Bull. Mater. Sci., Vol. 25, No. 6, November 2002, pp. 463–467. © Indian Academy of Sciences.

A novel method for sensing rotational speed, linear displacement and current using superconducting BPSCCO magnetic sensor

T K DEY*, A RAY and S K GHATAK[†]

Cryogenic Engineering Centre, [†]Department of Physics and Meteorology, Indian Institute of Technology, Kharagpur 721 302, India

Abstract. **For many decades, magnetic sensors have been of great assistance to mankind in variety of functions that include simple compass based navigational systems to devices that monitor the invisible biological activities. In industries magnetic sensors are in great demand for control and measurement of linear and rotary position sensing etc, because of its non destructive and contact less way of detection. Consequently, newer, smarter and cheaper materials are continuously being explored to suit the varied needs of technological requirements. In the present communication, the characteristics of a magnetic sensor, based on the non linear electromagnetic response of the weak links present in the polycrystalline BPSCCO superconductor are reported. The second harmonic response of sintered superconducting BPSCCO pellet in an alternating magnetic field at 40 kHz and 77 K being a strong linear function of low d.c. magnetic field has been utilized for the development of highly sensitive magnetic field sensors. The noise limited resolution of the sensor is found to be $3{\cdot}16 \times 10^{-9}$ T/√Hz for $H_{a.c.}$ = 16 Oe and frequency 40 kHz. We further demonstrate that such HTSC based magnetic sensors are capable of sensing the rotational speed, small displacement and direct current with good resolution. The experimental methods and results obtained are discussed.**

Keywords. **Magnetic sensor; superconductor; rotational speed sensor; displacement sensor.**

1. Introduction

The sensors those are in great demand in both the basic research and technological development have been developed to detect physical quantities like pressure, temperature, current, velocity (tachometer, flow meter etc), magnetic field and displacement among many other applications. Magnetic sensors are often preferred in automotive and industrial environments, because they offer several key advantages, viz. contact less measurements of mechanical quantities like angle of rotation, angular speed, and displacement etc. They are robust and inexpensive to fabricate. A majority of these sensors are based on the Hall effect, inductive effect and now-a-days anisotropic magnetoresistance (AMR) and giant magnetoresistance (GMR) effect. However, high temperature superconductors (HTSC) also keep their potential to be used as magnetic sensors. In presence of an alternating magnetic field of frequency (f), the polycrystalline HTSCs generate only the odd harmonics of magnetic susceptibility as coming out of their symmetric magnetization. However, superposition of a small d.c. field breaks this symmetry and brings the appearance of even harmonics. Amplitudes of the even harmonics are found to be a strongly linear function of applied d.c. field (Ghatak *et al* 1992; Khare *et al* 1997; Dey *et al* 1999). The origin of the harmonic generation and its modulation with d.c. magnetic field is explained elsewhere (Xenikos and Lamberger 1990; Muller 1990; Qin and Ong 1999). The observed linear dependence of the amplitude of the second harmonic response with low d.c. magnetic field can be exploited as a highly sensitive magnetic field sensor (Gallop *et al* 1988, 1989; Khare *et al* 1997; Dey *et al* 1999). Magnetic sensors, with the capability of sensing very low magnetic fields are of great technical and commercial significance. Some of the potential areas of applications of such kind of magnetic sensors are the non-destructive evaluation as well as rotational speed, linear displacement, current and cryogen flow sensing. To date a great variety of rotational speed sensors have been developed. Nevertheless numerous problems of measurements still remain open (Kwa and Wolffenbuttel 1991). Recently, Li *et al* (2001) reported an improved MEMS based rotation sensor capable of detecting rotation speed up to 6000 rpm. Similarly, the position sensors, based on different operation mechanisms viz. magneto-resistive (Williumson 1968), Hall effect (Kano *et al* 1990), magneto-inductive (Vertesy *et al* 1990), capacitive (Moore *et al* 1993), eddy current (Vasseur and Villat 1994), have been reported. Current sensing, on the other hand plays an important role especially in automotive applications (Pross *et al* 1999) for power management applications. In the present communication, we report our results on the development of a novel, inexpensive and highly sensitive high T_c based magnetic sensor and

*Author for correspondence

Table 1. The lattice parameters (a, b, c), density of the pellets and slopes of the best linear fit of the V_{2f} vs $H_{d.c.}$ plots for applied a.c. field of different amplitudes and for frequency f = 40 kHz for the three (Bi,Pb)-2223 samples. A (5·5 MPa), B (8 MPa) and C (11 MPa).

