Preliminary Research Concerning Measurements of the POLVAD Blood Chamber Volume Based on Helmholtz's Acoustic Resonator Principle

G. KONIECZNY, Z. OPILSKI AND T. PUSTELNY*

Department of Optoelectronics, Silesian University of Technology

Akademicka 2A, 44-100 Gliwice, Poland

The article presents researches concerning a system for a possible blood volume measurements applied in POLVAD prosthesis. The proposed solution is based on the Helmholtz resonance principle. The article shows the state of art in blood volume sensors for using in the POLVAD prosthesis and introduces a newly proposed solution. The construction of the sensor and the results of static tests are presented. The work is summarized with future development plans.

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1. Introduction

Nowadays many efforts are taken with the purpose of effective solutions of problems concerning elaboration of the artificial heart [1–10]. It is caused by an alarming increase of the number of people suffering from heart diseases. Not all cases qualify for a drug treatment. In the final stage of a heart failure the only option would be a heart transplant. For some years now there is an alternative — heart supporting devices. They help to a heart in pulsatile blood pumping, so that a heart can be healed in most cases, with the use of medicines. A Polish solution of this type is the external ventricular assist device POLVAD (Fig. 1) [1, 5, 11]. The POLVAD prosthesis can work as LVAD (left) and RVAD (right) providing both pulmonary and systemic circulation support. Two POLVAD's can realize a full heart support. POLVAD is driven by the POLPDU unit, which can simultaneously work with two devices of this type.

Fig. 1. Polish heart supporting device — POLVAD [1].

The future development of this kind of devices is the main goal of founding of the Polish Artificial Heart Program. The program aims at the introduction of a fully

implantable artificial heart prosthesis. The program is divided into five stages, which can be summarized in three main goals (Fig. 2) [11]:

- modification of the external heart support device (connected through the skin);
- development of internal (implantable) heart support devices;
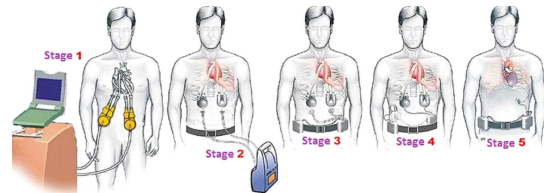- development of implantable artificial heart prosthesis.

Fig. 2. Stages of the development of heart prosthesis [11].

The artificial heart program should provide a solution of fully implantable internal heart prosthesis. To get to that point the internal heart supporting device must be developed. It will be based on the POLVAD. There is a lot of work to be done in the matter of reducing the total volume of the prosthesis, solving the biocompatibility issues and introducing the monitoring system.

The Department of Optoelectronics, Silesian University of Technology, Gliwice is taking part in the latter research — monitoring the prosthesis. Recent research includes the real time blood volume measurement system for the POLVAD prosthesis. Previously the Department developed pressure measurement solutions for the prosthesis [5, 6, 10].

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* corresponding author; e-mail: `tpustelny@polsl.pl`

2. State of art

Currently the state of the POLVAD prosthesis is not monitored by any additional sensors. Since the device itself is semitransparent, there was no need for a monitoring system. The decision whether the heart supporting process is optimal was made purely on the visual inspection of the prosthesis. The main disadvantages of this solution are the lack of automation in the prosthesis driving process and the problem with thru-skin connections in human ventricular system.

The prosthesis consists of a blood chamber, an air chamber and a separating membrane. At the input and output cannulas there are valves determining the direction of the blood flow. The membrane is put into motion by air pressure changes induced by the POLPDU unit (Fig. 3). The membrane movement makes the blood flow [11].
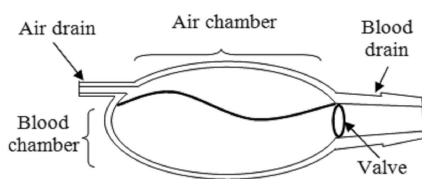

Fig. 3. Construction of the POLVAD [11].

The measurement of the blood volume is essential for the estimation of the blood flow parameters, as the current stroke volume providing feedback that can be used for the automation of the driving process of the heart prosthesis.

There are a few approaches to the blood volume measurement problem in the POLVAD prosthesis: inter-valve impedance measurement method [12], capacitance measurement method [12], the acoustic white noise based method [6], the optical amplitude sensor [9], measurement of the dynamic properties of the prosthesis casing [7], image recognition [10].

The solutions mentioned above proved to fit more or less for the purpose of the POLVAD blood volume measurement, but none of them proved reliable enough for incorporation in the final project. The most promising method, giving the best results was the acoustic white noise filtration (Fig. 4).
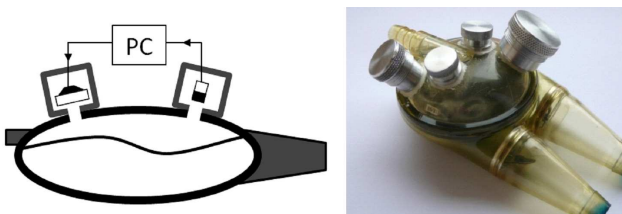

Fig. 4. Construction diagram of the first acoustic blood volume measurement system.

