INDUCTIVE-COUPLING SYSTEM FOR ABDOMINAL AORTIC ANEURYSMS MONITORING BASED ON PRESSURE SENSING

A.T. Sepúlveda[1,3], A. Moreira[2], F. Fachin[3], B.L. Wardle[3], J.M. Silva[4], A.J. Pontes[1], J.C. Viana[1] and L.A. Rocha[1]

[1]I3N/IPC-Institute for Nanostructures, Nanomodelling and Nanofabrication, University of Minho, Portugal
[2]University of Porto – Faculty of Engineering, Porto, Portugal
[3]Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, USA
[4]INESC Porto, University of Porto – Faculty of Engineering, Porto, Portugal

Abstract — **Permanently implanted sensors with continuous monitoring of pressure for cardiovascular applications are particularly attractive as they provide additional opportunities for better therapies and enhanced quality of life. In Abdominal Aortic Aneurysms (AAAs), where stent-grafts are frequently used for treatment, are exemplary applications for this type of device. This paper introduces a new carbon nanotube (CNT)-based flexible capacitive sensor along with two different reading systems based on inductive-coupling. The fabrication process for the flexible sensor and the main characteristics of the reading systems are presented, as well as simulation results and preliminary experimental results of CNT-PDMS elements. Electrical conductivity of PDMS membranes with embedded aligned CNTs is 10 S/m, in the direction perpendicular to the CNT axis.**

Keywords: Inductive-Coupling, Stent-Graft, Pressure Sensor, Carbon Nanotube.

I - Introduction

Abdominal aortic aneurysms (AAAs) are a common vascular disease affecting 12 per 100 000 persons-year [1] and are expected to increase with the rise in life's expectancy. Nowadays, two treatments are available: conventional surgical repair (open surgery) and endovascular aneurysm repair (EVAR). EVAR is a minimally invasive procedure in which a stent-graft is guided from the femoral artery to the affected artery segment in order to prevent wall rupture, thereby shielding the aneurysm from the blood pressure (BP). This treatment requires regular surveillance in order to detect and prevent complications such as graft migration, stent fracture, endoleaks, enlargement of the aneurysm sac, and AAA rupture. Despite the advances in EVAR in recent years, reintervation is still needed in ~10 % of patients [2]. Therefore, procedures for monitoring and supervising are crucial in detecting future problems and improving overall efficacy of AAS repair.

The sensing methods used in today's procedures require a long time to complete, causing discomfort to the patients while exposing them to carcinogenic risks [2-4] due to ionization radiation (e. g. computed tomography). Moreover, the results are not always accurate in the detection, leading in some cases to false-positive findings [4].

This work proposes a new method to monitor AAAs after the EVAR procedure. The monitoring system uses inductive-coupling to deliver energy and to communicate with a flexible capacitive sensor that is placed inside the aortic aneurysm sac, prefabricated and attached to the stent-graft. The proposed solution does not require any additional surgical intervention, and is passive except when read. The system should be able to incorporate multiple sensors (figure 1) rather than a single sensor to increase both the efficiency of the monitoring system, provide important information about the evolution of the aneurysm, as well as effectively eliminate false positives by providing statistical information as a function of spatial placement of the multiple sensors.

Each sensor comprises an LC resonant circuit, with a different oscillation frequency. The monitoring system is based on the deviation of the sensors' oscillation frequency by means of a capacitive pressure transducer. This paper focuses mainly on the telemetry reader system, the most critical block of the entire reading circuit, and on the fabrication technology of the pressure sensor, given requirements that the sensor be foldable, extremely flexible and characterized by a very small profile (in line with the minimally-invasive procedure used for endoprosthesis deployment).

This paper is divided in four major sections. Section II describes the two alternative circuits being developed for the communication with the sensors. Section III provides the details of the flexible sensor fabrication process. Section IV shows some of the preliminary results obtained and finally, section V highlights the conclusions and points out future work.

