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Transit Time Measurement of a Pressure Wave through an elastic tube based on LVDT sensors

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***Abstract* – Transit time is the propagation time of a pressure wave travelling between two sites in a medium. Such parameter is mainly implied in the biomedical field as a surrogate for the estimation of important markers of the cardiovascular system (e.g. blood pressure and arterial stiffness). The non-invasive transit time measurement is commonly used in clinical practice because it allows the continuous recording and monitoring of blood pressure. The development of an *in vitro* system able to reproduce the main cardiovascular characteristics is of primary importance for further investigations of the relationship between transit time and the arterial stiffness in order to predict the cardiovascular risk factors. The present work focuses on the development of a LVDT-based experimental set-up able to simulate transit time variations due to transmural pressure changes on an elastic tube. As validated in *in vivo* measurements, transit time and maximum radial tube displacement increment decrease with decreasing transmural pressure.**

I. INTRODUCTION

Transit time is defined as the time delay pressure wave takes to propagate between two different sites of a homogeneous elastic tube [1]. Such parameter has been mainly studied and applied in the clinical practice and in the biomedical field [1-2] since it is a physical quantity generally used to derive systolic and diastolic blood pressure as well as vessels stiffness. After some recent studies have shown a good correlation between invasive and non-invasive transit time measurements [3], the latter have been mostly used to estimate two novel indicators for blood pressure (BP) and arterial stiffness (AS) [4-5]. In fact, in recent years the interest around new indicators for BP and AS estimation has grown as a consequence of the increasing incidence of cardiovascular diseases worldwide [6]. The non-invasive assessment of such parameters plays a key role for the choice of measurement protocol and clinical instrumentation. Some authors suggested that one of the advantages of transit time measurement is the absence of cuffs in BP monitoring therefore bypassing both discrete measurements with continuous pressure monitoring and the use of inflatable cuffs avoiding vessel occlusion discomfort for patients [1,7-8]. Nowadays, different protocols can be found in literature that allow pulse transit time measurements *in vivo* [9-11]. Moreover, with the aim to investigate on the topic, devices that simulate the arterial behavior *in vitro* have been proposed in literature [12-16]: such systems are usually embedded with elastic tubes and sensors to provide measurements and indices related to BP or AS. Nevertheless, despite the scientific community interest on this topic, it is difficult to retrieve quantitative studies on transit time measurement in arterial simulators by mean of Linear Variable Differential Transformer (LVDT) sensors, as well as experimental studies on the transmural pressure effect on transit time for elastic tubes immersed in water. Since LVDT measurement setups are usually suitable for a huge number of applications in many fields [17-28], it's worth an in-depth investigation.

Therefore, the focus of this work is the estimation and monitoring of transit time of a pressure wave through an elastic tube equipped with two LVDTs, to establish its relationship with transmural pressure when inner and outer pressure conditions vary. The pressure wave traveling inside the tube, due to the action of a pressure generator, is the direct cause of its radial displacement variation. This cause-effect relation allows to determine, from the total radial displacement waveforms, the transit time between two different tube sites. In this work, such waveforms have been acquired through the implementation of a LVDT sensors-based experimental set-up, since LVDTs convert a displacement in a voltage signal. Therefore, a mathematical model is needed to describe all the parameters involved in the measurement protocol: the relationship between transmural pressure variation and the static radial displacement can be retrieved by mean of the theory of elasticity [29-30].

II. MATEMATICAL MODEL

By considering that the elastic component, used in this work, is an elastic tube with wall thickness h much smaller than its outer radius r_e, put under inner pressure p_i and outer pressure p_e, the most suitable mathematical model for the prediction of its elastic behaviour is related to solids geometrically axial-symmetric of cylindrical shape. The problem can be afforded with cylindrical coordinates r, θ and l as in the reference system (fig. 1A). A simplifying hypothesis is to consider the problem as flat since in this work the condition of very thin elements is truly verified (low ratio h/r_e). The elastic problem is defined on the basis of its main parameters such as σ_r and σ_θ i.e. the normal tensions acting in the radial and circumferential (or tangential) directions (fig. 1B) through which the static radial displacement u can be derived according to [29-30]. The final expression of u, can be written as follows:

$$u = \rho\left[(1-\nu)\left(p_i\beta^2 - p_e\right) + (1+\nu)\beta^2\frac{p_t}{\rho^2}\right]\frac{1}{1-\beta^2}\frac{r_e}{E} \quad (1)$$

where $p_t = p_i - p_e$ is the transmural pressure, $\beta = r_i / r_e$, with $0 \leq \beta \leq 1$, $\rho = r / r_e$, with $\beta \leq \rho \leq 1$, ν is the Poisson's ratio and E is the Young Modulus. From the above relationship, the elastic tube stiffness K can be related also to its transmural pressure [31] since $K = W/u = A{\cdot}p_t/u$, where W is the load applied and A the tube cross-section.

