Dynamic blood chamber volume estimation system for using in the POLVAD prosthesis

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Abstract

The paper presents a research into the blood volume measurements system, allowing for dynamic measurements, for a newly developed Polish heart supporting prosthesis (POLVAD). The current state of art in temporary blood volume measurements for the POLVAD is presented. Paper includes the theoretical basis of a new sensor solution as well as a prototype of a heart prosthesis with a newly developed measurement system. Article shows the development process of the proposed measurement system including static and dynamic measurements results. Future development plans are stated.

1. Introduction.

The main goal of cardiac development programs all over the world is a functioning, automated artificial heart prosthesis. Presently most of those programs have resulted in working artificial heart-supporting devices, which are a milestone on the way to the final solution. Basing on the principle of blood pumping two main types of such a kind of devices can be distinguished[1] – non-pulsatile and pulsatile ones. In Poland the solution currently used in patients is Polish Ventricular Assist Device (POLVAD), which is an extracorporeal pulsatile solution. It has been used for over a decade now. The special National Polish Artificial Heart Program was founded aiming at the development of new solutions of both pulsatile and non-pulsatile types. It focuses on development of new heart prostheses models and their automation.

The Department of Optoelectronics, Silesian University of Technology in Gliwice has been taking part in this program since the time it started researching solutions for monitoring of the pulsatile type prosthesis [1,2].

Previous works included research into new blood pressure measurement solutions for the prosthesis [1-4].

Fig.1. Polish heart supporting device – POLVAD [5].

Currently the program aims at the development of measurement systems (like minute cardiac output measurements, blood and air pressure measurements and blood oxygen saturation measurements) for pulsatile type prostheses, both the one currently used in patients (Fig.1) and newly developed by the Foundation of Cardiac Surgery Development, family of heart prostheses. The Department of Optoelectronics investigates methods for a blood volume measurements allowing for a cardiac output estimation.

2. State of art.

Semitransparent construction of the prosthesis caused no need for a monitoring system, since the current state of the blood filling state was visible. At any point medical staff could inspect the prosthesis, and decide whether the heart supporting process is optimal. The second possibility of monitoring the device, far less accurate, was analysis of pressure wave in the air duct between the POLPDU unit and the POLVAD prosthesis. This approach requires medical staff to monitor the state of the prosthesis and hinders the possibility of automation of the prosthesis driving and thus moving the prosthesis inside a human body in the future. Currently much effort is being made towards making the heart supporting solution more patient friendly and increase the mobility of the patient. This includes making a fully implantable heart prosthesis. This approach requires developing the solutions for measuring of the current state of the prosthesis.

The POLVAD (heart assisting device) consists of the blood chamber, air chamber and the membrane separating both chambers (Fig.2).

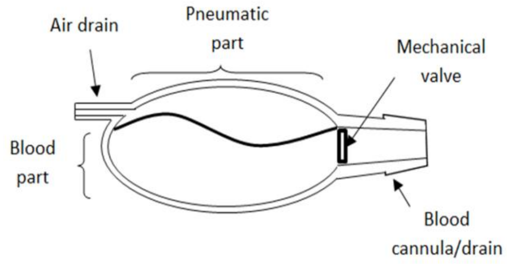

Fig.2. Construction diagram of the POLVAD.

The blood flow is being generated by the membrane, put into motion by the air pressure changes induced by the POLPDU unit, and the direction of the blood flow is determined by mechanical valves situated at the input and the output cannulas. The measurement of the blood chamber volume is essential for the estimation of blood flow parameters, like the current stroke volume, providing feedback that could be used for the automation of the driving process of the heart prosthesis.

There were a few approaches to the blood volume measurement problem in POLVAD prosthesis in the past. Among these solutions we can distinguish: inter-valve impedance measurement method, capacitance measurement [2], optical amplitude sensor, acoustic white noise based method[2], measurement with use of acceleration sensors[6], image recognition sensor[7]. None of the mentioned solutions could be used in the final project. Many solutions based on flow rate measurements both in air drain and blood drains are used in the world, but require measurements history in order to estimate the current blood chamber volume accurately. The blood chamber volume measurement problem was raised up again in Poland during the foundation of the Polish Artificial Heart Program. The new approach, proposed by the group from Department of Optoelectronics, Silesian University of Technology, Gliwice is based on an acoustic Helmholtz's resonator theory principles.

3. The Helmholtz resonator theory.

An acoustic Helmholtz's resonator is a restricted gas volume connected with other gas volumes with a use of apertures. In most cases the aperture takes a form of cylindrical neck, which adds an additional height dimension to equations.