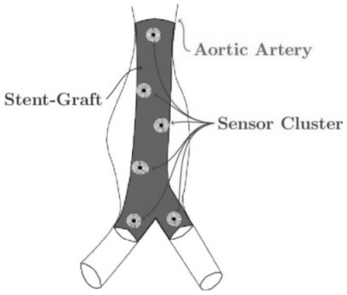

Figure 1: Abdominal aorta aneurysm after EVAR, featuring the sensor cluster attached to the stent-graft.

II - Reader/Sensors Communication

The system oscillation frequency was chosen to operate in the frequency band from 12.5 MHz to 20.0 MHz allocated specifically for medical applications. This frequency band was also selected because, unlike the low frequencies of operation, it does not require inductors and capacitors with large dimensions that would affect the overall sensors' area. Additionally, this band guarantees some protection against biological effects and interferences generated by other electronic equipment. The frequency band from 30.0 MHz to 37.5 MHz can also be adopted (the same rationale discussed before also applies).

Next, two different circuit methodologies under study to read the signals from the sensors are discussed.

A. *Reader Based on an Impulse Response*

The first method is based on the sensors' impulse response. Figure 2 shows the schematic of the system including both the reader and sensor circuits. The R_p and R_{tp} resistors are the parasitic resistances values from the inductors L_p and L_{tp}.

In order to read the sensors response, a square wave v_{vs} is sent through the inductor L_p that in turn activates the sensor by generating a magnetic field. Once the sensor is activated, the output v_o superimposes the signal sent by the reader (the input) plus the sensors' response.

The duplication of the circuit marked as "twin" is necessary for the successful reconstruction of the sensors' signal. The use of a square wave to activate the sensors has the drawback of producing a high number of harmonics in the reader's output preventing the recognition of the true signal sent by the sensors. To detect the sensors' signal, the "twin" circuit enables the elimination of the unwanted harmonics v_{to} by subtraction (v_o - v_{to}).

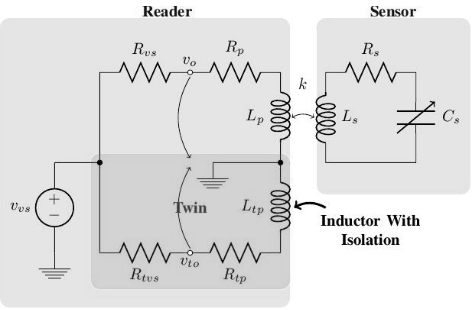

Figure 2: Reader's circuit based an impulse input.

B. *Reader Based on Power Transmission*

The second method is similar to the operation of a network analyzer, where sine waves with different frequencies are sent to the network to characterize the transmitted power. Since each sensor has an unique impedance at the oscillation frequency, this is reflected in the power transmitted when the sine wave frequency matches the sensors' oscillation frequency.

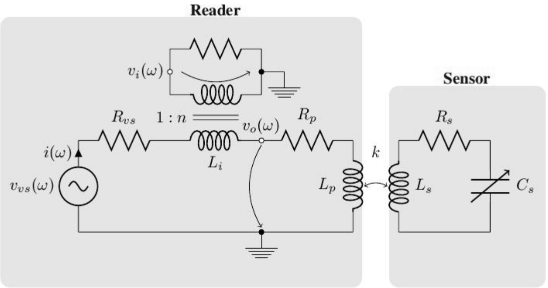

Figure 3: Reader's circuit based on the power transmission.

