Effect of magnetic anisotropy on magnetic shaking

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The effect of magnetic shaking on both the transverse and axial shielding factors (TSF and ASF) is investigated using open-ended cylindrical shields made of Metglas 2705M amorphous ribbons. Shaking enhancement is found to be strongly dependent on the orientation of the magnetic anisotropy of the shielding material, that is, the anisotropy axis should be aligned along the corresponding shielding direction to achieve a greater enhancement of the TSF or ASF. Magnetic shaking provides an ~40-fold increase in the TSF and only an ~twofold increase in the ASF for a shield consisting of a helical structure of the ribbons. The situation is almost completely different if the ribbons' structure is axial: ~twofold increase in the TSF and ~20-fold increase in the ASF. The shaking field intensity (~320 mOe at 1 kHz) for axial shielding is found to be about 10 times larger than that for transverse shielding. Experiments with a three-shell axial structure shield show an ~350-fold increase in the ASF (~40 000, which is one order larger than that of similar conventional shields). The TSF of this shield is, however, about one tenth of its ASF. Reorientation of the ribbons in the innermost shell, from an axial structure to a helical one, increases the total TSF (~50 000) while still maintaining a large ASF (~20 000). Hence, combining shells of helical and axial structures and having a proper distribution of the shielding material between them may allow the construction of an open shield with a large (>20 000) total ASF and TSF. [S0021-8979(99)55608-9]

I. INTRODUCTION

It was shown previously that magnetic shaking dramatically improves the transverse shielding factor of shields employing magnetic materials with a highly rectangular hysteresis loop, such as Meglas 2705M amorphous ribbons.[1] This large effect of magnetic shaking was observed while using open-ended cylindrical shields consisting of a helical structure of Metglas 2705M ribbons [see Fig. 1(a)]. By considering a highly rectangular shape of the hysteresis loop, it may be assumed that Metglas 2705M ribbons possess a uniaxial anisotropy with an easy axis lying along the casting direction. A simple, qualitative model of magnetic shaking suggests that a large enhancement of the permeability and, as a result, the shielding performance of a helical-structure shield exposed to transverse external field, is obtained since the magnetization process in this case is mainly affected by domain-wall motion.[2] On the other hand, a weaker shielding enhancement would be expected when a helical-structure shield is exposed to an axial external field. The external field is perpendicular to the easy axis of the shielding material in this case, and the magnetization process is mainly affected by the rotation of domain magnetization, and domain-wall motion mode plays only a minor role. It is important, however, to confirm quantitatively the above proposition both to provide further support to the existing physical model of magnetic shaking and to develop a new approach for constructing open-ended shields with high transverse and axial shielding performance. For the latter purpose, it is important to investigate how the orientation of the magnetic anisotropy affects the shaking enhancement of the shielding performance.

In this work we investigate the effect of magnetic shaking on both the transverse and axial shielding factors (the TSF and ASF) of magnetic shields consisting of various helical and axial structures of Metglas 2705M amorphous ribbons.

II. EXPERIMENTS WITH SINGLE-SHELL SHIELDS

In our preliminary experiments we used two miniature open-ended cylindrical shields (length, outer diameter, thickness: 50×10×0.2 mm) each consisting of six 50×50 mm squares cut from the amorphous ribbons. These square pieces of the material were wound around cylindrical bobbins in such a way that the ribbon casting direction is perpendicular to the bobbin axis in one shield and is parallel to it in the other. The square shape of the ribbons provides equal amounts of discontinuities for the magnetic flux flowing in the circumferencial direction. The short periphery of the shields with respect to the width of the amorphous ribbon allows us to minimize the number of discontinuities. Discontinuities for the magnetic flux flowing in the axial direction are practically absent since the ribbon squares fit the length of the shields.

Prior to measuring the shielding factors, hysteresis loops were measured with two toroidal coils provided for each of the shields. The shape of the hysteresis loops (see Fig. 2) reveals well-defined uniaxial anisotropy lying along the casting direction. In order to measure enhancement of the TSF and ASF, a 1 kHz magnetic shaking field was applied to the shields by single toroidal coils. The ASF and TSF were mea-

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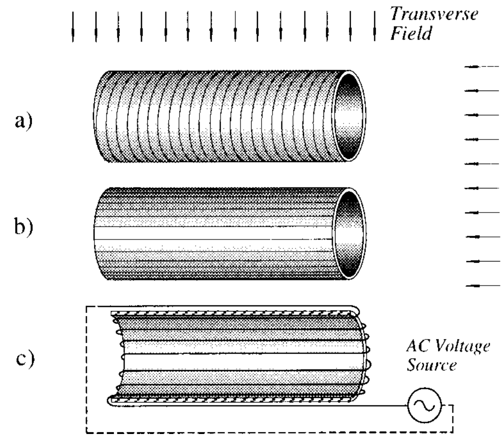

FIG. 1. Open-ended cylindrical shields employing Metglas ribbons. (a) Cylinder consisting of a helical structure of the ribbons. (b) Cylinder consisting of an axial structure of the ribbons. (c) Magnetic shaking by a toroidal coil.

sured at the shield centers by a miniature magnetoresistive sensor of the HMC 1022 type, manufactured by Honeywell. The shielding characteristics measured (the shielding factors versus the shaking field) are shown in Fig. 3 and the ASF and TSF are shown in Table I. In order to investigate the effect of the shaking field direction on shielding enhancement, magnetic shaking by solenoidal coils was also investigated. It was found, however, that shaking by either toroidal or solenoidal coils leads to approximately the same results. In order to minimize the leakage of the shaking field, we used, in the experiments that follow, magnetic shaking by toroidal coils only.

