Fast Track Communication

Distortion analysis of magnetic excitation—a novel approach for the non-destructive microstructural evaluation of ferromagnetic steel

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Abstract
The presence of a different ferromagnetic material, between the poles of a U-shaped iron-cored electromagnetic (EM) yoke, has been observed to introduce a distortion in the alternating excitation voltage \( V_E \) across the coil around the EM yoke. The influence of four different microstructural conditions of a ferromagnetic 18CrNiMo5 gear steel on the distortion behaviour of the magnetic excitation voltage has been investigated. The time derivative of the excitation voltage \( (dV_E/dt) \) plotted as a function of total applied voltage \( V_T \) has been found to show a unique shape for each sample with different microstructural conditions. The systematic changes in the height and position of the peak and the trough on the voltage–time derivative profile reflect the difference in the magnetization process for each microstructural condition. This study reveals the good potential of this simple method of distortion analysis of magnetic excitation for a variety of applications related to material evaluation of ferromagnetic steel components.

Keywords: distortion, magnetic excitation voltage, microstructures, ferritic steel
( Some figures may appear in colour only in the online journal)

1. Introduction

Magnetic methods such as hysteresis loop and magnetic Barkhausen noise are potential non-destructive testing methods for the evaluation of ferromagnetic materials [1–10]. A magnetic hysteresis loop is obtained by plotting magnetic induction as a function of applied cyclic magnetic field strength [1–5]. The magnetic Barkhausen noise signal profile is measured by plotting the voltage pulses induced in the pick-up coil as a function of applied cyclic magnetic field strength [9, 10].

Common to several applications, a cyclic magnetic field is generated by applying an alternating bi-polar voltage to an electromagnetic (EM) yoke with a suitable soft magnetic core material such as pure iron and Fe–Si steel to achieve a higher magnetic field strength with a lower current. Under a quasi-static excitation condition, the applied excitation voltage is linearly related to the applied magnetic field strength measured at the centre of the air gap in a U-shaped EM yoke (the open magnetic flux path circuit). However, when the magnetic field is measured on the surface of a ferromagnetic material placed between the poles of the U-shaped EM yoke (closed magnetic flux path circuit), the tangential surface magnetic field shows non-linear behaviour. This is considered as an influence of the magnetization behaviour of the ferritic steel introduced between the poles of the EM yoke [11]. It is expected
that the voltage applied across the excitation coil around the EM yoke will also be distorted reflecting the magnetization behaviour of the ferromagnetic steel sample placed in the loop. Since the magnetization behaviour strongly depends on the microstructure of the ferritic steel, it is expected that the analysis of the distortion of the excitation voltage could distinguish different microstructural grades of a ferritic steel.

The distortion analysis of magnetic excitation has been not studied previously for microstructural evaluation of ferritic steels to the best knowledge of the author. This is a simpler method compared to hysteresis loop and magnetic Barkhausen noise measurements. Using this new approach, this paper attempts to distinguish four different microstructural grades of a ferritic steel commonly used in gear industries.

2. Principle of the distortion analysis of magnetic excitation

The total voltage \( V_T \) applied is divided into the voltage across the excitation coil \( V_E \) and that across any current limiting resistor \( V_{RCL} \) in series in the circuit.

\[
V_T = V_E + V_{RCL}.
\]

It is known that the magnetic induction will affect only \( V_E \) which consists of a resistive component due to the coil resistance and inductive component. Then,

\[
V_E = Ri + L \frac{di}{dt} + i \frac{dL}{dt},
\]

Where \( R \) is the coil resistance and \( i \) is the current through the circuit and \( L \) is the inductance of the coil. For a simple solenoid, \( dL/dt = 0 \).

In an electromagnet with a soft magnetic core material, the inductance \( L \) becomes

\[
L = N^2 \mu A/l,
\]

where \( N \) is the number of turns in the coil, \( A \) is the area of flux path, \( \mu \) is the permeability of the flux path and \( l \) is the length of the flux path.

The inductance of the excitation circuit is a strong function of the permeability of the flux path. Rewriting equation (2),

\[
V_E = Ri + (N^2 \mu A/l) \left( \frac{di}{dt} + i \frac{dL}{dt} \right) + i \frac{d\mu}{dH} \left( \frac{dH}{dt} \right),
\]

when an EM yoke, with a finite air gap between the poles, is excited with a quasi-static (<1 Hz) triangular waveform voltage source, it is expected to cause a linear change in \( V_E \) (and applied magnetic field strength) due to the open loop and hence incomplete flux path resulting in the second and third terms on the right side of the equation (4) becoming insignificant. Even though the current will vary non-linearly with the effect of higher harmonics, the \( \left( \frac{di}{dt} \right) \) will be independent of any sample. The \( \left( \frac{d\mu}{dH} \right) \) is expected to linearly change in the air gap between the poles of the yoke in the absence of any ferromagnetic sample and become less significant as the yoke approaches saturation. However, there will be a small hysteresis in a cycle depending on the magnetic characteristics of the core material of the EM yoke. But, in the presence of another ferromagnetic material introduced in the flux path between the poles of the yoke, the change in \( V_E \) is expected to behave non-linearly due to the non-linear variation in rate of change of permeability \( \left( \frac{d\mu}{dH} \right) \).

