Modeling of a Ring for Blood Pressure Measurement in COMSOL Multiphysics® for Medical Applications

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***Abstract*– This paper explains the use of a model to design an implanted blood pressure monitoring system through simulations in COMSOL Multiphysics® by using FSI Module. These measurement systems need to have a minimal blood contact to reduce the thrombus formation, bleeding, and avoid vessel occlusion, which are associated with the conventional catheter-tip-based technique. The model employs an elastic sensing cuff, wrapped around the artery section, made of silicone filled with bio-compatible fluid with an immersed MEMS pressure sensor. From this mechanical interaction, the measured waveform represents a down-scaled version of the blood pressure waveform, where the simulation scale factor was 0.2859. From the analytical study, the scale factor was 0.2921, which results in an error of 2.1%. With this factor it is possible to adjust the measurement system for different medical applications.**

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I. Introduction

Currently, heart problems represent one of the main causes of death worldwide [1]. That is why great efforts are being made all over regarding medication development and treatment systems. Within these systems, one of the greatest challenges is *in-situ* blood pressure measurement for the corresponding monitoring and control. The most common technique used is through an invasive catheter that comes in contact with the blood flow as it is inserted into the artery [2]. However, this technique requires a surgical procedure and promotes blood pressure increase, bleeding, coagulation problems, and sensory reduction over time [1]. One of the implementations that measure blood pressure avoiding the aforementioned problems is the use of an elastic ring placed around the artery. This ring features an inner cavity filled with a fluid able to perceive and transmit the pressured exerted by the blood on the inner walls of the artery. This effect is achieved through the mechanical coupling between the artery and the ring. The pressure is transmitted to the inner fluid of the ring and is measured by a MEMS (Microelectromechanical System) that uses a built-in pressure sensor. Thus, a down-scale value of blood pressure is obtained. Fig. 1 shows a layout of the measurement system.

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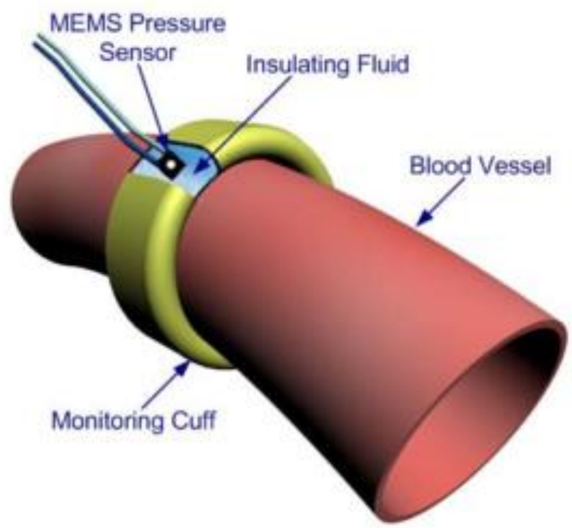

Fig. 1 Implantable external blood pressure monitoring system [3].

Since the measurement made represents a down-scale value of the real value, when designing the measurement system, it is necessary to make the corresponding adjustments to the data obtained from the measurements (post processing) [4]. The adjustment scale factor is one of the design parameters that depends on the mechanical features of the material used to manufacture the elastic ring, on the thickness of the ring's layers, and on the size of the inner fluid cavity. This work shows the design of a model in COMSOL Multiphysics® to get the measurement scale parameter of the system under study. First, an analytical study is presented with a mathematical model of the system. Them, the validation of the mathematical model was done with an implementation of the model in COMSOL Multiphysics® simulation software. At the end, the results of the simulation are showed and the related conclusions.

II. Analytical study

To carry out the study of the mechanical system, a cross-sectional scheme of the ring around the artery was prepared. It is shown in Fig 2.

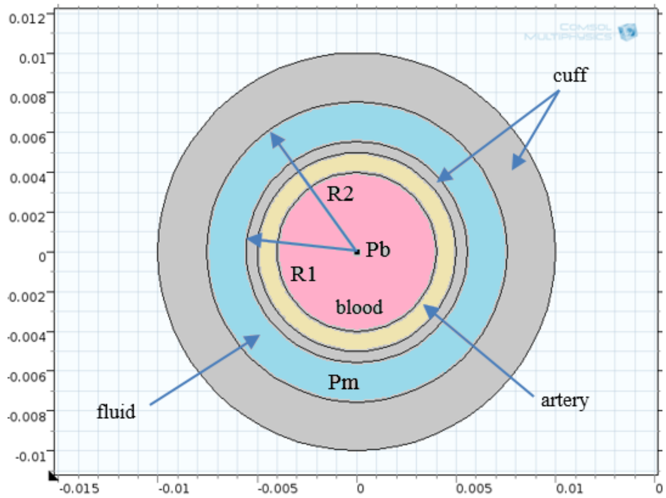

Fig. 2. Cross section of sensing cuff wrapped around blood vessel

From Hooke's law of elasticity, it was obtained the analysis equations to calculate the scale factor between the pressure gauged by the MEMS sensor (P_m) and the pressure exerted by the blood flow upon the arterial wall (P_b). The following equations match the P_m change according to P_b variations [5].

