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Modelling of a Magnetostrictive Torque Sensor

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Abstract— Existing magnetostrictive torque sensor designs typically measure the rotation of the saturation magnetization under an applied torque and their theoretical treatment revolves around the minimization of the free energy equation adapted according to the assumptions considered valid in each design. In the torque measurement design discussed in this paper, Ni-rich NiFe films have been electrodeposited on cylindrical austenitic steel rods. Contrary to existing designs, the excitation field is applied along the axial direction and is low enough to ensure that the resulting magnetization along the same direction remains in the linear region of the M(H) characteristic. Assuming homogeneous magnetization, positive magnetostriction constant λ, negligible hysteresis and demagnetizing fields, torque T may be expressed in terms of an effective uniaxial anisotropy constant Ku around 45° to the axial direction. It is shown, that for the proposed arrangement, the resulting M is the linear superposition of the effect of a torque-induced effective field and the excitation field, the applied field accounts for the vertical offset of the magnetization response and the applied torque increases the slope of the M(H) characteristic.

1. Introduction

The use of magnetostriction in torque sensing has resulted in several interesting designs, their advantage being the inherent contactless measurement: pre-strained amorphous FeSiB magnetostrictive ribbons have been glued around the rotating shaft with excitation and sensing coils placed around the rotating shaft to measure the change of the axial permeability due to the applied torque [1]; a magnetostrictive CoSiB ribbon attached around the shaft has been used with a yoke-type arrangement for the excitation and sensing elements [2,3] in order to pick up the changes in the flux emanating from the ribbon due to the surface stresses induced by the torque; excitation and pick up coil arrangements have been placed around a rotating shaft made of magnetostrictive steel [4] but the arrangement is complicated and the measurement suffers from the high hysteresis of this type of steel; the axial stress-induced magnetization component on a circumferentially pre-magnetized magnetostrictive ring and attached firmly around the rotating shaft [5,6,7] has been measured.

The magnetostrictive torque sensing arrangement presented in this work, utilizes NiFe films, of several microns, electrodeposited on nonmagnetic steel shafts, thus avoiding adhesives or other means of attaching the sensing element on the shaft (Fig. 1).

Static torque is applied on the free end of the shaft. The NiFe film lies inside a solenoid and is magnetized along the axial direction [4] which is also the measurement direction (Fig. 2). A sensing coil wound around the sensing element picks up the changes in axial susceptibility due to the torque induced stress field.

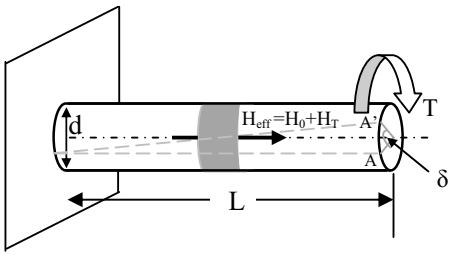

Figure 1 The torque sensing arrangement: The effective field H_{eff} along the axial direction is the sum of the applied field H_0 and the effective torque induced field H_T

This arrangement, contrary to other magnetostrictive torque sensors proposed in the literature [1,7] (i)does not measure the rotation of the magnetization under the effect of the applied torque but the change in

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differential susceptibility in the direction of the applied field, under the effect of the torque-induced effective field, H_{eff} and (ii) must not be saturated but instead it should be operated in the quasi-linear region of the NiFe hysteresis curve under low applied fields.

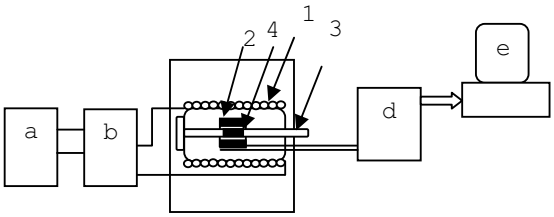

Figure 2 - Experimental setup (a) sine wave generator, (b)amplifier, (c) magnetometer: (1) excitation coil, (2) sensing coil, (3) cylindrical specimen, (4) NiFe magnetostrictive film, (d) data acquisition card, (e) computer

It must be noted, that the proposed sensing arrangement may also be used directly in shafts made of magnetostrictive materials, such as low carbon and martenstitic steels common in boat shafts, as long as hysteresis is compensated for by an appropriate hysteresis model. The sample preparation, measurement procedure and experimental results are briefly overviewed in the following section while the rest of the article presents the modelling of the proposed arrangement as proof of concept and optimization tool.

