DOUBLE HEADED PROBE FOR LOCAL PULSE WAVE VELOCITY ESTIMATION

A New Device for Hemodynamic Parameters Assessment

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Abstract: The present work proposes a new device for local pulse wave velocity (PWV), by using an innovative configuration of a double piezoelectric (PZ) sensor probe. PWV is assessed in one single location and involves the determination of time delay, between the signals acquired simultaneously by two PZs, 23 mm apart. The double probe (DP) is characterized in a dedicated test bench system, where two main studies were carried out. In the first one, the impulse response (IR) for each PZ sensor is determined and evaluated through the deconvolution method. In the second one, DP time resolution is estimated from a set of time delay algorithms and compared with the reference values, obtained through the signals of two pressure sensors. Results demonstrate the effectiveness of the inferred IRs in deconvolution purposes and the possibility of measure higher PWV values (≈ 19m/s), through the DP, with an error less than 10%.

1 INTRODUCTION

The velocity of propagation of the pulse pressure wave is recognized as the simplest and most reproducible process of assessing non-invasively arterial stiffness, pointed out as an important key factor of cardiovascular risk (Laurent *et al*, 2006). The use of electromechanical technology remains the golden standard for pulse wave velocity (PWV) measurement, as a result of its signal robustness, large bandwidth, low-price and ease of use. The methodology used in PWV assessment, requires the acquisition of pressure waves at two positions, separated from a distance, d, and the determination of time delay between the waves, defined as the pulse transit time, Δt. The main problems of this technique are related with the determination of time delay that strongly depends on the method that is used, and with the complexity in accurately estimating the distance between the recording sites (Segers *et al*, 2009).

An alternative approach that is presented in this work is to decrease the distance between the two measurement sites, as a solution for more accurate d estimations, thus providing information on local hemodynamics. Local PWV is an accurate marker of the degree of atherosclerosis and it is generally measured over carotid artery. The existing devices are essentially based on ultrasound methods and echotracking techniques but they have not been yet generalized to the clinical practice, due to poor PWV precision, in phantom studies or in-vivo experiments (Meinders *et al*, 2001). The most recent studies on this matter, investigated the precision of different signal processing methods for local PWV assessment, over short segments, by means of a M-line ultrasound system. The discrepancy between the results in phantom and in-vivo was considerably high, resulting in an unsuitable technique for clinical practice (Hermeling *et al*, 2008).

In the present work, an alternative device based on a double headed configuration of piezoelectric (PZ) sensors for local PWV assessment, is proposed.

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The probe is widely characterized on a test bench system, capable of reproducing important features of the cardiovascular system (Pereira *et al*, 2010).

2 MATERIALS

2.1 The Double Headed Probe

The configuration of the developed double headed probe (DP) is shown, in figure 1. The DP consists of two circular-shaped PZ sensors (MURATA® 7BB-12-9 Sounder, 12mm diameter), placed 23 mm apart and mounted on a triple double layer printed circuit board (PCB). The first and second PCB layers support the PZ discs, assuring the PZs oscillations due to their perforation and the third one incorporates the local signal conditioning electronics which is based on a voltage follower amplifier, set to a gain of ≈ 2, for each PZ. The probe's mechanical interface consists of two mushroom-shaped PVC pieces (15 mm diameter in top), located in the centre of the PZ discs. These elements are responsible for transmitting the distension imparted to tissues by the pressure waveform, to each PZ sensor.

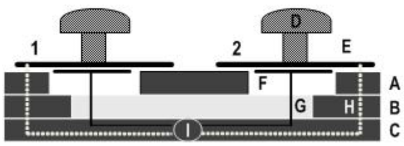

Figure 1: Cross section scheme of the double headed PZ probe. **A, B** - support layers; **C**- signal conditioning layer; **D**- 'mushroom' PVC interface **E** - PZ metal disk; **F**- PZ material **G** – PZ signal conductor **H** – ground conductor **I** – coaxial cable **1**- PZ_1; **2**- PZ_2.

2.2 The Test Bench System

For testing the probe, it was developed a dedicated test bench, diagrammatically shown in figure 2.

A pressure wave is generated by a piston mechanism coupled to a 0.7 mm stroke actuator, ACT, driven by a high voltage linear amplifier, HV, (Physik Instrumente GmbH P-287 and E-508, respectively) and launched into an 8mm internal diameter, 0.5 mm wall thickness silicone rubber tube, filled with water. The wave is then captured by the DP placed along the tube and by two pressure sensors PS1 and PS2 (Honeywell, 40PC015G1A), placed at the tube's extremities. The acquired signals are sampled at 12.5 ksps, through NI DAQ USB-6210, and stored for offline analysis using Matlab®.