					$dV/dH_{d.c.}$ (mV/Oe)			
Sample	a	b	c	Density (g/cc)	$H_{a.c.}$ = 16 Oe	13 Oe	10 Oe	8 Oe
A	5·41	5·41	37·02	5·398	0·72	1·25	1·92	3·16
B	5·4	5·4	37·01	5·531	0·24	0·43	0·68	0·94
C	5·4	5·4	37·01	5·862	0·15	0·27	0·41	0·58

demonstrate its utility for rotational speed, displacement and current sensing. To the best of our knowledge, application of HTSC based magnetic sensor for rotational speed, displacement and current sensing is being reported for the first time.

2. Materials and methods

The BPSCCO sensor used in the present work was prepared from high quality $Bi_{1·6}Pb_{0·4}Sr_2Ca_2Cu_3O_{10+d}$ precursor powder obtained from M/s CAN Superconductors, Czech Republic. The said powder was cold pressed in the form of cylindrical pellets (dia. ~ 12 mm, thickness ~ 4 mm) with pressures of 5·5 MPa, 8 MPa and 11 MPa and was subsequently sintered at 890°C for 6 h in air. The pellet was furnace cooled to room temperature slowly in air. T_c, lattice parameters and the densities of these samples are listed in table 1. The experimental arrangements for characterization of the magnetic sensor are described elsewhere (Dey *et al* 1999).

3. Results and discussion

3.1 *Magnetic field sensing using superconducting BPSCCO*

Figure 1 shows the experimental data in the range 0 < $H_{d.c.}$ < 4 G and the corresponding solid lines represent the best-fit linear relation. The slopes ($dV_{2f}/dH_{d.c.}$) of these linear fits are given in table 1. The rate of increase in the response is found to be higher for higher a.c. field amplitude and higher frequencies. This rate also increases as the density of the sample decreases. The field noise ($\sqrt{S_B}$), or the smallest field change, which could be detected by the sensor, is estimated from,

$$\sqrt{S_B} = [\Delta V/(dV/dH_{d.c.})],$$

where, ΔV is the voltage noise at the output of the lock-in amplifier and ($dV/dH_{d.c.}$) the transfer function of the sensor. The value of ($dV/dH_{d.c.}$) is known from the slope of the linear region of V_{2f} vs $H_{d.c.}$ plots. The highest noise sensitivity ($\sqrt{S_B}$) for our BPSCCO sensor (A) was found to be $3·16 \times 10^{-9}$ T/$\sqrt{\text{Hz}}$. This figure may be compared with the estimated theoretical limit of ~ 10^{-10} T/$\sqrt{\text{Hz}}$ (Gallop *et al* 1989).

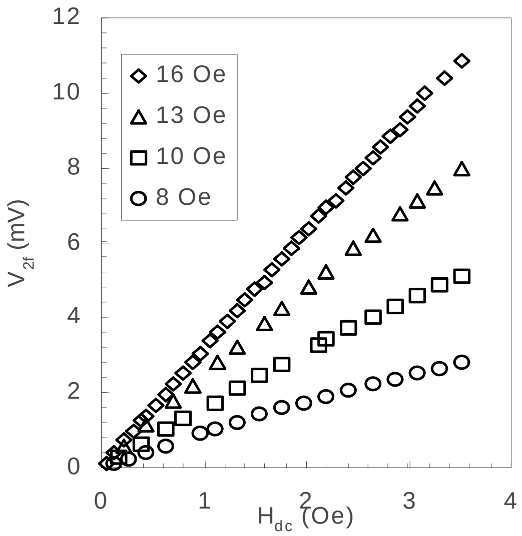

Figure 1. Second harmonic response of the (Bi,Pb)–2223 magnetic sensor as a function of d.c. field between 0 and 4 G at 40 kHz for different a.c. field amplitudes: $H_{a.c.}$ = 8, 10, 13 and 16 Oe.

3.2 *Sensor as rotational speed sensor*

Figure 2(a) shows the experimental arrangement for measuring the rotational speed of a commercial tape recorder motor. A wheel is connected to the motor, over which two small pieces of permanent magnets are attached at the periphery at diametrically opposite points. For every rotation of the wheel, the magnetic flux cuts the sensor twice. A pick up coil (50 turns, 46 swg enameled copper wire) is wound directly on the sample. The second harmonic amplitude of the applied frequency at the primary a.c. coil, induced in the pick up coil is detected by a lock-in-amplifier (Stanford, model SR 830). The output of the lock-in-amplifier is connected to a digital oscilloscope (HP, model 54502A). A frequency counter connected parallel to the oscilloscope reads twice the frequency of oscillation of the $2f$ signal generated in the magnetic sensor. The frequency of rotation of the motor was calibrated using an LDR.