The method applies measurements of the air chamber volume, estimating the current blood volume. It is based on the assumption that the air chamber volume can work as an acoustic filter. When applied to the white noise signal in the range of the acoustic frequencies it will filter certain frequencies, connected with the resonant properties of the air chamber, which change with its volume.

There is a direct relation between the peak frequency of about 4 kHz in the filtered acoustic signal and the corresponding air chamber volume (Fig. 5). The problem is the complexity of the real time filtered signal analysis. Real time analysis of the peak frequency in the frequency pack about 4 kHz is complicated, because there are a few frequencies in the filtered spectrum similar to the correct one. Also the durability of the acoustic parts introduced to fast air pressure changes cause problems concerning the lifetime of the measurement system.
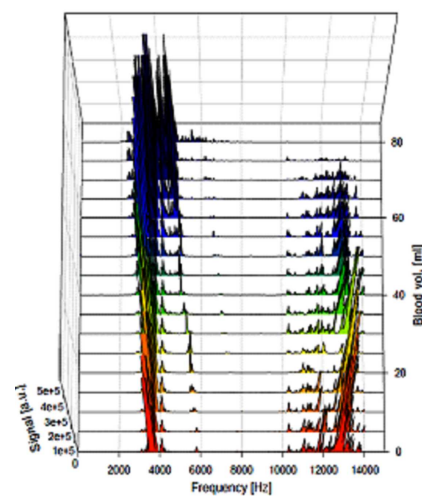

Fig. 5. Frequency characteristics of the air chamber after applying the white noise signal at different chamber volumes.

Within the Polish Artificial Heart Program a new blood measurement system is being developed. Since the acoustic method provided good measurement results, the new approach was also made in the field of acoustics. The new solution was supposed to avoid all the disadvantages of the previous method, permitting easy and accurate measurements ($< 10\%$ error). The new approach is based on the basis of Helmholtz's resonator theory with multiple volumes.

3. Helmholtz's resonator theory

A Helmholtz resonator is basically a closed gas volume with an aperture. Usually instead of a hole there is a cylindrical neck that adds an additional height dimension to the volume [13–15]. Air "trapped" inside the neck vibrates because of the springiness of the air.

In the simplest case, the resonator is situated inside an almost infinite volume (compared to the size of the

resonator), usually we deal with a situation of two connected resonators (Fig. 6.). The neck connecting both volumes has a cross-section area "A" and length "L".
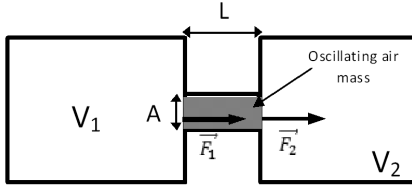

Fig. 6. Construction diagram of the two-chamber Helmholtz resonator.

The forces moving the air mass inside the neck, are caused by pressure changes inside both volumes. During the oscillation of the air mass, one volume is pushing the air in the neck to the other volume (overpressure) and the other volume pulls it because of underpressure. We can write the equation for total force moving the air mass

$$\boldsymbol{F}_T = \boldsymbol{F}_1 + \boldsymbol{F}_2 \,, \tag{1}$$

$$F_T = A\Delta P_1 + A\Delta P_2 \,, \tag{2}$$

$$\mathrm{d}P_1 = -\gamma \frac{\Delta V_1}{V_1} P_1 = -\gamma \frac{A\Delta x}{V_1} P_1 \,,$$

$$\mathrm{d}P_2 = -\gamma \frac{\Delta V_2}{V_2} P_2 = -\gamma \frac{A\Delta x}{V_2} P_2 \,. \tag{3}$$

Using Newton's acceleration law and the equation for gas mass inside the neck volume we get

$$a = \frac{F}{m} = \frac{A\Delta P_1 + A\Delta P_2}{m} = \frac{A\Delta P_1 + A\Delta P_2}{\rho A L}$$

$$= \frac{\Delta P_1 + \Delta P_2}{\rho L} \,. \tag{4}$$

Taking under consideration that we are dealing with a harmonic oscillator, the substitution $a = -4\pi^2 f^2 \Delta x$ can be used

$$\frac{-\gamma \frac{A\Delta x}{V_1} P_1 - \gamma \frac{A\Delta x}{V_2} P_2}{\rho L} = -4\pi^2 f^2 \Delta x \,, \tag{5}$$

$$-\gamma \frac{A\Delta x}{\rho L} \left(\frac{P_1}{V_1} + \frac{P_2}{V_2} \right) = -4\pi^2 f^2 \Delta x \,. \tag{6}$$

