Soft Magnets for Passive Attitude Stabilization of Small Satellites

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The spinning and oscillatory motions of small orbiting satellites can be damped exploiting the magnetic energy dissipation occurring in onboard soft magnetic strips, cyclically excited by the oscillation of the earth field component along their axis. In this paper we investigate the role played by the intrinsic magnetic properties of the material, the aspect ratio of the strips, and their mutual arrangement in achieving maximum energy dissipation under typical spacecraft working conditions. Grain-oriented Fe-Si, mumetal, and Fe-based amorphous alloys, all endowed with near-rectangular hysteresis loops, are considered. Their energy loss behaviour is calculated when, either as single strip samples or arranged into an array of strips, they are subjected to a slowly oscillating magnetic field of defined peak value, emulating the action of the earth magnetic field on the travelling satellite. The strip size and array layout leading to maximum energy loss are predicted. Amorphous alloys, combining high saturation magnetization with flexible hysteresis loop properties, are shown to lead to the best damping behaviour under both oscillating and spinning satellite motions. In the latter case the Fe-Si strips appear to provide comparably high damping effects, while inferior behaviour is always predicted with mumetal samples.

Index Terms—**Demagnetizing field, earth magnetic field, magnetic losses, space vehicle control.**

I. INTRODUCTION

SPACECRAFT orientation can be passively stabilized exploiting environmental forces in orbit, such as magnetic, gravity gradient, aerodynamic or solar pressure torques. These effects provide restoring torque about a prefixed direction and energy damping, thereby reducing the satellite oscillations amplitude and aligning the spacecraft axis with such a direction [1]. It has been proven by flight experience that soft magnetic rods or strips fastened to the satellite can provide this damping [2].

In the last decade interest in passive attitude stabilization has been renewed by widespread development of low Earth orbit scientific and educational micro- and nano-satellites missions, where the spacecrafts have masses ranging between 1 and 10 kg and the onboard resources are very limited [3], [4]. In such satellites a permanent magnet tends to align the spacecraft axis with the Earth’s magnetic field and soft magnetic rods or strips orthogonal to the magnet are exposed to an alternating field (period of the order of 10 - 1000 s) equal to the instantaneous component of the Earth’s field along the rod axis (Fig. 1). The soft magnets consequently provide, through their magnetic hysteresis loss, a frictional torque to the oscillating satellite. The damping performance of this system is a complex function of the intrinsic magnetic properties of the soft magnetic material, the peak field value, the aspect ratio of the strips and their magnetic interactions, with a further constraint imposed by the size of the spacecraft. Its quantitative prediction has not been attempted so far and empirical approaches have been followed regarding the choice of the material and the arrangement of the strips in the design of passive magnetic attitude control systems [3], [5]–[7].

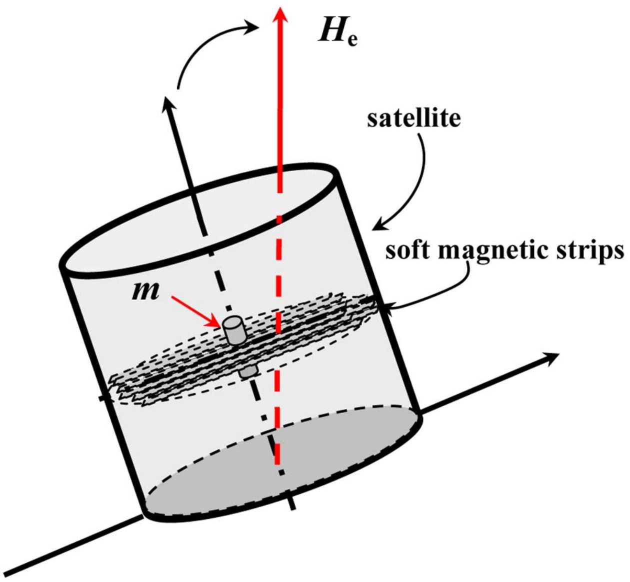

Fig. 1. Schematic arrangement of permanent magnet (moment $\boldsymbol{m}$) and soft magnetic strips in an orbiting satellite. The restoring torque $\boldsymbol{m} \times \mu_0 \boldsymbol{H}_\mathrm{e}$ makes the satellite oscillating around the direction of the earth magnetic field $\boldsymbol{H}_\mathrm{e}$ and magnetic hysteresis in the strips provides frictional torque.

