AC Magnetic Field-Induced Rotation in Levitating Magnetostrictive Wire

C. Luna, V. Raposo, G. Rauscher, and M. Vázquez

***Abstract*—The rotation of magnetostrictive wires under excitation of an alternating axial magnetic field is a phenomenon discovered few years ago. Previous results and a recent mechanical experiment indicate that the appearance of these rotations is related to the sample vibrations associated to magnetoelastic resonance. This surprising behavior is here experimentally reported in polycrystalline FeNi levitating wires. An introductory analysis considering the balance of gravitational, magnetic gradient, and eddy-current forces is additionally carried out.**

***Index Terms*—Magnetic forces, magnetic levitation, magnetoelastic resonance, magnetostriction.**

I. Introduction

MECHANICAL rotation is observed in magnetic wires with high magnetostriction constant under the excitation of axial alternating magnetic fields at suitable conditions. This phenomenon was first reported a few years ago in amorphous wires, which exhibit a simple domain structure [1], [2]. Later, this behavior was detected in wires with crystalline structure [3] and a much more complex domain structure, but always in samples with large enough magnetostriction (positive or negative), as experimentally shown by careful study of this phenomenon in as-cast and annealed FeSiBNbCu wires [4]. Therefore, the ac magnetic field-induced rotation is directly correlated with the magnetostrictive character of the sample. Both the sample length and field frequency dependence of the wire rotation indicate that the appearance of this effect is closely related to the formation of a magnetoelastic standing wave [1]. This rotational effect has been applied in studies of viscosimetry [5] and when a load is fixed to the end of the wire [6].

Similar rotations induced by mechanical vibrations excited by a membrane loudspeaker have been recently reported in magnetostrictive, nonmagnetostrictive, and even nonmagnetic wires [7]. This fact suggests that the mechanical vibrations, induced by magnetoelastic resonance in one case and by the loudspeaker membrane in the other, result in an effective coherent rotation determined by the boundary conditions, such as the friction between the wire and the glass tube holding the wire into the exciting coil.

The objective of this work has been to study this phenomenon in a further step, that is, considering the magnetic forces acting on the wire, placed in a vertical configuration, arising from the nonhomogeneity of the magnetic field created by the exciting solenoid. In this case, the rotation is observed in levitating magnetostrictive wire.

Manuscript received February 6, 2002; revised May 22, 2002.

C. Luna and M. Vázquez are with the Instituto de Ciencia de Materiales de Madrid-CSIC, 28049 Madrid, Spain (e-mail: cluna@icmm.csic.es; mvazquez@icmm.csic.es).

V. Raposo is with the Departamento de Física Aplicada, Universidad de Salamanca, 37008 Salamanca, Spain (e-mail: victor@usal.es).

G. Rauscher is with Vacuumschmelze GmbH, D-63450 Hanau, Germany.

Digital Object Identifier 10.1109/TMAG.2002.802407.

II. Samples and Experimental Techniques

Polycrystalline FeNi (Permenorm 5000H2) wires 3 mm in diameter and commercial NiCr wires 1 mm in diameter were employed in the experiments. The experimental setup for measuring the rotation frequency of wires is shown in Fig. 1. It is based on the measurement of the interference produced by the rotating wire on a laser beam. The wire was placed within a glass tube glued to the inner part of the solenoid generating the exciting ac magnetic field. Further experimental details can be found in [2]–[4]. In the “conventional” experiment, where the wire does not levitate, the solenoid is placed onto a planar glass piece, so that the wire also rests on that glass. A current is fed the coil from a function generator coupled with an amplifier to produce an axial alternating magnetic field.

In the experiment where the wire levitates, the solenoid is held 10 cm above the planar glass. In this case, a “levitation” distance is defined as the distance between the middle points of the coil and the levitating wire (see Fig. 1).

III. Results and Discussion

A. Rotation Without Levitation

The ac field-induced rotation of magnetostrictive wires appears at a spectrum of frequencies for the exciting magnetic field with fundamental and higher harmonics [1], [2]. The inset in Fig. 2 shows the rotational spectrum of the polycrystalline FeNi wire for an ac magnetic field of 15.2 kA/m.

The dependence of the rotation frequency of the wire with the amplitude of the ac exciting field (538 Hz) is plotted in Fig. 2. As observed, there is a very noticeable influence of the ac exciting field amplitude. For the rotation of the wire to be observed, a minimum threshold value is required. In fact, vibrations of the sample are often observed before that occurs. Increasing the amplitude results in an increase of the rotation frequency of the wire until a maximum is reached.