Figures 2(c) and (d) show the typical oscilloscope trace of the output of the lock-in amplifier corresponding to frequencies 750 rpm and 1980 rpm. Since the distribution and intensity of the magnetic field lines from the magnet pieces was not exactly identical, pure square wave pattern was not observed. It may be seen from figure 2(b) that the rpm estimated using the $2f$ signal when plotted with the calibrated speed of rotation of the motor, results in a linear plot with a slope of 45° which proves the exact correspondence between the actual speed of rotation of the motor and that obtained using the present $2f$ based HTSC magnetic sensor.

3.3 *Sensor as a displacement sensor*

The experimental set-up for the measurement of small displacement of a ferrite piece relative to the position of the sensor is shown in figure 3(a). The object that undergoes displacement is attached with a small piece of permanent magnet. As the proximity of the object and the sensor is closer, the density of magnetic flux that crosses the sensor increases. This in turn increases the induced second harmonic signal. Figure 3b shows the measured $2f$ amplitude when the object is vertically moved slowly away from the sensor. A linear response between the displacement and $2f$ is clearly evident up to ~ 3 mm. However, beyond this, the field profile of the magnet becomes nonlinear and the intensity rapidly decreases and the $2f$ signal becomes hardly detectable. The sensitivity of the present HTSC displacement sensor is close to 1 μm.

3.4 *Direct current sensing with the magnetic sensor*

For the current sensing application, the current to be detected is allowed to pass through a small solenoid with 200 turns of 40 swg copper wire kept just below the liquid N_2 dewar as shown in figure 4(a). The passage of direct current through the monitoring solenoid causes the generation of d.c. magnetic field and the sensor in turn generates the $2f$ signal. A linear response of the $2f$ amplitude as a function of sensing current is as shown in

