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Piezoelectric Self-Sensing System for Tactile Intraoperative Brain Tumor Delineation in Neurosurgery

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Abstract—**Mechanical characteristics of tumor and healthy tissue in the brain differ but slightly. The task of designing a system that is able to differentiate tissue dignity with high sensitivity is of great importance in neurosurgery. Even when localization of tumor by use of preoperative imaging techniques provides the surgeon with valuable information to decide where and what to resect, the brain shift due to change in pressure during skull opening demands the surgeon to define the limits of the tumor using tactile and visual differentiation. This paper contains a general description of the tactile sensor system based on a piezoelectric bimorph. The main parts of the measurement system are described and the selection of the electrical parameters for tactile differentiation is justified. Results are discussed for a series of measurements at different concentrations in gelatin phantoms.**

I. INTRODUCTION

Diagnosing a brain tumor is a frightening and worrying episode for the patient and his family. In addition to the health and life threatening, the patient fears the probability of a mental or physical disability as a consequence of the surgery. During neurosurgical resection of brain tumor surgeons' dexterity and wariness are of vital importance, which makes it an extremely challenging task. However, neurosurgical brain tumor resection is nowadays facilitated by the technological innovation of image guided surgery tools, such as neuronavigation. This tool supports the surgeon to localize and delineate a brain tumor [1,2]. Thus neuronavigation contributes on the one hand to achieve a most completely tumor resection and on the other hand to avoid functional brain impairment. Nevertheless, it is limited in accuracy due to brain shift caused by neurosurgical tissue manipulation during surgery, leading to a mismatch of preoperative acquired images.

Intraoperative magnetic resonance (IMR) images can also offer the possibility to evaluate brain shift and correct the localization of tumor during operation [3]. It results however to be an expensive and sophisticated tool because the brain shift is a dynamic process that demands iterative updating of the images [4], resulting into a time consuming procedure. Consequently tumor delineation is actually guided by the neurosurgeons' visual sense, magnified by the use of operation microscopes and the tactile perception, transmitted by the surgical instruments to the neurosurgeons fingers and hands. Tumor resection is in some degree therefore dependent from the surgeons' subjective perception; moreover tactile perception is limited to discriminate relative differences in tissue stiffness. The availability of a reliable sensor capable to estimate mechanical parameters of tissue as a further diagnostic criterion would be of particular importance in neurosurgical brain tumor resection.

Investigations to understand and imitate the human sense of touch are of great interest in different fields, like robotics. A tactile sensor must be capable to provide enough information on the mechanical characteristics of the touched object in order to differentiate it from others. The application of piezoelectric materials to design tactile sensors has been studied for many years and reported in diverse research works [5-7]. These materials show many advantages when using them to recognize surfaces, define contours or evaluate contact force/pressure. This paper reports our efforts to develop a tactile sensor based on a piezoelectric bimorph that can be used as an intraoperative add-on by the surgeon in order to improve tumor delineation.

II. MATERIALS AND METHODS

A. Piezoelectric Sensor

The main element of our sensor system is a PZT piezoelectric bimorph. It is composed by two piezoceramic plates attached to a common cantilever. A spherical plastic tip is placed to improve tissue contact. Two bimorphs are presented in Fig. 1; on the left side a bimorph with a simple fixing structure is shown and on the right side a second bimorph mounted into a housing jacket for better manipulation or adaptation into a robotic system. In both cases the bimorph is electrically isolated from the fixing structure and housing.

B. Operation Mode

A frequency sweep was performed to evaluate the dynamic response of the bimorph. First, electrical admittance Y was measured for a range of frequencies between 100 Hz and 10 kHz, see Fig. 2a. Four resonant peaks were found at about 180 Hz, 1100 Hz, 3200 Hz and 6000 Hz. A second frequency sweep was conducted to test sensitivity of the bimorph in the presence of load.

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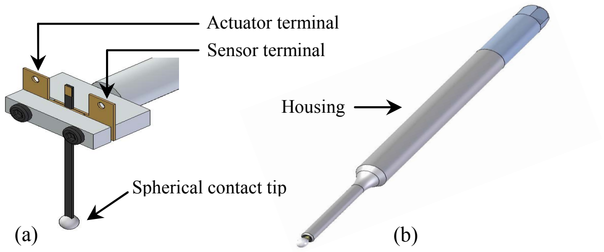

Fig. 1. Piezoelectric tactile sensor for tissue differentiation. (a) Bimorph on a simple fixing structure. (b) Bimorph mounted into housing

In this case the resonance peaks were highly damped, therefore this operation mode was not suitable for our purposes.