The input waveforms are programmed into an Agilent 33220A arbitrary waveform generator, WG and the DC level is controlled by a piston–mass combination, P-m, placed at the extremity of the tube, on the opposite side of the ACT ((Pereira *et al*, 2009).

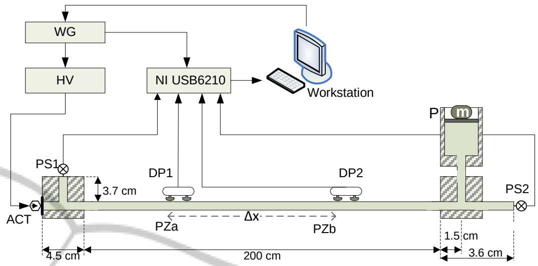

Figure 2: Schematic drawing of the test bench system.

3 METHODS

3.1 Double Probe Characterization

3.1.1 Impulse Response Determination

The electrical equivalent of a PZ sensor is more complex than a simple RC circuit, mainly if the sensor is attached to another mechanical structure. The first experiment carried out for DP characterization, consisted in determining the impulse response (IR) for each one of its sensing elements (i.e., mushroom probe plus PZ sensor electronics). To achieve this purpose, a technique based on a chirp signal that sweeps linearly a wide frequencies range (from 500 mHz to 1 kHz) was used. This sweep was generated by the WG and fed to the ACT, with direct actuation on the probe's interface. The spectra of the PZ output and of the sweep input signal were computed, and the correspondent transfer function was inferred. Through the inverse fast Fourier transform (IFFT), it was possible to determine the referred IR.

Test bench acquisitions were accomplished in order to apply the deconvolution principle to the DP output, and thus determine the effectiveness of the determined IRs.

3.1.2 Time Resolution Assessment

The main potential of the DP is focused on the ability to locally measure the PWV, with enough accuracy to be considered a valid device for clinical use. In order to assess DP time resolution performance, two main studies were carried out. The first one aimed at studying the PWV progress of two uncoupled PZs, regarding their separating distance, Δx. Two DPs, initially separated by 50 cm, were used: one of the probes (DP1) was static, while the other one (DP2) approached successively at intervals of 2 cm (figure 2). For each position, a Gaussian pressure wave (150 ms width) was delivered to the system. The second experiment intended to determine the precision of PWV measurements obtained with the DP, in 25 different tube's positions as well as the accuracy concerning the reference PWV values, estimated with pressure sensors. For each position, a burst of 10 Gaussian pressure waves (400 ms width) was reproduced by the ACT.

3.1.3 Algorithms for Time Delay Estimation

Time delay was estimated for two different settings: between the signals of both pressure sensors (considered as a reference time for PWV estimation) and between the signals of the DP PZ sensors. Three different algorithms were considered:

(a) Cross-Correlation - The ACT driving signal is used as a reference and time delay is calculated as the difference between the two maxima values, obtained from the cross-correlation between the ACT signal and the pressure/PZ signals amplitude;

(b) Zero-crossing - Due to the differentiator nature of the PZ sensors, zero-crossing point is used as a time reference for time delay estimation and it is determined through a linear fit on the zero crossing vicinity; and,

(c) Maximum amplitude - This algorithm uses a 6th degree polynomial fit in the maximum region to guarantee an accurate identification of the peaks.

4 RESULTS

4.1 Impulse Response Determination

The IRs obtained for each one of the PZ sensors are presented, in figure 3. The profiles obtained for each sensing element are equivalent, both in shape and in amplitude, and are very close to those expected for a simple differentiator circuit.

In figure 4, the effectiveness of the referred IRs is evaluated, through deconvolution method.

From the DP output and its IRs, it was possible to recover a programmed triangular pressure waveform of 500 ms width, sensed at the end of the tube. It is visible the striking similarity between the deconvolved pressure waves, determined for each PZ, as also the high correlation with the input

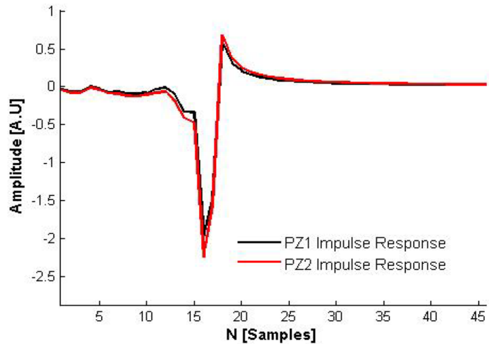

Figure 3: DP impulse responses.