B. Levitation

Levitation of the wire in the vertical configuration, as shown in Fig. 1, is achieved through alternating magnetic force generated by the exciting coil that periodically balances gravitation. A vertical oscillatory motion then results. The magnetic force is $\vec{F}_{\mathrm{mag}} = (\vec{M}\nabla)\vec{B}$, where $\vec{M}$ is the magnetic moment of the

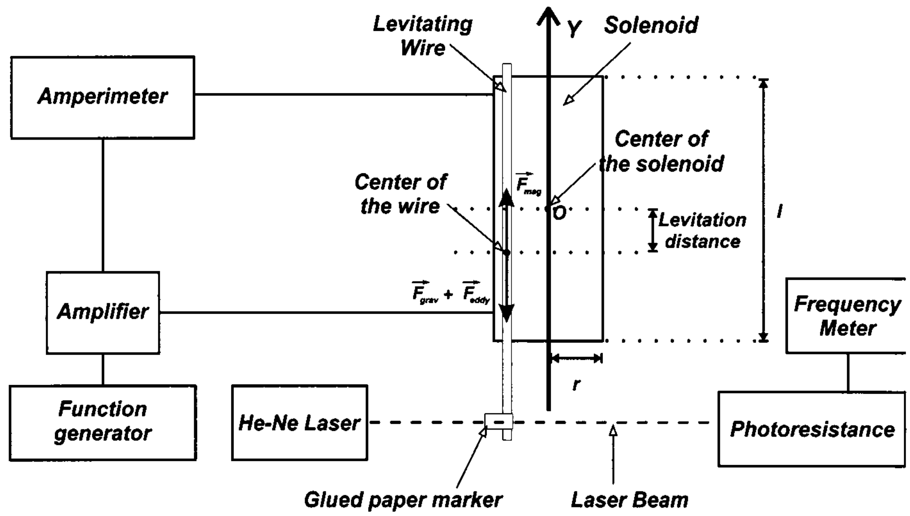

Fig. 1. Schematic diagram of the experimental setup for rotation measurements of levitating wires.

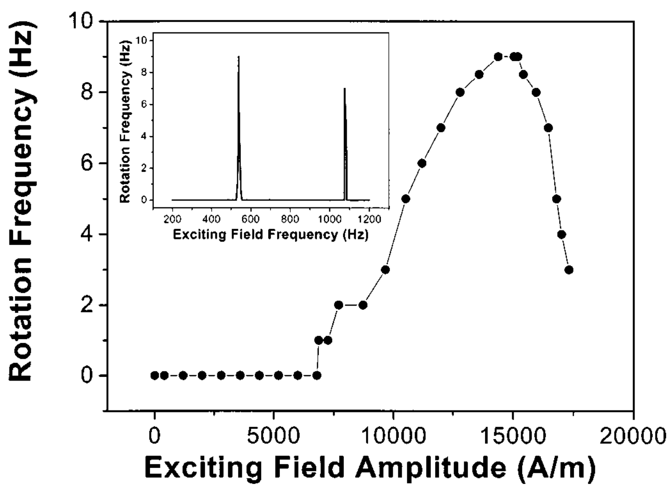

Fig. 2. Dependence of rotation frequency of the FeNi wire on exciting ac field amplitude (field frequency of 538 Hz). The inset shows the rotational spectrum obtained at 15.2 kA/m of the exciting field amplitude.

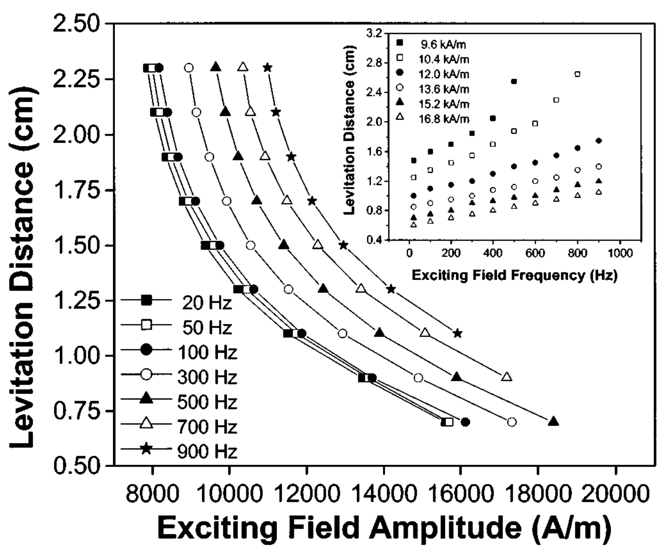

Fig. 3. Levitation distance as a function of amplitude of exciting field for a range of field frequency. Inset shows the dependence of the levitation distance on the exciting field frequency obtained at several values of field amplitude.