The results in Table I show that the shaking enhancement of the TSF or ASF is strongly dependent on whether the casting direction of the ribbons in the shield structures is oriented along the circumferencial or the axial direction. It provides evidence of the assumption made in Sec. I as to the basis of the existing qualitative model of magnetic shaking and predicts a larger shaking enhancement of shielding performance when the magnetic anisotropy is oriented along a chosen shielding direction. Hence, using a shielding material with the proper structure may be a key to obtaining a large shaking enhancement of transverse or axial shielding performance.

Our experiments that follow using relatively large scale shields also confirm the above statement. Two open-ended

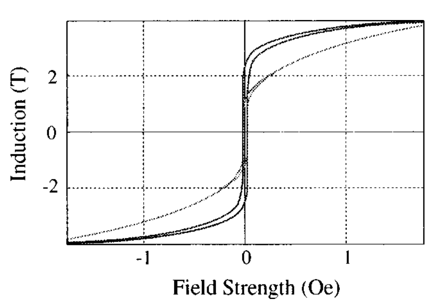

FIG. 2. Anisotropic properties of Metglas 2705M amorphous ribbon. The dark and bright lines correspond to hysteresis loops, which are measured parallel and perpendicular, respectively, to the ribbon length.

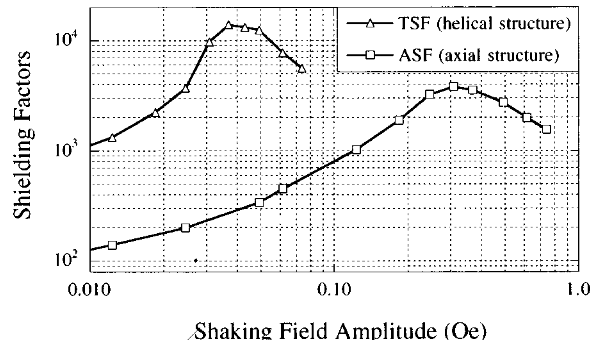

FIG. 3. Shielding characteristics: Transverse and axial shielding factor vs shaking field intensity.

cylindrical shields (length, outer diameter, thickness: 283 ×56×0.31 mm) consisting of helical [Fig. 1(a)] and axial [Fig. 1(b)] structures of Metglas 2705M amorphous ribbons were built for this purpose. The shielding factors were measured at the centers of these shields by a flux-gate magnetometer of the MAG-03 MC type, manufactured by Bartington, and are listed in Table I. The shaking field intensities, corresponding to maximum shaking enhancement of the shielding factors, are approximately equal to corresponding values of the same parameter obtained for miniature shields: ~50 mOe for the TSF and ~320 mOe for the ASF (see Fig. 3). The data in Table I shows that magnetic shaking provides an ~40-fold increase in the TSF and only an ~twofold increase in the ASF with a shield consisting of a helical structure of the ribbons [Fig. 1(a)]. The situation is almost completely different if the ribbons' structure is axial [Fig. 1(b)]: twofold increase in the TSF and ~20-fold increase in the ASF.

III. EXPERIMENTS WITH THREE-SHELL SHIELDS

Our objective is to investigate the axial shielding performance of a narrowly spaced multishell open-ended shield employing magnetic shaking. It is also interesting to compare the ASF of this shield with that provided by conventional high-permeability passive shields.[3] In order to make this comparison, we built a three-concentric-shell shield [Fig. 4(a)] which is an ~1:5 scaled model of an equivalent conventional Mu–metal passive shield.[3,4] To achieve maximum

TABLE I. Application of magnetic shaking to cylindrical shields consisting of different structures of Metglas 2705M ribbons.

Shield structure	TSF without shaking	TSF[a] with shaking	ASF without shaking	ASF[a] with shaking
Helical[b]	270	14 000	110	170
Axial	350	600	70	3800
Helical[c]	85	3800	7.6	17.4
Axial	38	45	64	1170

[a]Shielding factors corresponding to a maximum shaking enhancement are shown. The amplitudes of the external sinusoidal (2 Hz) transverse and axial fields are 0.3 Oe.
[b]Miniature shields.
[c]Large-scale shields.

