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A Preliminary Comparison of Three Methods for the Assessment of Pulse Wave Transit Time in an Arterial Simulator

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***Abstract* – Arterial simulators are useful tools to reproduce the Pulse Wave Velocity (PWV) behavior depending on vessel characteristics. This quantity is related to the Pulse Transit Time (PTT), i.e., the time interval required for the pulse wave to travel between two sites in a vessel. In the literature, there is a lack of comparison of PTT evaluation methods from signals acquired through arterial simulators. In the present study, three PTT estimation methods (peak-to-peak, tangent-secant and cross-correlation) have been applied to two signals simulating the pressure wave traveling in an Arterial Surrogate (AS) over time. Tests have been repeated for different imposed delays between the generated waveforms. From the obtained results, the cross-correlation method showed the lowest discrepancy values between estimated and imposed time delay.**

I. INTRODUCTION

Pulse Wave Velocity (PWV) measurement in human body vessels represents a well-known technique for preventing and detecting many cardiovascular diseases [1-3]. In the clinical environment, many devices can measure PWV by estimating the time required for the pulse wave to travel a known distance within a vessel [4]: this time interval is known in the literature as Pulse Transit Time (PTT). From the last decades of the XX century, many procedures have been implemented through signal analysis to estimate PTT from waveforms acquired by transducers on human bodies [5,6]: some of them resulted more reliable than others depending on the application and setup conditions. Over the years, a few arterial simulators have been developed to study *in vitro* the characteristics of vessels through PWV assessments [7]. Although these simulators have different configurations based on the phenomenon to be reproduced, they are usually based on the same main components: (a) a real vessel or an Arterial Surrogate (AS) connected to a hydraulic circuit, (b) a pumping system able to generate pulse waves and (c) a sensing system for the detection of the pulse wave transit inside the vessel [7]. However, there is a lack in the literature about the reliability of measurement methods to evaluate PTT on arterial simulators.

This work aims to test some of the well-known methods for PTT estimation on waveforms similar to that provided from a novel AS [8]. The use of simulated signals has the advantage of isolating the phenomenon of pressure wave propagation, depending on the characteristics of the system [9], from other phenomena that overlap, such as turbulence effects of the flow [10]: in this way, it is possible to evaluate the performance of methods applied only to PTT estimation. For this purpose, some numerical simulations have been implemented in MATLAB environment: two waveforms, such as those in Fig.1, have been generated, in order to reproduce the pressure pattern at two different sites on the AS during pressure pulse transit; these waveforms, have noise components and amplitude attenuation depending on the path traveled within the AS and its characteristics. Therefore, different delay values τ have been imposed between the two waveforms, which represent the PTT to be determined at the end of the simulation. Then, the waveforms are sampled and filtered to simulate the acquisition process. Finally, three methods for evaluating the PTT are applied.

In the next sections, the waveform characteristics and their processing have been described as well as the methods considered to evaluate the PTT; finally, the test results have been proposed and discussed.

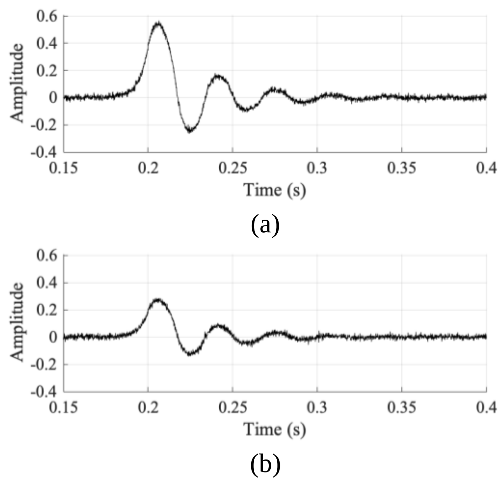

Fig. 1. Pressure waveforms over time: (a) in the first site and (b) the second one of the arterial surrogate.