sample and $\overrightarrow{B}$ is the magnetic field strength of the solenoid. As a consequence of the nonhomogeneity of the magnetic field at the ends of the solenoid, the generated magnetic force tries to maintain the wire at the center of the solenoid. The magnetic field strength B at the vertical axial coordinate y is

$$B=\frac{\mu_0 n I_0 S_{\mathrm{in}}(2\pi\nu t)}{2l}\left\{\frac{\frac{l}{2}+y}{\sqrt{r^2+\left(\frac{l}{2}+y\right)^2}}+\frac{\frac{l}{2}-y}{\sqrt{r^2+\left(\frac{l}{2}-y\right)^2}}\right\} \tag{1}$$

where n, l, and r are the number of turns, the length and the radius of the solenoid, respectively. The origin of the y coordinate is taken at the middle position of the solenoid. Then, the vertical magnetic force becomes

$$F_{\mathrm{mag}}=\frac{\mu_0 n I_0 S_{\mathrm{in}}(2\pi\nu t)}{2l} M_y\left[G(y)+G(-y)\right] \tag{2}$$

where M_y is the yth component of the magnetic moment of the sample and

$$G(y)=\frac{1}{\sqrt{r^2+\left(\frac{l}{2}+y\right)^2}}-\frac{\left(\frac{l}{2}+y\right)}{\left[r^2+\left(\frac{l}{2}+y\right)^2\right]^{3/2}}. \tag{3}$$

The frequency of the vertical oscillatory displacement of the wire is the same as the exciting field frequency of the magnetic. This can be easily observed by the eye for frequencies in the range of a few hertz. The amplitude of the oscillations decreases as field frequency increases. These oscillations are a consequence of the balance between the magnetic force trying to center the wire at the middle of the solenoid, where $\nabla\overrightarrow{B}$ vanishes and the opposing gravitational force $\overrightarrow{F}_{\mathrm{grav}}=m\overrightarrow{g}$.

Fig. 3 shows the dependence of the levitation distance (between the centers of the solenoid and the wire) on the exciting field amplitude for a range of frequencies. The evolution of the levitation distance on the exciting field frequency is given in the

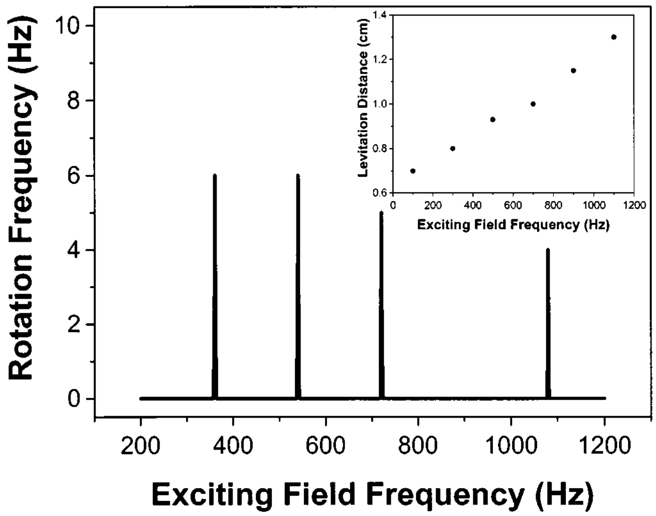

Fig. 4. Spectrum of rotation frequencies for levitating FeNi wire obtained at 15.2 kA/m. Inset shows dependence of the levitation distance on exciting field frequency obtained at 15.2 kA/m.

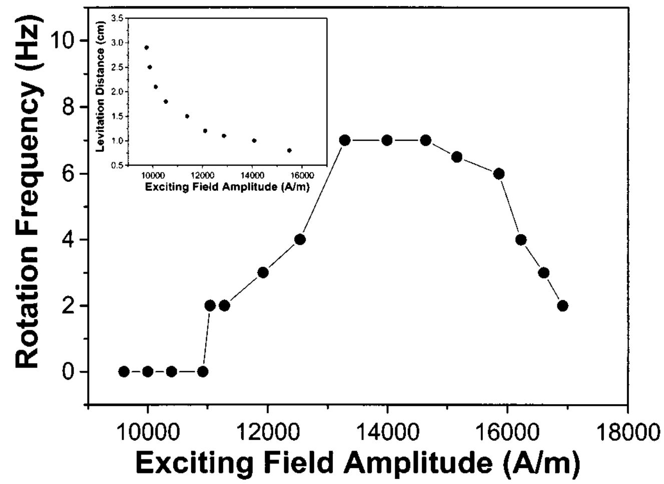

Fig. 5. Rotation frequency dependence on exciting field amplitude for levitating FeNi wire obtained at 541 Hz. Inset shows dependence of the levitation distance on exciting field amplitude obtained at 540 Hz.

