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A STRING MAGNETOMETER USING THE METHOD OF SMALL PERTURBATIONS

Subject and Purpose. *The existing interest in nanosized magnetic materials requires equipment for express post-synthesis measurements of magnetic properties of these nanostructures in such a way as to exclude any mechanical displacement of the sample. Although there exist plenty of methods and devices for studying magnetic properties of materials, the development of novel schemes based on the known techniques for examining properties of magnetic nanomaterials, for example magnetic nanopowders, is a hot problem. The measurement equipment of the sort will detect changes in the magnetic properties of materials over time and under the influence of various factors, such as temperature, external magnetic fields, stabilizing substances.*

Method and Methodology. *The developed setup for registering magnetic hysteresis loops is based on the method of small perturbations performed by an alternating magnetic field. The devised scheme combines conventional physical principles of both hysterometers and vibrating-sample magnetometers.*

Results. *With the aid of the developed setup, magnetic hysteresis loops of* $La_{0.775}Sr_{0.225}MnO_3$ *nanopowder have been obtained and compared with the data provided by the well-known technique. A good agreement was observed. The measurement error was 10%.*

Conclusion. *The suggested scheme can be used for the express registration of magnetic hysteresis loops of miscellaneous magnetic materials of various compositions, including nanoscale magnets.*

Keywords: *string magnetometer, magnetic hysteresis loop, magnetic nanoparticles, magnetization.*

The synthesis of novel magnetic materials requires development of tools for examining magnetic properties of these materials. Despite a huge variety of methods [1—6] for magnetometric studies of magnetic materials, most of them are based on the excitation of a small current from the investigated magnetic sample in a small circuit (coil). It is clear that the accuracy and sensitivity of techniques of the kind directly depend on the characteristics of the amplifiers and filters for this current excited. Yet, a possibility exists to raise sensitivity using the resonant methods [1, 6], which is a pressing problem. This has led us to work out schemes for the magnetic hysteresis loop registration with a mechanical vibration string as a measuring element [7—9]. In order to carry out express measurements using a string magnetometer, which makes up the purpose of this work, a laboratory setup based on the method of small perturbations was experimentally realized.

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In the proposed laboratory setup, the principle of vibrating-sample magnetometer [1] is used, where a string like a piece of a metal wire in stressed state plays the role of a vibrating element. A distinctive feature of the developed setup is the use of small perturbations [10, 11] of the studied sample when it is placed in a weak (~ 1 Oe) alternating magnetic field combined with an external constant magnetic field. Under the alternating field action, the magnetic sample performs sinusoidal oscillations. In so far as the sample is tightly bound to the string, the latter performs forced oscillations (self-oscillations) that are registered.

The schematic block diagram of the measuring setup is notable for its relative structural simplicity. Magnetic hysteresis loops of materials are recorded with an accuracy of 0.5 Oe of the magnetic field strength measurements. The developed laboratory setup has the advantage that the detector does not include an electromagnetic circuit, which reduces the electromagnetic interference.

1. Theoretical information

The developed scheme provides the signal $I = dB/dH$ registration by the well-known method of small perturbations. A similar approach is employed, for one, in electron paramagnetic resonance spectroscopy [10]. An alternating magnetic field, **h**, of a small magnitude (< 1 G) acts as a small perturbation. Simultaneously with the small **h** field, a large-value (up to 10 T) magnetic field $\mathbf{H}_0$, constant or slowly varying within 10 T, is applied to the sample, $\mathbf{H}_0 >> \mathbf{h}$. The total magnetic field acting on the sample is

$$\mathbf{H} = \mathbf{H}_0 + \mathbf{h}. \quad (1)$$

The measured dB/dH value approaches zero as the sample reaches its saturation magnetization. The presence of a gradient alternating field **h** causes the mechanical displacement of the test sample. The latter begins its periodic oscillations at the frequency $A_m \cos \Omega t$, where A_m is the amplitude and Ω is the frequency of the mechanical oscillations of the sample. The sample mechanical oscillations caused by the **h** field have the same frequency Ω as the resonance frequency of string oscillations. They are transferred to the string and subsequently converted into electrical or optical oscillations. The useful signal $B(H)$ takes the form

$$B(H) = \int I(H) dH,$$

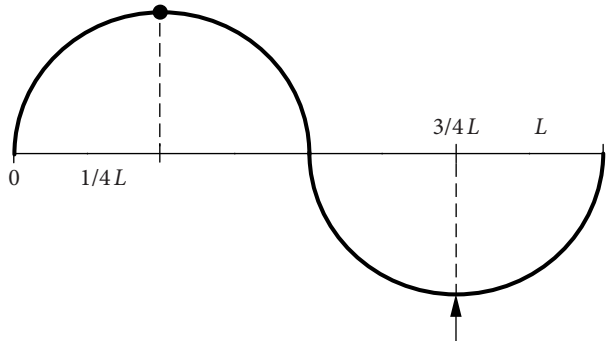

Fig. 1. Graphical representation of the second-mode ($n = 2$) eigenoscillation of the string. The black dot indicates the studied sample position and the arrow indicates the sensor position

where $I(H)$ is the signal amplitude. The frequency of the string oscillations has the generally accepted form [12]

$$\nu = u/2L,$$

where L is the string length and u is the velocity of the wave propagating along the string.