In this work we investigate in theory and experiment the energy dissipation of soft magnetic strips of grain-oriented Fe-Si, mumetal, and Fe-based amorphous alloys under the specific working conditions envisaged for attitude control of small satellites. We predict, for any material, the aspect ratio and the ordered arrangement of the strips leading to maximum energy dissipation. The study first concentrates on the determination of the intrinsic magnetic properties of the employed alloys, namely the initial magnetization curve and the hysteresis energy loss versus the peak polarization J_p. The way they combine with the geometrical features of the individual strips, including the decay of the magnetization along the strip length, in providing the energy loss under a slowly oscillating magnetic field is then investigated. Instrumental in

Manuscript received June 24, 2009; revised September 17, 2009; accepted September 18, 2009. Current version published January 20, 2010. Corresponding author: F. Fiorillo (e-mail: f.fiorillo@inrim.it)

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Digital Object Identifier 10.1109/TMAG.2009.2033345

maximizing the loss is the choice of materials endowed with intrinsic near-rectangular hysteresis loop. With the maximum strip length imposed by the size of the satellite, the degrees of freedom of the problem are, for any material, the width w and thickness d of the strip and the strip-to-strip gap h in the regular array to be housed in the spacecraft. By describing the dipolar interaction between the strips in terms of an equivalent augmented demagnetizing coefficient for each strip, the (w, d, h) set leading to maximum energy dissipation is obtained. Results are presented for peak field strengths $H_{\rm a}$ representative of the satellite spinning ($H_{\rm a} = 20$ A/m) and oscillating ($H_{\rm a} = 5$ A/m) regimes. It is predicted that maximum damping in the oscillating regime does occur with amorphous strip arrays. Under the larger field swing associated with satellite spinning, the Fe-Si grain-oriented strips can exhibit equally good damping properties, while poorer performances are always displayed by mumetal samples, the standard choice for passive attitude stabilization of micro- and nano-satellites [3].

II. Hysteresis Loss in a Soft Magnetic Strip

A first objective of our study is the determination of the dissipative response of individual magnetic strips to a slowly oscillating applied field of given low peak amplitude $H_{\rm a}$, finding out the conditions for maximum loss. It is apparent that extremely soft alloys may have too low losses to deserve interest. The ideal material would be one having, under a closed magnetic configuration, a saturating rectangular loop with coercive field $H_{\rm c} = H_{\rm a}$. But we have to use strips, whose length is imposed by the microsatellite size (200 mm in the present case) and whose aspect ratio, volume, and arrangement influence the total energy loss in a correlated fashion.

We have measured the quasi-static magnetic hysteresis loops ($f = 1$ Hz) from $J_{\rm p} = 10$ mT up to technical saturation in: 1) $\rm Fe_{78}B_{13}Si_9$ and $\rm Fe_{80}B_{10}Si_{10}$ amorphous ribbons (thickness $d = 20$ μm, width $w = 5$–10 mm), annealed under longitudinal saturating field at $T = 360$°C; 2) high-permeability grain-oriented Fe-Si strips, cut along the rolling direction from a 300 μm thick lamination (5 mm $\leq w \leq$ 20 mm), progressively thinned by chemical etching down to minimum thickness $d =$ 50 μm and stress relief annealed at 780°C; 3) mumetal wires of 1 mm^2 square cross-sectional area cut from the parent sheet by an electro-erosion process, annealed in vacuum at 1100°C and rapidly cooled below 700°C. All the prepared samples have length $l = 200$ mm. They are inserted into a 450 mm long solenoid, generating a highly uniform (within 1%) magnetic field over the whole sample length. The time derivative of the magnetic polarization ${\rm d}J/{\rm d}t$ is detected by a compensated 400-turn secondary winding, localized at centre of the strip under test. A supplementary narrow secondary winding can be moved from the center to the end of the strip, in order to measure the decay of the magnetization level. The magnetic hysteresis loops have been measured by a digital calibrated hysteresisgraph-wattmeter [8]. An Agilent 33220A function generator and a 200 VA DC-coupled NF-HSA power amplifier were used to supply the magnetic field. Signal detection, amplification, and analysis were performed using two SR560 low-noise signal amplifiers and a four-channel 14 bit 500 Msample/s TDS 714L oscilloscope.

