Design and Prototype Development of a Low-Cost Blood Flow Simulator for Vascular Phantoms

Matteo Zauli[1,2], Cristiana Corsi[1], Luca De Marchi[1,2]

[1] DEI-Department of Electrical, Electronic and Information Engineering, "Guglielmo Marconi",
University of Bologna, Bologna, Italy
[2] ARCES - Advanced Research Center on Electronic Systems, University of Bologna, Bologna, Italy

Abstract

Vascular phantoms can be used as in vitro test objects to explore flow behaviour in pathological conditions and novel ways of improving ultrasound diagnosis. This kind of phantom should be anatomically realistic both in terms of geometry, acoustic and physical properties. In particular, enhancing measurements reliability of in vitro models test needs a realistic physiological flow performed by a reliable phantom set-up.

This paper describes the design of a programmable flow pump system, designed to be used in an in vitro experimental studies. This system wants to overcome budget problem due mainly to expensive flowmeters. The proposed solution is to use a low cost device, not able to perform a reliable closed loop control, but suitable to obtain an ARX non-linear model of the hydraulic circuit thanks to Matlab tools. By using that model, it is possible to act an open loop control able to produce the targeted waveform with median deviation less than 9% and a similarity index of 0.98.

Here, we present also the flow rate calibration steps of the designed flow phantom set-up. In the current work, the flow pump system has been developed using Carotid artery Phantom (CaP), but thanks of its programmability it's possible to implement different flow profiles suitable for others flow phantoms.

1. Introduction

A vascular phantom should be anatomically realistic both in terms of geometry, acoustic and physical properties to have good ultrasound measurements using equipment like echograph and eco-doppler [1]. The reliability of in vitro models can be enhanced by simulating the blood stream according to the characteristics of the vascular portion, reproducing a realistic physiological flow which mimics patient-specific conditions for in vitro experimental studies. Such studies are very important for improving ultrasound diagnosis, calibrating instruments and as educational support.

In this context, we propose a *low-budget flow pump system* to produce physiological-specific stream in flow phantoms. In particular, we focused on the development of a flow phantom set-up for a carotid artery (*CaPs - Carotid artery Phantoms*). But, the system is programmable, so it is suitable for different flow phantoms thanks of its performances.

The CaPs used in the current work have been developed at the University of Bologna [2]. In particular, such phantoms are made by three main parts that simulate real vascular system: vessel, tissue around vessel and blood. Reproducing these parts it's possible thanks of three type of materials: Vessel Mimicking Material (VMM), Tissue Mimicking Material (TMM) and Blood Mimicking Fluid (BMF). It's possible to build CaP using two approaches: wall-less and walled. In the first one the vessel is obtained by realizing an empty channel in a TMM and a BMF is pumped trough the channel. This method enables the realization of complex geometries, but a wall-less phantom is prone to breakage due to BMF infiltrations in the TMM. Conversely, walled phantoms consist in tubular structures made of VMM, embedded in TMM and crossed by BMF. The CaP used to test the set-up designed is a walled phantom built up with *PVA-C* as VMM, *nylon-scatterer solution* as BMF and *water* for TMM only to have coupling with the ultrasound probe.

The flow pump system is a fundamental component of a phantom set-up. It is usually realized with expensive [3] [4] and bulky components to power a pulsatile flow rate into a vascular phantom. The cost and form factor may limit the use of such conventional system. In this paper, a novel programmable flow pump is proposed to overcome these problems with compact and cheap sub-components. The main parts of this set-up are two: i) the hydraulic circuit and ii) the control system. The *hydraulic circuit* has a liquid reservoir, one centrifugal pump, one ultrasound flow sensor and the CaPs. Each components has been chosen to

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suite the flow profile in carotid artery, but taking in account also other phantom types. The control system is powered by a microcontroller-based circuit board, which enables a flow loop which simulates either the full circulatory system, or a profile measured locally. The control algorithm is based on an open-loop approach and on a Non-linear ARX model of the hydraulic circuit where fluid is pumped. Such model it's obtained during a calibration time of the system, this procedure has two phases: first of acquisition by embedded flowmeter and a second one of data elaboration by Matlab to generate a certain PWM vector useful to control the centrifugal pump.