Figure 3 shows the schematic of the described system. The transformer captures the current *i(ω)* that is being drawn and converts the current to a proportional voltage $v_i(\omega)$ that is used to calculate the proportional transmitted power as described in equation 1:

$$\overline{P} = \frac{1}{n}\cdot\sum_{j=0}^{n} P_j(\omega) \equiv \frac{1}{n}\cdot\sum_{j=0}^{n} v_{ij}(\omega)v_{oj}(\omega) \qquad (1)$$

III - Sensors' Fabrication and Specifications

Given the characteristics of the application (the sensor will be attached to the stent-graft), the capacitive sensor must be foldable, extremely flexible and characterized by a very small profile. In addition, the technology should be simple and biocompatible. Silicon based microtechnologies are widely used in implantable medical devices [5], but due to the application specifications, a new fabrication process is introduced.

The proposed fabrication process uses carbon nanotubes (CNTs) to build the conductive elements, namely the inductor and the capacitor electrodes. The CNTs are embedded in a flexible substrate of polydimethylsiloxane (PDMS), a transparent, nontoxic and biocompatible silicone elastomer.

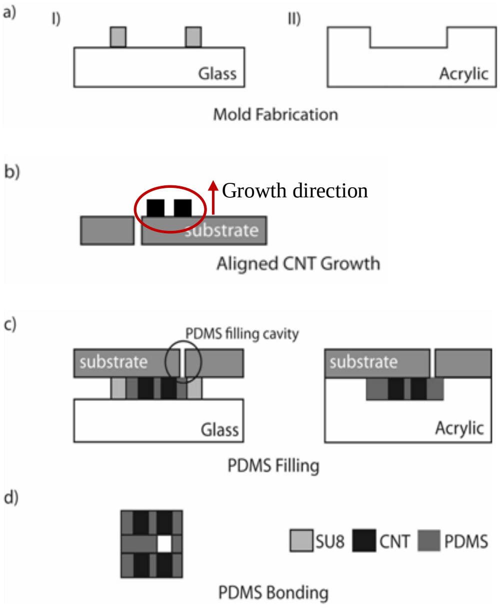

Figure 4: Fabrication process flow for the development of a flexible pressure sensor.

The fabrication process flow for the development of the flexible pressure sensor is schematically presented in figure 4. Two different approaches are being pursued to manufacture the flexible CNTs embedded PDMS films (figure 4). On one side, molds are fabricated using SU-8, a photoresist resin with excellent lithographic and optical characteristics (figure 4a-I). The high structural ratio of SU-8 allows obtaining structures with high dimensional control, an essential property to enable accurate control of the PDMS membrane thickness. On the other side, acrylic molds are produced by CNC milling (figure 4a-II). This technique presents some advantages relatively to SU-8 molding, such as lower costs and faster production times, but it is associated with poorer dimensional control.

The electric components (capacitor electrodes and inductor) are based on continuous aligned CNTs, as shown in figure 4b. Chemical vapor deposition (CVD) is used to grow forests or "carpets" of vertically-aligned CNTs (VACNTs) [6]. A SC silicon substrate with patterned with 1/10nm Fe/Al_2O_3 catalyst and placed in a horizontal quartz tube furnace at atmospheric pressure at 750 ºC [7] for the CNT growth. This method has the advantage of allowing the growth of high purity, high yield and vertically aligned continuous CNTs. Figure 5 shows two different experimental structures obtained using this method. The CNTs are nominally 8 nm in dia., contain 2-3 walls, and spaced ~80 nm apart giving a bulk volume fraction of ~1%.

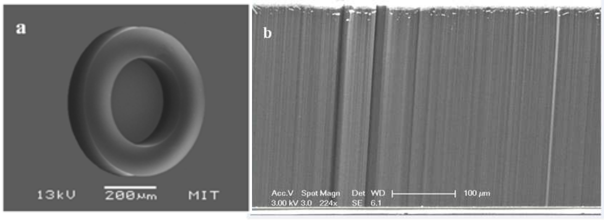

Figure 5: SEM images of two different CNT-based structures: a) "zero" shape and b) forest (no shape) of CNTs.

