Application of electromagnetic methods in force sensing, with emphasis on micro, nano and pico ranges

D M Ştefănescu
Senior Consultant, Romanian Measurement Society
E-mail: stefidanro@yahoo.com

Abstract. This paper reviews, compares and classifies some precision electromagnetic methods used for measuring force and related quantities. Several sensing devices are described (magnetoresistive, magnetostrictive and hall elements) as well as complex equipment (AFM, EMFC and SQUID), covering a wide variety of applications in the range of micro-, nano- and piconewtons.

1. Introduction
As compared with classical strain gauges technique, the electromagnetic measurements feature a high sensitivity in detecting smallest changes, resulting in very high resolution in the range of micro-, nano- and piconewtons.

There are several ways to sense magnetic fields, most of them based on the intimate correlation between magnetic and electric phenomena [1]. Specific differences are:

○ The magnetoelectric (ME) effect is the appearance of an electric polarization P in a material when a magnetic field H is applied, and conversely,
○ The electromagnetic (EM) effect is the appearance of a magnetization M in a material when an electric field E is applied.

Any electromagnetic system includes at least a coil, an air gap and a magnet made of ferromagnetic materials [2]. The main function of every electromagnet is the conversion of supplied electrical energy into mechanical work, actuating specific tools. This process is reversible and a lot of force transducers (FTs) are based on electromagnetic methods or principles. Significant quantities and energetical conversion processes are shown in Fig. 1.

![Fig. 1. Schematic of electro-magneto-mechanical energy conversion for actuators and transducers.](image)

2. Classification
Among the various works trying to systematically deal with electromagnetic principles used in measurement of mechanical quantities, the most recent and complete is [3]. In Fig. 2 are indicated the chapters (C) where they are presented.

It is remarkable that more than half of the dozen selected types of force transducers presented in the above-mentioned book are connected with the electromagnetic measurements:

○ Magnetoresistive (parametrical): from anisotropic (AMR) to giant (GMR);
○ Elastomagnetic, based on magnetostrictive effects (Villary – change of magnetic susceptibility due to applied mechanical load, or Matteucci – helical anisotropy and magnetomotive force induced by a torque);
○ Galvanomagnetic (based on Hall elements);
○ Electrodynamic, i.e. force balance principle;
Resonant transducers: vibrating wire (VW), double-ended tuning fork (DETF);
Electromagnetic acoustic transducer (EMAT);
Optoelectromagnetic, e.g. Lorentz force magnetic field sensor with optical readout [4].

Fig. 2. Relative sensitivity for various magnetic field measurement techniques. Magnetic induction $B$ is expressed in T (tesla).

3. Applications

3.1. Magnetoresistive
Sahoo et al. [5] presented a novel MagnetoResistive-sensor-based Scanning Probe Microscopy (MR-SPM) technique (Fig. 3). The basic idea is to convert the cantilever motion into a relative displacement between its micromagnet and a multilayered GMR sensor chip. When the cantilever experiences a tip-sample force, its deflection is translated into an electrical resistance change as a function of the magnetic field, with 84 pm resolution over 1 MHz bandwidth.

Fig. 3. Scanning probe microscopy (SPM) based on magnetoresistive sensing:
a) Approach – retract curve of resistance change, b) Experimental setup.

3.2. Magnetostrictive
A research group from Auburn University developed a MagnetoStrictive MicroCantilever (MSMC) as a sensing platform actuated by a magnetic field [6]. Due to its magnetic nature, the microcantilever vibration results in an emission of a magnetic signal, which is sensed using a pickup coil (the simplest electromagnetic measuring configuration).

3.3. Galvanomagnetic (Hall)
A multifunctional sensing device with two Hall elements and a magnet (all embedded in silicone rubber) to detect the normal contact force and the temperature is presented in [7]. When a magnetic field is applied at a right angle to the current flow, a small Hall voltage $V_{HR}$ appears across the semiconductor plate (Fig. 4). When this tactile sensor contacts with a finger, the magnetic field strength at the Hall element increases, because the silicone rubber is deformed by the normal contact force. The limited space does not permit to illustrate the wide range of applications based upon Hall devices [3].
3.4. Electrodynamic (EMFC)

Diethold et al. discuss the determination of spring constants of AFM (atomic force microscopy) cantilevers using force – displacement measuring equipment based on electromagnetic force compensated (EMFC) transducer [8], as shown in Fig. 5. This equipment can also be used for flow, angle and other mechanical quantities measurements.