$$\Delta P_m = \eta \Delta P_b \tag{1}$$

$$\eta = \frac{\left(\frac{R_1}{R_2}\right)^2 K_{outside-CW}}{K_{BW} + K_{inside-CW} + \left(\frac{R_1}{R_2}\right)^2 K_{outside-CW}} \tag{2}$$

Where η is the scale factor, R_1 the outer radius of the ring's inner wall, R_2 the inner radius of the outer wall, $K_{outside-CW}$ the elastic module of the outer wall of the ring, $K_{inside-CW}$ the elastic module of the inner wall and K_{BW} the elastic module of the arterial wall.

Recalling that for a higher elastic module, more rigid is the material. If the elastic module of the outer wall is much higher than the elastic module of the inner ring and of the artery, the scale factor tends to be 1, which is a desirable condition in any measurement system. However, this condition causes greater mechanical restraint on the artery leading to physical injuries (hardening, deformities, etc.). Contrary to the foregoing, if the elastic module of the outer ring is much lower than the other two, the factor tends to be 0, a condition that presents sensitivity problems in the measurement system because variations in the fluid pressure in the inner cavity of the ring would be very small with respect to those from the arterial wall. Therefore, it is recommended to use scale values in the range of $0.1 - 0.3$ [2].

A silicone produced by Dow Corning Company was selected as ring material for this study. The material is known as *SILASTIC® MDX4-4210 Biomedical Grade Elastometer with Catalyst* [6]. Its characteristics allow it to be used in medical applications. Also, it presents an elastic module (Young Module) in the $0.003 - 0.03\ GPa$ range, a Poisson relation between $0.47 - 0.49$, and a density between $1110 - 1140\ kg/m^3$ [7]. Table 1 summarizes the geometrical dimensions of the model:

Table 1. Sensing cuff size parameters

Dimension	**Value [mm]**
Outer radius of the artery	5.00
Thickness of the artery	1.25
R_1, outer radius, inner ring	5.55
R_2, inner radius, outer ring	7.25
R_e, outer radius of the ring	10.00

From the previous parameters and material properties, the scale factor was calculated (equation 2) and a value of 0.2921 was obtained.

III. Implementation in COMSOL Multiphysics®

A tridimensional model of the ring was implemented through COMSOL Multiphysics®. Considering the parameters in Table 1, the geometry of the model was developed using COMSOL geometric construction tools, Fig. 3.

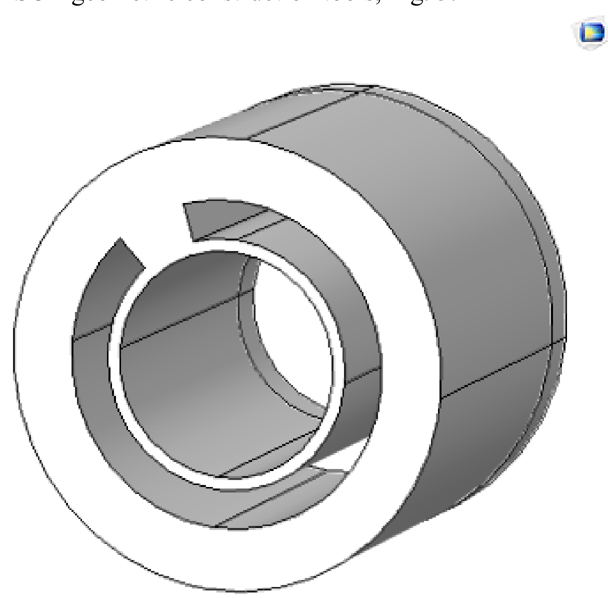

Fig. 3. Sensing cuff

Then, the ring was fitted together with a 10 cm section of the artery with a wall thickness of 1.75 mm, Fig. 4.

