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Y. Brunet, J. Biarrotte, Pascal Tixador. Lateral Damping in a Magnet-High Tc SC System. Journal de Physique III, 1997, 7 (3), pp.609-618. 10.1051/jp3:1997145 . jpa-00249603

HAL Id: jpa-00249603

<https://hal.science/jpa-00249603>

Submitted on 4 Feb 2008

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Lateral Damping in a Magnet-High T_c SC System

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(Received 23 July 1996, revised 25 October 1996, accepted 9 December 1996)

PACS 74.25 Ha – Magnetic properties

PACS.74 60.Ge – Flux pinning, flux creep and flux-line lattice dynamics

PACS 85.25 Ly – Superconducting magnets, magnetic levitation devices

Abstract. — The properties shown by a magnet levitating above a high T_c superconductor pellet can lead to use them in magnetic bearings or other applications such as coupling devices or dampers. The levitation properties and the static stability are well demonstrated but it is not clear if their damping properties are sufficient for applications to avoid any active damping device. The work presented here studies the damping of the oscillations of a magnet above a superconducting pellet, in a pendulum device where displacements and forces are simultaneously measured. Magnet and superconducting pellet dimensions are of the same order. The pulsation of the harmonic motion is governed by the static lateral forces but the damping seems to be dependent on the initial amplitudes. In our configuration, even for the first oscillations, the damping is less efficient than with copper at 77 K, and the small oscillations are quite undamped.

Résumé. — Les propriétés de lévitation entre un aimant permanent et un supraconducteur massif à haute température critique permettent d'envisager leur utilisation dans des paliers magnétiques ou dans d'autres applications (coupleurs, amortisseurs). Si leurs propriétés de lévitation et de stabilité statique sont démontrées, une des clés de leur application est leur stabilité dynamique, qui doit permettre de réaliser des dispositifs entièrement passifs performants. Ce travail présente une étude de l'amortissement à l'aide d'un dispositif permettant de mesurer en même temps les oscillations et les forces entre un aimant vibrant librement au-dessus d'une pastille supraconductrice, les deux éléments ayant des tailles analogues. La pulsation du mouvement harmonique amorti vérifie bien un comportement dans lequel les forces latérales modifient la pulsation propre, les propriétés d'amortissement paraissent non linéaires et dépendent de l'amplitude des oscillations. Dans notre configuration, même en prenant les premières oscillations, l'amortissement est moins performant que celui que l'on obtient avec du cuivre à la même température, et les petites oscillations sont peu amorties.

1. Introduction

The interaction between a high T_c superconductor and a permanent magnet produces large levitation and restoring forces, either in the vertical or in the lateral directions. The major potential application foreseen for this configuration is the magnetic bearing in order to obtain fully passive and stable suspensions.

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Although the stiffness of such configurations is quite large, it is not clear that the dissipative effects are sufficient to provide a good damping of the oscillations. Some authors report very effective damping [1] but for small oscillations the dynamics seem to follow an elastic behaviour.

Many parameters may have an influence on the properties of superconducting levitation: the relative sizes of the magnet and the superconducting pellet, the cooling method (field cooling – FC – or zero-field cooling – ZFC), the structure of the permanent magnet which determines the magnetic field intensity gradients, the properties of the superconducting pellets (texturation) which allow to obtain large J_c and superconducting grain sizes.

The damping itself may depend on several mechanisms involving the motion of the flux lines: flux flow [2], flux creep and flux pinning leading to hysteretic effects explained using the critical-state model of Bean [3] or Kim [4] and dynamic stiffness may depend on the oscillation amplitude [5]. The vibrating reed technique is a powerful tool to study the static and dynamic properties of the flux lines [6]. Some computational approaches [7] have been attempted to correlate experiments and numerical results and reference [8] describes an actuator for controlling the vibration (although the main interest of using superconducting levitation instead of pure magnetic levitation is to allow stable configurations!)

In this paper the impulse response of a vibrating permanent magnet above a superconducting pellet is studied, for FC and ZFC conditions, for different heights of levitation and initial conditions.

