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Validation and testing of a MEMS piezoelectric permanent magnet current sensor with vibration canceling

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ABSTRACT

The work presented here documents the characterization and testing of a novel, proximity-based AC current sensor. By using a pair of cross-coupled MEMS piezoelectric cantilevers that have oppositely-oriented magnets on their free ends, a sensor has been created that needs no external power source and that measures AC current without the need for galvanic contact with, or fully encircling of, the current-carrying conductor. The resulting device is 11.2 mm long and has an output sensitivity of 5.8 mV/G at 6.8 mm from the center of the conductor. The sensor device has been characterized at frequencies of 60–200 Hz. Common-mode rejection ratio calculations demonstrate the effectiveness of the cancellation technique at frequencies other than those corresponding to the first resonant mode of the device.

1. Introduction

The concepts of non-contact magnetic field, and thus current, sensing have origins from the same period as the very beginnings of the electric power grid. From the first studies of the Hall Effect by Edwin Hall in 1879 to the invention of the current transformer in 1886, methods and technologies for measurement of AC current were being developed in parallel to methods of generating that same current. Historically, these sensing technologies were only sparingly deployed, as there was a lack of sufficient computing resources to process the resulting data [1]. The advancements in computing technologies in the last few decades, however, may finally serve to enable wide-scale, ubiquitous sensing.

The potential applications of ubiquitous, non-contact current sensing include (but are not limited to) distribution-grid-level “smart grid” monitoring, and residential and commercial submetering. The emphasis of this research, however, is on the development of the sensing component only; given this narrowed focus, any technologies considered must be well-suited to the devices and platforms to which they might be connected. Such sensors should be capable of operating in low-power environments (i.e., wireless sensor nodes), and should have magnetic field sensitivities that are of appropriate magnitudes for the signals being sensed and the sensing platforms to which they are connected. Also, to be usable in real applications, the sensors should be able to effectively reject noise signals from external sources (magnetic, vibrational).

Non-galvanic current sensing can be achieved through the measurement of magnetic fields. Within this expanded category of sensors, technologies are either “encircling,” e.g. current transformers (CT) and Rogowski coils, or “non-encircling” proximity-based. The recent proximity-based sensors in the literature may be further classified as Hall Effect, magnetic tunnel junction, delta-f resonant, or piezoresistive, plus other “unique” technologies that are not readily-classified into the more-common previous categories.

Within the category of encircling devices, two of research groups have recently presented technologies designed for low-power, ubiquitous sensing. The first group, Porcarelli et al. [2], demonstrated a dual-purpose current transformer. The device is connected to a charging and energy storage circuit by default, but may be switched so that the output may instead be used for measurement. Huang et al. [3], by comparison, also detailed a switching system, but with more-sophisticated multiplexing and rectification circuitry designed for maximal power extraction from the conductor being measured.

The broad category of proximity-based sensors contains technologies at nearly every stage of maturity. However, even within the highly-mature subcategory of Hall Effect devices, there have

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been a number of recent advances. The first such technology, developed by Tsai et al. [4] is capable of sensing DC and AC magnetic fields of up to 3500 G, though this sensor requires several milliamps of supply current to operate. The second device, a 3-axis sensor by Wang and Misra [5], only operates over a range of ±300 G but only requires a 40 μA supply.

Magnetic tunnel junction sensing, first documented by Jullierre [6] in 1975, has also been the subject of numerous research efforts. The first of these devices, by Breth et al. [7], achieves a sensitivity of 2.64 mV/G with very low power consumption (20 μW), but requires a precision current source and low noise amplifier to achieve these targets. The next device, from Ferreira et al. [8], achieves 13.3 mV/G, but consumes nearly 300 μW of power to accomplish this measurement. Sanchez et al. [9] continue this trend of sensitivity and power consumption, reporting 50 mV/G but requiring 2.15 mW of power to achieve this result. Yin and Liou [10], by comparison, demonstrate 19.2 V/G with only 20 μW of power consumption, though the device saturates at only 0.005 G.

Resonant-type, “delta-f”, structures are the third group of proximity sensors in recent work. Such devices typically require extremely little power to operate, in large part due to their use of high-quality-factor resonators. A notable recent example of this approach is that of Hui et al. [11], in which a resonant aluminum nitride (AlN) structure is subjected to DC magnetic fields. Hui’s device utilized a network analyzer to track the resulting changes to the resonant frequency of the structure. Wang and Maeda [12] recently modeled a similar device, which uses lead zirconate titanate and permanent magnets to measure AC magnetic fields, that is estimated to require 0.21 μW of power to operate, excluding the phase tracking circuitry.

Another category of mechanical, magnetic field sensors uses piezoresistive elements. In 2011, Lin and Du [13] presented a model of a cross-shaped structure in which a ferromagnetic film is used to induce strain in piezoresistive film layers. However, Lin and Du predict a sensitivity of only 60 μV/G for this structure. By comparison, Herrera-May et al. [14] uses Lorentz forces in current-carrying MEMS structures as a source of piezoresistive strain, requiring nearly 16 mW of power for sensor operation.