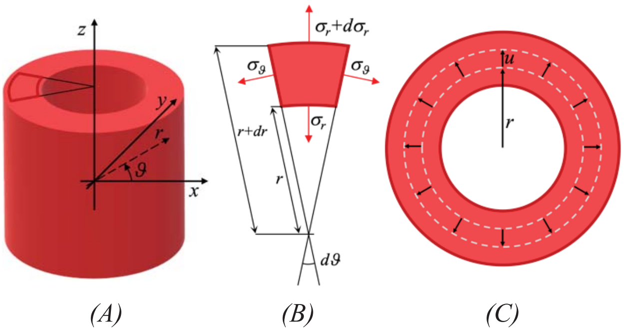

Fig. 1. (A) Cylindrical coordinates system; (B) Equilibrium of the element of volume in the plane r-θ; (C) Static radial displacements u.

When a peristaltic pump is connected in series with the elastic tube, a pressure variation Δp_i is induced so that a further time-varying contribution $\Delta u(t)$ to the static radial displacement u is caused:

$$U(t) = u + \Delta u(t) \quad (2)$$

The waveform described in (2) is the one recorded from the LVDT sensors: u represents an offset due to the equilibrium between inner and outer pressures, while Δu is related to the pressure variation. The maximum radial displacement increment Δu_{max} can be retrieved from the LVDT mean voltage peaks V_p by mean of its sensitivity S through the relationship:

$$\Delta u_{max} = \frac{V_p}{S} \quad (3)$$

Therefore, the radial displacement variation is directly proportional to the LVDT output voltage, which is in turn related to the transmural pressure.

III. MATERIALS AND METHODS

The experimental set-up designed and realized in the present work is constituted by the following components:

- an elastic tube in silicone material with inner diameter of 25 mm and wall thickness of 1.5 mm, an approximated length of 50 cm. The tube is immersed in distilled water within a water tank;
- a water tank, equipped with a graduated scale to measure the distilled water height respect to the elastic tube above mentioned;
- an analog pressure gage, being able to measure the pressure p_i inside the tube;
- a peristaltic pump to cause the time-varying radial displacement. Its pumping frequency has been set at f_{pump} = 3.7 Hz, to stabilize the whole system by avoiding its resonance;
- a manual pump to maintain the circuit pressurized;
- two LVDT sensors, supported by holders, and proper conditioning modules, able to measure the radial displacement variations in two different distant points of the tube;
- a bulb thermometer to control temperature variations that could influence the silicon hose Young Modulus.

Tests have been conducted on two different inner pressure values (30 kPa and 50 kPa above the atmospheric pressure), at different water heights starting from 10.0 cm above the tube with seven steps of 2.5 cm each in order to simulate a variation of the elastic tube stiffness. The voltage signals acquired from LVDT sensors have been recorded through a National Instruments acquisition DAQ system (model USB-6251) and properly stored through an in-house LabVIEW VI. The sensors used in this work are two different models of general purpose LVDTs, i.e. HR500 and HR2000 of Measurements Specialties™, and have different sensitivity. The acquisition sampling frequency f_s has been set at 10 kHz and the acquisition protocol has been designed to guarantee d = 20 s signal duration.

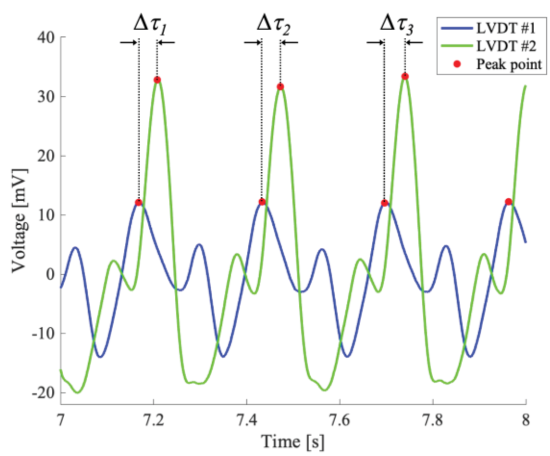

Fig. 2. Differences between the peak time instants of the two LVDT waveforms for inner pressure p_i = 50 kPa.