The measurements were performed on open samples and the intrinsic magnetization curve had to be retrieved from the measured one by determining the effective field $H = H_{\rm a} - H_{\rm dem}$. The demagnetizing field $H_{\rm dem} = (N_{\rm d}/\mu_0)J$ (with μ_0 the magnetic constant) is easily obtained by experiments, because the employed alloys have intrinsic near-rectangular major hysteresis loop and the slope of the measured loop around the coercive field is solely related to the fluxmetric (i.e., at the strip center) demagnetizing coefficient $N_{\rm d}$ [9]. By testing a number of strips with a variety of (w, d) combinations, we find $N_{\rm d} = \eta d$, with the proportionality constant η ranging between $0.125\ m^{-1}$ for $w = 1$ to $1.2\ m^{-1}$ for $w = 20$ mm. Fig. 2 shows the so-obtained intrinsic initial magnetization curves in the four different investigated alloys. The dashed lines represent the demagnetizing relationship $H = H_{\rm a} - (N_{\rm d}/\mu_0)J$, shown in this figure for a wide set of $N_{\rm d}$ values and for a peak applied field $H_{\rm a} = 20$ A/m. In any strip sample with defined w and d (i.e., $N_{\rm d}$ value) the peak values $(H_{\rm p}, J_{\rm p})$ at the strip center are given by the intercept of the magnetization curve with the appropriate demagnetizing line. Fig. 3 shows the measured dependence on $J_{\rm p}$ of the hysteresis energy loss per unit volume $W_{\rm h}(J_{\rm p})$ in the four different investigated soft magnetic alloys. A power law $W_{\rm h}(J_{\rm p}) \propto J_{\rm p}^n$ closely applies in all cases, with the exponent n taking the values: $n = 1.29$ in $\rm Fe_{78}B_{13}Si_9$, $n = 1.43$ in $\rm Fe_{80}B_{10}Si_{10}$, $n = 1.72$ in GO Fe-Si, $n = 1.97$ in mumetal. *Based on this property, we can calculate the energy dissipated in the whole sample starting from the specific loss measured in the mid cross section of the strip.* To this end, we consider the decay of the magnetization from the strip center to the ends. It is experimentally shown that such a decay follows, whatever the material permeability and the strip aspect ratio, the law $J(z)/J(0) = (1 - bz^m)$, where z is the distance from the center. b is a constant and m typically ranges, depending on the material, between 1.5 and 2.5. Applying our knowledge of the $J(z)/J(0)$ behavior to the $W_{\rm h}(J_{\rm p})$ properties shown in Fig. 3, we immediately obtain the specific energy loss averaged over the whole strip under the applied field of peak value $H_{\rm a}$

$$W_{\rm h}(H_{\rm a}, N_{\rm d}) = (2/l) \cdot W_{\rm h}(H_{\rm a}, N_{\rm d}; z = 0) \cdot \int_0^{l/2} (1 - bz^m)^n {\rm d}z. \quad (1)$$

In this equation $W_{\rm h}\ (H_{\rm a}, N_{\rm d}; z = 0)$ represents the specific loss at the center of the strip, obtained as described before, and the exponent n depends, according to Fig. 3, on the type of alloy. Equation (1), applied to the experiments, eventually results in the simple relationship $W_{\rm h}(H_{\rm a}, N_{\rm d}) = k_{\rm w} W_{\rm h}(H_{\rm a}, N_{\rm d}; z = 0)$, with the coefficient $k_{\rm w}$ ranging between 0.55 and 0.65, depending on the material. In view of this weak dependence, we simplify the calculations by taking $k_{\rm w} = 0.60$ everywhere.