For this reason, a different concept was implemented for the measurement. One piezoceramic plate of the bimorph is used to generate the vibration of the beam (i.e. function as actuator) applying a sinusoidal voltage to its electrode and the common cantilever. The other plate is used as a sensor, see Fig. 3. Based on the direct piezoelectric effect, the generated voltage is a function of the deflection of the bimorph. Analytical equations to determine the amount of generated voltage of piezoelectric bimorphs can be found in [8-9]. Fig. 2b presents the frequency sweep measurement of the ratio of both plates' voltages for a frequency range from 100 Hz to 10 kHz. The ratio G is determined as:

$$G = \frac{U_{Sensor}}{U_{Actuator}}$$

Where $U_{Actuator}$ is the driving voltage and U_{Sensor} is the voltage generated in the piezoelectric plate that is used as a sensor. The sweep shows the same four different resonant peaks as in the measurement of Y, with the difference that a clear identification of each resonance frequency is observed. A second sweep performed in the presence of load showed that all the resonance peaks, except from the first one around 200Hz, were slightly damped in the presence of load. Also a small frequency shift was appreciated. It is assumed that frequency and amplitude of the resonance peaks depend on the mechanical impedance of the whole system. When the bimorph is subject to certain load, the total mechanical impedance changes and an amplitude reduction in G as a shift in the frequency of the resonance peaks is observed. Therefore this mode of operation was selected for our measurements.

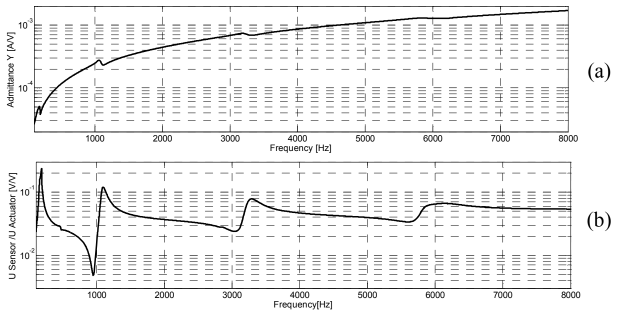

Fig. 2. Frequency response of the tactile sensor: (a) Measurement of electrical admittance Y. (b) Measurement of ratio G.

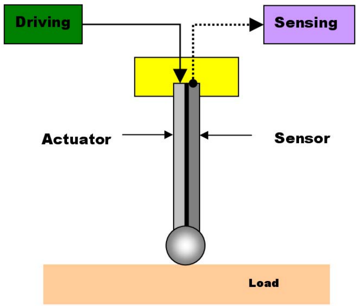

Fig. 3. Piezoelectric bimorph. One piezoceramic plate is used to sense and the other to actuate.

C. *Gelatin Tissue Phantoms*

Brain tumor tissue consistency may range from a nearly liquid state up to a rather solid constitution in the case of tumor calcification. In order to mimic some of the physical properties of the brain tissue, gelatin powder was used to elaborate phantoms at different concentrations. These gelatin probes were produced to imitate marginal tissue consistency differences, which are crucial but difficult to distinguish by a neurosurgeon, in contrast to the extreme consistency values that are relatively easy to differentiate. Turgay et al. [10] reported that tissue can be modeled using a discrete 1-D viscoelastic model to identify its mechanical parameters. The application of this model is limited, but suitable for tissue delineation and differentiation. To validate this model, we conducted experimental measurements to a series of gelatin phantoms at different concentrations. Fig. 4 shows the stiffness measured at the surface of several gelatins. Stiffness increases directly proportional to the concentration of gelatin almost in a linear way.

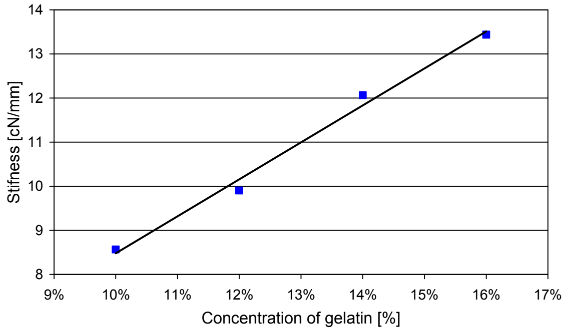

Fig. 4. Experimental measurement of stiffness on gelatin phantoms.

To visualize the effect of damping a pulse response was performed. A small force was applied on the phantom's surface during a short period of time and the vibration was measured using a laser interferometer and recorded using a digital oscilloscope. Fig. 5 shows the response of four different phantoms. For higher concentrations of gelatin the amplitude of the vibration is reduced or damped faster than for lower concentrations in the same amount of time; therefore it is easily seen that damping depends on the concentration of gelatin.