The resonant vibrations of an air mass inside the neck are caused by the springiness of the air. The simplest case includes the closed resonator volume connected with a second resonator of almost infinite volume (compared to the first resonator's volume). If both resonators are comparable in size (Fig.3), both volumes influence the resonant frequency.

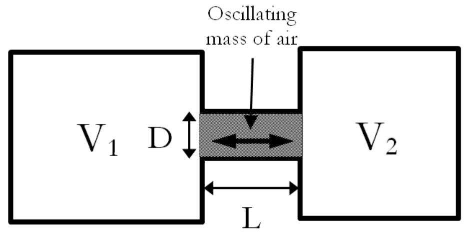

Fig.3. Construction diagram of the two-chamber Helmholtz resonator.

Forces moving the air mass inside the neck, are caused by the pressure differences inside both volumes. The equation for the resonant frequency takes a form (1).

$$f \cong \frac{c}{2\pi}\sqrt{\frac{A}{L}\left(\frac{1}{V_1}+\frac{1}{V_2}\right)} \qquad (1)$$

The oscillation of gas mass, inside the neck, depends on connected resonators volumes (V_1 and V_2), the area of a cross-section of the neck(A) and the length (L) of the neck, therefore it is possible to estimate volume of one chamber, knowing the resonant frequency of the vibrating air mass, dimensions of the neck and the volume of the second chamber.

4. The measurement method.

The proposed measurement method consists of an acoustic path (acoustic Helmholtz's resonator) providing the acoustic feedback loop and an electronic path – electronic circuit realizing positive feedback loop. The signal is being introduced into the prosthesis using the speaker and detected using an acoustic detector (microphone). The electronic circuit amplifies and conditions (Automatic Gain Control circuit) the detected signal and drives the speaker (Fig.4.). The measurement system excited on single dominant frequency which could be estimated using simple frequency counter. The frequency is dependent on acoustic properties of the resonator.

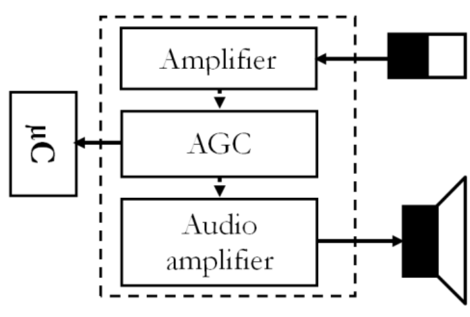

Fig.4. Electronic circuit used for static measurements.

The sound emitter and sound detector are situated inside the additional sensor chamber built on top of the pneumatic chamber (Fig.5.). The first attempts were made on the POLVAD-MEV (Fig.1) prosthesis with an additional sensor chamber attached. The sensor chamber volume is constant therefore the resonant frequency of the system is only dependent on the volume of the air chamber of the prosthesis. Since the total volume of the prosthesis is constant, the blood chamber volume can be easily estimated.

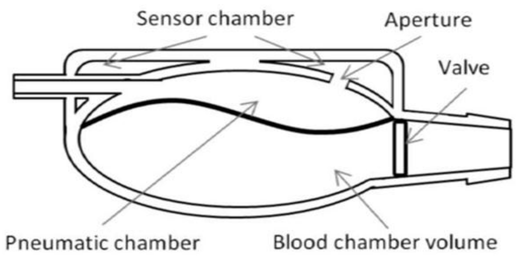

Fig.5. The prosthesis with an additional sensor chamber.

The system was investigated during static measurements [3]. The successful results of static measurements were basis for the dynamic properties investigation. The static characteristic has been incorporated into the microcontroller system, realizing the direct calculation of the current volume of the blood chamber. During initial tests the noise caused by the working POLVAD prosthesis hindered the measurements with the required accuracy (10%). The main source of the noise was found to be the POLVAD's valves. The noise was present in the lower spectrum of the acoustic frequencies (<100Hz)[3].

To avoid noise related problems modifications have been made. The filtration methods both in electronic circuit and at the acoustic detector were proposed, for the purpose of noise (mainly caused by the valves) reduction. The use of a speaker instead of a microphone allowed for the physical filtration in the lower frequencies spectrum and electronic filters electronically limited the higher frequencies excitation of the measurement system [4]. The diagram of the final electronic measurement system is shown in Fig.6.