Next, the CNTs are embedded into the polymer matrix (PDMS). This step is schematically represented in Figure 4c, for both SU-8 and acrylic molds. The substrate is placed against the molds, and the PDMS is introduced in the cavities through a hole, followed by the curing of the elastomer. This follows similar procedures demonstrated for SU-8 and several epoxies [7, 8, 9 and 10] that utilize the CNT alignment to enhance capillary action of drawing the polymer into the aligned CNT network.

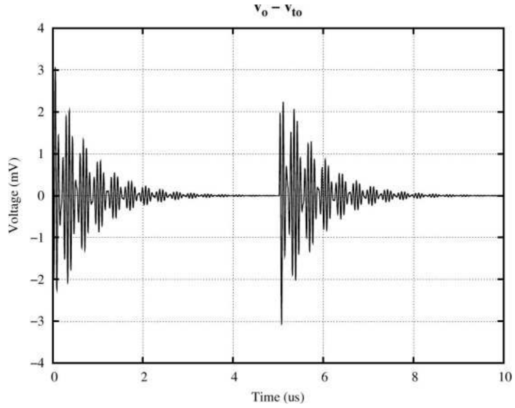

Figure 6: Agilent ADS transient simulation of the reader's circuit due to an impulse input.

The flexible pressure sensor is composed of three thin layers, with the top and bottom layers defining the inductor and the electrodes, and the middle one defining the dielectric (air). This configuration requires bonding of PDMS membranes. In [11], five different bonding techniques were tested and the highest reported bond strength was obtained for both partial curing and uncured PDMS adhesive techniques. The latter approach has proven successful in our work as well, and will be used for future experimentation (figure 4d).

Regarding the main specifications for the transduction element (pressure sensor), namely dynamic range, resolution and accuracy, they can be retrieved from the maximum values of blood pressure within the human body and required accuracy and maximum errors admitted by the legislation for pressure measurement devices [12]. For aortic aneurysm pressure measurement the sensor should have a dynamic range between 20mmHg and 250mmHz, a 1mmHg resolution and an absolute accuracy below 5mmHg [13].

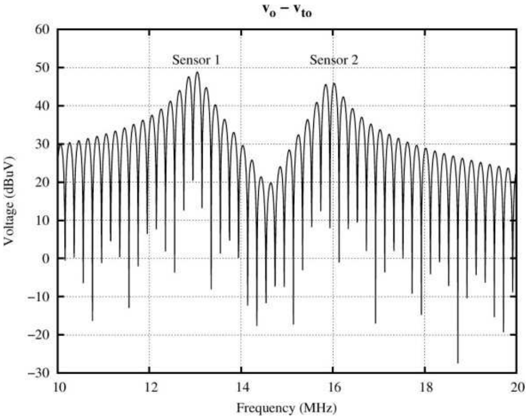

Figure 7: Agilent ADS Fourier analysis of the reader's circuit based on the impulse response.

IV - Results

A. Reader

The simulation results of the circuits described earlier are presented in this section. Figure 7 shows the response (V_0-V_{t0}) of two different sensors ($L_{S1}=10uH$, $C_{S1}=14pF$ and $L_{S2}=10uH$, $C_{S2}=10pF$ and $k_{s1}=0.06$, $k_{s2}=0.06$, $k_{s12}=0.01$) when a square wave is applied to the reader. Figure 7 shows the Fourier transform of the response signal of Figure 6. These simulations consider ideal components and therefore the output shows no distortion. Small asymmetries in the real case will cause deviations in the circuits that fail to completely eliminate the harmonics in the output signal, contributing to distortion after the subtraction operation. Moreover, the differential amplifiers used have finite values of common mode rejection ratio (CMRR) and therefore the subtraction operation is also not ideal.

The simulation results from the 2nd approach, the circuit based on the power transmission, are presented in Figure 8. This circuit presents some advantages relatively to the impulse response based reader since it does not require subtraction and consequently has a lower output distortion. On the negative side, this circuit is more complex due to the sine wave frequency sweeping and requires more time to acquire the complete data.

