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Technical note

Simple implantable wireless sensor platform to measure pressure and force

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ABSTRACT

Smart implants have the potential to enable personalized care regimens for patients. However, the integration of smart implants into daily clinical practice is limited by the size and cost of available sensing technology. Passive resonant sensors are an attractive alternative to traditional sensing technologies because they obviate the need for on-sensor signal conditioning or telemetry and are substantially simpler, smaller, less expensive, and more robust than other sensing methods. We have developed a novel simple, passive sensing platform that is adaptable to a variety of applications. Sensors consist of only two disconnected parallel Archimedean spiral coils and an intervening solid dielectric layer. When exposed to force or pressure, the resonant frequency of the circuit shifts which can be measured wirelessly. We fabricated prototype pressure sensors and force sensors and compared their performance to a lumped parameter model which predicts sensor behavior. The sensors exhibited a linear response ($R^2 > 0.91$) to dynamic changes in pressure or force with excellent sensitivity. Experimental data were within 13.3% and 6.2% of the values predicted by the model for force and pressure respectively. Results demonstrate that the sensors can be adapted to measure various measurands through a span of sensitivities and ranges by appropriate selection of the intervening layer.

1. Introduction

The use of patient-specific data to drive personal care regimens has significant potential for optimizing medical treatments [1]. One approach to collecting patient-specific data is through the use of “smart implants”. Smart implants serve not only a therapeutic capacity, but also are instrumented with sensing technology to provide diagnostic data. In orthopaedic surgery, the relatively large size of the implants provides an ideal vehicle for introducing diagnostic technology into the body.

Smart implants also have value as research tools. The measurement of *in vivo* forces in orthopaedic implants has been used to provide a better understanding of knee [2], hip [3], spine [4], shoulder [5], and fracture fixation biomechanics [6]. Yet, despite the potential clinical value, the use of smart implants has thus far been limited to small cohorts of patients. This is largely due to the complexity and expense of the sensing technology [7,8].

Smart orthopaedic implants have traditionally been instrumented with strain gauges and telemetry systems. These require a power source, signal conditioning circuitry, and a telemetry system to transduce and wirelessly transmit data [8,9]. Even with low power integrated circuits and inductive coupling for power, these circuits are complex and the large footprint requires substantial modifications to the host implant to incorporate the circuits [7]. Fundamentally, the integration of smart implants into daily clinical practice is limited by the size and cost of available sensing technology and the required modifications to host implants [7,8].

Passive resonant sensors are an attractive alternative to traditional sensing technologies [10]; they consist only of a passively powered resonant circuit (no on-board battery or power storage) whose resonant behavior is altered by the measurand of interest [11]. Resonant circuits consist of an inductive element (L) and capacitive element (C) whose interaction allows the circuit to preferentially absorb energy (and resonate) at a given frequency. Sensing is achieved through a variable inductive or capacitive element

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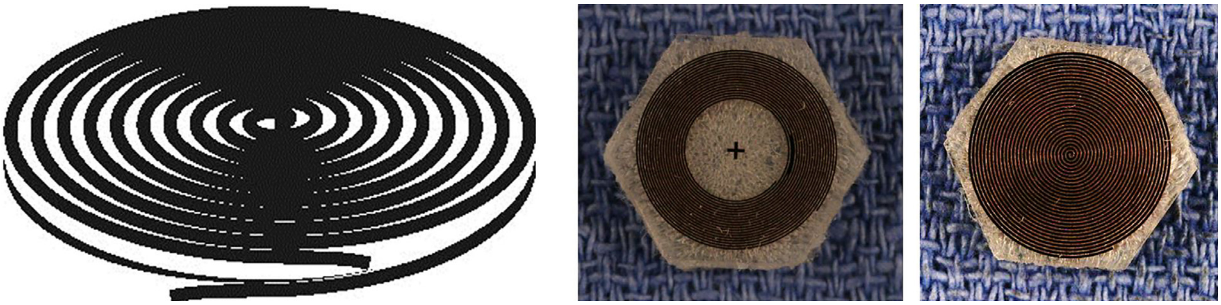

Fig. 1. Sensors are comprised of only two Archimedean coils and an intervening solid dielectric (left). Prototype pressure (center) and force (right) sensors were fabricated for testing.

[10]. A change in inductance or capacitance shifts the resonant frequency of the sensor which can be wirelessly interrogated using a coupled external antenna [12]. This obviates the need for remote (on-sensor) signal conditioning or telemetry and allows the sensors to be substantially simpler, smaller, less expensive, and more robust than other sensing methods.