A final “category” of proximity-based sensors is “unique” sensing approaches. The first of these papers (a predecessor of the devices in this work), was presented by Leland [15]. Leland’s sensors use an aluminum nitride cantilever and “printed” permanent magnet to measure magnetic fields with a sensitivity of 7 mV/G. The Leland device, however, has extremely-low capacitance (1–5 pF) and has high thermal noise due to the use of a very large bias resistor (>1 GΩ). Mustafa and Khan [16] also propose a sensor using a cantilever and permanent magnet, though their cantilever sensor is non-piezoelectric and instead relies on changes in the parallel-plate capacitance between the cantilever and the substrate. A third unique approach, in development by a group including Chen [17,18] and Cheng [19], relies on a small, flat coil constructed on a flexible substrate that is subsequently attached to a two-conductor (“zip cord”) wire. This flat coil sensor, based on inductive coupling, requires no power supply, but only achieves 25 μV/G sensitivity. The final “unique” sensor, produced by Bakhoum [20], is also a “zero power consumption” device. The Bakhoum device uses a radioactive tritium disc together with a pair of concentric p-n junctions to measure a wide range (0.01–1000 G) of magnetic fields. However, the sensor produces substantial output noise due to the random nature of the radioactive decay.

2. Sensor designs

The theory behind piezoelectric permanent magnet (PEM) sensing has been described extensively by Leland [21–23], and is only summarized here. As reported by Wagner et al. [24], when a permanent magnet is placed in an external magnetic field (such as that from a current-carrying conductor), a body force in the magnet develops according to:

$$\vec{F}_m = \int\int\int_{V_m} \nabla\left(\vec{B}_m \cdot \vec{H}\right) \mathrm{d}V_m \tag{1}$$

where $\vec{B}_m$ is the net magnetic flux of the magnet in units of tesla, V_m is the volume of the magnet, and $\vec{H}$ is the magnetic intensity due to the current in the wire, in units of A/m. If this magnet is connected to the free end of a piezoelectric cantilever, the resulting force will produce a strain in the piezoelectric material and generate charge. Furthermore, if the electrodes of the piezoelectric material are connected electrically to a resistance R_{amp}, then current will flow and a voltage will develop across this resistance. If the source of this magnetic field is a current-carrying conductor, then this arrangement will produce a voltage proportional to the current in the wire; as in Fig. 1.

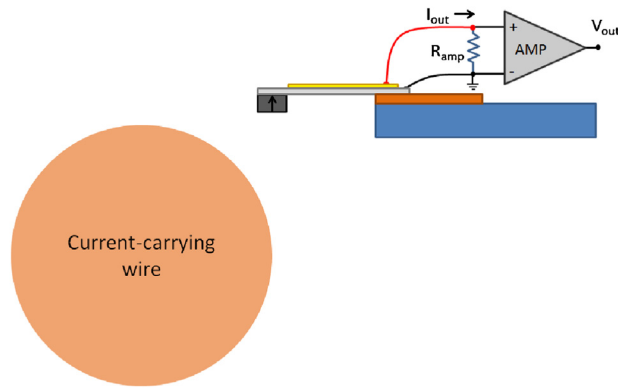

Fig. 1. Side view of a piezoelectric permanent magnet current sensor, close to a current-carrying wire, from Sherman [25].

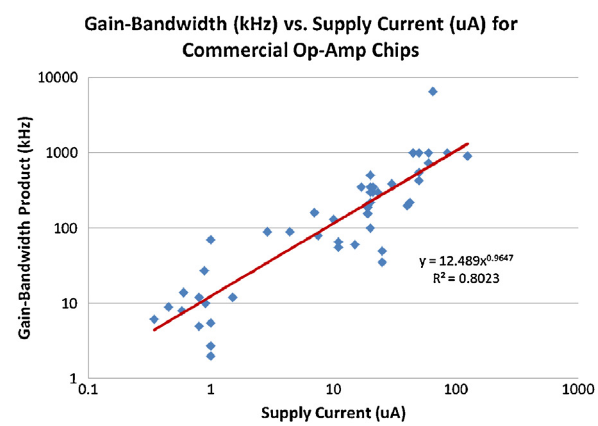

Fig. 2. Gain-bandwidth vs. supply current for a number of commercially-available amplifier ICs, from Sherman [25].

Early, single-cantilever versions of the piezoelectric permanent magnet sensor, such as the Leland [15] devices, do fulfill several of the requirements for enabling ubiquitous low-power sensing. First and foremost, due to the incorporation of charge-generating piezoelectric materials, the sensor itself is self-powered and only needs (at most) an amplifier for gain and filtering. Assuming that the signal being measured is mains frequency (50 or 60 Hz) plus some number of harmonics (the exact count varies by application), if the raw sensor output is sufficiently large then an amplifier with a gain-bandwidth of a few kilohertz should be sufficient. As Fig. 2 illustrates, there are several sub-1 μA