2. Components and design

The designed flow phantom set-up is made by two parts: hydraulic circuit and control system. The set-up is shown schematically in Fig. 1, where it's possible to identify a flow loop (liquid reserve, centrifugal pump, flowmeter, carotid artery) and a control part (power supply, signal condition and MCU).

The choice of the components was performed taking in account a good balance between cost and performances. The target is to offer a low cost set-up, but with good performances (i.e. capable to simulate realistic physiological flows) and flexible (i.e. programmable for different phantoms).

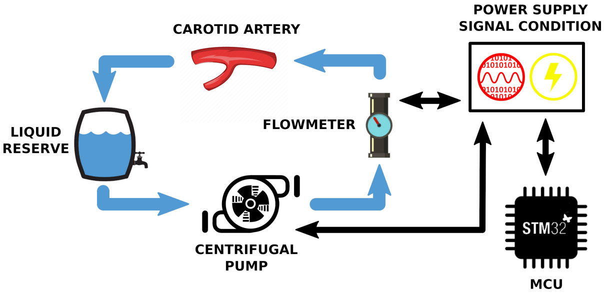

Figure 1. Designed flow phantom set-up scheme.

2.1. Hydraulic circuit

The most relevant characteristics for a physiological waveform are maximum flow rate, minimum flow rate and highest value of first time derivative. The hydraulic circuit must adequately mimic these characteristics to simulate the pulsatile flow rate of real systems. In particular, the maximum flow rate and its dynamic characteristics have a strong influence in the pump selection which, in its turn, heavily impacts the design of the remaining system components.

The hydraulic circuit consists of 4 main components interconnected by a flexible silicon pipe. These devices are: liquid reservoir, centrifugal pump, flowmeter and the carotid artery phantom. Each component was carefully selected to perform the flow simulation: 1) liquid reservoir contains the liquid (BMF) pumped into flow loop. It has a capacity of around 3 litres; 2) the centrifugal pump is a TCS Micropumps M510S-180, chosen because of its maximum flow rate 8000 ml/min (free flow), robust high quality aluminium case and BLDC motor connection (no integrated controller); 3) flowmeter is a low cost ultrasonic transducer by Cynergy3 (model UF08B100). Such transducer has a measurement range from 0.4 ml/min to 8000 ml/min, maximum precision of 3% of reading, response time better than 0.1 seconds and an ABS plastic case. Finally, 4) the CaP is the one described in [2].

2.2. Control system

The flow control sub-system is constituted by three circuit boards: one for power supply and signal conditioning, a BLDC motor controller board and a microcontroller based circuit board.

The microcontroller board is a discovery board by ST Microelectronics (STM32F746G-Discovery). This board was chosen because it features the STM32F746NGH6, a high performances MCU. The Discovery board has a 4.3-inch 480x272 color LCD-TFT with capacitive touch screen which enables the implementation of a user-friendly interface to operate the flow phantom set-up. Moreover this ST development board has been chosen for its easy connections to microcontroller's GPIO.

The BLDC motor controller board is an EQi-V2 provided by the same manufacturer of the pump, TCS Micropumps. It supports a power supply from 12 V up to 30 V and requires a 0-5 V signal to produce various flow rates. An additional feature, not exploited in the current work, is the possibility to reverse flow rate through a control pin and RPM measurement by a pulse output pin.

The power supply and signal conditioning board is a circuit which generates multiple reference voltages, for the different needs of system devices, and interfaces some components. In particular, it interfaces the pump and the flowmeter to enable PWM control of the pump and acquisition reading from ultrasonic flowmeter, by applying the suitable voltage level shifts to the MCU's GPIOs.