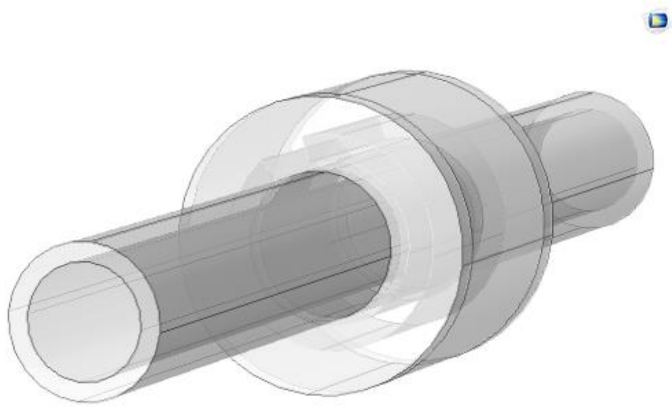

Fig. 4. Sensing cuff wrapped around blood vessel

To have the mechanical properties of the material selected for the ring, a new material was added to COMSOL's library of materials under the name MDX4-4210. Regarding the ring's inner chamber, water was used as fluid from the library of materials.

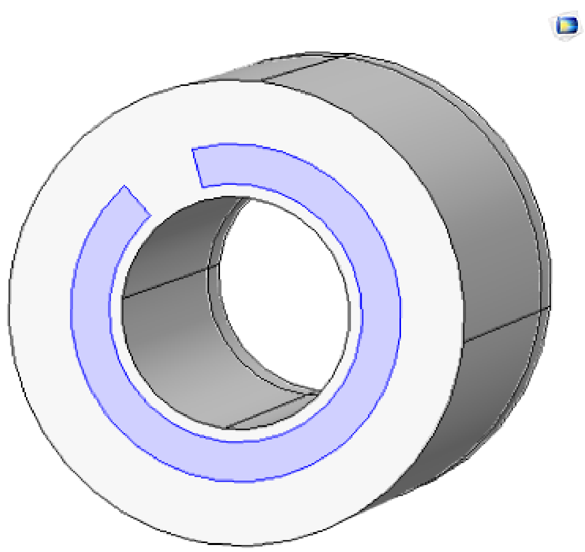

Fig. 5. Fluid domain (inner chamber)

To study the mechanical interaction between the blood flow, the arterial wall, and the ring, the Fluid-Structure Interaction (FSI) module was used. Thus, pressure changes produce a normal net force on the surface that can be translated into a possible deformity in elastic materials. This way, the ring being mechanically fitted to the arterial wall and the deformities (expansions and contractions) of the artery produce a transmission towards the inner fluid pressure in the ring. Therefore, it is possible to measure the pressure variations of the ring's inner fluid caused by the variations from the blood flow pressure. Pressure losses caused by mechanical couplings in charge of transmission generate a lower measured value, hence this model allows to obtain a measurement scale value according to ring dimensions and material properties.

For the simulation, a temporary study was conducted where, as a boundary condition, a mathematical function was established to model the blood pressure wave produced by the heart at the entrance of the aortic arch [8] [9]. Fig. 6 shows the pressure wave used in the simulation as a boundary condition at the entrance of the artery.

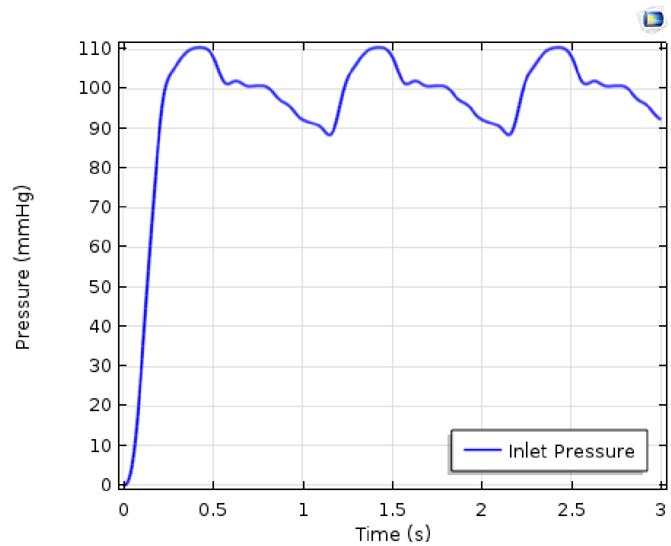

Fig. 6. Blood pressure wave at blood vessel input

IV. RESULTS

The first result of the simulation was the displacement undergone by the ring due to the contraction and expansion of the artery caused by blood pressure change. Fig. 7 reveals the displacement in radial direction of the artery surface on a point of contact with the elastic ring. The maximum displacement occurs with the systolic peak pressure with a value of 60.16 μm.