The signals post-processing has been carried out through an in-house software in MATLAB environment. Firstly, the offset has been removed, afterwards a Butterworth low-pass filtering to neglect all the unwanted high frequency components. A threshold algorithm has been applied to 70% of the maximum recorded value to detect the peaks of each signal. Once the maximum peaks have been found, the transit time $\Delta\tau$ has been estimated as the mean value of the differences $\Delta\tau_i$ (i = 1, 2, …, n with n = 74) between the peak time instants of the two LVDT waveforms (fig. 2):

$$\Delta\tau = \frac{1}{N_p}\sum_{i=1}^{N_p}\Delta\tau_i = \frac{1}{N_p}\sum_{i=1}^{N_p}\left(t_{p2,i} - t_{p1,i}\right) \tag{4}$$

where N_p is the number of peaks detected on the two LVDT waveforms lasting d and defined as:

$$N_p = f_{pump} \cdot d \tag{5}$$

IV. RESULTS AND DISCUSSION

Transit time variation with increasing water height at two different inner pressures and room temperature (T = 19 ± 2°C) are reported in table 1 and shown in fig. 3. The results are expressed as mean value and standard deviation (SD) due to the repeatability of the measurement method. Each standard uncertainty corresponds to the dispersion of the adjacent peak distances $\Delta\tau$ measured from the LVDTs waveforms.

Table 1. Transit time results from acquisition protocol at constant temperature.

Water height (cm)	Outer pressure p_e (kPa)	$\Delta\tau$ (ms)	
		p_i = 30 kPa	p_i = 50 kPa
10.0 ± 0.1	0.98 ± 0.10	48.6 ± 2.1	42.2 ± 1.8
12.5 ± 0.1	1.23 ± 0.10	43.4 ± 2.4	40.4 ± 2.9
15.0 ± 0.1	1.47 ± 0.10	40.5 ± 2.6	35.6 ± 2.9
17.5 ± 0.1	1.72 ± 0.10	41.4 ± 2.2	31.2 ± 2.5
20.0 ± 0.1	1.96 ± 0.10	41.0 ± 2.0	30.4 ± 2.0
22.5 ± 0.1	2.21 ± 0.10	40.9 ± 2.4	29.5 ± 2.1
25.0 ± 0.1	2.45 ± 0.10	39.6 ± 1.8	27.2 ± 2.0

Water height is reported as height above the tube. Data have been reported as mean ± SD. Inner pressures uncertainties have been estimated as 5% of the nominal value, resulting in p_i = 30±2 kPa and p_i = 50±3 kPa.

As shown in table 1, transit time values tend to decrease with increasing water height (i.e. increasing outer pressure p_e) and the standard deviation values have not a significant excursion, suggesting a systematic behavior. A least squares regression has been applied to compute the angular coefficient A and the intercept B of the best straight line that approximates the relationship between the outer pressure p_e and the transit time $\Delta\tau$. In fig. 5 the straight lines for both 30 kPa and 50 kPa inner pressures are represented. The results show negative angular coefficients (A_{30} = –0.5 and A_{50} = –1.0), therefore suggesting a decreasing trend for transit time (R^2 = 0.63 and R^2 = 0.94 respectively).

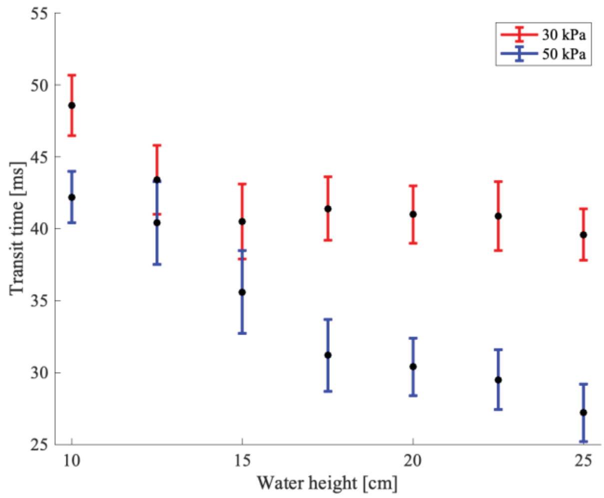

Fig. 3. Transit time and water height relationship with error bars due to standard uncertainties.