Therefore, the power supply and signal condition board acts as a bridge between the STM32F7-Discovery board and the flow sensor as well as the pump. The Discovery board controls flow rate using PWM signal applied to the EQi-V2 motor controller which drives the centrifugal pump. Conversely, the flow sensor gives a PWM output whose frequency is proportional to the flow rate reading.

2.3. Design

The flow loop control is an open-loop control which needs a suitable calibration procedures. In this work, the initial calibration is performed using a closed-loop control, whose aim is to iteratively select the control sequence which outputs the desired flow values at specific time samples. The closed-loop control is shown schematically in Fig. 2. Unfortunately the feedback provided by the flowmeter has a low (and irregular) sample rate (see Fig. 3 green track), this means that the flowmeter output is not able to reproduce high flow dynamic, like carotid artery profile. Therefore, the closed-loop control is used only to perform a rough comparison between the desired flow (described by the two programmed vectors) and real one (measured by flowmeter). Despite these limitations, the results of such comparison can be fed to the Matlab tool *System Identification* in order to build the hydraulic circuit model. In particular, an ARX non-linear model was used in this work.

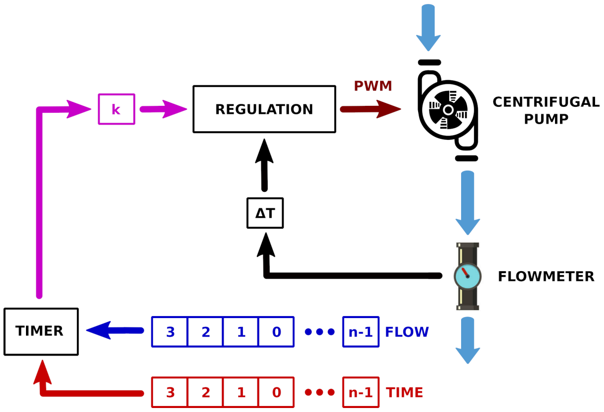

Figure 2. Closed-loop control.

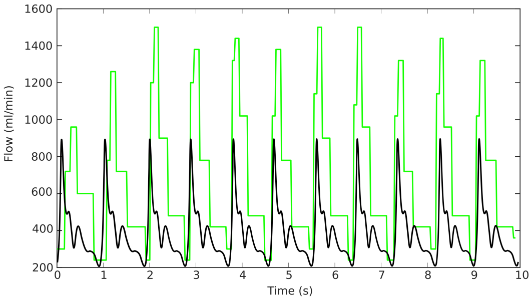

Figure 3. Target flow black track, flowmeter acquisitions green track.

The ARX model allows to calculate an appropriate PWM motor controller board input vector to have the desired output flow rate. This vector is programmed in the open-loop control mode (open-loop algorithm shown in Fig. 4) and it enables the flow simulation.

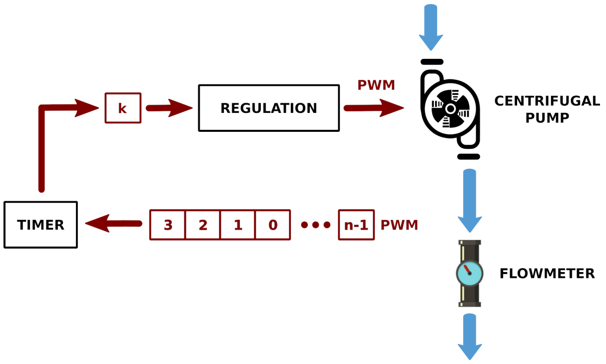

Figure 4. Open-loop control.

This method, closed-loop calibration and open-loop flow generation, allows to overcome the necessity of a high-cost high-sample rate flow sensor. Moreover, in designing the final device, a special care was devoted to dimensions and usability. A compact case was developed to host the electronics boards and hydraulic components, including a liquid reservoir of 3 litres. The flow simulator case has inlet and outlet silicon pipes to connect the vessel phantom (Fig. 5 (a)). In Fig. 5 (b), it is possible to see the flow phantom set-up connected to a CaP placed in a white case adapter.