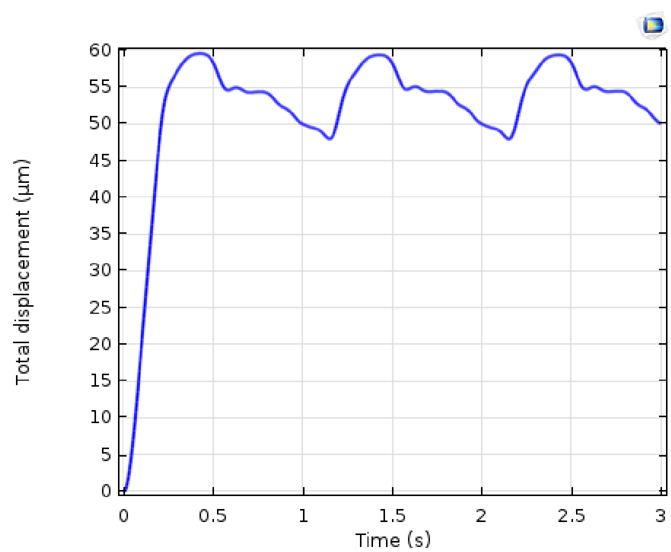

Fig. 7. Total displacement of the external artery wall

To analyze displacement throughout the ring's volume, Fig. 8 shows the total displacement of the ring for the time of the systolic peak pressure. The maximum displacement is $63.04\ \mu m$ at a point in the inner ring. The previous result was expected since the outer ring is thicker and works as a mechanical resistance to inner ring deformation; an effect that allows the transmission of pressure to the ring's cavity fluid.

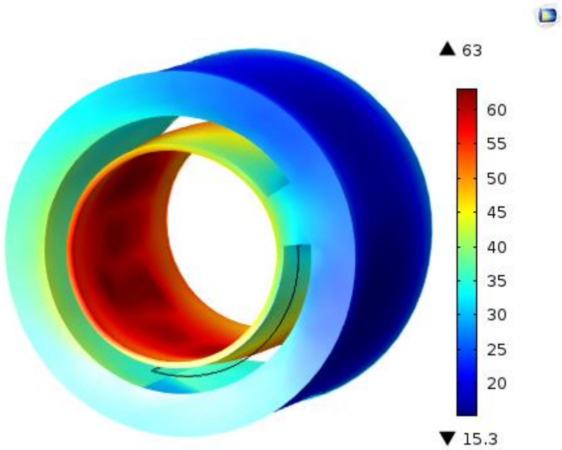

Fig. 8. Total displacement at time $t = 1.4s$

Fig. 9 shows the blood pressure wave and the wave of pressure measured at the inner cavity of the ring. To get the scale factor of the wave measured, both pressure values are taken for a same time and the scale factor is calculated between them. That is how a scale value of 0.2859 was obtained. When comparing the value obtained in the simulation with the theoretical value, the error rate percentage was 2.1%.

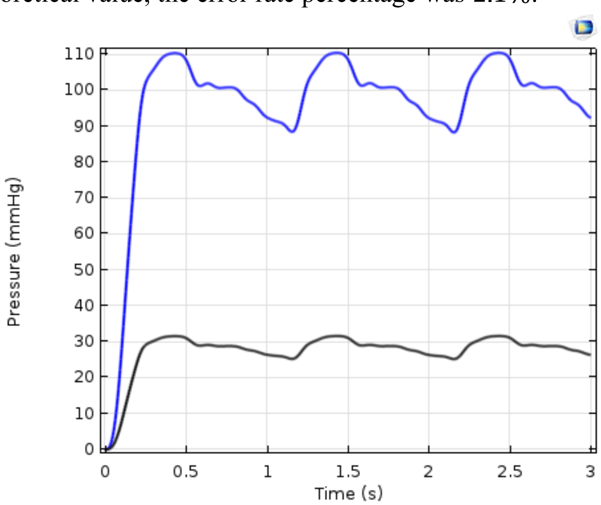

Fig. 9. Blood pressure wave (blue) and fluid pressure wave (black)

V. Conclusions

This model allows us to estimate the scale value of the blood pressure measuring system under study so that it is possible to make geometrical redesigns, material changes, changes in operating conditions, among other necessary modifications. It is thus possible to perform an optimization process in the design of the ring according to the medical application for which it was intended or the type of patient who requires it, according to age and health condition. As, for instance, an older adult exhibits a higher degree of stiffness in the arterial walls than a young person, and a child has smaller diameter arteries.

V. Future Works

The next works consist in design a specific process to fabricated a scaled version of the model with the specific materials and techniques required. Is important to record that the objective is to have a biocompatible system, and the materials, shapes and stiffness are another important design requirement. Another related work is the monitoring system, include the design of the pressure sensor and the electronic data acquisition system with the next post-processing data. This effort is part of a research project at Costa Rica Institute of Technology, where there are a work team with the design of a ventricular assist device (VAD) for use it as a medical device to treat different heart problems.

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