2. Experimental Procedure

The experiments are performed with a pendulum apparatus instrumented to give simultaneously the lateral displacement and the vertical and horizontal forces (Fig. 1). The displacement is optically detected and acceleration sensors measure the forces exerted on the nitrogen vessel supporting the superconducting pellet. This vessel is held up by flexible rubber supports in order to lower the friction forces and the differential voltage of the sensors gives a linear relation for the displacement.

The vertical force is obtained with a force sensor located under the nitrogen vessel and the vertical position can be adjusted using a linear potentiometer.

The initial positioning of the magnet with respect to the superconductor is made with two sets of photodiode sensors (not shown in Fig. 1), one in the x -direction and the other in the y -direction, in order to have reproducible results. A platinum resistance has been placed beside the superconducting pellet to control the liquid nitrogen level.

The NdFeB magnet is either cylindrical ($h = 10$ mm, $\varnothing = 22$ mm) or with an alternating polarity configuration [9] but the results presented here have been obtained with the cylindrical magnet, uniaxially magnetized in the vertical direction. The 20 mm thick and 22 mm diameter YBaCuO pellet has been textured in a strong magnetic field to obtain high J_c and large grains [10]. The remanent axial flux mapping shown in Figure 2, obtained using a Hall probe at 0.5 mm above the superconducting pellet, makes visible 4 grains, the larger one with a critical current $J_c \approx B_r/\mu_0 a$ of about 10^7 A m⁻².

As the cylindrical symmetry of our superconducting pellet is not perfect (as it would be the case for a monograin pellet), the amplitude of the lateral forces varies when the pellet is rotated 90° around its axis [11]. When the axis of the magnet is out of line with the magnetic axis of the superconducting pellet, defined by the largest grain, the oscillations are centered on this grain as shown in Figure 3.

The apparatus has been calibrated replacing the superconducting pellet by a cylinder of copper. The restoring forces have been visualized: they are of the order of some 10^{-2} N and they result from the viscous damping of the induced currents. They can be read as $d\theta/dt$

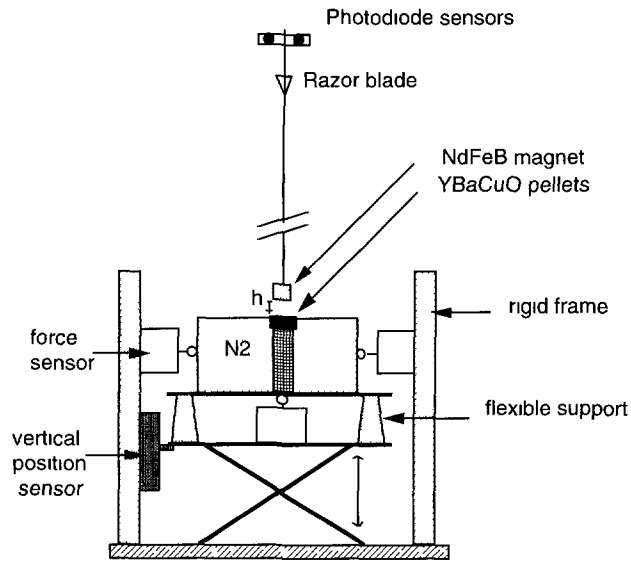


Fig 1. — Experimental arrangement

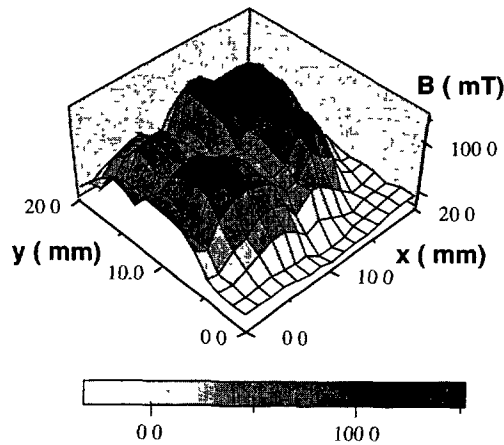


Fig 2 — Remanent axial flux mapping of the YBaCuO Pellet. Vertical axis is in mT and horizontal axes are in mm

contributions (see Eq. (1)) as the signal, although the sensitivity of the force measurements is rather low, looks in quadrature with the displacement (Fig. 4).

