tag{3}$$

The higher is the $S_{\text{X-Y}}$ value, the greater is the ability to point out phenomena that distinguishes class X from class Y. On the contrary, D expresses the per cent variation of the same parameter P.

Thanks to the good characteristics of the signal conditioning chain and data acquisition system, standard deviation of some parameters are quite low, leading to very high values for S index. To include the repeatability error, mainly due to the difficulties in coupling probe with specimen, we have computed another index, called S^*, that considers the maximum variation of the P parameter among 4 different measurement campaigns instead of using the standard deviation σ computed over 20 consecutive readouts.

TABLE 1. Selected features performances.

	E0	E1	M1	Mu	Z	ϕ
Lin_{LMS} [%FS]	2.97	2.43	26.4	11.6	10.2	14.0
$S_{100\text{-}200\ \text{MPa}}$	22.60	8.36	2.38	45.50	7.22	38.10
$D_{100\text{-}200\ \text{MPa}}$[%]	7.20	8.41	0.45	0.80	0.49	0.19
$S^*_{100\text{-}200\ \text{MPa}}$	0.38	0.46	0.30	2.00	1.60	1.00

It is evident there is not a single parameter with optimal performances; thus the best approach is probably multivariate analysis. Moreover, supposing to utilize non-linear multivariate techniques, like Neural Network, linearity error is not significant.

As regards energetic parameters, it is possible to notice that E1 has a better sensibility (D index); its S value is lower than E0 one since the corresponding observation time is about ¼ (i.e. the positive bursts central portion). In fact, if we consider S^* instead of S, E1 is lightly better.

The signal shape parameter (M1) shows worse performances with respect to energetic parameters, but they carry uncorrelated information. In addition, it seems to be more immune to environmental noise.

Parameters related to excitation signals and hysteresis cycle show a good repeatability ($S^*\geq 1$), even if they are characterized by a poor sensitivity ($D<1$).

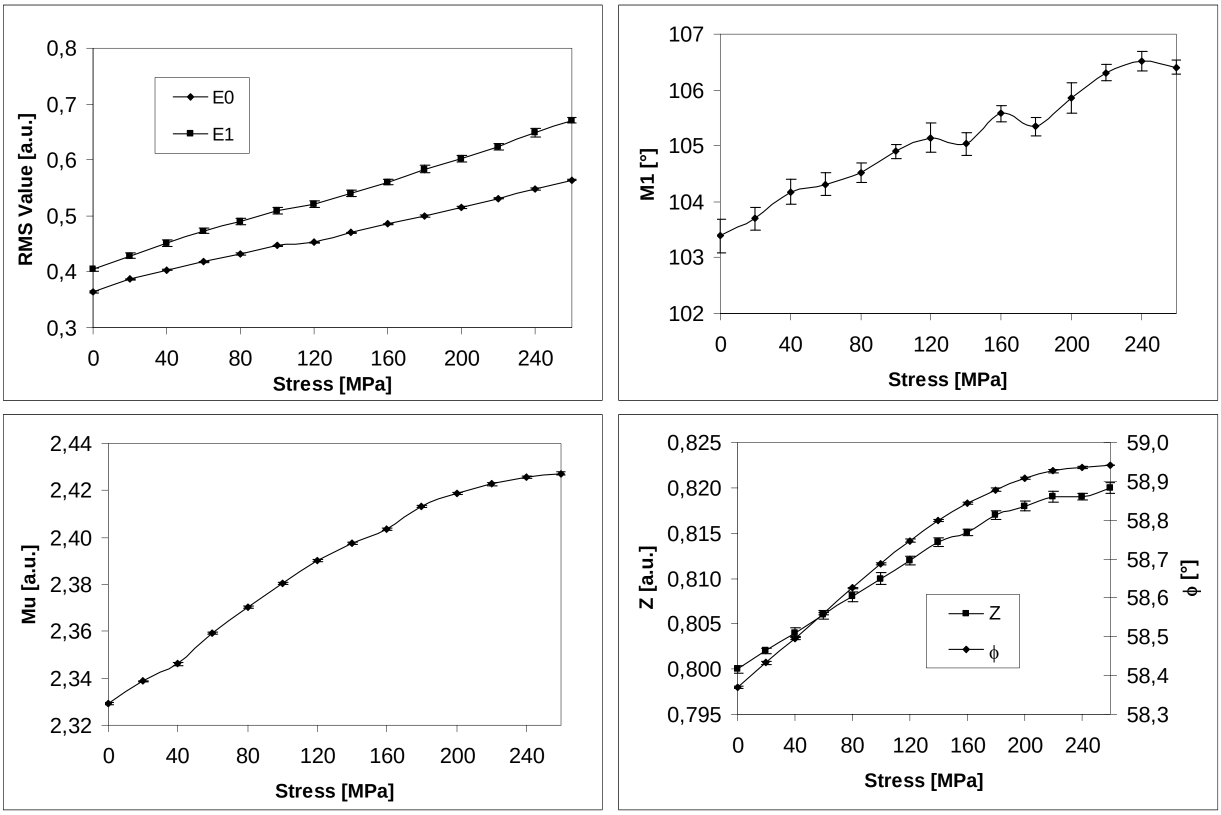


Fig. 6. Selected feature values vs. applied tensile stress.

5. CONCLUSIONS

In this paper a new and versatile instrument for BN analysis has been presented. It is not only possible to evaluate the BN, as usual, but even retrieve information about the hysteresis cycle. An handy probe has been purposely developed, starting from traditional arrangement. The aim is to improve material classification supporting BN features with parameters extracted from the hysteresis cycle. The whole instrument is controlled by a PC, letting the user to set the best measurement condition.

Thanks to the multivariate approach it is possible to obtain good repeatability and resolution, characteristics essential for NDT of ferromagnetic materials.

However, BN analysis is still in its research phase and is flanked by other traditional techniques as X-ray diffraction or ultrasonic NDT.

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