The estimated trends, for both 30 kPa and 50 kPa, agree with the experimental data available in the current literature [4,11], therefore suggesting the goodness of the achieved results.

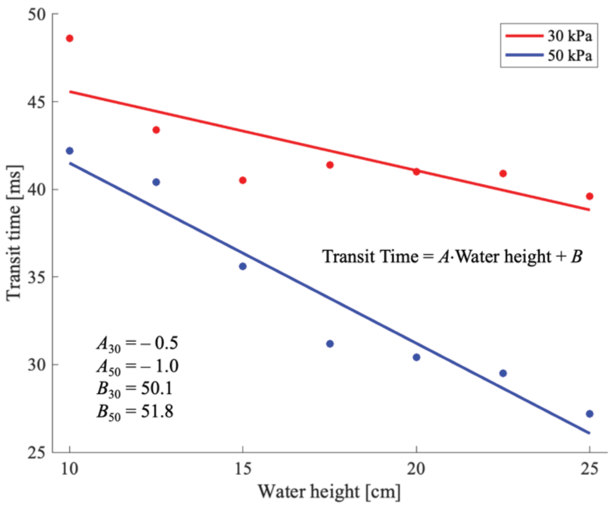

Fig. 4. Least squares method applied to the mean transit time values for increasing outer pressure.

On the other hand, the stiffness increase due to the outer pressure variation, causes a lowering of Δu_{max} that is transduced in a lower LVDT output voltage, as physically expected. With the aim to confirm it, the maximum radial displacement increment Δu_{max} has been estimated, at a constant inner pressure p_i = 50 kPa, from the LVDT HR500 output voltage through eq. (3), assuming constant the sensitivity S over the measurement range (table 2). In common clinical practice, there is experimental evidence that Δu_{max} is in the order of about 10% with respect to the aortic radius (~12.5 mm), therefore resulting in about 1 mm of displacement for healthy subjects [32,33]. The order of magnitude of the results obtained in this work for Δu_{max} is coherent with the experimental data retrieved from literature, and differences may be attributed to the following factors:

- a higher Young Modulus E for silicone material with respect to the aortic tissue;
- the tube movement limitation caused by the LVDT core weight, resulting in the lowering of each peak voltage amplitude;
- signal filtering in the post-processing phase for low frequency trend removal (related to low frequency oscillations of the elastic tube).

On the other hand, Δu_{max} decreases as a consequence of the increased p_e as expected. In fact, the elastic tube is limited in the radial movement because of the increasing water weight.

Table 2. Variation of Δu_{max} for decreasing transmural pressure p_t values.

Outer pressure p_e (kPa)	**Transmural pressure p_t (kPa)**	**Mean LVDT voltage peak (mV)**	**Maximum radial displacement increment Δu_{max} (mm)**
0.98 ± 0.10	49.0 ± 2.9	32.2 ± 0.7	0.28 ± 0.04
1.23 ± 0.10	48.8 ± 2.9	31.2 ± 1.0	0.27 ± 0.04
1.47 ± 0.10	48.5 ± 2.9	30.3 ± 0.9	0.26 ± 0.04
1.72 ± 0.10	48.3 ± 2.9	29.9 ± 1.0	0.25 ± 0.04
1.96 ± 0.10	48.0 ± 2.9	29.7 ± 0.8	0.25 ± 0.04
2.21 ± 0.10	47.8 ± 2.9	28.6 ± 0.6	0.24 ± 0.04
2.45 ± 0.10	47.5 ± 2.9	27.2 ± 0.6	0.23 ± 0.04

The transmural pressure p_t has been evaluated at 50 kPa inner pressure p_i. The uncertainty of the maximum radial displacemnet increment Δu_{max} has been estimated from the LVDT data sheet, as the typical instrumental. The sensitivity S for the LVDT considered is retrieved from the data sheet and equal to 27.6 mV/V/mm.

The results shown in table 1 and 2 are affected by some limitations of the experimental set-up. In particular, LVDT sensors affect both transit time and radial displacement measurements because of the inertial effect caused by their core weight. In fact, the latter does not allow an instantaneous tracking of the elastic tube movement, then resulting in a lack of displacement measurement accuracy. It has been observed that at the end of the descending phase, the core hits the tube causing a spurious pressure wave that travels (backwards and forwards) along the tube and acts as an artefact by interfering with the pressure wave of interest. Depending on the interference type (constructive or destructive), the waveform shape changes therefore causing a possible mismatch in the peak detection, affecting the transit time estimation. Despite all the disadvantages, the trends found for both transit time $\Delta\tau$ and radial displacement increment Δu_{max} (fig. 4 and fig. 5) are promising. Therefore, further studies on the topic are planned with a proper upgrade of the experimental set-up.