3. Experimental Results and Discussion

The amplitude decay of the lateral motion of the magnet initially deviated from a small angle θ_0 is displayed in Figure 3. Although it looks like an usual damped-harmonic system (as for a mass, a spring and a viscous damper), some distinctive characteristics appear:

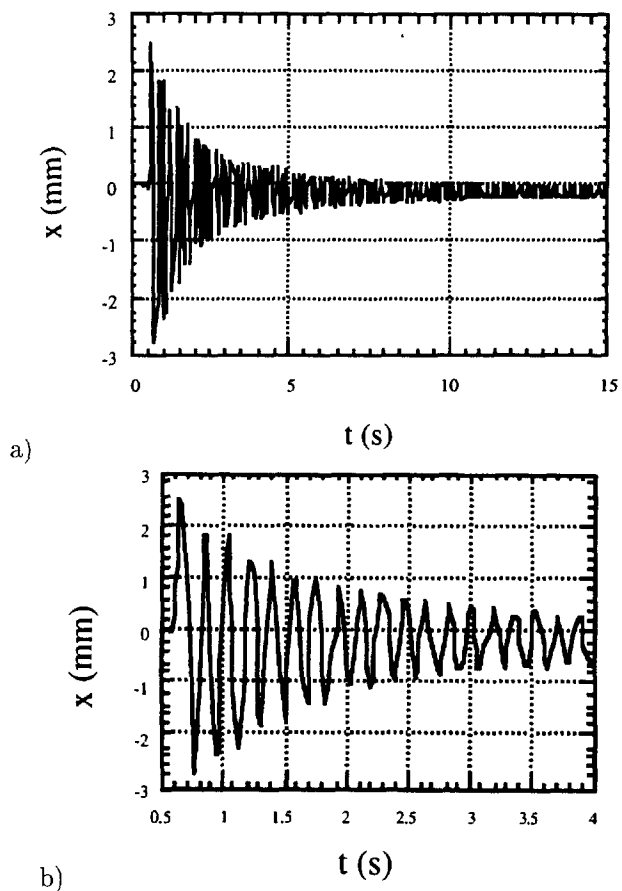


Fig. 3. — Impulse response of the damped free lateral oscillation (FC at $z_0 = h = 6$ mm, so that the vertical force is zero).

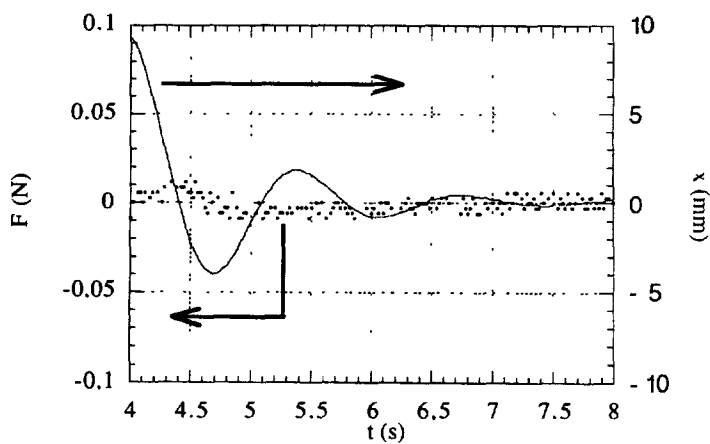


Fig. 4. — Damping and restoring forces for copper at 77 K (the height of levitation, h — see Fig. 1 —, is sufficiently high to give an harmonic behaviour)

