New sensors for measuring $M$ and $H$ in high magnetic fields

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Abstract

Two different small flat pick-up coil (FPC) devices, a flat pick-up coil developed at the TU-Vienna using a thin film technique, and a wire-wound flat pick-up coil commercially available, are compared for the characterization of magnetic materials in high pulsed magnetic fields. The FPC devices allow measuring the local surface magnetization. A small Hall probe to perform local magnetization measurements at high pulse field was also tested. The non-linear dependence of such probe was corrected mathematically and the results were compared with pick-up coils measurements. Magnetic viscosity measurement using the Hall probe is presented.

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1. Introduction

The majority of the measurements for characterizing magnetic materials in high pulsed field magnetometers are done using pick-up coil systems which are wound around the sample [1,2]. It is the aim of this work to present different and new sensors for characterizing magnetic materials in high pulsed fields. The pick-up system for measuring the magnetic moment in a transient field consists of two parts, a sensing device which delivers a signal $u_1(t)\sim(d(H + M))/dt$, and the compensation device which delivers a signal $u_2(t)\sim dH/dt$. Subtracting $u_2(t)$ to $u_1(t)$ gets a signal proportional to $dM/dt$, which is physically relevant.

Fig. 1 shows a diagram of the sample holder, with a sensing device (Si) located at the center of the sample surface and a compensation device (Ci), which is situated 15 mm from the sensing coil in the $z$ direction. The sample should have flat surfaces to guarantee the best sample–sensor coupling. An additional flat pick-up coil device (FPC) (SH) is also attached to register the induced signal of the applied field. Due to its known effective area ($A_{eff}$), the field calibration can be performed using the law of induction [3].
2. The FPCs

A flat pick-up coil developed at the TU-Vienna using a thin film technique (TFC) was designed to measure the surface flux of permanent magnets in a pulse field hysteresograph. A full description of the TFC design and construction is reported elsewhere [4]. The size of the TFC is $3 \times \frac{3}{4} \text{mm}^2$ with $A_{\text{eff}} = 4 \text{cm}^2$. The resistance is about $150 \text{k\Omega}$ and the inductance of the coils is approximately $26 \text{mH}$, which was calculated by the formulas reported by Mohan et al. [5]. The wire-wound flat pick-up coil (WWC)\(^1\) has the following features: diameter $d = 2.5 \text{ mm}$, thickness $h = 0.5 \text{ mm}$, resistance around $100 \text{\Omega}$, $A_{\text{eff}} = 5.5 \text{ cm}^2$, and its inductance $L \sim 43 \mu\text{H}$. In this case the manufacturer provides $A_{\text{eff}}$ for each WWC. The induced signal resulting from the FPC is of a few mV. Electronic compensation was performed using a high input impedance differential amplifier. A zerosignal is always obtained and it can be removed if one stores it on the PC, giving compensation of $10^{-5}$ [6]. Two pulses, one with sample and a second one without sample to register the zerosignal, are necessary to obtain the hysteresis loop of the studied material [6].

Hysteresis measurements at the center of an isotropic Ba–M ferrite sample (HF8/22)\(^2\) with diameter $d = 10 \text{ mm}$ and height $h = 3 \text{ mm}$ were performed using both FPC. Fig. 2 shows the hysteresis loops as obtained with both FPC systems. The hysteresis loop obtained with the TFC system agrees with the one obtained using the WWC system, suggesting that when the TFC system is well compensated the high output resistance of the TFC has no influence in the shape of the loop.

The TFC is very sensitive to capacitance variations due to its high resistance. A small variation of 20 pF between the stray capacitance of the sensing TFC and the compensation TFC could result in a degradation of the resulting hysteresis loop. The electronic recording system is usually connected through long cables due to harsh environmental conditions in pulsed field experiments. Electric simulations were performed using the software Microcap (release 5.0).

Fig. 3 shows the circuit diagram used for the simulation. C1 represents the capacitor battery ($8 \text{ mF}$ with an initial voltage of $400 \text{ V}$) and $L_m$ ($242 \mu\text{H}$) is the magnet. The sensing (s) and the compensation (c) pick-up coils are represented by

\(^1\)The WWC is produced by MAGNET-PHYSIK Dr. Steingroover GmbH, named point coil.

a simple model using an inductor \((L_s, L_c)\), a resistor \((R_s, R_c)\) and a capacitor \((C_s, C_c)\) [7]. The resistors \(R_{in_s}\) and \(R_{in_c}\) (1 M\(\Omega\)) represent the input resistance of the differential amplifier. The coupling factor of the magnet with the sensing coil \((K_1)\) and with the compensation coil \((K_2)\) were chosen the same \((0.00215)\). Three simulations were performed and Table 1 gives the values that were used for each case.

