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Development of capacitive pure bending strain sensor for wireless spinal fusion monitoring

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Abstract

A MEMS (microelectromechanical system) capacitive-based pure bending strain sensor is presented for use in spinal fusion monitoring. The sensor is designed to interface with a telemetry system that does not require a battery and contained in a housing that is attached to spinal fusion rods. The cantilever structure of the sensor is composed of two parallel plates with a narrow gap and a conjoint end. Nine permutations of the design with different metal coverage areas (14 mm^2, 9.3 mm^2 and 4.7 mm^2) and gaps (3 μm, 6 μm and 7.4 μm) were examined. The nominal capacitance ranges from 7.6 pF to 42 pF. The capacitance changes 31.4–65.1% for a strain range of 0–1000 $\mu\varepsilon$ depending on the design parameters. An analytical model is developed for the sensor mounted to a cantilever test bar and compared to experimental results of actual devices. The model and experimental results show an average difference of 5% for all nine designs investigated. The final sensor design achieved a linear gauge factor of 252 and was fabricated for the spinal fusion application.
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Keywords: Bending strain sensor; Capacitive; Cantilever structure; Microelectromechanical system (MEMS); Spinal fusion monitoring

1. Introduction

Titanium or stainless steel rods are implanted to stabilize vertebrae movement during spinal fusion surgery, which allows bone grafts to fuse two or more vertebrae. Radiograph images (X-rays), computed tomography scans (CT) and magnetic resonance imaging (MRI) procedures are used to assess fusion progress and diagnose problems during patient recovery. However, the imaging techniques yield subjective results [1] and as a consequence, result in unnecessary exploratory surgeries to ascertain the efficacy of the spinal fusion surgery.

Typical spinal fusion fixation hardware is shown in Fig. 1. As the grafted bone fuses, the bending strain of the implanted rod decreases as the load is transferred to the fused vertebrae [2]. Therefore, bending strain can be used as an alternative method to monitor the progress of spinal fusion. Although most strain gauges are capable of measuring axial strain due to tension and compression or their equivalents derived from bending, a sensitive bending strain sensor that only responds to bending strain is also desirable for spinal fusion purpose. The strain sensor is expected to measure 1000 $\mu\varepsilon$ based on an adult of 200 pounds in a corpectomy model under bending with 2 stainless spinal fusion rods (6.4 mm in diameter and 50.8 mm long) implanted [3]. An in vivo wireless inductively powered strain measurement system has been developed to make this measurement practical. Capacitive bending strain sensors are attractive for this application because of their low current requirement for sensing and associated circuitry [4]. MEMS capacitive sensors using wireless data transmission have been evaluated in many applications such as humidity [5,6], temperature [6] and pressure sensing devices [6–10]. The telemetry approach to monitor strain uses inductively coupled battery-less technology similar to the technology used in Radio Frequency IDentification (RFID) devices [6–11]. The Spinal Fusion Measurement Implant (SFMI) consists of a sensitive bending strain sensor, inductively powered telemetry circuitry and an antenna packaged in a hermetically sealed housing that attaches to the diameter spinal fusion rod. The distance between two vertebrae is about 25.4 mm in the lumber region,

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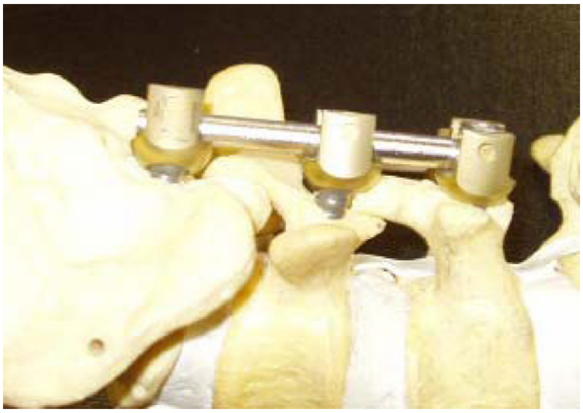

Fig. 1. A typical spinal fusion fixation instrumentation.

