Review on “Low-Noise Permalloy Ring-Cores for Fluxgate Magnetometers” by David M. Miles et al.

General Comments

The manuscript is devoted to reproduction and detailed documenting of the manufacturing process of ring-core fluxgate sensors based on Ni81.3-Mo6-Fe soft magnetic alloy. This low-noise material was successfully used as a sensor magnetic core in many science-grade fluxgate magnetometers with excellent offset stability and noise level. The renewed techniques and developed equipment is a good base for further experiments with soft magnetic materials for achieving the goal of creating extremely low-noise fluxgate sensors.
The paper is well prepared and easy to understand.
The authors tried to reproduce the sensor developed by Gordon et al. (1968) and produced by Infinetics Inc. as a S1000 ring-cores till 1996. However, Gordon et al. (1968) paper inspired other research groups (for instance, in Germany and former USSR) to experiment with similar magnetic alloys and they reported even better noise level of fluxgate sensors with smaller cores.
Yu.V. Afanassiev, one of the leaders of these researches in former USSR, collected many useful information on fluxgate magnetometers in his book “Ferrozondovye pribory (Fluxgate instruments)” issued in Russian in 1986 and in English translation as a part of the book “Fluxgate Magnetometers for Space Research” by G. Musmann and Yu. Afanassiev in 2010. In the next section, along with other comments, I will try to give some citations from the latter book, which are highly relevant to the paper content.

Specific Comments

p. 2, l. 13-14, *“A preferred ferromagnetic material used in fluxgate sensors is 6-81 permalloy containing 6% molybdenum, 81.3% nickel, and the remainder iron.”*

Perhaps, the soft magnetic alloy with the similar composition (Ni81Mo6Fe) is produced by Aperam company:
https://www.aperam.com/specialty-alloys-offer/product-categories
https://www.aperam.com/sites/default/files/documents/2018-01/Strip_SUPERMIMPHY_LLS.pdf

If this alloy is commercially available, what are the main reasons to prepare custom-made samples?

In the paper Afanas’ev et al. (1977) noises of the five alloys (79%-83% of Nickel) with low saturation magnetostriction coefficients and different heat treatment modes were analyzed in the rod-cores (130x2.8x0.1 mm) fluxgates. Three of them 83NiV (Ni82.5-

84.2V3.8-4.2Fe), 81NiMo/special (Ni80.5-81.7Mo4.7-5.2Ti2.5-3.2Fe) and 82Ni6Mo (Ni81.0-81.8Mo5.8-6.2Fe) had similar noise levels.

Other examples of the 81-6 Mo permalloy use in fluxgate sensors are given in:

1) Auster et al. (2008):

> "The ring-cores used for Themis have been developed by Karl Heinz Fornacon in Germany for more than 20 years (Müller et al. 1998). The main design goals have always been low noise and offset stability over a wide temperature range and period of time. Material selection and preparation as well as a proper thermal treatment are the key steps to achieve the performance parameters required for the Themis mission. The applied soft-magnetic material, a 13Fe-81Ni-6Mo alloy, is rolled to a foil of 20 µm thickness. Ribbons with a width of 2 mm are cut and 7 turns of it are wound on a bobbin made from Inconel.
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> ...
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> The selection of the ring-cores relies on an extended test procedure. After winding the excitation coil directly onto the ring core bobbins the noise of each ring core is measured before and after a specific aging process which consists of ultra sonic treatment, vibration, and temperature cycling. The sensor noise at 1 Hz of a ring core with a diameter of 13 mm is typically less than 5 pT/√Hz as shown in Fig. 2."

2) Musmann (2010), p. 140-142:

> "...This core is made by winding a thin Permalloy 82NiMo tape of 0.02 mm gauge and 1.5 mm width, polished, degreased and coated with a heat resistant insulation over a metallic bobbin and annealing them together. … The six turns are wound into the groove with constant tension where the end is being fixed to the preceding turn one by spot welding."

The core diameter was 13.2 mm. The sensor droved at the excitation frequency f=12.5 kHz had noise level < 5 pT $Hz^{-1/2}$ at 1 Hz with amplitude of the excitation field 2-2.5 kA m^{-1} and < 3 pT $Hz^{-1/2}$ with 3-3.3 kA m^{-1}. These average results were obtained by testing over 100 specimens.

p. 9, l. 7-9,

"The assembled fluxgate ring-cores were heat treated to produce high-permeability, low-coercivity, and repeatable re-magnetization properties in the ferromagnetic material that the authors hypothesize produced a relatively stress-free crystalline structure and therefore low magnetic noise. This approach was guided by the theory of the origin of fluxgate magnetic noise developed in Narod (2014). The heat treatment was intended to develop the largest possible grains in the given thickness of the permalloy foil without developing undesirable fabric where the easy axes directions are misaligned with respect to the desired magnetizing direction (e.g., Major and Martin, 1970; Odani, 1964)."