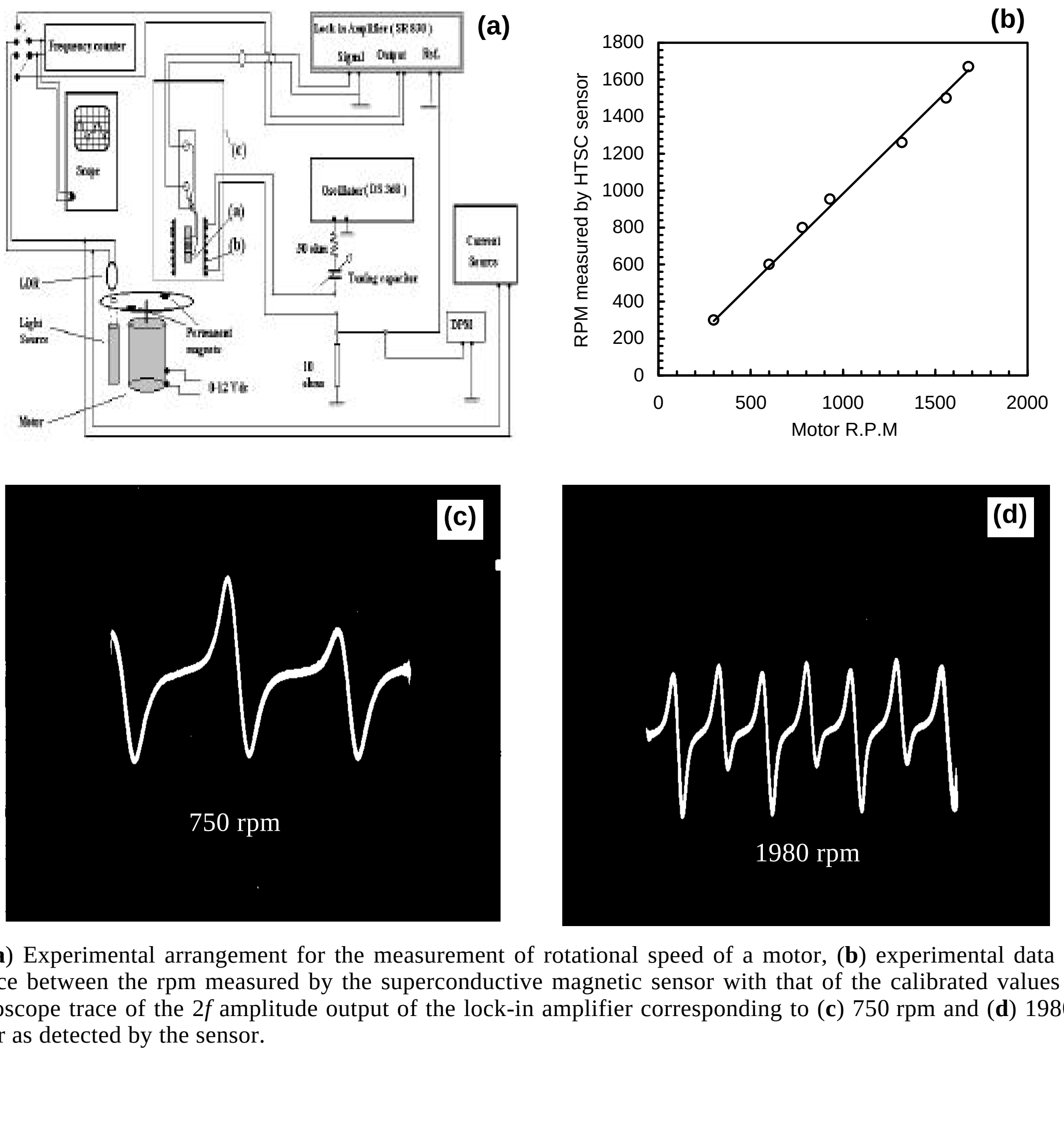

Figure 2. (**a**) Experimental arrangement for the measurement of rotational speed of a motor, (**b**) experimental data showing the correspondence between the rpm measured by the superconductive magnetic sensor with that of the calibrated values using LDR, typical oscilloscope trace of the $2f$ amplitude output of the lock-in amplifier corresponding to (**c**) 750 rpm and (**d**) 1980 rpm of the rotating motor as detected by the sensor.

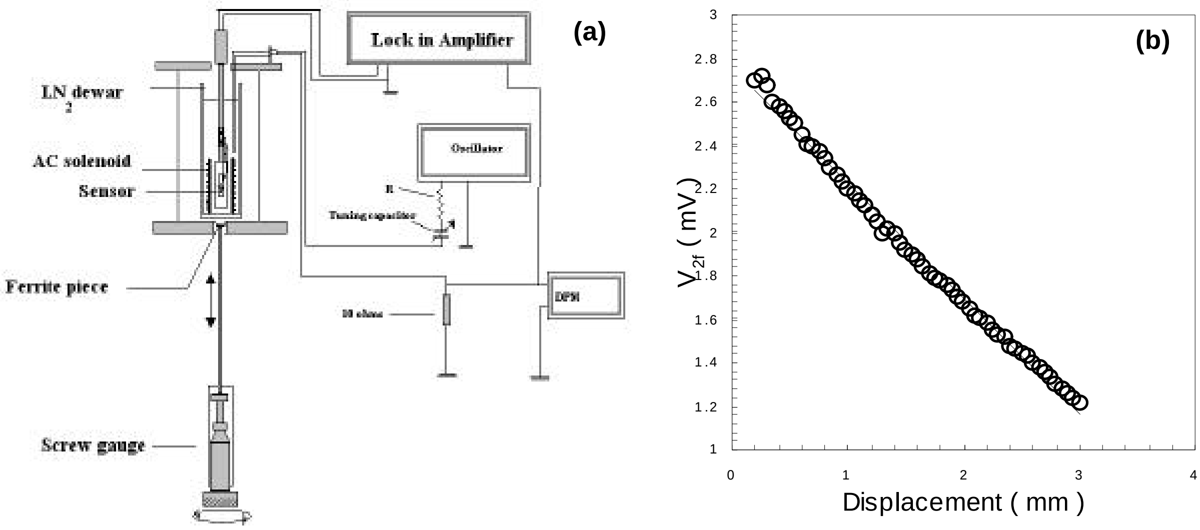

Figure 3. (**a**) Experimental arrangement for the measurement of linear displacement and (**b**) second harmonic voltages of the superconductive magnetic sensor as function of small displacements.