II. WAVEFORMS GENERATION

In an arterial simulator, ASs response can be modeled based on a second-order system behavior in which the mass of the system is constituted by the fluid inside the vessel, while the elastic and the damper elements are related to viscoelastic properties of the hose [11]. When a perturbation, e.g., a pressure pulse occurs, the pressure trend in two different sites of the vessel can be described by waveforms like the example shown in Fig. 1: curves are characterized by a maximum amplitude A_{max}, an oscillatory movement component, that depends on the system's fundamental frequency f_n, and a damping component due to pressure losses along the vessel and the viscoelastic properties [9].

In this work, to simulate the transit of a pulse wave through two different sites on an AS, a couple of waveforms ($y_{1,o}$ and $y_{2,o}$) have been independently generated in a MATLAB environment, considering that the maximum amplitude of the second one has been reduced by 50% compared to the first one to take into account the losses along the vessel. In this study, it is assumed that there is no significant change in the frequency content between the two waveforms: in fact, the two measurement sites are considered to be close to each other, e.g., tens of centimeters [12]. The main specifications of both generated waveforms are listed in Table 1.

Table 1. Characteristics of the simulated waveforms.

Characteristic	Value
Sample number	10^5
Duration	1 s
Fundamental frequency f_n	30 Hz
Maximum amplitude of $y_{1,o}$	$A_1 = 0.55$
Maximum amplitude of $y_{2,o}$	A_2 = 50% of A_1

In order to simulate a real data acquisition process, the following components of noise have been added to the generated signals:

- gaussian noise, whose amplitude has been obtained by setting a fixed Signal-to-Noise Ratio (SNR);

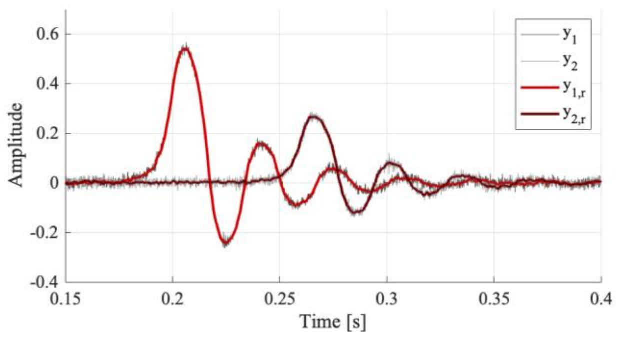

Fig. 2. Waveforms with noise components ($y_{1,r}$ and $y_{2,r}$) and filtered waveforms (y_1 and y_2).

Table 2. Characteristics of noise components and of low-pass filter.

Component		Characteristic	Value
Noise	Gaussian	SNR	15
	Power grid	Amplitude A_{np}	0.002
		Frequency f_{np}	50 Hz
	Bending vibrations	Amplitude A_{nb}	0.01
		Frequency f_{nb}	5 Hz
Low-pass filter		Cut-off frequency f_C	1 kHz

- a 50 Hz interference (n_P) from the power grid;
- a 5 Hz bending vibration (n_B) of the AS.

The resulting signals ($y_{1,r}$ and $y_{2,r}$) have been collected at a sampling rate of 10^4 S/s.

Finally, the two waveforms have been filtered before being processed by the PTT measurement methods. In Fig. 2 the two signals are shown before and after the filtering process. In particular, a low-pass filter has been applied based on a zero-phase filtering technique by processing data first forward and then backward. This allowed preserving the two waveforms in the time domain [13]. In Table 2 the characteristics of noise components and low-pass filter are reported.

III. TRANSIT-TIME ESTIMATION METHODS

In this section the three methods applied for the PTT evaluation are outlined: they are the Peak-to-Peak (PP), the Tangent-Secant (TS) and the Cross Correlation (CC) method, respectively.

A. Peak-to-Peak method

In the peak-to-peak method, the PTT estimation is carried out by assessing the time distance between the main peaks of the waveforms, as shown in Fig. 3.