The string is fixed at both ends with tension. Therefore, u depends on the string tension force, T, and the string mass per unit length, ρ [12]. The string is a one-dimensional mechanical-type resonator with resonant oscillations whose wavelength is determined by the string length L. From the wave equation [12], it follows

$$\lambda_n = 2L/n,$$

where n is the oscillation mode (n = 1, 2, 3...).

The wavelength is uniquely related to the frequency whose spectrum is determined by the phase velocity $u = \omega/k = 2\pi\nu \cdot \frac{\lambda}{2\pi} = \nu\lambda$. On the other hand, the rate of solid state oscillations depends on the string tension force T as follows

$$u = \sqrt{T/\rho}.$$

Hence, the eigenoscillation spectrum of the string is given by the formula

$$\nu_n = \frac{\sqrt{T/\rho}}{2L} n.$$

The registration of the useful signal from the sample was carried out at the second ($n = 2$) mode. A gain in the signal amplitude can be obtained by pla-

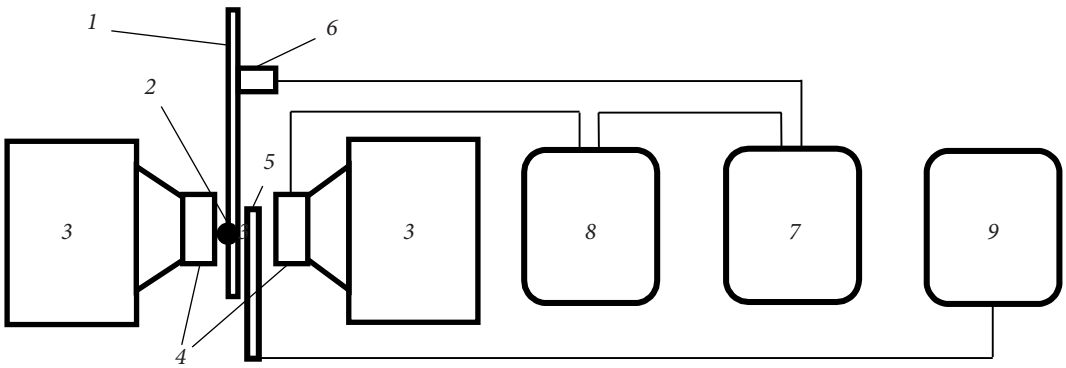

Fig. 2. Schematic block diagram of the measuring setup based on the developed technique: *1* — support bar with a string, *2* — sample, *3* — electromagnet with concentrators, *4* — modulation coils, *5* — magnetic field sensor with amplifier, *6* — vibration sensor, *7* — synchronous detector, *8* — audio frequency generator with amplifier, and *9* — analog-to-digital converter

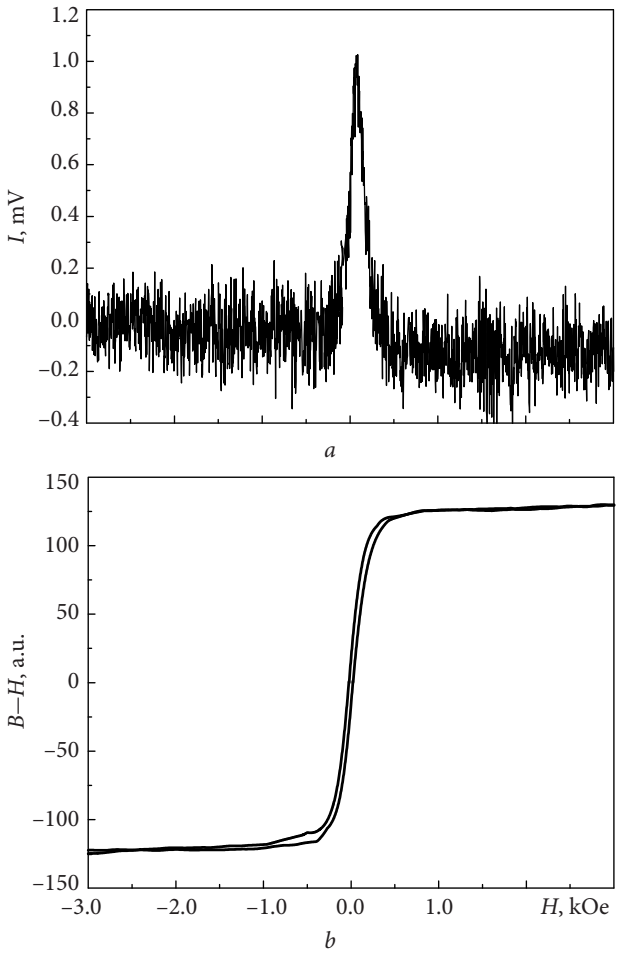

Fig. 3. Signal intensity *I* depending on external magnetic field *H* (*a*) and magnetic hysteresis loop recorded using the developed technique for $La_{0.775}Sr_{0.225}MnO_3$ nanoparticles (*b*)

cing the sample and the sensor at the oscillation antinodes, i.e. at the points corresponding, respectively, to a quarter and three quarters of the length of the string, as shown in Fig. 1.