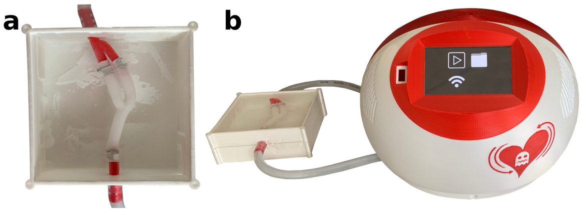

Figure 5. (a) Vascular Phantom (b) Flow Simulator Prototype

3. Tests and performance evaluation

In order to evaluate the performances of the designed flow phantom set-up, since the vascular phantom under studies is meant to be used for ultrasonic acquisitions, it was used an eco-doppler machine. Using this device, it is possible to evaluate the waveform generation with respect to the targeted one. In Fig. 6, the yellow track illustrates the target flow profile (i.e. a typical carotid artery profile) and the two black tracks are the measurements of the actual flow acquired with a magnetic flowmeter (upper curve) and with the ecodoppler machine (lower one), respectively. In table 1, target values of the carotid flow profile analysed are collected and compared with eco-doppler measurements of flow rate generated by the programmable flow set-up designed. In these acquisitions, the maximum deviation of the simulated flux with respect to the target value is equal to 40% at the diastole peak (610 ml/min instead of 430 ml/min). Apart from this isolated case, the median deviation is less than 9% and the similarity index (SI) is 0.98. The similarity index formula is shown below, where φ_t and φ_m are respectively target values vector and measured values vector from table 1.

$$SI(\varphi_t, \varphi_m) = \frac{|\varphi_t^t \varphi_m|^2}{(\varphi_t^t \varphi_t)(\varphi_m^t \varphi_m)}$$

Since SI is close to one, the agreement between target values and measured values can be considered very good.

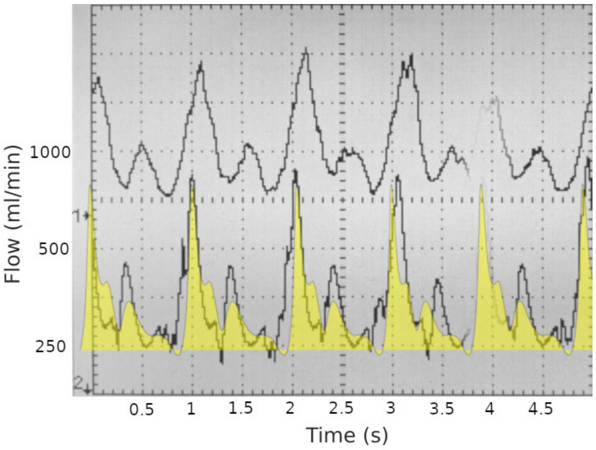

Figure 6. Magnetic flowmeter and eco-doppler acquisitions.

4. Conclusions

A new flow phantom set-up that overcomes problems such as cost, size and usability is proposed in this paper. To minimize size and enhance usability, it has been developed a system with a GUI and 3D printing techniques to fit in a very compact case the hydraulic and control components.

The developed flow phantom set-up is a low-cost device, thanks to the introduction of a calibration phase based on a ARX model which overcomes the sample rate limitations of low cost flowmeters. The reported performances showed that a carotid physiological flow has been reliably generated, with minimal deviation of the achieved flow values with respect to the targeted ones.

Table 1. Samples each 45 ms, comparison between carotid flow profile target value and measured value by ecodoppler.

Sample	Target value	Measured value
1	250	300
2	360	390
3	710	700
4	875	850
5	660	640
6	520	510
7	500	480
8	480	450
9	395	360
10	325	290
11	395	520
12	430	610
13	420	520
14	380	450
15	340	380
16	320	360
17	305	300
18	300	280
19	300	260
20	295	250

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Address for correspondence:

Matteo Zauli
University of Bologna-DEI, V.le Risorgimento, 2, 40136, Bologna, Italy
matteo.zauli7@unibo.it