We are now in a position to predict the evolution with (w, d) of the total energy loss per cycle $W = W_{\rm h}(H_{\rm a}, N_{\rm d}) \cdot V$ in a strip of volume $V = wdl$ subjected to the oscillating field $H_{\rm a}$. We present in Figs. 4 and 5 two representative results concerning 5 mm wide strips. The two considered field values are intended to emulate the spacecraft oscillating regime ($H_{\rm a} = 5$ A/m) and spinning regime ($H_{\rm a} = 20$ A/m), respectively. It is observed that the energy loss in the strip attains a maximum

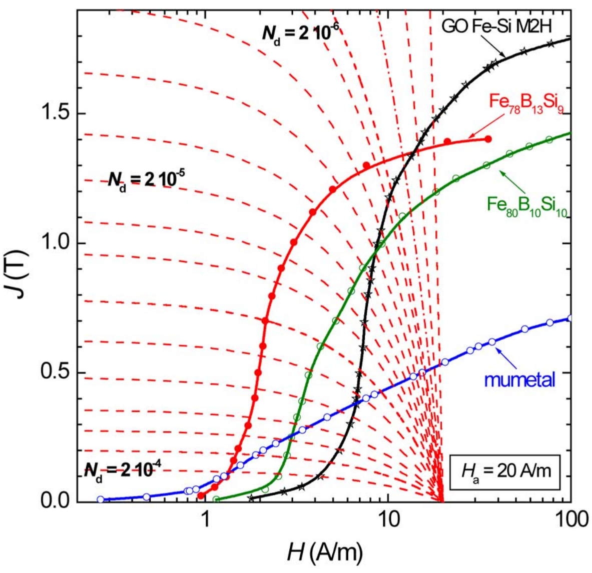

Fig. 2. Initial magnetization curve in the investigated amorphous and crystalline alloys. The J_p value attained at midsection in a strip of defined fluxmetric demagnetization coefficient N_d under the applied field H_a is given by the intersection of the corresponding demagnetizing curve $H = H_\mathrm{a} - (N_\mathrm{d}/\mu_0)J$ (dashed lines) with the magnetization curve.

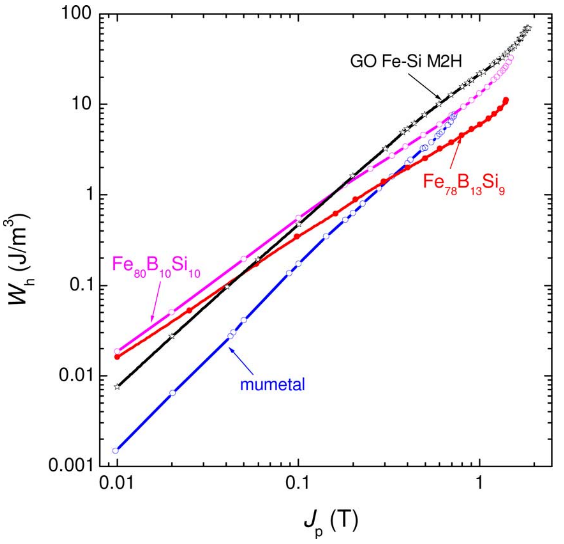

Fig. 3. Hysteresis (quasi-static) energy loss per cycle and unit volume versus peak polarization J_p. It approximately follows the power law $W_\mathrm{h} \propto J_\mathrm{p}^n$, with n ranging between 1.29 ($\mathrm{Fe_{78}B_{13}Si_9}$) and 1.97 (mumetal).

value at a defined thickness d_max, which is predicted to decrease by increasing the strip width. With $H_\mathrm{a} = 5$ A/m the optimal thickness d_max in mumetal passes, for example, from 150 μm for $w = 1$ mm to 20 μm for $w = 10$ mm. It is apparent in Fig. 4 that amorphous ribbons display superior dissipative performances, a role taken up by the GO Fe-Si strips at higher applied fields (Fig. 5). However, high-permeability GO Fe-Si strips do not withstand thinning below $d = 50$ μm without deterioration of their magnetic properties. Special laboratory products, like extra-thin tertiary recrystallized GO Fe-Si laminations [10], might be invoked for this special application.