Gorobei and Gorobei (1981) experimentally showed that a low-temperature (800 °C) annealing of Nickel-Molybdenum alloys yields lower noise level than a high-temperature (1000, 1150 °C) annealing recommended in Gordon et al. (1968).
Müller et al. (1998) had confirmed this result for alloys Ni81Mo6Fe and Ni80Mo6Fe and showed that the minimal noise level achieved for fine-grained (grain < 13 µm) samples.

p. 6, l. 10-19,

"*The bobbins were manufactured from Inconel x750 that was selected as being non-magnetic and providing high rigidity even at the elevated temperatures of the heat treatment required to optimize the magnetic properties of the ring-core. However, Inconel x750 was a imperfect match to the permalloy sense element in terms of linear thermal expansion (12.6 ppm °C*$^{-1}$ *for Inconel x750, and estimated to be about 11.6 ppm °C*$^{-1}$

for 6-81 permalloy). Properties for the Inconel x750 were taken from the Special Metals Group of Companies data sheet, Unified Numbering System for Metals and Alloys, reference UNS N07750. The immediate impact of the thermal mismatch was differential expansion during the heat treatment leading to a loose fit of the permalloy strip on the bobbin in the final ring-core assembly. The differential expansion may also have enhanced the magnetic noise by introducing mechanical stress during the heat treatment and if the final ring-core assembly was operated over a wide temperature range. This effect has not yet been investigated in detail. For future designs, alternative bobbin materials that are a closer thermal match are being explored."

One of the possible solutions of this problem (matching linear thermal expansion coefficients of a bobbin and a ferromagnetic core) were proposed earlier in Musmann (2010), p. 107, last paragraph:
"… for example the alloy NiMo+X…(non-magnetic alloy with a high specific resistance ρ=1.5 – 1.5 $\Omega mm^2 m^{-1}$, a high melting temperature (1350 °C) and linear expansion coefficient close to that of permalloy ($\alpha=12\cdot10^{-6}\ K^{-1}$))"

Probably the same alloy was mentioned in Afanassiev et al. (1980), where authors proposed to use for core bobbins (instead of Inconel x750) the high resistance Nickel-Molybdenum alloy ($Mo_{22-24}Cr_{2.5-2.9}Al_{1.8-2.2}Ni_{bal}$, НМ23ХЮ in Russian notation) due to its 2-3 times lower magnetic susceptibility and better matching the linear temperature coefficient with that of permalloy.

p. 6, l. 21,

"A custom 4 kg ingot of 6-81 permalloy was created using a vacuum arc furnace to create a 50–50 alloy of molybdenum and nickel and then melting in the remaining constituents in a conventional furnace."

Gordon et al. (1968) used "induction-melting electrolytic iron and nickel in a hydrogen atmosphere, adding molybdenum, and pouring in helium."
What was the reason of using slightly different approach for ingot preparation?

p. 8, l. 1-6,

"*The Permalloy strips were coated with magnesium oxide (an electrical insulator) to prevent the formation of spot welds between layers when the strip was attached by electrical discharge welding, and to prevent the tightly-wound layers from fusing with each other during heat treatments. This insulator was created using an established process (Bill Billingsley Sr, personal communication) from milk of magnesia, MgOH diluted with water to reduce its viscosity and form a consistent thin layer. The strip was dipped, hung up, and allowed to air dry (Figure 8a). During the heat treatment the milk of magnesia residue (Figure 8b) formed a thin but robust layer of magnesium oxide MgO that electrically isolates each layer and minimises eddy currents."*

The other possible insulation coatings were mentioned in Musmann (2010), p. 107, third paragraph from the bottom:
"Before winding, the tape must be degreased and covered by a heat-resistant insulator. These operations are often performed during the winding process. For insulation, electrolysis is applied and the tape is coated with different suspensions.
During electrolysis, an insulating substance being in a suspension state is applied to the tape surface electrostatically. Use is made of different suspensions: silicon dioxide in acetone, magnesium oxide in carbon tetrachloride, ammonium oxide in methyl alcohol and others. The tape in the electrolysis is transported at 1 to 3 m/min. The covering thickness is regulated by changing the speed, the suspension concentration, and the applied voltage."

p. 8, l. 13-20,

"The end of the permalloy strip was spot welded to the bottom of the channel cut into the outer circumference of the bobbin. The strip was cut to length such that the start and end of the strip were aligned. ... The spiral winding was terminated by scraping away a small amount of the oxide layer (Figure 9b) and spot-welding the end of the strip down to the layer immediately underneath (Figure 9c)"

The method of fixing a soft magnetic strip to a bobbin is given in Musmann (2010), p. 155, Section "Ring Core Design and Manufacturing":

"...After etching of the cutting zone the tape is wound (normally 6-12 windings) and fixed on a bobbin. One end of the tape may be fixed on the bobbin using point electrowelding. Then the tape is wound under stress and the end of outer winding is electrowelded to the previous one"

Was the permalloy strip wound with constant tension?

Technical corrections

p. 16, l. 5-11

What were a sample frequency of the analyzed time series and the lowest frequency of the power spectral density estimations?

p. 17, Fig. 19. Histograms for materials "Infinetics 3 µm..." and "This Process 100 µm…" are poorly distinguishable in a grayscale image.

References

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