Fig. 4 shows the difference between the voltage of both coils \((L_s, L_c)\) for the three cases. The ideal case represents the condition when both channels have the same stray capacitance’s value. For any value of \(R\), 100 \(\Omega\) and 155 k\(\Omega\) where used in two separate runs, the difference is equal to zero. The WWC case shows that the influence of the capacitance’s values difference is negligible in the resulting voltage difference of both coils. The TFC case shows how small variations in the capacitance values of both channels affect the resulting compensation, and therefore the obtained hysteresis loop. In this case, the most characteristic degradation of the hysteresis loop is that the zerosignal is not reproducible between the two pulses, and it does not give the correct compensation as a result of the capacitance variation between both channels of the compensated TFC system.

The magnetization calibration with the FPC systems is difficult. A non-linear dependence with respect to the volume of the specimen was found. Preliminary studies show a quadratic distance dependence of the induced signal, see Fig. 5, which may be responsible for the complex volume behavior. Studies are still in progress [8].

The field calibration for hysteresis and anisotropy field measurements is performed usually by the metamagnetic transition of a MnF\(_2\) single crystal [9], or by selecting the anisotropy field \((H_A)\) of BaFe\(_{12}\)O\(_{19}\) [1,10]. In this case, the field calibration was performed using the law of induction. These coils have a well known \(A_{eff}\), and the field calibration constant, expressed in T/V s, can be obtained mathematically [3].

Local hysteresis loops as well as anisotropy field \((H_A)\) measurements were performed on Nd–Fe–B and M-type ferrites permanent magnets samples with different dimensions. The small dimensions of the FPC allows measuring local hysteresis loops in large magnetic samples and the eddy current effect

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**Table 1**

Values used for the simulation of the FPC systems

<table>
<thead>
<tr>
<th>Case</th>
<th>(R_s) ((\Omega))</th>
<th>(R_c) ((\Omega))</th>
<th>(C_s) (pF)</th>
<th>(C_c) (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>(R)</td>
<td>(R)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>WWC</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>520</td>
</tr>
<tr>
<td>TFC</td>
<td>155k</td>
<td>155k</td>
<td>500</td>
<td>520</td>
</tr>
</tbody>
</table>
in large conducting magnetic metallic samples, see examples in Ref. [3].

3. The Hall probe

A commercial Hall probe\(^3\) (HP) was used for studying its behavior under pulsed magnetic fields. A compensated Hall probe (CHP) system was designed using two HP. The two HP were connected in series to the same current source (IS) to avoid a current mismatch between both. The HP compared to the pick-up coil is considered a nonlinear device. First tests comparing the characteristic of a HP with that of a pick-up coil in a pulsed system applying fields up to 10 T show small nonlinearities (less than 10\%) at low fields, but also at higher fields. Plotting the Hall voltage over the integrated voltage of an induction coil needs a fit applying the following function:

\[
U_H = c_0 + c_1 U_{\text{ind}} + c_2 U_{\text{ind}}^2 + c_3 U_{\text{ind}}^3. \tag{1}
\]

With (1) the transfer function \(U_H = f(H)\) can be linearized. The CHP system was used to measure the local hysteresis loop at the center of the HF8/22 sample. If the above-described nonlinearity is not corrected, the difference between the shape of the loop using the FPC system and the CHP system is significant, especially close to saturation (of the order of 30\%). However, applying the mathematical correction described in Eq. (1) delivers a reasonable agreement between the two loops as shown in Fig. 6.

The disadvantage of the HP device is that the signal of the here used system is smaller than that of the FPC. Additionally it is nonlinear, which needs a careful correction. This correction function depends on the specific Hall probe but it is also temperature sensitive. There exists also Hall probes which shows better linearity in field ranges up to 30 T. The advantage of a Hall probe system might be that they are nowadays available up to very small sizes of the order of micrometers.

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\(^3\)KSV10 developed by Phillips, with thickness \(t = 1 \text{ mm}\) and diameter \(d = 4 \text{ mm}\).
Another unique advantage is that using a Hall probe allows after applying a field pulse the direct observation of magnetic viscosity effects on hard magnetic materials, see Fig. 7.

4. Conclusions

The FPC open a new way for investigating magnetic materials in high pulsed magnetic fields. The FPC represent a good choice for studying the homogeneity of magnetization at the surface of large technical magnetic samples. The low resistance of the pick-up WWC is an advantage over the pick-up TFC. The TFC is very sensitive to capacitance variations due to its high output resistance. The Hall probe may be used for hysteresis measurements, but careful correction should be done. The Hall probe is a good sensor to measure the magnetization time dependence after applying a pulsed field.

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