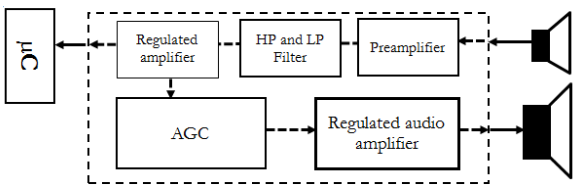

Fig.6. The final measurement system diagram.

The first prototype constructed at the Department of Optoelectronics was tested dynamically at the Foundation of Cardiac Surgery Development. Software written in Labview environment was used for data presentation and acquisition. The results of those measurements were satisfying. The construction of a new prosthesis was modeled at the Foundation of Cardiac Surgery Development and the prototype was made in the rapid prototyping process. In the new prototype, the sensor chamber was made an integral part of the prosthesis (Fig.7).

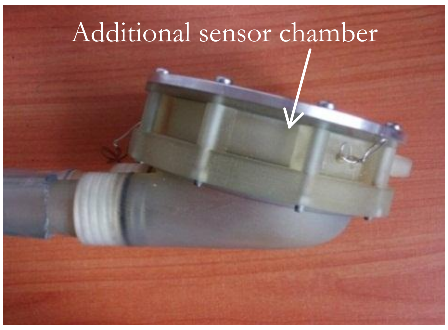

Fig.7. The POLVAD with the acoustic sensor prototype.

The new prototype was investigated in static and dynamic test.

5. Results

The prototype was scaled during static tests at the Department of Optoelectronics, Silesian University of Technology in Gliwice and the dynamic were conducted on the human circulatory model at the Foundation for Cardiac Surgery Development in Zabrze. The static characteristic presenting the relation between air chamber volume and the resonant frequency can be seen in Fig.8.

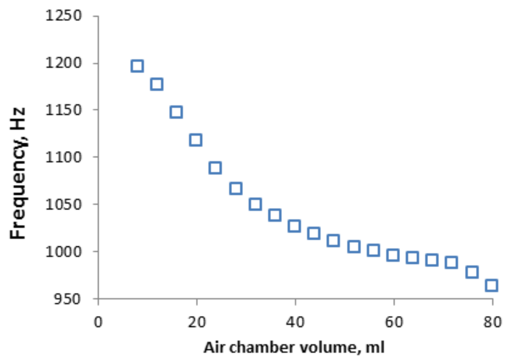

Fig.8. Static characteristic of the measurement system.

Exemplary dynamic results are shown in Fig.9. The graph shows the acoustic blood volume measurements and the output cannula flow rate measurement results. The flow meter detects flow only when blood-like liquid is ejected from the POLVAD prosthesis (high signal from the flow rate meter during the falling edge of the blood volume measurement curve). The volume estimated using the flow rate meter is included in the Fig.9.

Results of the volume measurements from both methods can be compared only for the liquid ejection cycle. the POLVAD valves work.

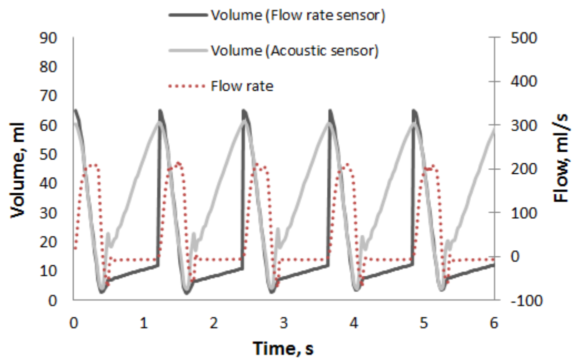

Fig.9. Exemplary results of the dynamic measurements.

Both curves are showing the similar volume of the blood ejected from the prosthesis.

The tested sensor was working correctly in range of allowed supporting speeds and air driving pressures used in an experiment.

6. Conclusions

The conducted researches both at the Department of Optoelectronics and at the Foundation for Cardiac Surgery Development proved that the acoustic method based on the Helmholtz's resonance theory can be used for determination of the temporary blood chamber volume in the family of the POLVAD prostheses. It allows for direct measurements of the temporary volume of the blood chamber without the need for measurement history, which is required when using flow rate based measurement methods (ie. ultrasound flow rate sensor). The method is noninvasive to the blood environment and sufficiently accurate (<10%). The further investigation will focus on the miniaturization of the electronics and improvement in an acquisition algorithm (aiming at the improvement in an acquisition speed and accuracy of measurement results). The miniaturized system will be scaled and tested both statically an dynamically in a presence of reference measurement systems. The solution is a subject to a patent[8].

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