2. Materials and methods

0.10 m long cylindrical NiFe films were electrodeposited on non magnetic austenitic stainless steel 316L (USA AISI) shafts of 10mm diameter and 0.30 m long [8]. A sinusoidal field is generated inside a long solenoid at the centre of which, where the field is expected to be homogeneous, the electroplated shaft is placed. Compensation coils are wound in series opposition to the sensing coil. Static torque is applied by means of suspended standard weights at the free end of a 0.50 m arm fitted perpendicular to the shaft. Two series of measurements have been carried out with (i) increasing torque, T, at constant excitation field magnitude, H_0 (ii) increasing H_0 at constant T. The voltage waveform induced at the ends of a pickup coil placed around the centre of the NiFe sample is measured via a NI 6251card. Following Faraday's law of induction, the output voltage, *V(t)*, is proportional to the sample's differential susceptibility χ_{diff} (Fig. 2). Figs. 3-4 show the measured peak value of the output voltage V_{peak} for a $Ni_{60}Fe_{40}$ sample. The field axis in Fig. 4 is in arbitrary units (au). V_{peak} is proportional to the maximum slope of the hysteresis curve *M(H)* for this sample:

$$V_{peak} \propto \chi_{diff}(H_0) = \frac{dM}{dH}\Big|_{H_0} \quad (1)$$

where H_0 is the applied field magnitude which sets the operating point in the linear region of the *M(H)* curve. Hysteresis is assumed negligible for this type of material.

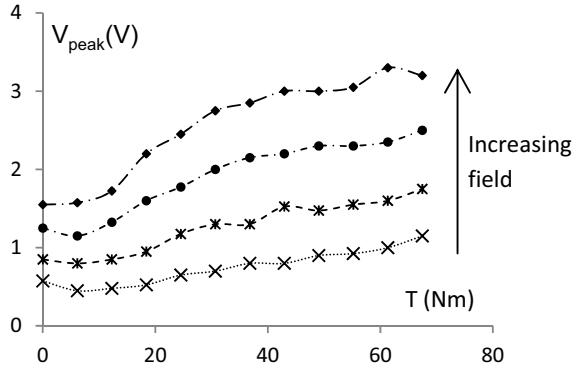

Figure 3 – Output voltage peak, V_{peak}, vs torque T at increasing applied fields.

When torque *T* is applied, the effective field H_{eff} acting on the axial differential susceptibility measured, $\chi_{diff}(H_{eff})$, is the sum of the applied field magnitude H_0 and a torque induced axial component H_T:

$$H_{eff}=H_0+H_T \quad (2)$$

For an applied bias field H_0 such that the resulting *M* is in the linear region of the *M(H)* characteristic, a linear dependence, as the one shown in Fig. 4, may be assumed: $\chi_{diff} = \alpha H_{eff}$, where *a* is the slope of the differential susceptibility field dependence. Then, the resulting V_{peak} increases almost linearly with torque *T* (Fig. 3) for a given applied field H_0:

$$V_{peak}(T)=V(H_0)+k_1T \quad (3)$$

where k_1 is a constant related to the magnetization curve and reflecting the sensitivity of the film at the given operating point.

At constant *T*:

$$V_{peak}(H)=a'H_{eff} \quad (4)$$

a' is the slope of the $\chi_{diff}(H_{eff})$ characteristic for the given *T* (Fig. 4) :

$$a' = a + k_2H_T \quad (5)$$

where k_2 is a constant.

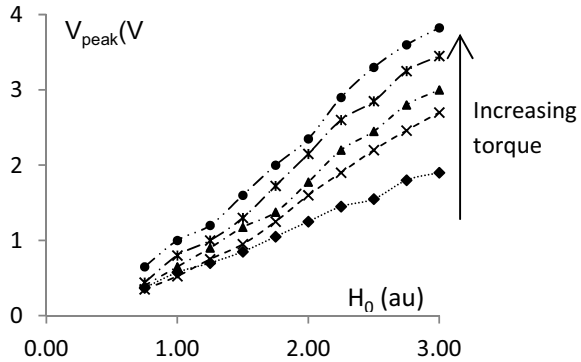

Figure 4– Output voltage peak, V_{peak}, vs applied field H_0 (arbitrary units) at increasing torque levels.

3. Sensor modelling

In the case of a shaft under torque T (Fig.1) with modulus of rigidity G, the surface shear strain ε is proportional to shaft's diameter d and the displacement angle δ and inversely proportional to the shaft's length L:

$$\varepsilon = \frac{d\delta}{2L} \quad (6)$$

The surface shear stress σ is propotrional to the strain ε

$$\sigma = G\varepsilon = G\frac{d\delta}{2L} \quad (7)$$

Torque T is proportional to σ and the polar moment of inertia of the shaft's cross section J and inversely proportional to the diameter d:

$$T = \frac{2}{d}\sigma J \quad (8)$$

Hence, stress and torque are related via:

$$\sigma = \frac{16T}{\pi d^3} \quad (9)$$

The torque related orthogonal stresses σ, as given by (9), induce a uniaxial anisotropy K_u at an angle ϕ, which is close to 45° [1]:

$$K_u = \frac{3}{2}\lambda\sigma = \frac{48}{\pi d^3}\frac{G_{NiFe}}{G_{steel}}\lambda T \quad (10)$$

where λ is the magnetostrictive constant of the sensing element, G_{NiFe} is the modulus of rigidity of the NiFe film deposited on the shaft and G_{steel} is the modulus of rigidity of the steel substrate.

The anisotropy energy term is then written as:

$$E_K = K_u sin^2\theta \quad (11)$$

where θ is the angle of M with the induced easy axis.