The present study is aimed at demonstrating this effect of the non-linear distortion of magnetic excitation experimentally and attempt to distinguish different microstructural grades of ferromagnetic steel.

3. Experimental

The schematic of the experimental set-up used to demonstrate the distortion of magnetic excitation is shown in figure 1. A bi-polar triangular waveform at a frequency of 0.4 Hz is generated through the NI-PCI-6111 DAQ card using LabVIEW software.
which is fed to a bi-polar power amplifier. The alternating voltage output (±20 V) of the power amplifier is used to excite the EM yoke (figure 1) made with commercially pure iron as the core material. The excitation coil around the EM yoke is connected to a current limiting resistor ($R_{CL}$) in series. The EM yoke has an air gap of 25 mm between its poles. The voltage signal across the excitation coil wound around the EM yoke ($V_E$) is passed through a 100 Hz low pass frequency filter to remove any high frequency noise in the signal. Even though, $V_T$ can be expressed as per equation (1), the $V_T$ can be tapped directly from the voltage source output as an independent variable without having any distortion effect as $V_E$. The total excitation voltage ($V_T$) and the voltage across the excitation coil ($V_E$) are acquired over 4 cycles of magnetization with a total duration of 10 s at a sampling frequency of 100 kHz. The data is smoothed further by averaging over four magnetization cycles. The average voltage across the excitation coil ($V_E$) is plotted as a function of total voltage ($V_T$). The average voltage across the excitation coil ($V_E$) is also differentiated with time to obtain ($dV_E/dt$) and plotted as a function of total voltage ($V_T$) for further analysis.

Gear steel, commonly designated as 18CrNiMo5 steel, is received in its as-rolled (AR) condition. Rectangular bar samples of 70 mm × 20 mm × 5 mm were made from the AR steel bar. The bar samples were subjected to different heat treatments to obtain different microstructures. The sample in the AR condition is expected to be harder due to the high dislocation density generated by the rolling process. An isothermal annealing (IA) process is carried out to obtain a two-phase microstructure with a ∼75% volume fraction of ferrite and ∼25% volume fraction of pearlite phases. A spheroidizing annealing (SPA) process is carried out to obtain a microstructure with more volume fraction of ferrite phase and spheroidized carbides. Another quenched and tempered (QT) process is carried out to obtain a microstructure with tempered lath martensite and fine carbide precipitates. The distinct microstructural variation is expected to cause differences in the magnetization processes due to the different interactions of magnetic domain walls with microstructural features. The variation in micro-magnetization processes will result in a variation in the rate of change of permeability. This is expected to cause different extents of distortion in excitation coil voltages ($V_E$).

4. Results and discussion

The typical variations in voltage across the coil around the EM yoke ($V_E$) measured without any sample (only air gap) and with an isothermally annealed (IA) 18CrNiMo5 steel sample is shown for a total duration of 10 s over four cycles of magnetization in figure 2. The variation in average $V_E$ as a function of total applied voltage ($V_T$) is shown in figure 3 for half the magnetization cycle ($−V_{T_{max}}$ to $V_{T_{max}}$).

![Figure 2](image1.png)  
**Figure 2.** Typical variations in voltage across the EM yoke ($V_E$) measured without any sample and with an isothermally annealed (IA) 18CrNiMo5 steel bar sample is shown for a total duration of 10 s over four cycles of magnetization. The distortion in excitation coil voltage ($V_E$) with the IA sample can be noticed clearly.

![Figure 3](image2.png)  
**Figure 3.** Variations in average voltage across the EM yoke ($V_E$) as a function of total applied excitation voltage ($V_T$) measured without any sample and with different heat-treated 18CrNiMo5 steel bar samples for half the magnetization cycle ($−V_{T_{max}}$ to $V_{T_{max}}$).

![Figure 4](image3.png)  
**Figure 4.** Variations in the time derivative of the voltage across the EM yoke ($dV_E/dt$) as a function of total applied excitation voltage ($V_T$) measured without any sample and with different heat-treated 18CrNiMo5 steel bar samples for half the magnetization cycle ($−V_{T_{max}}$ to $V_{T_{max}}$).
which the variation in the time derivative of voltage across the coil around the EM yoke \((dV_E/dt)\) is plotted as a function of total applied excitation voltage \((V_T)\) for half the magnetization cycle \((-V_{T_{\text{max}}} \text{ to } +V_{T_{\text{max}}})\). The other half is symmetrical, but is in the negative side which is not shown here for better clarity.