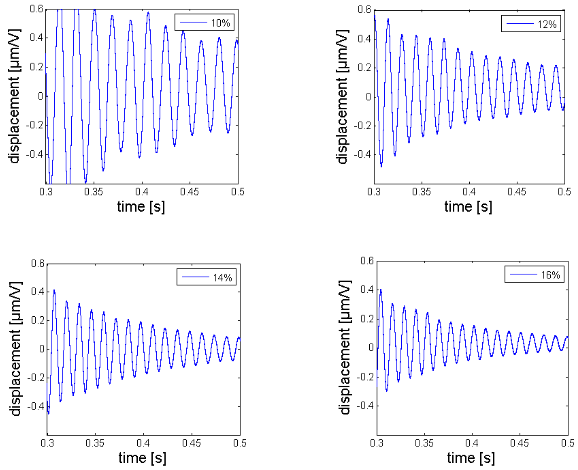

Fig. 5. Vibration damping measured on different gelatine phantoms.

D. *Measurement Concept*

To probe the sensitivity of the sensor system, four different gelatin phantoms were prepared at concentrations of 10%, 12%, 14% and 16%. It is assumed that a soft and constant contact exists between the tip of the bimorph and the surface of the gelatin during all the measurements.

To make contact with the gelatin, the bimorph is mounted into a precision linear stage remotely controlled. In addition, a precision scale is used to measure the contact force. Changes in gelatin concentration lead to changes in stiffness and damping. The maximum value of *G* in the near of a resonance mode is influenced by changes in the damping (i.e. reduction in amplitude) and the value of the resonance frequency is shifted by changes in stiffness (i.e. to higher values). The electronic measurement system is compounded by the following elements: a function generator from National Instruments® to drive the bimorph, and a data acquisition card from the same company to measure the driving voltage $U_{Actuator}$ and the generated voltage U_{Sensor}. The measurement system is fully automated and controlled by a program developed in Labview®, where the main electrical parameters are calculated: frequency, amplitude of both signals, phase difference and the ratio *G*.

The bimorph is driven using a sinusoidal voltage at constant amplitude of 1 Volt. The contact force for all measurements is set at 10 cN and controlled using a linear stage. Frequency sweeps from 1 kHz to 10 kHz were performed for all the concentrations. Then frequency sweeps in the vicinity of the resonance peaks around 1150 Hz, 3250 Hz and 6500 Hz were also performed. Results are presented in the next section.

III. RESULTS AND DISCUSSION

The frequency sweep presented in Fig. 6 shows that the sensor system in presence of load behaves as expected. In this figure, three resonance peaks can be identified with the same behavior: increments in the concentration of gelatin generate a clear amplitude reduction of the maximum value of *G* and a shift in the resonance frequency to higher values. For a better visualization, a zoom made on each resonant peak is presented at the bottom part of the figure. Presumably, the first resonance peak is the best operation point for the sensor system due to its higher output and almost linear response to variations of gelatin concentration. However, the use of higher resonance frequencies is possible with the utilization of very high sensitive electronic measurement systems.

Moreover, the evaluation of the phase difference provides important information for the design of the sensor system. The result of the frequency sweeps in the vicinity of the resonance peaks around 1150 Hz, 3250 Hz and 6500 Hz shows that the value of the phase difference at the maximum point of *G* remains practically constant. This behavior is valid for all the resonance peaks measured. As an example, the measurement of the first two resonance peaks is illustrated in Fig. 7. Considering that the phase difference is almost constant for tissue phantoms with slightly differences in their mechanical properties, it is very suitable to use our sensor in combination with a frequency control system based on the evaluation of the phase (e.g. Phase-Locked Loop PLL), which will provide a fast evaluation and determination of the maximum amplitude of *G* and the value of the resonance frequency.

Creation of models to describe the contact process between the bimorph and the gelatin at different conditions (e.g. wet surface) will follow to get a better understanding of the behavior of the sensor under real conditions. In addition, measurements on brain tissue of animals will be conducted to determine the feasibility of our sensor system.

IV. CONCLUSION

Experimental measurements on several tissue phantoms show that our sensor system is able to differentiate small variations in the concentration of gelatin. In order to simplify the measurement technique, the sensor system can be driven directly in resonance using resonant control electronics based on phase comparison using a PLL.

The tactile sensor exhibits a high sensitivity exceeding human tactile perception in determination of tissue damping and stiffness characteristics. Nevertheless the sensor is not applicable as a stand-alone diagnosis tool for tumor detection, since evaluation of damping and stiffness are non-sufficient parameters for a complete characterization of the mechanical properties of tissue. The tactile sensor will be relevant as an add-on tool for intraoperative tumor detection, increasing resection safety. Furthermore tactile sensor elements will be highly interesting in combination