V. CONCLUSIONS

In the present work, a LVDT-based experimental set-up to simulate variations of transit time through an elastic tube under different transmural pressure conditions, has been developed and tested. Firstly, the mathematical model related to the main system parameters has been illustrated to explicit the relationship between the total radial displacement and the transmural pressure. After that the above mentioned set-up has been used and equipped with two LVDT sensors to acquire radial displacement waveforms and measure transit time between two different recording sites on the elastic tube. The results achieved are coherent with literature and suggest that such experimental set-up can reproduce the physical behavior of the transit time variation with increasing stiffness of the elastic tube: in fact, as confirmed in current literature, the transit time and maximum radial tube displacement have been found to decrease with decreasing transmural pressure despite the limitations encountered for LVDT technology. To overcome such limitations a new experimental set-up is going to be arranged with different measurement instruments based on non-contact techniques such as laser Doppler vibrometry or laser interferometry, for carrying out further in-depth studies on the topic.

REFERENCES

[1] Peter L, Noury N, Cerny M. *A review of methods for non-invasive and continuous blood pressure monitoring: Pulse transit time method is promising?*, IRBM, 2014; 35(5): 271-82.

[2] He F. *Wave propagation in an elastic tube: a numerical study*, International Journal of Computational Fluid Dynamics, 2013; 27(3): 164-72.

[3] Gao M, Olivier NB, Mukkamala R. *Comparison of noninvasive pulse transit time estimates as markers of blood pressure using invasive pulse transit time measurements as a reference*, Physiol Rep, 2016; 4(10): e12768.

[4] Kounalakis SN, Geladas ND. *The Role of Pulse Transit Time as an Index of Arterial Stiffness During Exercise*, Cardiovasc Eng, 2009; 9(3): 92-7.

[5] Proença J, Muehlsteff J, Aubert X, Carvalho P. *Is Pulse Transit Time a good indicator of Blood Pressure changes during short physical exercise in a young population?*, Conf Proc IEEE Eng Med Biol Soc, 2010; 2010: 598-601.

[6] Wilkins E, Wilson L, Wickramasinghe K, et al. *European Cardiovascular Disease Statistics 2017*. European Heart Network, 2017, Brussels.

[7] Gao M, Cheng HM, Sung SH, Chen CH, Olivier NB, Mukkamala R. *Estimation of Pulse Transit Time as a*

Function of Blood Pressure Using a Nonlinear Arterial Tube-Load Model, IEEE Trans Biomed Eng, 2017; 64(7): 1524-34.

[8] Esmaili A, Kachuee M, Shabany M. *Nonlinear Cuffless Blood Pressure Estimation of Healthy Subjects Using Pulse Transit Time and Arrival Time*, IEEE Transactions on Instrumentation and Measurement, 2017; 66(12): 3299-308.

[9] Payne RA, Symeonides CN, Webb DJ, Maxwell SRJ. *Pulse transit time measured from the ECG: an unreliable marker of beat-to-beat blood pressure*, J Appl Physiol, 2006; 100(1): 136-41.

[10] Bang S, Lee C, Park J, Cho MC, Yoon YG, Cho SH. *A Pulse Transit Time Measurement Method Based on Electrocardiography and Bioimpedance*, IEEE Biomedical Circuits and Systems Conference, 2009; 153-6.

[11] Mukkamala R, Hahn J-O, Inan OT, Mestha LK, et al. *Towards Ubiquitous Blood Pressure Monitoring via Pulse Transit Time: Theory and Practice*, IEEE Trans Biomed Eng, 2015; 62(8): 1879-901.

[12] Njoum H, Kyriacou PA. *In vitro validation of measurement of volume elastic modulus using photoplethysmography*, Med Eng Phys, 2018; 52: 10-21.

[13] Papageorgiou GL, Jones NB. *Photoelectric transducer for measuring the length and diameter of elastic vessels*, Journal of Biomedical Engineering, 1985; 7(4): 295-300.

[14] Lillie JS, Liberson AS, Mix D, Schwarz KQ, Chandra A, Phillips DB, Day SW, Borkholder DA. *Pulse Wave Velocity Prediction and Compliance Assessment in Elastic Arterial Segments*, Cardiovasc Eng Technol, 2015; 6(1): 49-58.