inset of Fig. 3, the parameter now being the amplitude of the ac field. This evolution where increasing the frequency results in an increase of the levitation distance should be noted. In order to interpret it, the effect of induced eddy currents should be considered. Therefore, an additional magnetic field $\overrightarrow{H}_{\mathrm{eddy}}$ and force $\overrightarrow{F}_{\mathrm{eddy}}$ are involved in the motion. As $\overrightarrow{F}_{\mathrm{eddy}}$ opposes $\overrightarrow{F}_{\mathrm{mag}}$, the effective magnetic force balancing gravitation is reduced and the levitation distance increases. Experimentally, the presence of such eddy currents is further supported by the detected increase of temperature of the wire. This force arising from eddy currents depends on geometry, resistivity, and permeability of the sample and increases with the frequency of the exciting magnetic field. An additional experiment has been performed on a commercial NiCr wire of which the resistivity is 110 $\mu\Omega \cdot$ cm, larger than that of the FeNi wire (45 $\mu\Omega \cdot$ cm), and the radius and susceptibility are comparatively smaller. In this case, the levitation distance remains constant within the range of the investigated frequencies and the increase of temperature is very modest.

C. Rotation in Levitating Magnetostrictive Wires

Magnetostrictive wires can exhibit both levitation and ac field-induced rotation. The rotational spectrum of levitating FeNi wire for the same field amplitude as that of the inset in Fig. 2 is shown in Fig. 4. Two new resonance peaks are now observed. While for nonlevitating wire, rotation was observed at 538 and 1075 Hz, the four frequencies of the spectrum now observed are 360, 541, 721, and 1080 Hz. Assuming the fundamental frequency were at 180 Hz, the other resonance frequencies would correspond to higher harmonics (nevertheless, no rotation is detected at 900-Hz frequency). The larger number of observed frequencies could be associated with the reduction of the friction in levitation.

Fig. 5 shows the rotation frequency and levitation distance as a function of the amplitude of the exciting field. A similar result as that shown in Fig. 2 is now obtained with a maximum rotation at a given field amplitude. Again, vibrations are observed before a threshold amplitude is reached. Eventually, an increment of the diameter of the glass tube results in stronger transverse vibrations induced by magnetoelastic resonance and the transverse instability of the levitation that finally may not give rise to coherent rotation.

IV. Conclusion

Alternating magnetic field-induced rotation in levitating magnetostrictive wire has been reported. The results can be useful for the development of novel rotor devices.

Acknowledgment

The authors would like to thank Dr. A. P. Zhukov for helpful comments.

References

[1] H. Chiriac, C. S. Marinescu, and T.-A. Ovári, “Large gyromagnetic effect in FeSiB amorphous wires,” *IEEE Trans. Magn.*, vol. 33, pp. 3349–3351, Sept. 1997.

[2] F. J. Castaño, M. Vázquez, D.-X. Chen, M. Tena, C. Prados, E. Pina, A. Hernando, and G. Rivero, “Magneto-mechanical rotation of magnetostrictive amorphous wires,” *Appl. Phys. Lett.*, vol. 75, pp. 2117–2119, 1999.

[3] V. Raposo, T.-A. Ovári, and M. Vázquez, “AC field induced rotation of magnetostrictive nickel wires,” *IEEE Trans. Magn.*, vol. 37, pp. 2705–2707, July 2001.

[4] V. Raposo, A. Mitra, Y. F. Li, and M. Vázquez, “Spontaneous mechanical rotation of as-cast and annealed FeSiBNbCu wires under high-frequency axial AC field,” *J. Phys. D: Appl. Phys.*, vol. 34, pp. 1346–1351, 2001.

[5] M. Vázquez, F. Castaño, T. A. Ovari, V. Raposo, and A. Hernando, “New viscosimeter based on the ac field induced rotation of magnetostrictive amorphous wires,” *Sens. Actuators*, vol. A 91, pp. 112–115, 2001.

[6] T. Sugino, M. Takezawa, T. Honda, and J. Yamasaki, “Basic load characteristics of magnetostrictive amorphous wire micro-rotor,” *IEEE Trans. Magn.*, vol. 37, pp. 2871–2873, July 2001.

[7] V. Raposo, C. Luna, and M. Vázquez, “Rotation in magnetic wire induced by AC field and mechanic vibrations,” *J. Magn. Magn. Mater.*, to be published.