NEW TORQUE SENSORS USING AMORPHOUS MAGNETOSTRICTIVE RIBBONS WITH SLITS

by

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SYNOPSIS

New sensitive torque sensors for motors, automobiles, industrial robots and various rotating machines are presented using amorphous magnetostrictive ribbons. These amorphous ribbons are cut to form a striped pattern and then adhered strongly with an araldite on rotationary shafts. In this case, a pair of amorphous ribbons are fixed on one shaft to set up the angles of the stripes or slits into $\pm 45°$ regarding the shaft axis in each ribbon. These two ribbons are non-contactly inserted in two coils and form two cores. A two-core multivibartor bridge circuit with a dc output is constituted as a sensitive and quick-response torque sensor. Torques of $-0.8 \sim 0.8$ Kg-m are very linearly detected using a 8-mm diameter stainless steel shaft with the nonlinearity and the hysteresis of less than 0.5 %FS.

INTRODUCTION

Torque is one of the most basic varialbles of rotational shaft dynamics in various motors and actuators for their high-performance controls such as the vector controls [1]. However, high performance/cost torque sensors built in these drive systems have not been developed up to now. These sensors should have non-contactness for high reliability, high sensitivity for high signal to noise ratio, high linearity, quick response, high operating temperature such as 130°C for automobile applications, operation with dc voltage sources for matching with microcomputers, and low cost.

In this paper, new high-performance torque sensors are presented using iron-rich amorphous magnetostrictive ribbons [2]. In these torque sensors, a pair of ribbons are cut to introduce some slits and then strongly adhered on a rotationary shaft aligning the slits of each ribbon in parallel with $\pm 45°$ directions regarding the shaft axis, respectively. These two ribbons are non-contactly inserted into two coils, respectively, and form two cores. A two-core multivibrator bridge circuit with a dc output is constituted for sensitive and reliable torque sensor circuit, in which only the stable and non-aging rotational magnetization regions of amorphous ribbons are used. Torque shaft-diameter ratio, T/D of 100 kg are accurately detected with the nonlinearity and the hysteresis of less than 0.5 %FS. A torque sensor with narrow amorphous magnetostrictive ribbons fixed on a rotationary shaft are also reported independently using an ac exciting method [3].

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AMORPHOUS RIBBONS WITH SLITS

Iron-rich amorphous magnetostrictive ribbons have high saturation magnetostriction constant and high permeability. Therefore, their magnetic properties are very sensitive against stresses and strains due to sensitive magnetostriction effects or stress-magnetic effects [5]. When we cut the ribbons into narrow pieces or introduce slits, a shape anisotropy can be introduced in the amorphous ribbons which have isotropic magnetostriction and almost isotropic magnetization.

Fig. 1 shows the effect of slits for square shape amorphous ribbon using $Fe_{81}B_{13.5}Si_{3.5}C_2$ (Hitachi Metals Co.). Variation of 60-Hz BH loops for $H = H_\parallel$ and $H_\perp$ are shown in (a)–(d), where N_S is the number of slits with 1-mm width each. Even one slit gives the specimen the large demagnetizing field H_d $(= -N_d M / \mu_o$; N_d: demagnetizing coefficient, M: magnetization and μ_o: permeability in vaccum) against $H_\perp$ application due to magnetic poles at the slit, and decreases remarkably the normal permeability μ_n as shown in (b). Further decreasing of μ_n with increasing N_s are shown in (c) and (d). Slits with zero width each also remarkably decrease μ_n. Therefore, when we adhere the ribbon on a rotationary shaft aligning the direction of slits to the direction of shearing stress, σ, due to the applied torque T, the positive and negative torques are detected due to the shape anisotropy. That is, when a positive T is applied to the shaft, σ acts as a tensile stress to the ribbon with the slit angle of 45°, while σ acts as a compressive stress to the ribbon with $-45°$.