[15] Khir AW, Parker KH. *Measurements of wave speed and reflected waves in elastic tubes and bifurcations*, J Biomech, 2002; 35(6): 775-83.

[16] Yang T-H, Kim JU, Kim Y-M, Koo J-H, Woo S-Y. *A New Blood Pulsation Simulator Platform Incorporating Cardiovascular Physiology for Evaluating Radial Pulse Waveform*, J Healthc Eng, 2019; 2019: 4938063.

[17] Fioriti E, Roselli I, Tatì A, Romano R, De Canio G. *Ancient Monuments Analysis by Motion Magnification*, IMEKO International Conference on Metrology for Archaeology and Cultural Heritage, 2017; 150-4.

[18] Degli Agosti R, Jouve L, Greppin H. *Computer-assisted measurements of plant growth with Linear Variable Differential Transformer (LVDT) sensors*, Archives des Sciences Journal, 1997; 50(3): 233-44.

[19] de Souza CP, Wanderley MB. *Conversion from geometrical to electrical model of LVDT*, 16th IMEKO TC4 Symposium Exploring New Frontiers of Instrumentation and Methods for Electrical and Electronic Measurements, 2008; 22-4.

[20] Scuro C, Carnì DL, Lamonaca F, Olivito RS, Milani G. *An innovative structural health monitoring system for the preliminary study of an ancient anti-seismic construction technique*, 2019 IMEKO TC-4 International Conference on Metrology for Archaeology and Cultural Heritage, Florence, Italy, 2019.

[21] Kammegne MJT, Botez RM, Grigorie LT, Mamou M, Mébarki Y. *A new hybrid control methodology for a morphing aircraft wing-tip actuation mechanism*, Aeronautical Journal, 2019; 123(1269): 1757-87.

[22] Orsini F, Fuiano F, Fiori G, Scorza A, Sciuto SA. *Temperature influence on viscosity measurements in a rheometer prototype for medical applications: a case study*, IEEE International Symposium on Medical Measurements and Applications (MeMeA) 2019; 1-5.

[23] Durante MG, Di Sarno L, Sica S, Mylonakis G, Taylor CA, Simonelli AL. *Experimental measurements of geotechnical systems in 1-g tests*, 20th IMEKO TC4 International Symposium and18th International Workshop on ADC Modelling and Testing, Research on Electric and Electronic Measurement for the Economic Upturn, Benevento, Italy, 2014.

[24] Jefriyanto W, Saka BGM, Pineng M, Djamal M. *Development of LVDT (Linear Variable Differential Transformer) sensor as land displacement sensor*, J Phys: Conf Ser, 2020; 1528: 012041.

[25] Scorza A, Battista L, Silvestri S, Sciuto SA. *Design and Development of a Rheometer for Biological Fluids of Limited Availability*, Rev Sci Instrum, 2014; 85(10): 105105.

[26] Doostmohamadi A, Karamloo M, Afzali-Naniz O. *Effect of polyolefin macro fibers and handmade GFRP anchorage system on improving the bonding behavior of GFRP bars embedded in self-compacting lightweight concrete*, Construction and Building Materials, 2020; 253: 119230.

[27] Rome K, Webb P. *Development of a Clinical Instrument to Measure Heel Pad Indentation*, Clin Biomech, 2000; 15(4): 298-300.

[28] Pottinger SJ, Lamprou D, Knoll AK, Lappas VJ. *Impact of Plasma Noise on a Direct Thrust Measurement System*, Rev Sci Instrum, 2012; 83(3): 033504.

[29] Budynas RG. *Advanced Strength and Applied Stress Analysis*, 2nd edition, McGraw-Hill, 1999.

[30] Budynas RG, Nisbett JK. *Mechanical Engineering Design*, 10th edition, Shigley's, McGraw-Hill, 2015.

[31] Baumgart F. *Stiffness – an unknown world of mechanical science?*, Injury, 2000; 31(2): S-B14-23.

[32] de Beaufort HWL, Nauta FJH, Conti M, Cellitti E, Trentin C, et al. *Extensibility and Distensibility of the Thoracic Aorta in Patients with Aneurysm*, Eur J Vasc Endovasc Surg, 2017; 53(2): 199-205.

[33] Legerer C, Almsherqi ZA, Dokos S, McLachlan CS. *Computational evaluation of an extra-aortic elastic-wrap applied to simulated aging anisotropic human aorta models*, Sci Rep, 2019; 9(1): 20109.