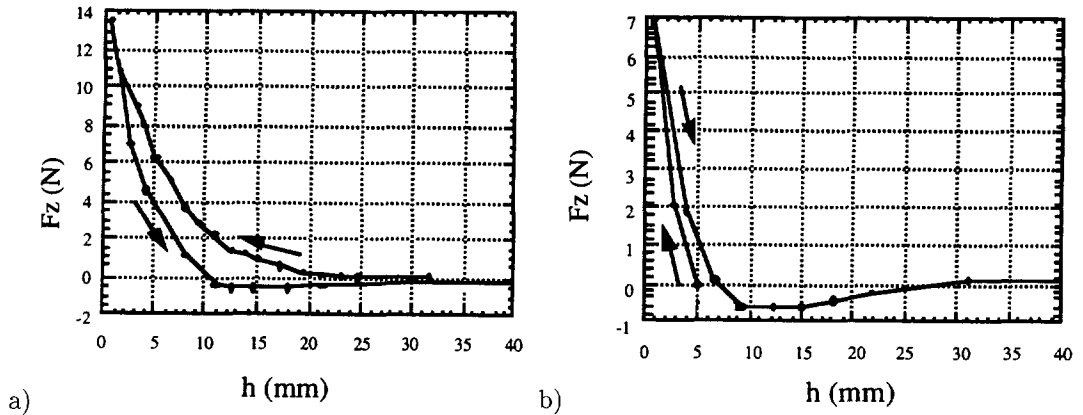


Fig 5 — Vertical forces obtained with the cylindrical magnet and the YBaCuO Pellet. a) ZFC, b) FC. $z_0 = 5$ mm

- if the first oscillations are well damped, the damping turns to be very small for small amplitudes: it remains free oscillations which decay with the natural frequency (background frequency) of the magnet without magnetic interaction with the superconducting pellet ($\tau \approx 30$ s),

- the pulsation of the oscillation waveform remains slightly constant;
 - using different initial lateral deviation, the damping appears to depend on the initial deviation.

Although no systematic measurements have been made rotating the axis of the superconducting pellet, these comportments have been reported for different superconducting pellets and configuration of magnets: reference [9] describes the same damping properties for a coupling device with 6 superconducting pellets and 6 SmCo magnets made of 4 small magnets with alternating polarity.

The interaction of a permanent magnet and a superconductor gives rise to vertical and lateral forces modifying the natural motion of the magnet when moved from its equilibrium position. Assuming small deviations, the torque equation leads to

$$J \frac{d^2\theta}{dt} + k \frac{d\theta}{dt} + (Mg L_g \pm F_z L) \theta + F_x L = 0 \quad (1)$$

where J is the moment of inertia of the moving part, L the length of the pendulum and L_g the position of the center of inertia; F_z and F_x are the static levitation and lateral forces acting on the magnet and k is a viscous-like damping coefficient including air friction and damping torques varying as $d\theta/dt$. As the vertical force can be attractive or repulsive depending for example on the conditions of cooling (Fig. 5), a sign has to be assigned to F_z .

The relation between the lateral restoring force and the displacement depends on the shape of the magnet and on the granular structure of the superconductor. For standard sintered granular superconductor, reference [12] shows a non-linear dependence, but for textured materials, nearly linear shape are reported [1–13] and reference [9] details the relation between the transverse forces and the deviation with the configuration of the magnet. For a cylindrical uniaxial magnet the relation between F_x and x is nearly linear and our measurements confirm this behaviour (Fig. 6).

