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A Semiconductor Strain Gage Tactile Transducer

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Abstract* - This paper describes the development of a semiconductor strain gage tactile transducer. It was designed with the goal of measuring finger forces without affecting the hand dexterity. The transducer structure was manufactured with stainless steel and has small dimensions (4 mm diameter and 1 mm thickness). It is light and suitable to connect to the finger pads. It has a device that prevents its damage when overforces are applied. The semiconductor strain gage was used due its small size and high sensitivity, although it has high temperature sensitivity. Theory, design and construction details are presented. The signal conditioning circuit is very simple because the semiconductor strain gage sensitivity is high. It presents linear response from 0 to 100 N, 0.5 N resolution, fall time of 7.2 ms, good repeatability, and small hysteresis. The semiconductor strain gage transducer has characteristics that can make it very useful in Rehabilitation Engineering, Robotics, and Medicine.

Key-words* - Semiconductor strain gage, tactile transducer, force sensor, finger force, semiconductor sensor.

I. INTRODUCTION

Various kinds of finger and hand force sensors have been developed based on different technologies. They are useful for clinical evaluation of hand function, hand rehabilitation devices, neuromuscular control research, functional neuromuscular stimulation prostheses, biomechanical studies, and robotics [1] – [3]. The literature contains numerous reviews of tactile sensing technology [2] – [9]. Tactile sensors must be easy to use and not be encubering to normal patient movements. They should be low mass, small size, and easily adjust to an individual's fingers. Conventional force sensors are inadequate for measuring hand forces produced during manual work activities of daily living. Usually they are large and bulky for attaching directly to the hands and fingers or too fragile to withstand the high forces exerted by the hand [2]. Desired characteristics for a finger force sensor are: spatial resolution of 2-3 mm, load range of 0.1 to 100 N, response time of 0.1 to 100 N, low hysteresis, compliant, and robust packaging [10]. Silicon piezoresistive sensors, manufactures by ICSensors Inc., (USA) were used in a system designed for measuring forces during delivery of newborns. Each sensor could measure 9 N in a linear range [11]. Jensen, Radwin, and Webster measured finger forces with coductive polymer sensors [12]. The drawbacks for these sensors are its poor repeatability, low range force, and high hysteresis. Beebe et al. presented a silicon-based tactile sensor for finger mounted applications [2]. The sensor consists of a circular silicon diaphragm over a sealed cavity with a solid dome providing force-to-pressure transduction to the diaphragm. The sensor was tested for forces up to 30 N and presented some hysteresis [2]. Da Silva, Carvalho, and Silva described the main characteristics of a metallic strain gage tactil transducer. It measured forces over a range of 0 to 100 N, with a resolution of 0.3 N, and excellent repeatability. The main limitation of this transducer is its large size that makes it suitable only to measure forces in the thumb [10]. In this paper we describe the construction details, calibration, and response characteristics of transducer constructed with a commercially available semiconductor strain gage. Its small size, ruggedness, good accuracy, excellent repeatability, capacity of overforce protection, and force range make it adequate for attaching to the distal finger pads.

II. MATERIALS AND METHODS

Figure 1 and 2 shows the cross section and the bottom view of the transducer. The dimensions are in millimeters. The transducer structure was constructed with stainless steel, type 15-5PH.