The function $B(H)$ recorded is proportional to the magnetic induction B [1]. Therefore, the graph of the experimentally obtained function represents a magnetic hysteresis loop of the magnet examined. The normalization of the B value to those of the known magnetic materials makes it possible to get the B values of the studied materials.

2. Experiment and discussion

The developed string magnetometer is based on a support bar carrying a thin wire playing the role of the string. In Fig. 2, studied sample *2* is bound to string *1*. The sample is exposed to the **H** field given by expression (1). The $\mathbf{H}_0$ field is produced by electromagnet *3*, and the field **h** is generated by two coreless induction coils *4* (modulation coils). Magnetic field sensor *5* records **H** field values. Also, string *1* carries vibration sensor *6* that converts mechanical vibrations of the string into the electric response from the sample. The electric response signal enters synchronous detector *7* and personal computer. The reference signal is generated by audio frequency generator *8*. The **H** field value is recorded by the external unit of analog-to-digital converter *9*.

Fig. 3 shows the $I(H)$ dependence in the form of the $B(H)$ derivative. When the sample field reaches its saturation, the signal from the sample almost vanishes (Fig. 3, *a*). The integration of the obtained graph corresponding to (1) restores the magnetic hysteresis loop of the sample (Fig. 3, *b*).

In the experiment, magnetic hysteresis loops were obtained for a studied sample with a known shape of the magnetic hysteresis loop [13], known

coercive force and saturation magnetization. For the studied sample, we took $La_{0.775}Sr_{0.225}MnO_3$ (LSM) nanoparticles synthesized by the method of solid-phase reactions at T = 1 650 °C [13]. The LSM nanoparticles were given a spherical shape with the sample diameter d = 2 mm. The sample was fastened to the string (see Fig. 1). The known values of saturation magnetization and mass make it possible to estimate the sample induction and normalize the measured values.

The registered measurements of the studied sample have shown a good agreement between the shape and value of the coercive force of the hysteresis loops, a measurement error being no worse than 10%. Notice that the measurement accuracy is unlimited and can be significantly improved not only by technical refinements of particular blocks and components but, also, by employing well-known statistical averaging methods, prolongation of each measurement point, etc. Similar methods are used in commercial magnetometers. Obviously, the developed technique does not claim on a high measurement accuracy and does not rank with expensive commercial designs. The main advantage is the availability of express registration of magnetic hysteresis loops of various materials, including nanoscale ones.

Conclusions

A new laboratory setup for the magnetic hysteresis loop registration has been developed and experimentally realized. This technique is applicable for studying magnetic materials, including nanoscale substances. It has been shown that the technique can be applied to both bulky and nanoscale magnetic materials. A structural simplicity and a block-type design allow assembling a string magnetometer with measurement accuracy on request. The obtained measurement results have been compared with the data from the well-known SQUID-magnetometer technique. Their good agreement has been shown. The measurement error keeps within 10%.

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СТРУННИЙ МАГНІТОМЕТР ІЗ ЗАСТОСУВАННЯМ МЕТОДУ МАЛИХ ЗБУРЕНЬ

Предмет і мета роботи. Інтерес виробників наукового обладнання до нанорозмірних магнітних матеріалів вимагає розробки пристроїв для безконтактних експрес-вимірювань їх магнітних властивостей. Незважаючи на безліч відомих методів та пристроїв для вивчення магнітних властивостей наноматеріалів (зокрема, магнітних нанопорошків), розроблення нового устаткування у цій галузі залишається важливим завданням. Такі вимірювальні пристрої дозволять виявляти зміну магнітних властивостей наноматеріалів у часі та під впливом різних факторів — температури, зовнішнього магнітного поля та хімічного впливу стабілізуючих речовин.

Методи і методологія роботи. Принцип роботи розробленого авторами устаткування для отримання петель магнітного гістерезису заснований на методі малих збурень з використанням зовнішнього магнітного поля. Розроблений струнний магнітометр поєднує у собі традиційні фізичні принципи роботи гістерометрів і вібромагнітометрів.

Результати роботи. За допомогою розробленого устаткування автори отримали петлі магнітного гістерезису нанопорошку $La_{0.775}Sr_{0.225}MnO_3$. Порівняльний аналіз результатів експериментальних досліджень і даних, отриманих за відомою методикою, виявив їхню добру узгодженість з похибкою 10 %.

Висновок. Розроблений авторами струнний магнітометр може бути використаний для експрес-реєстрації петель магнітного гістерезису магнітних матеріалів різного складу, у тому числі нанорозмірних магнетиків.

Ключові слова: *струнний магнітометр, петля магнітного гістерезису, намагнічування.*