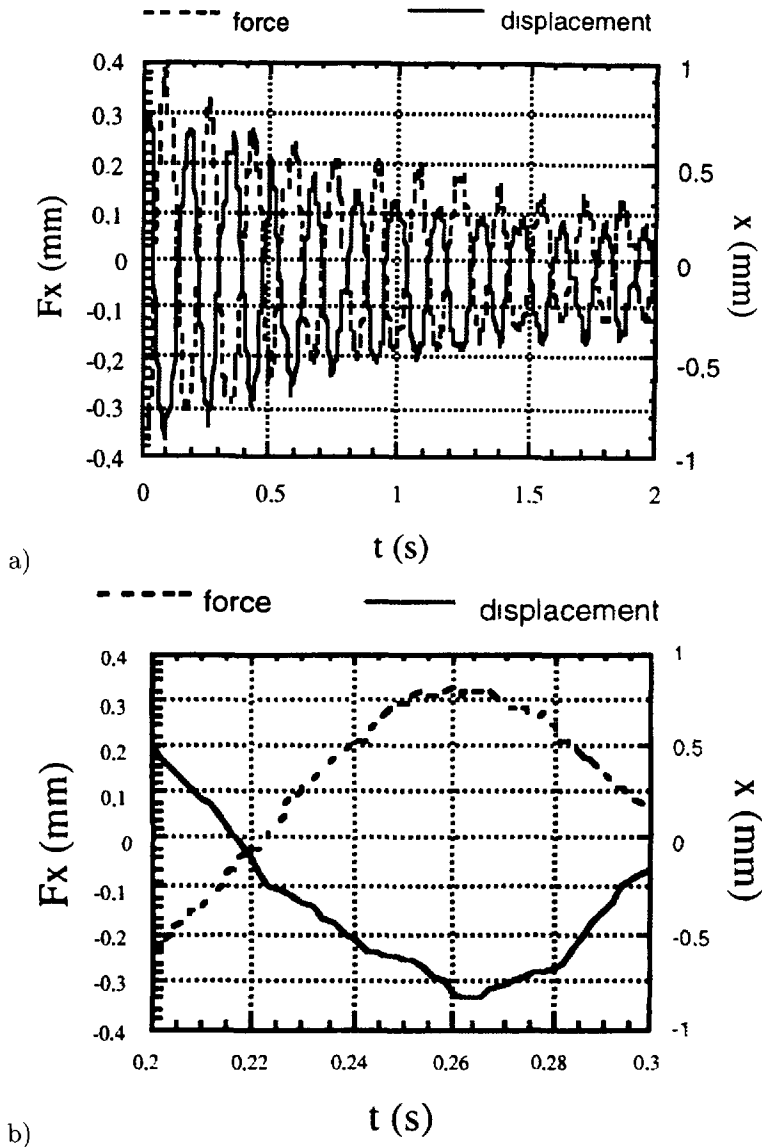


Fig. 6. — Displacement and lateral force for FC conditions ($z_0 = 6$ mm, $h = 4.5$ mm). The enlargement shows that the relation between F_x and x is nearly linear (the sign of F_x has been inverted to have a worth reading figure)

In our experiment, for ZFC and FC conditions, h is maintained so that the weight is not completely compensated by the levitation forces; as these forces are independent of the lateral displacement, the pulsation ω_0 is essentially a function of the lateral restoring force.

In these conditions, the dynamic equation for the magnet may be represented by equation (2):

$$\frac{d^2\theta}{dt^2} + \frac{\omega_0}{Q} \frac{d\theta}{dt} + \omega_0^2\theta = 0 \quad (2)$$