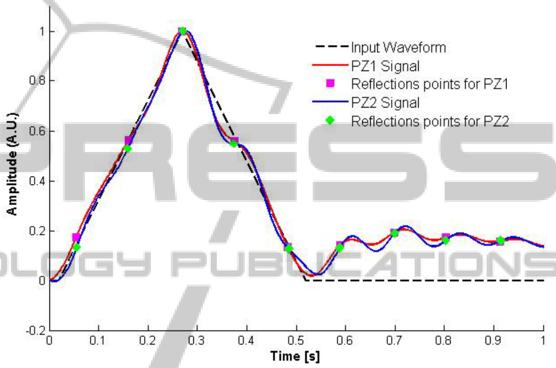

Figure 4: Deconvolved signals obtained from DP output and DP IRs.

waveform. The presence of inflection points correspond to the influence of reflected waves, generated by the two reflection sites at the extremities of the tube. Although deconvolution was used in the present study, as an auxiliary technique in DP characterization, the encouraging results obtained above, suggest that it can be used as an alternative method that allows the precise recovery of the original pressure waveform. Future work will be pursued up in order to determine the application of this IRs to other systems (e.g.: human carotid).

4.2 Time Resolution Assessment

In figure 5, the PWV obtained for two uncoupled PZ sensors, in successively smaller separation distances is illustrated.

In general, the relative error in PWV increases as the distance between the two PZ decreases. For Δx longer than 12 cm, the PZs PWV values are close to the reference values. For Δx smaller than 12 cm, the PZs PWV values diverge from the pressure sensors values and an increase of the error is visible, mainly in the maximum amplitude algorithm.

Figure 6 compares the PWV values obtained

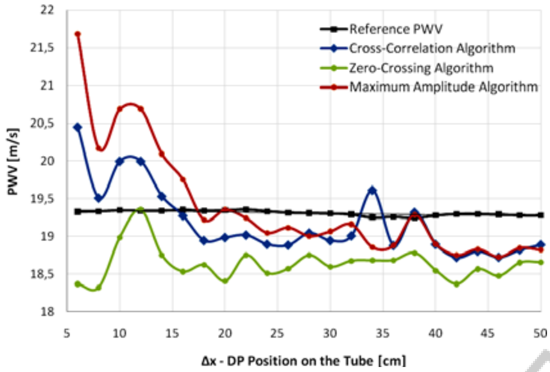

Figure 5: PWV values of uncloupled PZs and pressure sensors, yielded by the three algorithms.

through DP, along 25 different consecutive positions with the reference PWV values. Only the cross-correlation algorithm was implemented for time delay estimation, due to the previous best results.

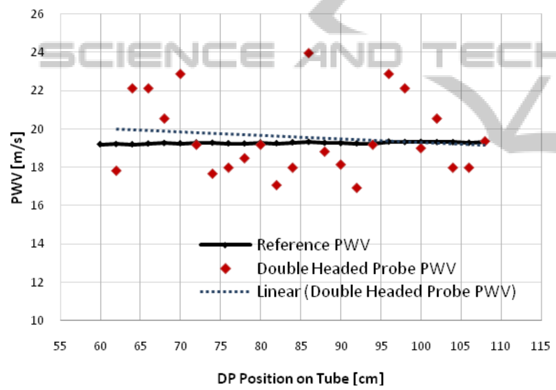

Figure 6: Dispersion of PWV values obtained through DP and pressure sensors, along 25 consecutive locations.

Both PWV distributions are correlated however the dispersion of them is still quite different. Actually, the referred PWV distributions present a mean value and a standard deviation of 19.26 ± 0.04 m/s (pressure sensors set) and 19.55 ± 2.02 m/s (DP set), matching up a coefficient of variation of 0.21% and 10.32%, respectively. In addition, the relative error between the two sets is about 8.11%.

Since this higher DP dispersion may have its basis in lower statistics or mechanical drawbacks (e.g. geometry of mushroom interfaces, effective distance between the PZ sensors, etc.), future work will be pursued up at this stage.

5 CONCLUSIONS

A novel device for PWV assessment, based on a double configuration of PZ sensors is presented and successfully characterized on a dedicated test bench system.

Local PWV was measured with enough accuracy (relative error < 10%) in test bench experiments, through DP. Although studies to validate the clinical use of DP are still required, this device seems to be a valid alternative to local PWV stand alone devices.

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