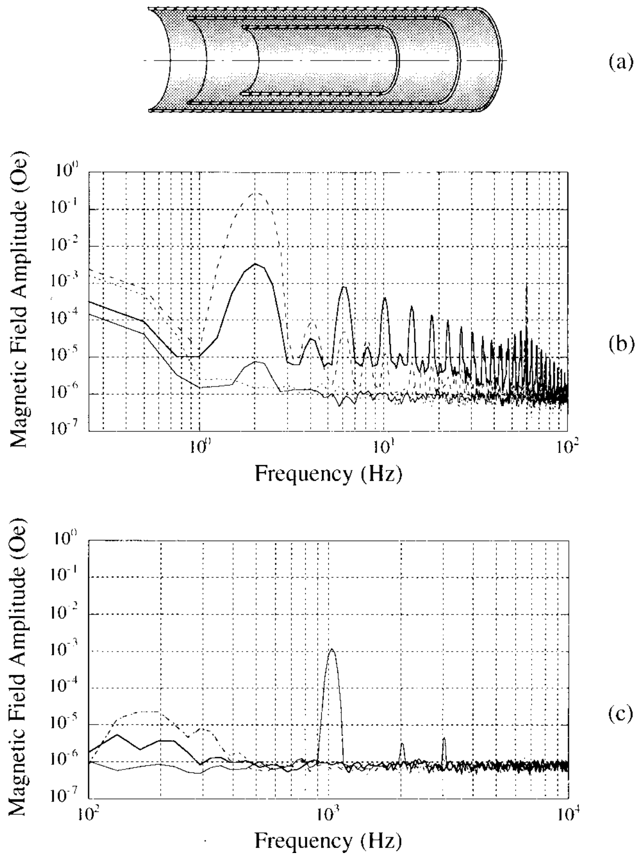

FIG. 4. Spectrograms of the axial field measured at the center of a three-shell cylindrical shield. Dotted lines represent ambient magnetic field. Dashed lines represent a sinusoidal low-frequency (2 Hz) external magnetic field of 0.3 Oe amplitude applied along the shield axis. Thick and thin solid lines, respectively, characterize the magnetic field at the shield center without and with magnetic shaking applied.

shaking enhancement of the ASF, each shell of the shield is provided with an axial structure of Metglas 2705M amorphous ribbons. Table II shows the axial shielding performance for each shell as well as that for the complete three-shell shield. Application of magnetic shaking results in an ~350-fold increase in the total ASF (from ~115 to ~39 800). The total ASF, ~40 000, obtained due to magnetic shaking is one order larger than that, ~4500, of a conventional Mu–metal shield of a similar geometry.[4]

Figures 4(b) and 4(c) demonstrate the effectiveness of magnetic shaking in a relatively wide frequency range. The

TABLE II. Three-shell axial-structure cylindrical shield employing magnetic shaking.

Shell[a]	Diameter (mm)	Length (mm)	ASF[b] without shaking	ASF[b] with shaking
Outer	56	283	54	1170
Middle	53.5	206	61	664
Inner	50	146	57	162
Total			115	39 800

[a]All shells consist of an axial [see Fig. 1(b)] structure of Metglas 2705M ribbons of the same (~0.3 mm) total thickness.
[b]The amplitude of the sinusoidal (2 Hz) external axial field is 0.3 Oe.

dashed lines represent a low-frequency, 2 Hz, sinusoidal external magnetic field applied to the shield. As one can see, the experimental setup for generating external field produces a series of harmonics, which gradually decay from about −70 dBc at 4 Hz to practically zero at 1 kHz. It is interesting that due to the nonlinearity of the shielding material the shield examined in its passive mode, without applying magnetic shaking, amplifies odd harmonics of the external field by a factor of 20–30. It is important to note, however, that employment of magnetic shaking not only dramatically reduces the external field at the carrier frequency (2 Hz) but it also almost completely reduces the harmonics of this field. One can also see from Fig. 4(c) that, although magnetic shaking introduces a leakage of the excitation field, these components can easily be filtered out since they are located relatively far from a low-frequency region where magnetic fields of interest, such as a biomagnetic field, are involved. The leakage of the shaking field can also be effectively suppressed by an additional passive electromagnetic shielding shell placed in the innermost shell of the shield. Moreover, our experiments show that magnetic shaking at higher frequencies, 50 kHz and higher, can also be successfully employed. It enables one to locate leakage field components further away from the low-frequency region of the spectrum and increases the effectiveness of an additional electromagnetic shielding as well.

Investigation of the transverse shielding performance of the designed shield shows a relatively low TSF, one that is about one tenth (~3600) of its ASF. Reorientation of the ribbons in the innermost shell of the shield, from an axial structure to a helical one, results in a larger total TSF (~50 000) while still maintaining a relatively large ASF (~20 000). Hence, combining shells of different structures and having proper distribution of the shielding material between them may allow the construction of an open shield with a large (>20 000) total ASF and TSF.

IV. CONCLUSIONS

The effect of magnetic anisotropy on magnetic shaking is investigated for the first time to the best of our knowledge. It is found that aligning anisotropy axis of Metglas 2705M amorphous ribbons along the desired shielding direction is an important condition for obtaining a strong shaking enhancement of the shielding performance. An optimum shaking field intensity for effective axial shielding is found to be about 10 times larger than that for effective transverse shielding. Experiments with a three-shell axial-structure open-ended shield show an extremely large (~40 000) ASF and about a one order lower TSF. It is shown that by combining shield shells of different structures and by having the proper distribution of the shielding material between them the construction of an open shield with a large (>20 000) total ASF and TSF is possible.

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