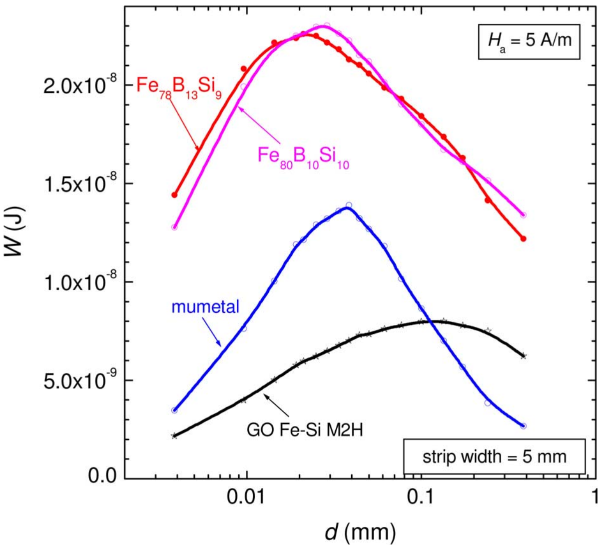

Fig. 4. Predicted total energy loss per cycle versus thickness d of a soft magnetic strip of width $w = 5$ mm subjected to a slowly oscillating field of peak amplitude $H_\mathrm{a} = 5$ A/m.

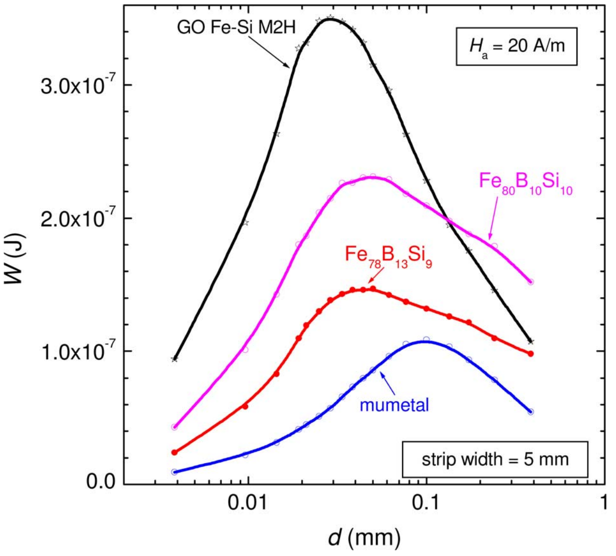

Fig. 5. As in Fig. 4 for an applied oscillating field $H_\mathrm{a} = 20$ A/m.

III. HYSTERESIS LOSS OF AN ARRAY OF STRIPS

The conventional literature approach to passive attitude stabilization by magnetic damping is based on the use of a small number of non-interacting Fe-Ni rods. We show that magnetic damping can be maximized applying regular arrays of interacting soft magnetic strips. Such arrays are to be laid flat on the equatorial plane of the satellite, perpendicular to the pivoting permanent magnet and its field lines (Fig. 1).

The behavior of an infinite (i.e., sufficiently wide) array of identical strips can be reduced to the behavior of an individual strip, subjected to the applied field, its own demagnetizing field, and the magnetostatic interaction with all the other elements of the array. We state that any strip of the quasi-infinite array behaves as if it were alone and endowed with an effective augmented (fluxmetric) demagnetizing coefficient $N_\mathrm{d,eff}$. Taking a strip at $x = 0$, we write $N_\mathrm{d,eff}(x = 0) = N_\mathrm{d} + \sum_i k_\mathrm{d}(x_\mathrm{i})$,