Fig. 2 represents the experimental apparatus for measuring the change of BH loops of a pair of adhered amorphous slitted ribbons against applied torque. As-prepared $Fe_{81}B_{13.5}Si_{3.5}C_2$ ribbons with 20-mm width and 0.2-mm wide and 3-mm interval slits
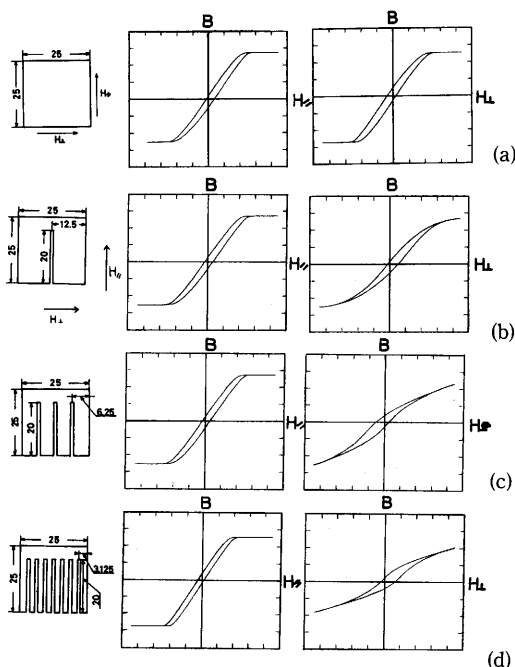

Fig. 1. Effect of slit on BH loops of $Fe_{81}B_{13.5}$ $Si_{3.5}C_2$ amorphous square ribbons.
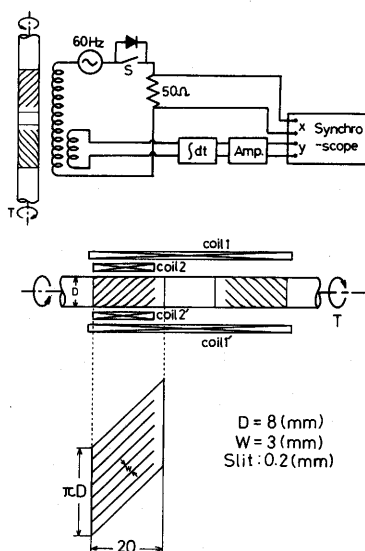
Fig. 2. Experimental apparatus for measuring BH loops of slitted amorphous cores.

adhered around a 8-mm diameter stainless steel shaft. Coil 1–1′ is a exciting coil through which a 60 Hz sinusoidal field H or its rectified $\bar{H}$ are applied in the shaft-axis direction. The coil 2–2′ is the pick-up coil for measuring the ribbon flux in the shaft-axis direction through an integrator. In the left ribbon, a positive and negative torques induce a tensile and a compressive stresses in the slit direction, respectively. Table 1 illustrates the characteristics of as-prepared $Fe_{81}B_{13.5}Si_{3.5}C_2$ ribbons used in the torque sensors.

Fig. 3 shows the 60 Hz BH loops of the left ribbon core in Fig. 2 for H and $\bar{H}$ with the parameter T of 1.0, 0, -1.0 Kg-m. Positive and negative T increases and decreases μ_n, respectively due to the change of magnetization vector rotation and 90° domain rotation against the tensile and compressive stresses. BH loop characteristics against $\bar{H}$ are utilized in the multivibrator type torque sensors as expressed later.

Table 1. Characteristics of as-prepared $Fe_{81}B_{13.5}OSi_{3.5}C_2$ amorphous ribbon

B_s	16.1 kG
B_r	6.7 kG
H_c	0.08 Oe
ρ	125 $\mu\Omega$-cm
T_c	360 °C
T_x	485 °C
σ_{max}	260 kg/mm²
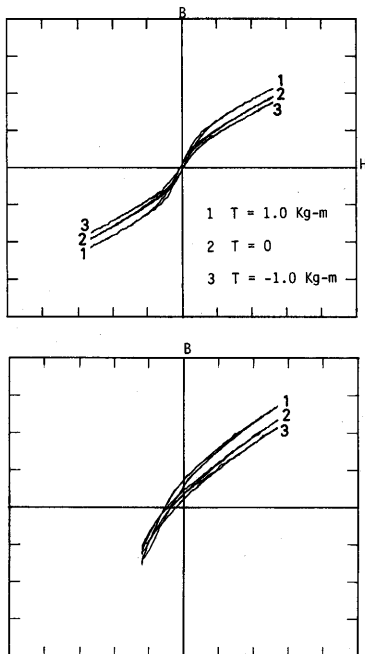
Fig. 3. 60 Hz BH loops of $Fe_{81}B_{13.5}Si_{3.5}C_2$ slitted ribbon cores for application of torque.