It can be noticed from figure 4 that the \((dV_E/dt)\) is more or less constant when there is no sample between the poles of EM yoke. The sharp change in \((dV_E/dt)\) at both the ends corresponds to the change in direction of the voltage (direction of applied magnetic field). The variation in \((dV_E/dt)\) profile with a ferromagnetic steel sample shows a peak and a trough. The height and position of both the peak and trough are different for each heat-treated sample.

It can be realized that the differentiation of \(V_E\) in equation (4) is more complicated and the \((dV_E/dt)\) will be a function of \((d\mu/dt)\) and \((d^2\mu/dt^2)\) as well as \(i\) and \((di/dt)\). The effect of \(i\) and \((di/dt)\) can be ignored as they are independent of any sample. The variation in \((dV_E/dt)\) will be influenced by the rate of change of permeability of the ferromagnetic sample introduced in the flux path. The distortion of \(V_E\) is mainly contributed to by the effects of Faraday’s law and Lenz’s law of magnetic induction in response to the changing magnetization of a ferromagnetic sample in the flux path. The variation in \(V_E\) deviates with an increase corresponding to the demagnetization of the sample and then decreases again corresponding to the remagnetization of the sample in a half cycle of magnetization as can be observed in figure 3. With respect to this, the \((dV_E/dt)\) profile shows a peak corresponding to the demagnetization section and a trough corresponding to the remagnetization section during the cyclic magnetization process as can be observed in figure 4. This satisfies the effects of Faraday’s law/Lenz’s law of induction and also shows the effect of the different magnetization behaviours of ferromagnetic samples with different microstructures.

The optical micrographs of different heat-treated samples are shown in figures 5(a)–(d). The AR sample shows bainitic structure (figure 5(a)) and is expected to contain a high dislocation density due to plastic deformation of the steel bar during the rolling process. However, the dislocation structure can be observed only in transmission electron microscopy (TEM). The isothermally annealed (IA) sample shows a mixture of ferrite phase (white grains) and pearlite phase (dark grains) (figure 5(b)). The spheroidizing annealed (SPA) sample shows dominant ferrite grains with a dispersion of spheroidized carbide particles (figure 5(c)). The quenched and tempered (QT) sample shows tempered low carbon lath martensite with fine carbide precipitates (figure 5(d)).

The unique shape of the \((dV_E/dt)\) profiles (figure 4) clearly indicates the difference in magnetization process and hence the difference in the rate of change of permeability \((d\mu/dt)\) in these ferritic steel samples with different microstructural
features. The positions of the peak and the trough for the AR sample occur at the highest voltages ($V_T$) and gradually shift to lower voltages for 1A, QT and SPA samples respectively. This indicates the softening of the microstructure with heat treatment. The heights of the peak and trough also vary with microstructural conditions.

It is interesting to note that the section of the ($dV_E/dt$) profile between the peak and the trough exhibit different slope changes for each microstructural condition. This section of the ($dV_E/dt$) profile shows two-slope behaviour for all samples except the AR sample. The two-slope behaviour could be an indication of a different magnetization process in different metallurgical phases at different magnetic field strengths (applied voltages) as discussed earlier to explain the two-peak behaviour of magnetic Barkhausen noise (MBN) profiles [3, 5]. The interaction of magnetic domain walls with different microstructural features such as ferrite grain boundaries, pearlitic lamellar structure, martensitic lath boundaries, intergranular and intra-granular carbide precipitates, etc will occur at different ranges of magnetic field strengths (applied voltages) and will affect the rate of change of permeability. This variation in micro-magnetization process will affect the excitation voltage across the coil around the EM yoke resulting in the distortion of $V_E$ and hence in the ($dV_E/dt$) profile.

The unique behaviour of the ($dV_E/dt$) profile dependent on the microstructural condition can be used to evaluate different heat-treated material qualities of ferritic steels. Further detailed analysis of the ($dV_E/dt$) profile could help in correlating the variation in specific microstructural features and mechanical properties of the ferritic steel. However, it is important to realize that, apart from the influence of different microstructural conditions, the distortion behaviour will also be affected by the geometry of the ferritic steel sample due to the effect of the demagnetization factor and the distribution of the magnetic field strength in the sample. Further understanding of this phenomenon of distortion of magnetic excitation is in progress.

5. Conclusions

This study clearly shows that the excitation voltage ($V_E$) across the coil around the EM yoke is distorted in the presence of a ferromagnetic sample placed between the poles.

The different extent of distortion is uniquely and more distinctly reflected by the shape of the time derivative profile of the $V_E$. The systematic shift in the height and position of the peak and the trough in the ($dV_E/dt$) profile can be used to identify different microstructural grades of a ferritic steel.

The distortion behaviour depends on the microstructural condition of the sample supporting the influence of variation in the rate of change of permeability associated with different magnetization processes in ferromagnetic samples with different microstructures.

This study shows the good potential of this method of distortion analysis of magnetic excitation for a variety of applications related to material evaluation of ferromagnetic steel components. Further study is required for a better understanding of this phenomenon of distortion of magnetic excitation and its correlation to microstructural and mechanical properties of ferromagnetic materials/components.

Acknowledgments

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