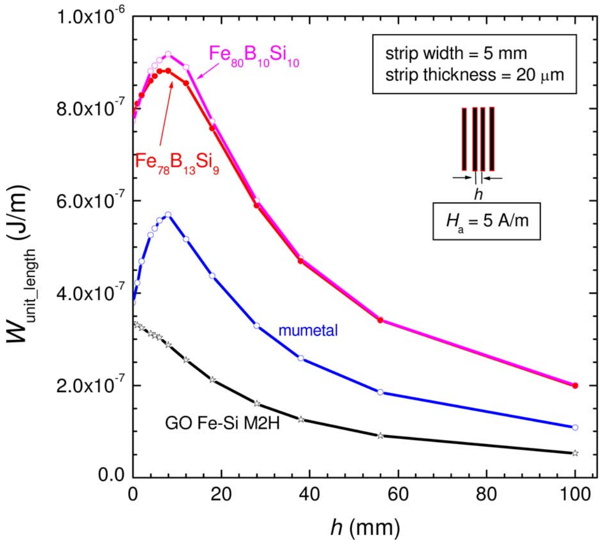

Fig. 6. Energy loss per unit array length calculated for an extended arrangement of 200 mm long, 5 mm wide, and 20 μm thick soft magnetic strips separated by the gap h. Oscillating regime ($H_a = 5$ A/m).

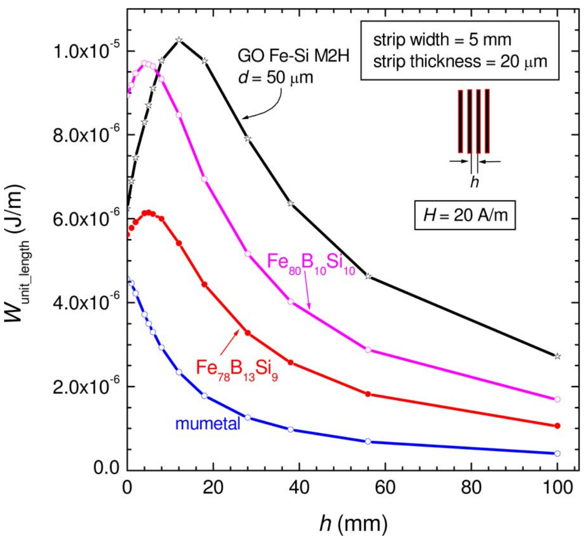

Fig. 7. As in Fig. 6 for an applied field $H_a = 20$ A/m (spinning regime). The practical thickness limit $d = 50$ μm is taken for the GO Fe-Si strips.

where $k_d(x_i)$ plays the role of an additional contribution to N_d generated by the strip located at the coordinate x_i. We express k_d (x_i) in terms of coulombian interaction $k_d(x_i) = \gamma w d \cdot (\beta)/((\beta^2 + x_i^2)^{3/2})$, where the values of the constants γ and β are obtained by direct experiments on an extended array of strips tested in a large diameter solenoid. Having reduced the problem of the array of strips to that of a single strip with augmented demagnetizing coefficient, we repeat the previously illustrated procedure for the calculation of the energy loss and we eventually arrive at finding the arrangement of the strips leading to maximum loss per unit length of the array. Fig. 6 shows that an arrangement of this kind is obtained for the spacecraft oscillating regime ($H_a = 5$ A/m) with an array of 20 μm thick 5 mm wide amorphous ribbons separated by a 10 mm gap. Similar behaviors are obtained with either wider or thicker strips. It is apparent that arranging widely separated strips is far from convenient from the viewpoint of optimizing the damping features of the array. Fig. 7 shows the damping response of the strip array in the spinning regime. The excellent behavior of the array made of 50 μm thick GO Fe-Si strips is put in evidence.

IV. CONCLUSION

Optimal passive stabilization of orbiting micro-satellites can be envisaged by suitable arrangement of onboard soft magnetic strips dissipating magnetic energy during the slow oscillatory and spinning motions of the spacecraft in the earth magnetic field. Maximum energy loss is predicted to occur using an array of suitably spaced Fe-based amorphous strips. The calculations are made starting from the experimental knowledge of the intrinsic magnetization curve and hysteresis energy loss of the investigated soft magnets attuned to the behavior of open strips excited by a slowly oscillating field of defined peak amplitude. The strip aspect ratio leading in different soft magnets to maximum loss is obtained. The transition from the single strip behavior to the many-strip array is treated lumping the effect of the magnetostatic interactions into an equivalent augmented demagnetizing coefficient for the individual strip, to which the problem is correspondingly reduced.

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