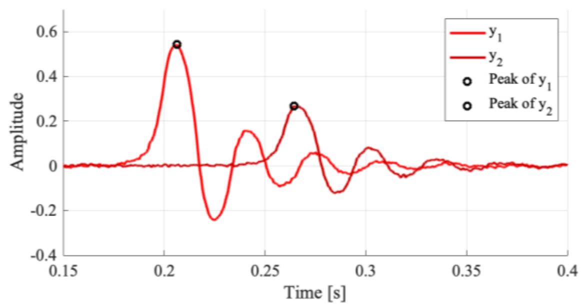

Fig. 3. Example of individuation of waveforms peaks with peak-to-peak method.

B. Tangent-Secant method

In the tangent-secant method, the PTT is estimated by calculating the time distance between the waveforms' feet [5]. In particular, the maximum point of the first derivative over time of each signal has been first evaluated, then the

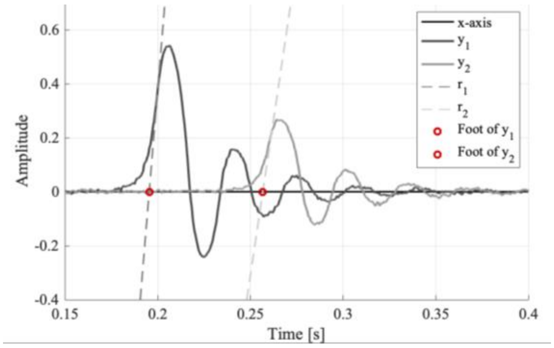

Fig. 4. Individuation of waveforms foot with tangent-secant method.

tangent line has been drawn on each waveform at that point. The foot of the waveform has been identified by the intersection between the tangent line and the *x*-axis (Fig. 4). A 35% threshold of the maximum amplitude of the signal has been set to ensure that the forefront of the waveform is considered.

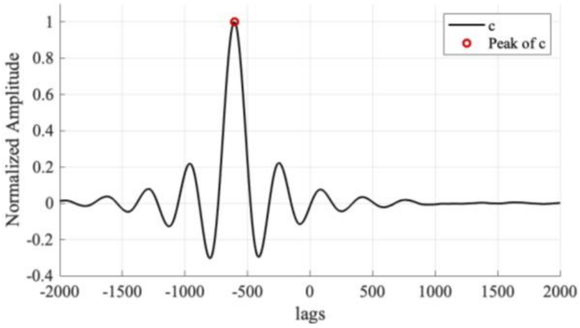

Fig. 5. Example of peak individuation of cross-correlation function.

Table 3. Distribution assigned to variables in MCSs.

Variable	Distribution	Variability
Imposed delay	Uniform	$\tau \pm 1\%$
Cut-off frequency	Uniform	$f_C \pm 1\%$
Amplitude of n_P	Uniform	$A_{np} \pm 1\%$
Amplitude of n_B	Uniform	$A_{nb} \pm 1\%$

C. Cross-Correlation method

The cross-correlation method is usually used to evaluate the similarity degree of two waveforms [14]. By applying this method to the waveforms, the second (y_2) is shifted along the *x*-axis step by step (one step is called lag – one lag corresponds to one sampling period), then, the integral of the product between y_1 and y_2 is calculated for each position: in the cross-correlation function (Fig. 5) the distance of the peak from zero multiplied by the sampling period is representative of the time distance between the two waveforms, that is the PTT.

IV. MONTE CARLO SIMULATION

To test the repeatability of the three methods applied to the AS, eleven Monte Carlo simulations (MCSs) have been carried out, one for each value of imposed delay τ, with 10^4 iterations each. Values of τ have been selected considering reasonable values of PTT measured locally in vessels, e.g., tens of centimeters, in which the PWV varies from physiological to pathological conditions, i.e., in the range 5-15 $m \cdot s^{-1}$ [4,15]. A distribution has been assigned to each value τ to consider the uncertainty given by the digital computational process. Noise contributions, added to waveforms, have been generated at each iteration. In addition, a distribution has been assigned to the cut frequency of the low-pass filter to evaluate the

Table 4. Results of the three methods with respect to imposed delay values.