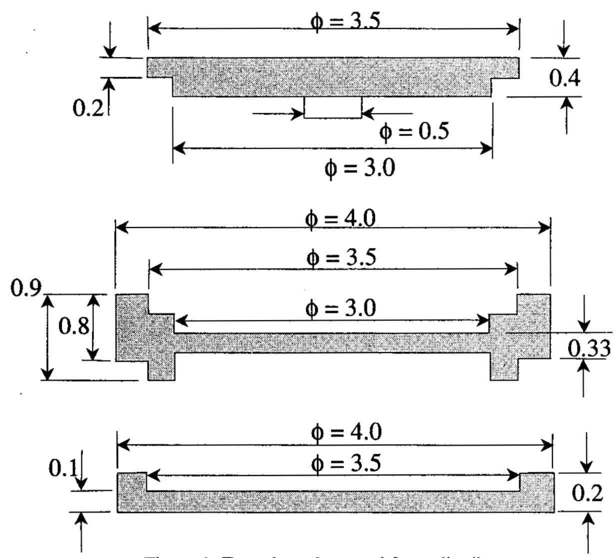

Figure 1. Transducer base and force distributor

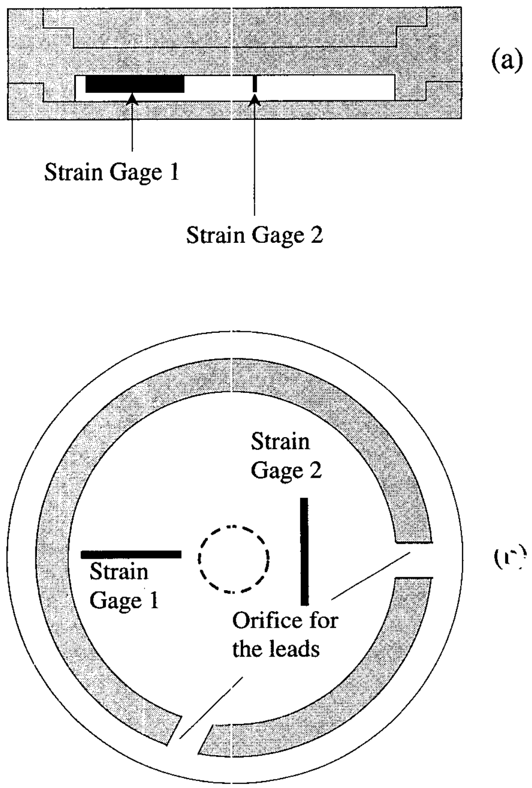

Figure 2. (a) Transducer base-force distributor set with the strain gages; (b) Bottom view of the transducer structure.

Entran Sensors & Electronics (USA) type ESB-20-500, matched semiconductor strain gages, were placed under the web, one for measuring radial strain (strain gage 1) and one for measuring tangential strain (strain gage 2). The strain gages were configured as a half Wheatstone bridge.

The flexural rigity at the web center was calculated using the equation [13]:

$$D = \frac{Eh^3}{12(1-\mu^2)} \qquad (1)$$

where **E** is the modulus of elasticity, **h** is the diaphragm thickness and μ is the Poisson's ratio.

By considering force distributed concentrically, the largest deflection at the web center is given by:

$$\delta = \frac{P.c^2}{4.D}\left(\log\frac{a}{c} + \frac{c^2}{4a^2}\right) \qquad (2)$$

where **P** is the pressure (kgf/mm^2), **a** is the web radius (mm), and **c** is the radius of the area where the force is applied (mm).

The largest stress that can be applied at the web center is calculated by the equation:

$$(\sigma)_{max} = \frac{3}{2}(1+\mu)\frac{P}{\pi h^2}\left(\log\frac{a}{c} + \frac{c^2}{4a^2}\right) \qquad (3)$$

At the transducer structure there is a ring manufactured over the web that protects the transducer against overforces.

The resistance change of a semiconductor strain gage can be calculated as a function of the membrane stress. There is a contribution to resistance change from stress that are longitudinal (σ_l) and transverse (σ_t) with respect to current flow. Assuming that the mechanical stresses are constant over the strain gages, the total resistance change ΔR is given by [14]:

$$\frac{\Delta R}{R} = \sigma_l\pi_l + \sigma_t\pi_t \qquad (4)$$

where R is the resistance at 25 °C for a constant supply current and no applied stress and π_l and π_t are the longitudinal and transverse piezoresistance coefficients, respectively. Note that dimensional changes are not taken into account in (4).

$$\pi_l = \pi_{11} + 2(\pi_{44} + \pi_{12} - \pi_{11})(l_1^2m_1^2 + l_1^2n_1^2 + m_1^2n_1^2) \qquad (5)$$

$$\pi_t = \pi_{12} - (\pi_{44} + \pi_{12} - \pi_{11})(l_1^2m_1^2 + l_1^2n_1^2 + m_1^2n_1^2) \qquad (6)$$

where l_1, m_1 and n_1 are coordinates of the semiconductor strain gages with respect to the silicon crystal axes and π_{44}, π_{12}, π_{11} are the adiabatic piezoresistance coefficients.

Materials with a minimum in the <111> direction have their maximum π_l and π_t along the crystal axes. The value of the <111> π_l and π_t is obtained from (5) and (6) respectively, setting $l_1^2 = m_1^2 = l_1^2 = 1/3$:

$$(\pi_l)_{<111>} = \frac{1}{3}(\pi_{11} + 2\pi_{12} + \pi_{44}) \qquad (7)$$

$$(\pi_t)_{<111>} = \frac{1}{3}(\pi_{11} + 2\pi_{12} - \pi_{44}) \qquad (8)$$

To strain gages with silicon type P (like Entran strain gages) π_{44} is more important than the other two coefficients. Equation (4) is thus approximated for p-type resistors by [15]:

$$\frac{\Delta R}{R} = \frac{\pi_{44}}{2}(\sigma_t + \sigma_l) \quad (9)$$

where $\pi_{44} = 138.1 \times 10^{-11}Pa^{-1}$ for silicon.