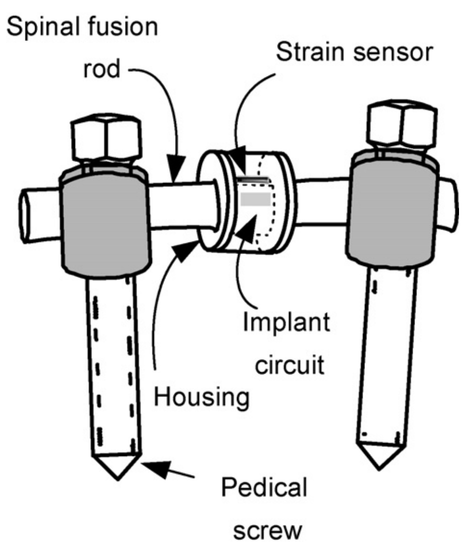

Fig. 2. The SFMI implant attached to a spinal fusion rod.

making the maximum length of the housing limited to approximately 12.5 mm long. Therefore, it is desirable that the sensor length be less than 10 mm. The housing is installed between two pedicle screws, as illustrated in Fig. 2, and will transfer the bending strain from the rod to the sensor as described in Ref. [12]. The curved surface of the rod is compensated with the 2 mm thick plastic housing which conforms to the rod and is trimmed 1 mm down to provide a flat area of 2 mm × 10 mm for the sensor to mount. This paper focuses on the development and optimization of the custom bending strain capacitive sensing element needed for SFMI applications.

2. Background

The SFMI application requires a high bending strain sensitivity with enough nominal capacitance to avoid loss due to parasitic capacitance, compatibility with an inductively powered circuit, and suitable dimensions for system packaging. These characteristics were primarily considered when reviewing limited examples of previous parallel plate capacitive strain sensors in the literature.

The basic concept of the capacitive strain sensor features a pair of metalized parallel plates with a dielectric gap. The sensing mechanism manifests itself in varying either the area of the plate, the gap between the plates, or the dielectric medium between the plates. A number of parallel plate sensor designs with a variable air gap were analyzed by Procter and Strong [13]. These sensors generally exhibited low nominal capacitance and sensitivity due to the large gap. In an attempt to increase the nominal capacitance in a non-air gap design, Arshak et al. [14] demonstrated a sensor with a parallel plate structure and a thick-film dielectric material. The dielectric film between the two plates was compressed during bending, thus expanding the film in area and decreasing the thickness from the perspective of the electrodes. These changes in the film geometry lead to a high gauge factor of 75–80 with a 15–25 μm gap based on a uniform model. The capacitive gauge factor is defined by the fractional change in capacitance with respect to strain. This thick-film dielectric produced both capacitive and resistive responses to strain making this approach electrically unique, but undesirable for the SFMI application due to power consumption. In another design, Arshak et al. invoked the change in permittivity of a dielectric material resulting in a gauge factor of 3.5–6, with a 150 μm gap [15]. This variable permittivity approach exhibits limited sensitivity that showed no dependency on its dimension (the gauge factor is constant and only depends on the "piezocapacitive" effect). This low gauge factor approach would require additional circuitry that is not desired for this implant design.

In general, the change in gap between the parallel plates due to applied strain is very small. Therefore to obtain high sensitivity, these changes need to be as large as possible with respect to the unstrained gap. Designs that maximize the change in gap and minimize the unstrained gap are optimal. Using non-air dielectrics to increase the gauge factor has been shown to be successful but has disadvantages such as less ideal electrical properties and more complex fabrication.

3. Sensor design

The bending strain sensor described herein meets the requirements of high nominal capacitance, high sensitivity, and compact dimensions. It utilizes a variable gap configuration comprised of silicon and glass beams that are bonded at one end and open at the opposing end. The bottom silicon plate was affixed to the bending test structure. As the structure bends, the bottom plate conforms to the structure and moves away from the straight top plate. The gap therefore widens along the stretch of the sensor, providing an effective mechanical amplification of the gap not seen in the typical uniform gap sensors [14,15]. To achieve high sensitivity, a combination of a narrow gap and relatively long plates are required. Sensitivity is also geometry dependent and can be changed not only by changing the initial gap and length but also by concentrating the metal areas to the more mobile opening end of the plates. Three coverage configurations of the metal areas, as shown in Fig. 3, with each having three different initial gaps configurations (not shown) were developed to characterize the sensor's response. The air dielectric provides for low