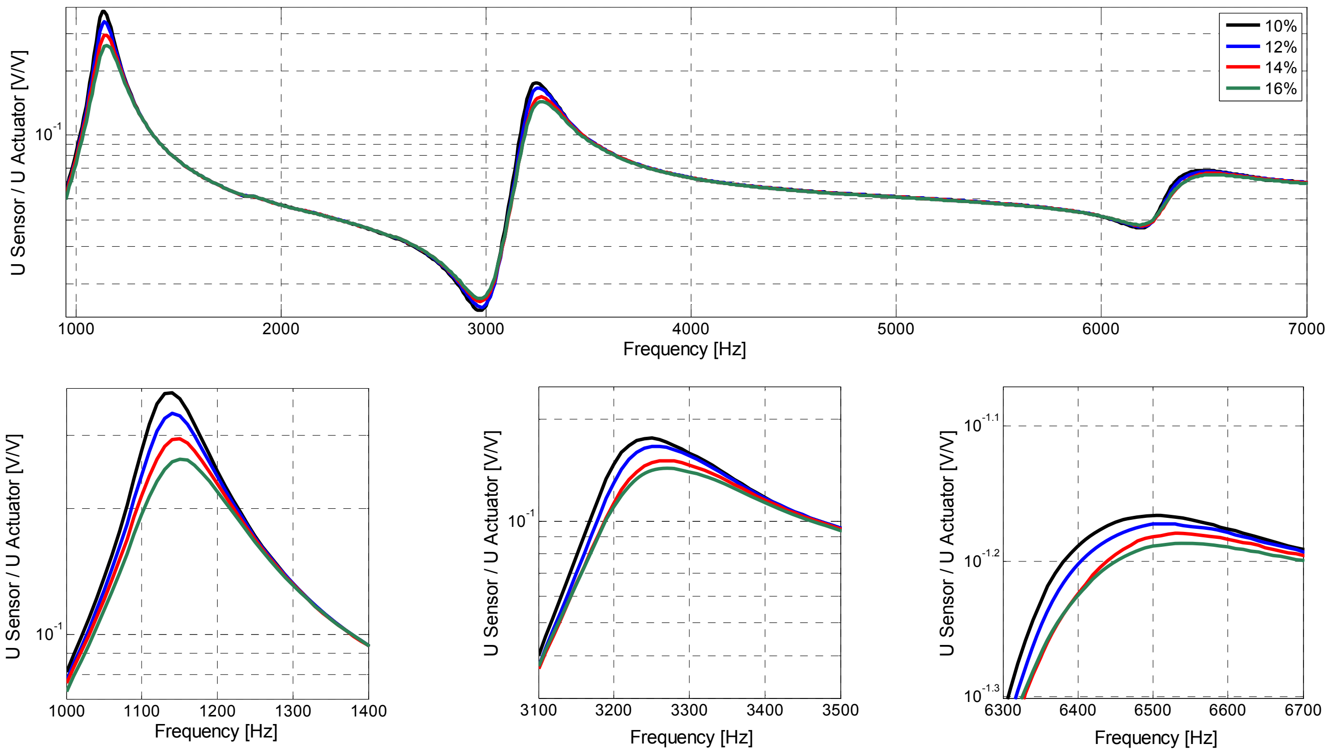

Fig. 6. Frequency sweep response for a series of gelatine phantoms at different concentrations and the correspondent zoom to the three resonance peaks found in the measurement. All resonance peaks exhibit sensitivity to the change in gelatine concentration.

and integration with further biophysically sensor elements like sensor elements with a spectroscopic mode of functioning. In thus a manner a highly integrated multi-sensor element would be interesting in a future robotic guided tissue ablation.

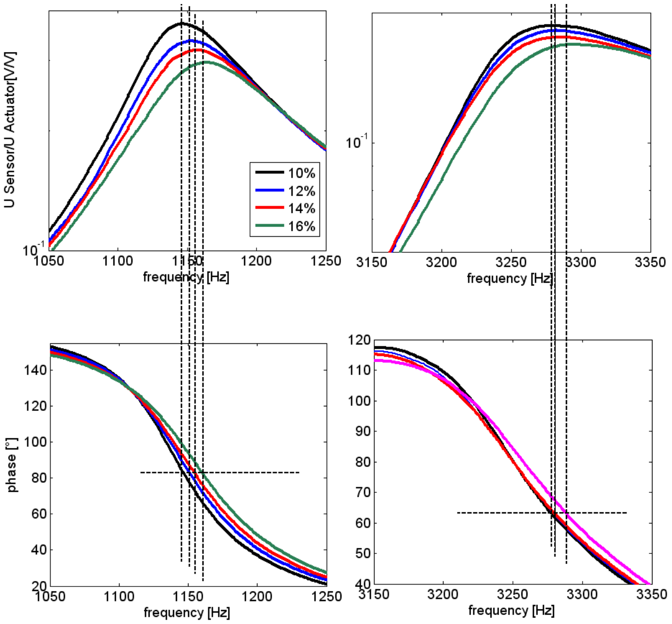

Fig. 7. Frequency sweep response of two different resonance peaks. Phase remains constant for each value of maximum *G*.

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