The demagnetizing energy term can be ignored in this setup with no loss of generality because the NiFe film is much shorter than the excitation solenoid and immersed at the center of the magnetizing field while the pickup coil is shorter than the NiFe film and positioned around the center of the film. The only other contributing energy term is the applied field energy E_H:

$$E_H = -\boldsymbol{M}\cdot\boldsymbol{H_0} = -MH_0cos(\varphi-\theta) \quad (12)$$

where ϕ is the angle of the applied field H_0 with the induced easy axis.

The minimization of the total energy with respect to θ yields:

$$\frac{dE}{d\theta} = -MHsin(\varphi-\theta) + 2K_u sin\theta cos\theta \quad (13)$$

the solution of which corresponds to the coherent rotation mechanism described by the Stoner-Wohlfarth model.

Next, we define the effective field H_{eff} as the field that satisfies the relationship:

$$-MH_0sin(\varphi-\theta) + 2K_u sin\theta cos\theta = -MH_{eff}sin(\varphi-\theta) \quad (14)$$

Given (2), the torque induced field, H_T, is deduced from (14):

$$H_T = \frac{K_u sin2\theta}{M(cos\varphi sin\theta - sin\varphi cos\theta)} \quad (15)$$

H_T is proportional to the torque induced anisotropy K_u and hence to T, as given by (10), and it depends on the angle ϕ that H_0 forms with the induced easy axis. At $\phi = 0$, *ie* when H_0 is applied at 0° to the easy axis, H_T is maximum, which is consistent with results on other sensor designs based on the maximum rotation of M.

In the absence of torque T, $H_T = 0$, and $H_{eff} = H_0$. In the proposed setup, φ= -45°, *ie* H_0 is applied along the axial direction of the rod and

$$H_{eff} = H_0 + \frac{K_u sin2\theta}{\frac{\sqrt{2}}{2}M(cos\theta - sin\theta)} \quad (16)$$

The dependence of H_T on torque T and the magnetization angle θ is shown in Fig. 5 for various angles ϕ of the applied field H_0 with the torque induced easy axis.

The calculated results shown refer to a $Ni_{60}Fe_{40}$ sample with λ= +2.5 x10^{-5}. The moduli of rigidity are taken to be G_{steel}= 90 x 10^9 N/m^2 and G_{NiFe} =70 x 10^9 N/m^2.

In agreement with the analysis of the experimental data in the previous section, the torque induced field H_T varies proportionally with the torque T. Angle θ controls the slope of the curve and reflects the balance between the applied field E_H, and the torque induced anisotopy energy E_K.

Figure 5 shows the computed dependence of torque induced field H_T on the applied torque for two different applied field angles ϕ.

The proposed modeling approach describes adequately the experimental results. The simplifying assumptions underlying the solution account for the deviations of the experimental results from the linear behavior.

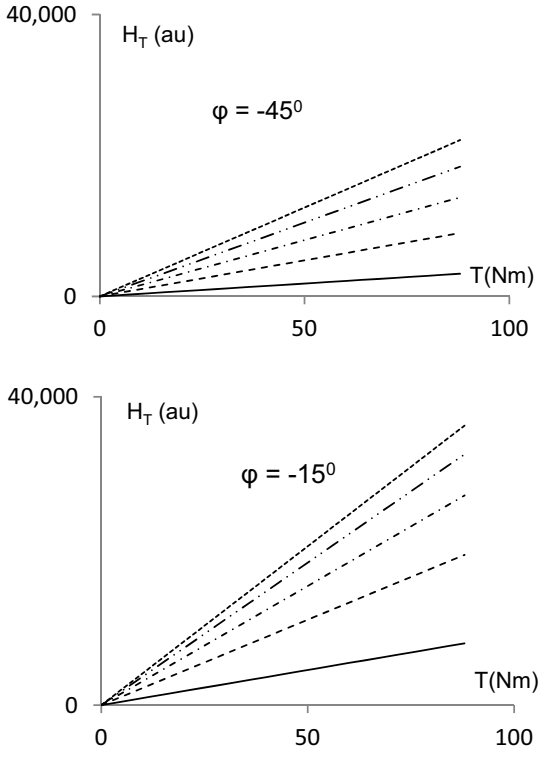

Figure 5 – The dependence of torque induced field H_T on applied torque T for increasing values of θ (solid line corresponds to smallest angle value) and φ=-45^0, -15^0

4. Conclusions

Our theoretical treatment aims in explaining the experimental observations of a torque sensor arrangement which differs from existing designs in the following points: (i) the magnetostrictive film is electrodeposited on the shaft thus avoiding adhesives or other invasive attachment methods (ii) the excitation and the readout of the sensor are both along the axial direction with no need for preprocessing of the magnetic properties of the sensor (iii) the sensor is operated in the linear part of the M(H) away from saturation and therefore low fields are needed (iv) the output does not depend on the readout of the rotation of the magnetization but on the superposition of a torque induced field and the applied field, along the axial direction. The output voltage is proportional to the applied torque. The applied field bias sets the operating point and accounts for the vertical offset of the output voltage. The arrangement can also be used directly on magnetostrictive shafts, as long as hysteresis is compensated.

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