	Peak-to-Peak		Tangent-Secant		Cross-Correlation	
Imposed delay τ (ms)	**Estimated delay** (ms)	**Discrepancy** (ms)	**Estimated delay** (ms)	**Discrepancy** (ms)	**Estimated delay** (ms)	**Discrepancy** (ms)
10.4 ± 0.1	10.6 ± 0.9	0.2 ± 0.9	11.1± 0.7	0.7 ± 0.7	10.4 ± 0.1	0.0 ± 0.1
15.7 ± 0.1	15.8 ± 0.9	0.1 ± 0.9	16.5 ± 0.7	0.8 ± 0.7	15.7 ± 0.1	0.0 ± 0.1
20.1 ± 0.1	20.0 ± 0.9	0.1 ± 0.9	20.8 ± 0.7	0.7 ± 0.7	20.1 ± 0.1	0.0 ± 0.1
25.3 ± 0.1	25.3 ± 0.9	0.0 ± 0.9	25.9 ± 0.7	0.6 ± 0.7	25.3 ± 0.1	0.0 ± 0.1
30.9 ± 0.1	31.1 ± 0.9	0.2 ± 0.9	31.6 ± 0.7	0.7 ± 0.7	30.9 ± 0.1	0.0 ± 0.1
35.3 ± 0.1	35.4 ± 0.9	0.1 ± 0.9	36.0 ± 0.7	0.7 ± 0.7	35.3 ± 0.1	0.0 ± 0.1
40.1 ± 0.1	40.0 ± 0.9	0.1 ± 0.9	40.8 ± 0.7	0.7 ± 0.7	40.1 ± 0.1	0.0 ± 0.1
45.6 ± 0.1	45.6 ± 0.9	0.0 ± 0.9	46.2 ± 0.7	0.6 ± 0.7	45.6 ± 0.1	0.0 ± 0.1
50.2 ± 0.1	50.3 ± 0.9	0.1 ± 0.9	50.9 ± 0.7	0.7 ± 0.7	50.2 ± 0.1	0.0 ± 0.1
55.9 ± 0.1	56.0 ± 0.9	0.1 ± 0.9	56.7 ± 0.7	0.8 ± 0.7	55.9 ± 0.1	0.0 ± 0.1
60.5 ± 0.1	60.4 ± 0.9	0.1 ± 0.9	61.2 ± 0.7	0.7 ± 0.7	60.5 ± 0.1	0.0 ± 0.1

Outcomes are expressed as mean ± Standard Deviation (SD).

contribution of filtering. In Table 3, the specifications of all variables considered in the MCSs are listed.

V. RESULTS AND DISCUSSIONS

Results of the simulations are listed in Table 4. Considering the discrepancy between attended and measured values, the TS method shows a higher gap, with a maximum discrepancy of 0.8 ms, whereas PP and CC methods are comparable with maximum discrepancies of 0.1 ms and 0.0 ms, respectively. The restrained discrepancies are likely due to the fact that the generated waveforms do not include all the frequency contents characterizing actual waveforms acquired from the arterial simulator. As regards the standard deviation (SD) values, PP and TS methods are 0.9 ms and 0.7 ms, respectively, and they keep constant for increasing time delays. On the other hand, SD values for the CC method are smaller than the others (i.e., ± 0.1 ms) since the temporal resolution, determined by the sampling frequency setting, in this case, represents the main uncertainty contribution.

VI. CONCLUSIONS

In this work, through Monte Carlo simulations, in MatLab environment, three computational methods for the PTT estimation have been compared: peak-to-peak, tangent-secant and cross-correlation. The methods have been applied to simulated signals from an arterial simulator. In particular, two waveforms have been generated with different amplitudes at which low-frequency noise and Gaussian noise components have been appended. The two signals have been shifted by different delay values to simulate changing in PTT. Results highlight the cross-correlation method is characterized by the lowest discrepancy value (0.0 ± 0.1 ms), while peak-to-peak and tangent-secant methods are characterized by maximum discrepancies of 0.2 ± 0.9 ms and 0.8 ± 0.7 ms, respectively. In the near future, it will be important to improve the PTT measurement procedure in order to apply the methods on experimentally acquired signals.