B. Sensors' Process Fabrication Characterization

The key step of the fabrication process is the CNT's impregnation by PDMS, and respective mechanical and electrical properties (required for the sensor design). Both acrylic and SU8 molds have been fabricated

(Figure 9), and are being used to build the PDMS flexible membranes with embedded aligned CNTs (Figure 10).

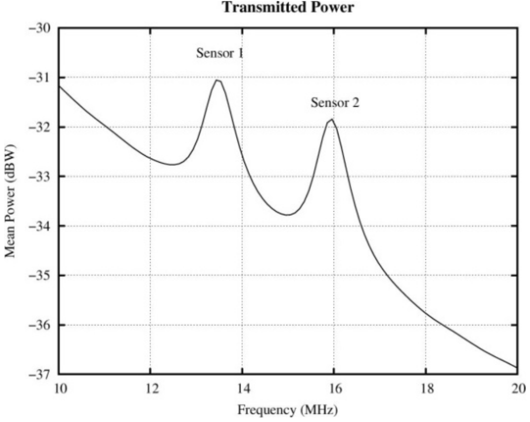

Figure 8: Agilent ADS simulation of the reader's circuit based on the transmitted power.

First measurements to a series of samples (PDMS membranes with embedded CNTs) indicate an electrical conductivity of 11,43 S/m with standard deviation of 13,37 S/m in the direction perpendicular to the CNT axis. Recent work has shown that conductivity in the direction parallel to CNTs for polymer-nanocomposites containing aligned CNTs is 10-100X that in the direction perpendicular to the CNT axis [14] (as found herein for PDMS).

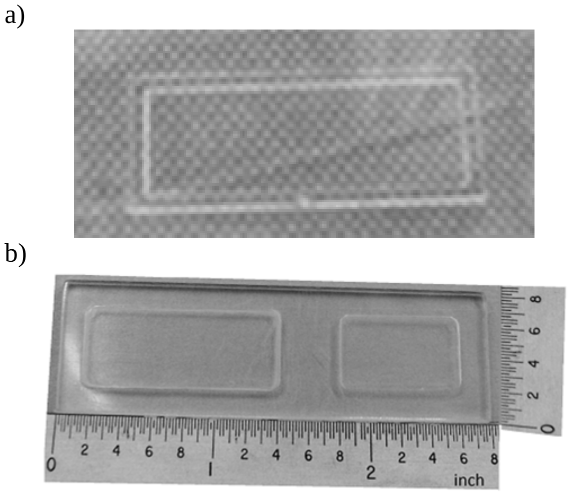

Figure 9: Fabricated a) SU-8 and b) acrylic molds for the production of PDMS membranes.

V - Conclusions

This paper presented two different solutions for wireless monitoring of AAA based on implantable flexible pressure sensors. The first solution (impulse response) does not require high circuit complexity while the second solution, based on power transmission, is more complex with regard to the sinusoidal source controllability, but enables an improved and more information-rich output signal to be captured.

The flexible pressure sensors will be based on flexible PDMS membranes with embedded CNTs. The process is under mechanical and electrical characterization and first functional pressure sensors are expected soon. Prototypes of the telemetric reading system are also under development and will provide more data to access which of the two solutions will perform better.

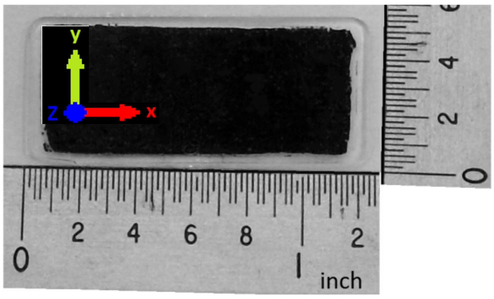

Figure 10: PDMS membrane with embedded CNTs (the "z" axis corresponds to the direction of CNTs).

Acknowledgments

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