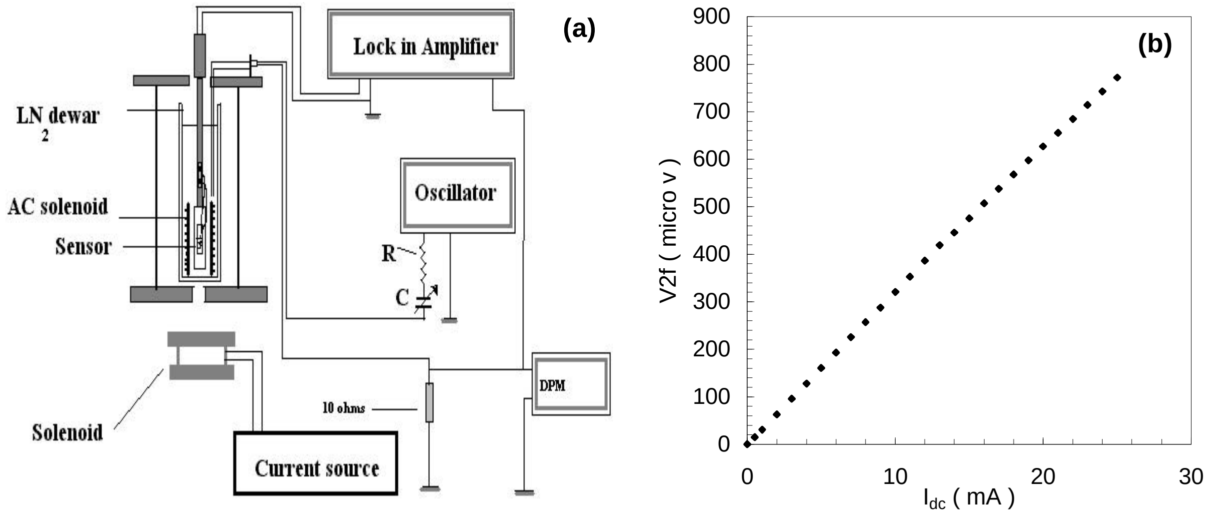

Figure 4. (**a**) Experimental arrangement for current sensing by a superconducting 2*f* based magnetic sensor and (**b**) the variation of the second harmonic voltage as a function of the current flowing through the solenoid.

figure 4(b). The sensitivity of our present sensor is found to be 31·4 μV/mA. However, this sensitivity could be controlled to higher figure by using the solenoid with higher number of turns connected to current measuring circuit. This would increase the magnetic flux density crossing the sample and hence the 2*f* signal.

4. Conclusions

An HTSC based magnetic sensor capable of sensing the rotational speed, displacement and current is reported. The sensor operates at liquid N_2 temperature and having the noise sensitivity of ~ $3{\cdot}6 \times 10^{-9}\,\mathrm{T}/\sqrt{\mathrm{Hz}}$. The sensor is capable of measuring rotational speed up to 2000 rpm (± 1 rpm) and small displacement in the range from ~ 0 and 3 mm and the direct current in any circuit.

Acknowledgement

One of the authors (AR) is grateful to the Department of Science and Technology, New Delhi, for providing financial assistance in the form of a Senior Research Fellowship.

References

Dey T K, Chattopadhyay M K and Ghatak S K 1999 *Sensors and Actuators* **B55** 222

Gallop J C, Lilleyaman S, Langham C D, Redcliffe W J, Gee M and Stewart M 1988 *Cryogenics* **28** 691

Gallop J C, Lilleyaman S, Langham C D, Redcliffe W J and Stewart M 1989 *IEEE Trans*. *Magn*. **25** 896

Ghatak S K, Mitra A K and Sen D 1992 *Phys*. *Rev*. **B45** 951

Kano Y, Hasebe S, Huang C, Yamada T and Inubuse M 1990 *IEEE Trans. Magn*. **26** 2023

Khare N, Gupta A K, Srivastava S K, Khare S and Padmanaban V P N 1997 *Meas*. *Sci*. *Technol*. **8** 29

Kwa T A and Wolffenbuttel R F 1991 *IEEE Transducers* 24

Li Wen J, Mei Tao and Sun W 2001 *Sensors and Actuators* **A89** 56

Moore T D, Turner S and Speake C C 1993 *Meas*. *Sci*. *Technol*. **4** 1519

Muller K H 1990 *Physica* **C168** 585

Pross A, Lewis C and Hesketh T 1999 *Sensors and Actuators* **A76** 72

Qin M J and Ong C K 1999 *Phys*. *Rev*. **B61** 9786

Vasseur P and Villat A 1994 *Meas*. *Sci*. *Technol*. **5** 889

Vertesy G, Szollosy J and Lovas A 1990 *IEEE Trans*. *Magn*. **26** 2026

Williumson W J 1968 *IEEE Trans*. *Magn*. **4** 162

Xenikos D G and Lamberger T R 1990 *Phys*. *Rev*. **B41** 869