Two proposals for improving the EMFC systems are:
- Double force compensation using two coils (coarse and fine adjustments) [9];
- Replacing the weighing pan with a Roberval type active elastic element (strain-gauged double guided cantilever beam) while the feedback force is generated with an electromagnetic force transducer (EMFT) or "forcer" [10].

3.5. Superconducting Quantum Interference Device (SQUID)

The piconewton force standard system from KRISS utilizes the magnetic flux quantization in a superconducting ring at the position of zero magnetic fields [11]. When a soft cantilever with an anisotropic magnetic sample at its end is placed in a uniform magnetic field, a varying magnetic torque is exerted on the cantilever, depending on its deflection (Fig. 6). The applied magnetic force can be increased or decreased by a step estimated as 0.184 pN for a niobium ring having inner and outer radii 5 μm and 10 μm, respectively, and thickness 50 nm.
3.6. Other Electromagnetic Methods / Principles

Other force measuring methods by electromagnetic means are just mentioned:
- Floating-magnetic principle for microforce sensor in microbiological applications, measuring ± 100 μN with 20 nN resolution (like AFM microcantilevers) (Fig. 7) [12];
- Manipulation of skyrmions (tiny nanometer-sized magnetic vortices found at the surface of magnetic materials) using mechanical force (F = 10 nN) [13].

Fig. 7. Floating-magnetic principle for microforce biosensor.

4. Conclusion

Comparing the electromagnetic methods, the magnetoresistors (especially GMR) detect a larger magnetic field than the Hall-effect sensors but the latter satisfy a wider range of applications related to the measurement of mechanical forces. And, these Hall devices have the best linearity among all electromagnetic force transducers. Specialized electromagnetic devices for micro- (EMFC), nano- (AFM and SPM), and picoforce (SQUID) measurements were also presented.

References

[1] Wang Y, Li J and Viehland D 2014 Magnetoelectrics for magnetic sensor applications: status, challenges and perspectives Materials Today 17 269–275
[2] Gadyuchko A, Kireev V and Rosenbaum S 2015 Potentials of magnetic measurement technology in development and production of electromagnetic actuators Proc. IMEKO XXI World Congress (Prague, Czech Republic) pp 578–583
[3] Ştefănescu D M 2011 Handbook of Force Transducers – Principles and Components (Berlin and Heidelberg: Springer-Verlag)
[4] Keplinger F, Kvasnica S, Jachimowicz A, Kohl F, Steurer J and Hauser H 2004 Lorentz force based magnetic field sensor with optical readout Sensors and Actuators A: Physical 110 112–118
[5] Sahoo D R, Sebastian A, Häberle W, Pozidis H and Eleftheriou E 2011 Scanning probe microscopy based on magnetoresistive sensing Nanotechnology 22, 145501
[6] Fu S L, Zhang K, Chen I-H, Petrenko V A and Cheng Z 2007 Magnetoostrictive microcantilever as an advanced transducer for biosensors Sensors 7 2929–2941
[7] Yuji J and Shiraki S 2013 Magnetic tactile sensing method with Hall element for artificial finger Kumamoto National College of Technology, Yatsushiro, Japan PDF on 31 July 2013
[8] Diethold C, Kühnel M, Ivanov T, Rangelow I W and Fröhlich T 2015 Determination of AFM-cantilever spring constants using the TU Ilmenau force displacement measurement device Proc. IMEKO XXI World Congress (Prague, Czech Republic) pp 175–180
[9] Choi I-M, Choi D-J and Kim S H 2002 Double force compensation method to enhance the performance of a null balance force sensor Japan Society of Applied Physics 41 3987–3993
[10] Izumo N and Nagane Y 2000 Super-hybrid-sensor for new balances ACTA APMF 2000 Eds Tojo T and Ohgushi K (Tsukuba, Japan)
[11] Choi J-H, Lee K-C, Kim Y-W and Kim M-S 2007 Characterization of quantum-weight generating cantilever device CD Proc. IMEKO Int. Conf. Cultivating Metrological Knowledge (Merida, Mexico) Session 1.1
[12] Cherry A, Abadie J and Piat E 2007 Microforce sensor for microbiological applications based on a floating-magnetic principle Laboratoire d’Automatique de Besançon, 21 March 2007
[13] Nii Y, Nakajima T, Kikkawa A, Yamasaki Y, Ohishi K, Suzuki J, Taguchi Y, Arima T, Tokura Y and Iwasa Y 2015 Uniaxial stress control of skyrmion phase Nature Communications RIKEN press release in Materials Today 13 October 2015