We have developed a novel, passive sensing platform that is adaptable to a variety of applications [13–15]. Sensors consist of only two disconnected parallel Archimedean spiral coils separated by a solid intervening dielectric layer (Fig. 1). The disconnected coils inductively and capacitively couple to form a resonant circuit whose resonance is dependent on the separation distance between the coils [14]. When exposed to a stimulus (i.e., force or pressure), changes in displacement between the two coils shifts the resonant frequency of the circuit which can then be measured wirelessly.

This sensor platform is adaptable to a variety of geometries, sizes, sensitivities, and ranges. We have developed a lumped constant circuit model of the two coils to predict sensor performance. The purpose of this study was to fabricate and test prototype wireless sensors that measure pressure or force and to compare performance of the sensors to our lumped parameter model.

2. Methods

2.1. Sensor description

Fundamentally, the sensors are passive displacement transducers. Any stimulus that affects a change in the displacement between the two coils (Δl) causes a shift in the resonant frequency of the sensor. The sensitivity to a particular measurand (i.e., force or pressure) is dictated by the properties of the intervening dielectric layer. If the intervening layer has material properties such that it deforms under low forces, the sensor can be used to measure small changes in force. If the intervening layer deforms with a change in temperature, the sensor can be used transduce temperature, etc.

The resonant frequency of the sensor can be detected wirelessly by monitoring the spectrum of the return loss parameter (S_{11} parameter) via a network analyzer or using the well-established grid dip method [16].

2.2. Sensor behavior

Although the system contains no discrete electrical components or connections between the two coils, the resonant behavior of the system can be approximated as a lumped constant LC circuit. We have developed a model to calculate the total distributed inductance (L_T) and total capacitance (C_T) of the two-coil system. The lumped parameter model was developed by adapting inductive power transfer theory for planar spiral antennas. Approximations of mutual capacitance between the two coils, parasitic capacitance between turns of a single coil, inductive coupling between coils, and single coil inductance based on inductive power transfer were used to model the system.

Determination of the total distributed inductance and total capacitance allows for prediction of sensor resonant frequency (f_0) by the simplified expression:

$$f_0 = \frac{1}{2\pi\sqrt{L_T C_T}} \tag{1}$$

The self-inductance of a single planar spiral coil (L_{Coil}) can be modeled as [17]:

$$L_{Coil} = \frac{\mu_0 n^2 d_{avg} c_1}{2}\left(\ln\left(\frac{c_2}{\rho}\right) + c_3\rho + c_4\rho^2\right) \tag{2}$$

Where μ_0 is the permeability of free space, n is the number turns in the coil, d_{avg} is the average diameter of the coil ($d_{avg} = (d_{out} + d_{in})/2$), where d_{in} and d_{out} are the inner and outer diameters of the coil, respectively, and $\rho = (d_{out} - d_{in})/(d_{out} + d_{in})$. The constants c_1, c_2, c_3, and c_4 are empirical corrections for a circular coil geometry and are 1.0, 2.46, 0 and 0.2, respectively. These constants have been previously derived in detail by Mohan et al. for planar spiral coils [17].

From applications in wireless power transfer [18], the mutual inductance between two planar coils (L_M) is determined by approximating each turn of the coil as a circular ring and by summing the mutual inductance (M) between each turn of the first coil (i) with each turn of the second coil (j) [19]:

$$L_M = \sum_{i=1}^{n}\sum_{j=1}^{n} M_{ij} \tag{3}$$

These inductances contribute to the lumped constant circuit approximation. The total distributed inductance of the system is the inductances of each coil and mutual inductance between coils configured in parallel [20]:

$$L_T = \frac{L_1 L_2 - {L_M}^2}{L_1 + L_2 - 2L_M} \tag{4}$$

where L_T is the total distributed inductance of the circuit, L_1 and L_2 are the self-inductances of each of the individual coils and L_M is the mutual inductance between the two coils.

Even though the system lacks a discrete capacitor, the sensors exhibit both capacitive coupling between the two coils and self-capacitance of a single coil. The single coil capacitance is achieved through coupling between adjacent turns within the same coil and as such, the individual coils exhibit self-resonant behavior [18].

The total capacitance of electrically connected, stacked spiral inductors is well defined [21]. However, there are several assumptions inherent in these calculations (such as perfect inductive coupling between inductors and negligible inter-turn capacitive coupling) that are not valid for disconnected coils [22]. For our sensors, we have approximated the total capacitance of the system

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