REFERENCES

[1] I. S. Mackenzie, I. B. Wilkinson, J. R. Cockcroft, “Assessment of arterial stiffness in clinical practice,” QJM, vol.95, No.2, February 2002, pp.67–74.

[2] B. Williams, G. Mancia, W. Spiering, E. A. Rosei, M. Azizi, M. Burnier, et al., “2018 ESC/ESH guidelines for the management of arterial hypertension: the task force for the management of arterial hypertension of the European society of cardiology and the European society of hypertension,” J. Hypertens., vol.36, No.10, October 2018, pp.1953–2041.

[3] S. P. Glasser, D. K. Arnett, G. E. McVeigh, S. M. Finkelstein, A. J. Bank, D. J. Morgan, J. N. Cohn, “Vascular compliance and cardiovascular disease: a risk factor or a marker?”, Am. J. Hypertens., vol.10, No.10, October 1997, pp.1175–1189.

[4] G. Fiori, F. Fuiano, A. Scorza, S. Conforto, S. A. Sciuto, “Non-invasive methods for PWV measurement in blood vessel stiffness assessment”, IEEE Rev. Biomed. Eng., vol.15, January 2022, pp.169–183.

[5] Y. C. Chiu, P. W. Arand, S. G. Shroff, T. Feldman, J. D. Carroll, “Determination of pulse wave velocities with computerized algorithms”, American Heart Journal, vol.121, No.5, May 1991, pp. 1460–1470.

[6] S. C. Millasseau, A. D. Stewart, S. J. Patel, S. R. Redwood, P. J. Chowienczyk, “Evaluation of carotid-femoral pulse wave velocity: Influence of timing algorithm and heart rate”, Hypertension, vol.45, No.2, January 2005, pp. 222–226.

[7] F. Fuiano, A. Scorza, S. A. Sciuto, “Functional and Metrological Issues in Arterial Simulators for Biomedical Testing Applications: A Review”, Metrology, vol.2, No.3, pp. 360–386.

[8] F. Fuiano, G. Fiori, A. Scorza, S. A. Sciuto, “A novel experimental set-up for Young Modulus Assessment through Transit Time measurements in Biomedical applications,” Proc. of 2021 IEEE MetroInd4.0&IoT, 2021, pp. 117–121.

[9] M. S. Ghidaoui, M. Zhao, D. A. McInnis, D. H. Axworthy, “A Review of Water Hammer Theory and Practice”, ASME. Appl. Mech. Rev., vol.58, No.1, January 2005, pp. 49–76.

[10] Y. C. Fung, “Biodynamics: circulation”, 1st edition, Springer, 1984.

[11] Y. C. Fung, “Biomechanics: mechanical properties of living tissues”, 2nd edition, Springer, 1993.

[12] F. Fuiano, G. Fiori, F. Vurchio, A. Scorza, S. A. Sciuto, “Transit Time Measurement of a Pressure Wave through an elastic tube based on LVDT sensors,” Proc. of. 24th IMEKO TC4 International Symposium, 2020, pp. 321–326.

[13] S. K. Mitra, “Digital Signal Processing”, 2nd ed, McGraw-Hill, New York, USA, 2001.

[14] M. Benthin, P. Dahl, R. Ruzicka, K. Lindström, “Calculation of pulse-wave velocity using cross correlation—Effects of reflexes in the arterial tree”, Ultrasound in Medicine & Biology”, vol.17, No.5, 1991, pp. 461–469.

[15] T. Pereira, C. Correia, J. Cardoso, “Novel Methods for Pulse Wave Velocity Measurement”, J Med Biol Eng, vol.35, No.5, October 2015, pp. 555–565.