For n-type resistors, π_{44} can be negleted, and we obtain:

$$\frac{\Delta R}{R} = \frac{\pi_{11} + \pi_{12}}{2}(\sigma_t + \sigma_l) \quad (10)$$

where $\pi_{11} = -102.2 \times 10^{-11}Pa^{-1}$ and where $\pi_{12} = 53.4 \times 10^{-11}Pa^{-1}$ for silicon.

It is noted that (9) are only valid for uniform stress field or if the resistor dimensions are small compared to the membrane size.

Due the high gage factor of the semiconductor strain gages, it was not necessary to use an amplifier with a high gain. An instrumentation amplifier with a gain of 50 was used. Analog data was sampled using a 12-bit data acquisition board (National Instruments, model AT-MIO-16E-10), the software LabVIEW and a Pentium computer.

The transducer was calibrated against a load cell Excel type MS-50 (SP-Brazil). A modified drill press was used to apply compressing forces to the load cell and to the semiconductor strain gage tactil transducer.

III. RESULTS AND DISCUSSION

The transducer was tested mounted on a rigid substrate.

In order to evaluate the transducer performance static and dynamic calibration was performed. The static calibration was done by increasing the applied force up to 100 N and then decreasing back to zero. Figure 3 illustrates the transducer response.

Hysteresis is negligible and linearity is good (R=0.998). The force sensitivity was 0.05 V/N.

Resolution is defined as the smallest change in measured value to which the system will respond. For this semiconductor strain gage tactile transducer the resolution was 0.5 N.

An oscilloscope Tektronix, model Tekscope, connected to a computer with the software Wavestar was used to measure the transducer fall time. A force step of 100 N was applied to the transducer and fastly removed. Fall time was estimated from the time needed for the transducer output to achieve 63% of its steady value. The measured fall time was 7.2 ms.

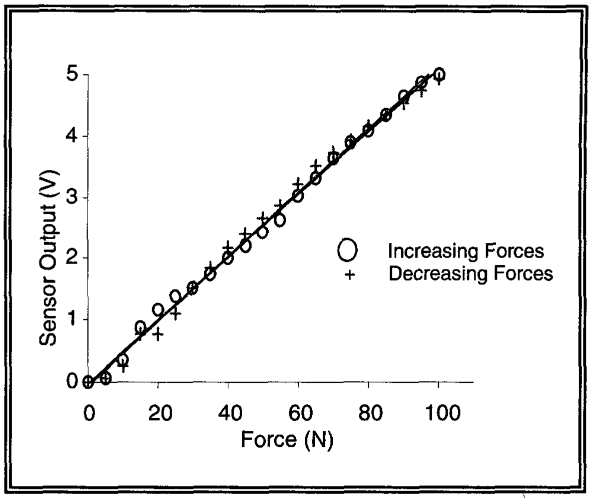

Figure 3. Representative static curve.

Figure 4 shows the response when a aleatory time variant force was applied, with a modified drill press, to the transducer.

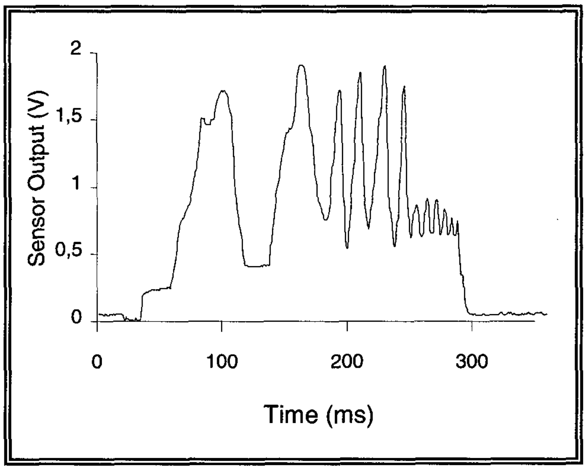

Figure 4. Transducer response to a time variant force.

IV. CONCLUSIONS

The main motivation for the development of this work was the challenge of manufacturing a sufficiently small tactile transducer for measuring finger forces without encubering the finger dexterity. The goal was attained with the development of a 4 mm diameter and 1 mm thick semiconductor strain gage tactile transducer.

The transducer is rugged, has protection against overforces, presents linear response up to 100 N, good repeatability, resolution of 0.5 N, fall time of 7.2 ms, and negligible hysteresis.

The signal conditioning circuit is very simple because the transducer sensitivity is high.

Due its small size and good response characteristics this transducer can be very useful in Rehabilitation Engineering, Ergonomics, and Robotics.

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