$R_b = 2.0$ kΩ $VR_1 = 500$ Ω
$C_b = 10$ μF $VR_2 = 50$ kΩ
$R_L = 10$ Ω $VR_3 = 50$ Ω
$C_L = 47$ μF $VR_4 = 50$ Ω
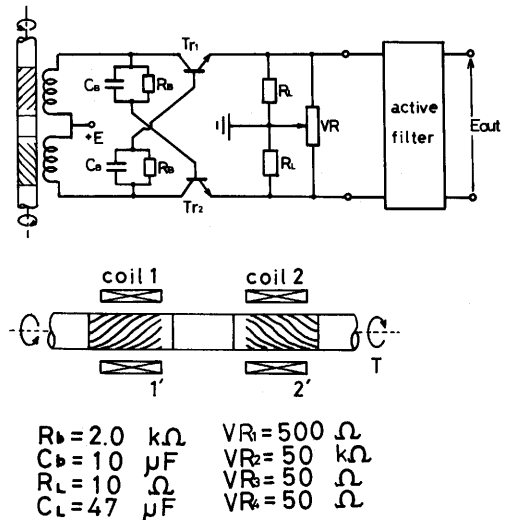
Fig. 4. Torque sensor with two-core multivibrator bridge.

TORQUE SENSOR WITH TWO-CORE MULTIVIBRATOR BRIDGE

Fig. 4 represents the newly constituted torque sensor circuit with two-core multivibrator

bridge. T_{r1} and T_{r2} are the switching transistors, R_b and C_b the commutating elements, R_1s dammy resistors, and VR is the zero adjustive variable resistor. Two cores and two R_1s constitutes a bridge circuit which can accurately detect the discrepancy of the inductances of the two cores when a torque is applied. Two cores are magnetized with one-directional current in each half cycle of the multivibrating self oscillation. In this case, the flux in the two cores vary in the mainly rotational magnetization regions in which amorphous ribbons operate stably and almost zero aging [4]. The oscillation frequency, f_o, of the two-core multivibrator can be easily raised up to several-hundred kHz due to the high electric resistivity of amorphous alloys, and therefore, this torque sensor has the quick-response characteristics. DC output and dc voltage source operation matches with the microcomputers in the torque control systems in "Mechatronics" field.

Fig. 5 shows the experimental results for torque detection using the torque sensor with dc source voltage E of 6 V for T of -0.2–0.2 Kg-m. The number of turn of the two windings, N_w, are 200 each, and f_o is 35 kHz. Very linear characteristics with almost zero hysteresis are obtained.
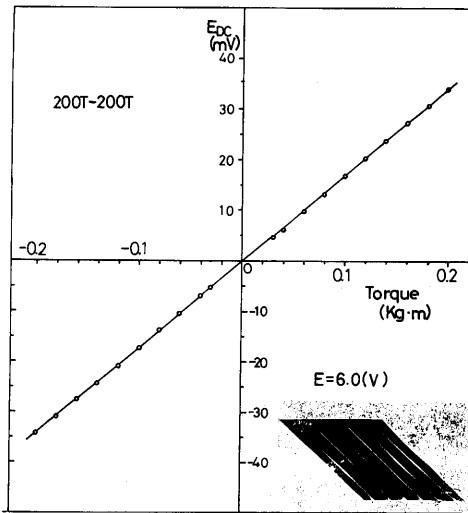

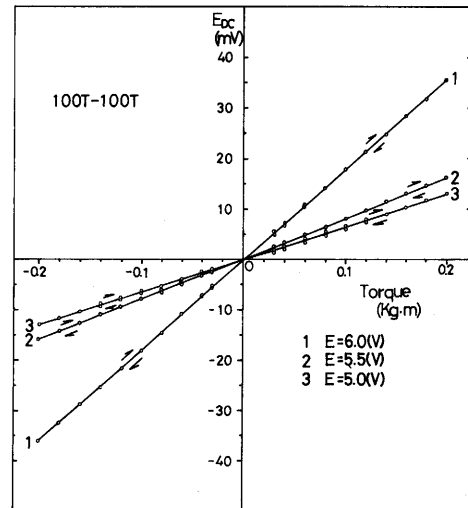Fig. 5. Experimental results for torque detection at E=6 V.

Fig. 6. Experimental results for torque detection.

Fig. 6 illustrates the output voltage of the sensor, E_{dc}, versus T characteristics with $N_w = 100$. E_{dc} increases with increasing E, and hysteresis for three lines are less than 0.5%FS. Values of f_o (and the collector current) are 71 kHz (130 mA) and 139 kHz (38 mA) for E of 6 V and 5 V, respectively.

These accurate and quick response new torque sensors are expected to apply to the mechatronics field such as automobiles, industrial robots, and various power motor drive systems.

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