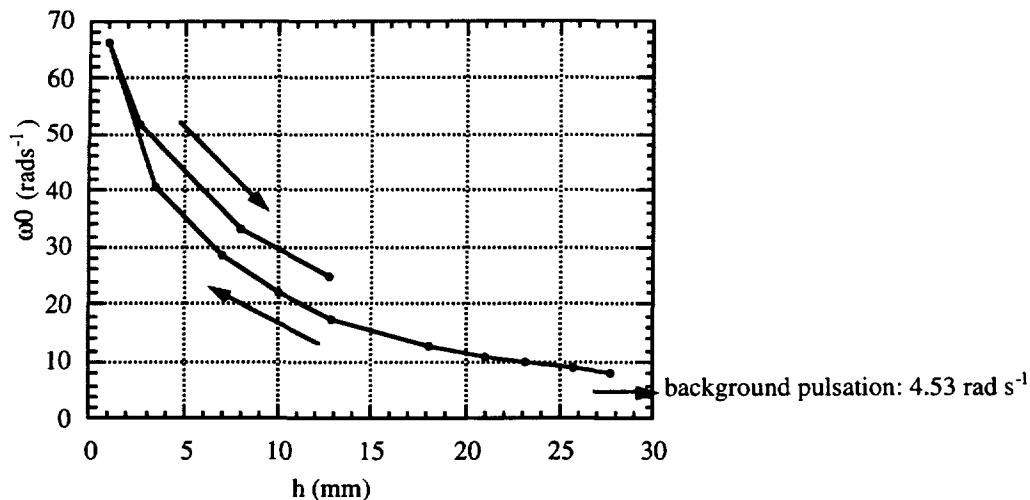


Fig. 7 — Variation of the pulsation ω_0 with the height of levitation (ZFC)

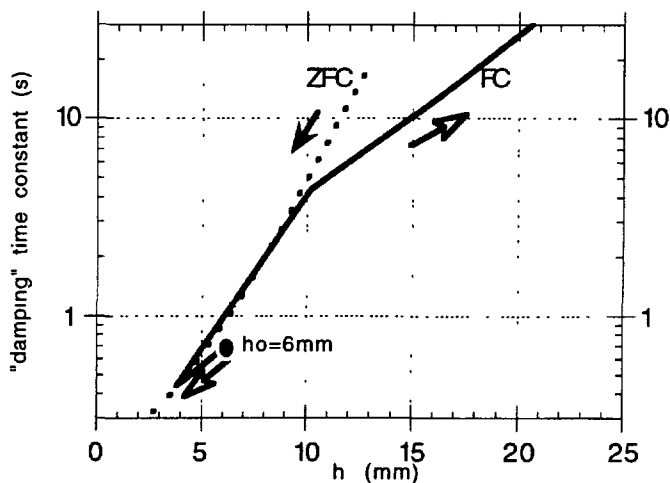


Fig. 8. — Large amplitude damping for FC and ZFC conditions

where Q is the quality factor of the oscillating system. The pulsation ω_0 depends on the lateral static stiffness. As the lateral restoring force decreases quite exponentially with the height of levitation [14] for this field configuration, ω_0 decreases exponentially with h (Fig. 7) and reproduces the hysteretic behaviour of the forces [1].

For large oscillations the damping is effective but decreases with the amplitude. The "damping time constant" measured for large oscillations increases quite exponentially with h , both in field cooling and zero field cooling conditions, but remains in our conditions ≈ 3 times worse than with copper at 77 K (Fig. 8).

Dissipative process such as induced currents or viscous friction cannot explain a time dependent damping. The elastic motion of the flux line, which arises for small deviations [5–15] less

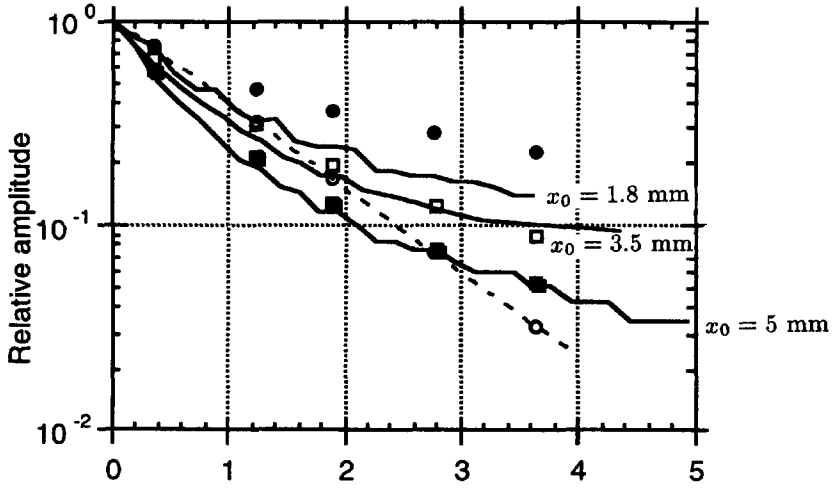


Fig. 9. — Relative variation of the amplitude of the oscillations for different values of the initial impulse (Field Cooling Mode). Experimental results: (—), $x_0 = 1.8, 3.5$ and 5 mm. Numerical results: (—○—), $n = 2$; (●) $n = 3$, $x_0 = 5$ mm, (■) $n = 2.5$; $x_0 = 5$ mm. (□) $n = 2.5$; $x_0 = 2.5$ mm

than $10 \mu\text{m}$, cannot explain the fall in the damping for amplitudes of the order of $300 \mu\text{m}$.

Classical hysteretic damping, where the losses per cycle depend on the square of the amplitude displacement, leads to a time independent damping identical to a system described with the equation (2) which, with linear coefficients and for high Q , gives a dissipated energy per cycle proportional to the square of the deviation amplitude.

When a magnet moves above the superconducting pellet, the lateral restoring force shows some hysteresis [1] and associated losses damp its motion. This hysteretic behaviour of superconductors can be described using the Bean's model [3]: for variations of the magnetic field lower than the full penetration induction B_p , the flux lines motion dissipates [13] as $\frac{1}{J_c} \frac{d[\Delta B]^3}{dt}$, where ΔB is the magnetic field variation at the surface, leading to drag forces varying as ΔB^3 . Assuming a quasi-elliptic hysteresis loop [16] (this assumption is usual for ferromagnetic materials) the losses per cycle are proportional to the square of the maximum displacement.

In order to take into account a non-linear behaviour able to describe our results, we describe the hysteretic power dissipation as $k_d \frac{\theta_{\text{max}}^n}{T}$, where θ_{max} is the later maximum deviation of θ , T being the period of the oscillation and k_d a stiffness coefficient which has to be determined to fit with the experimental results. The associated torque is then $\Gamma_d \approx \varepsilon k_d |\theta_{\text{max}}^{n-1}|$ with $\varepsilon = \text{sign} \frac{d\theta}{dt}$ in order to have a drag torque. Then equation (2) becomes, with a viscous drag constant k_b describing the background viscous damping,

$$\frac{d^2\theta}{dt^2} + \varepsilon k_d |\theta_{\text{max}}^{n-1}| + k_b \frac{d\theta}{dt} + \omega_0^2 \theta = 0 \quad (3)$$

which can be solved numerically for different values of n .

As expected, Figure 9 shows that a value of $n = 2$ gives a time independent damping time constant, which is moreover independent of the initial amplitude. Values of $n \approx 2.5$ give a

good agreement between the experimental and numerical results, both for the dependence on the initial amplitude and for the evolution of the damping with time.

Size effects (magnet and superconducting pellet have nearly the same dimensions) might be important to describe this comportment. In our experiments, the lateral deviations are always smaller (< 15%) than the radius of the superconducting pellet reducing possible edge effects: furthermore, these effects produce destabilising forces and would lead to lower the damping at large amplitude which is the opposite of the measured effects. Others experiments [9] using small magnets with alternating polarity have shown the same shading off of the damping with the oscillation amplitude.

Considering that the losses depends on J_c^{-1} , the presence of several grains in the superconducting pellet may partially explain the damping evolution: for large deviations, the magnet oscillates around the axis of the superconducting pellet, seeing a "mean" J_c value corresponding to the different grains. For small deviations, the magnet oscillates around the axis of the main grain, which has the higher J_c (in our case, see Fig. 2, the highest J_c can be estimated to twice the "mean" J_c): this will lead to smaller losses and to lower damping. As the change of oscillation axis may depend on the dissipative process, this may explain the progressive evolution of the damping with time

More experimental results and a more careful analysis are necessary but it remains that the lateral damping decay with amplitude shown here is an obstacle for the use of superconducting dampers.

Acknowledgments

The authors would like to express their thanks to EPM Matformag for supplying the superconductor pellets.

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