If we claim that the pressure inside both volumes is approximately the same

$$P_1 \cong P_2 \tag{7}$$

and after simple mathematical operations we get

$$\frac{\gamma P}{\rho} \frac{A}{4\pi^2 L} \left(\frac{1}{V_1} + \frac{1}{V_2} \right) \cong f^2 \,. \tag{8}$$

By introducing the sound speed equation into (8), the final equation for the resonant frequency takes the form (9):

$$f \cong \frac{c}{2\pi} \sqrt{\frac{A}{L} \left(\frac{1}{V_1} + \frac{1}{V_2} \right)} \,. \tag{9}$$

It can be seen that this case might be treated as a parallel connection of two volumes. When one of the volumes is infinite, we receive Eq. (10):

$$f \cong \frac{c}{2\pi} \sqrt{\frac{A}{LV}} \,. \tag{10}$$

Equation (9) shows that the frequency of the gas mass oscillation in the neck depends on the volume of the closed gas chambers (V_1 and V_2), the area of the necks and their length. If the neck parameters, one chamber volume and the properties of the gas, do not change drastically with time, the frequency depends only on the closed V_2 volume.

4. Blood volume measurement system based on the Helmholtz resonator method

In previous researches the acoustic method based on white noise generation proved most promising; a new approach was also made in the field of acoustics. The new approach was based on the basis of Helmholtz's resonator theory with multiple volumes. The measurement system consists of two parts: the electronic and acoustic parts. The acoustic part is realized making use of a transmitter (speaker) and a receiver (microphone). Both these acoustic elements are situated inside the additional aluminum chamber, connected with the POLVAD air chamber by a cylindrical aperture. Both the air chamber and additional sensor chamber act as a two-chamber Helmholtz resonator (described in Sect. 3 of the article). The electronic part is used to realize the positive feedback between the acoustic part elements (Fig. 7).
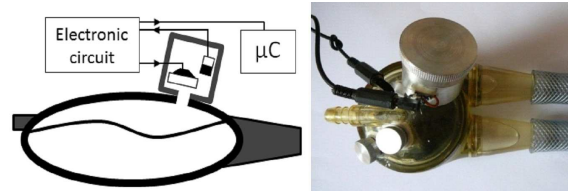

Fig. 7. Construction diagram of the Helmholtz resonator based acoustic blood volume measurement system.

Any signal from the microphone with a preamplifier is passed to the automatic gain control (AGC) part. The AGC circuit realizes the amplification of the signal to the desired level, not allowing the signal to get distorted. It is needed because the detected level of the acoustic signal varies with the position of the membrane (changes of the chamber size). The AGC adjusts the signal to the desired amplitude, allowing a stable driving of the audio amplifier. The gain coefficient of AGC can be modified to meet the requirements of measurements. The audio amplifier drives the loudspeaker. The amplitude of the output signal (volume) can also be modified (Fig. 8). This

two stage gain control provides means for measurement signal volume reduction, making the measurement more passable for the patient.
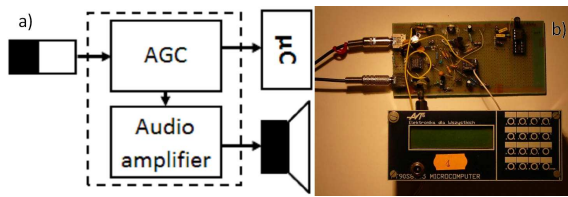

Fig. 8. Electronic circuit diagram (a) and actual circuit board with microcontroller (b).

The acoustic signal from the chamber (the Helmholtz resonance frequencies) is detected by the microphone, amplified by the AGC and put back into the sensor chamber through the loudspeaker and detected back by the microphone. It is constantly traveling in a closed loop, and dominating frequency changes following from the changes of the air chamber volume. Exemplary frequency characteristics for different air chamber volumes are shown in Fig. 9a. The dominant frequency rises with the decreasing air chamber volume (Fig. 9b).
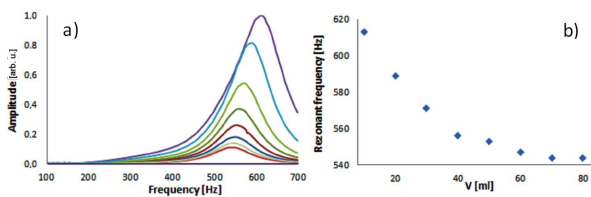

Fig. 9. Frequency characteristics of the Helmholtz resonator measurement system at the different air chamber volumes (a) and the dominant frequency versus the air chamber volume (b).

The resonant frequency peaks are wide (Fig. 9a), which suggests that the quality of the resonator might be better. By modifying the aperture area and "neck" length we can modify the width of the frequency peaks (smaller diameter of the aperture). But this changes the blood volume versus frequency characteristics — the frequency changes with volume are smaller. The resulting characteristics are compromised between the precision of measurements (high frequency changes with changes of the air chamber volume) and the peak width.

Resulting characteristics (Fig. 9a) are easier to analyze than the ones given by the white noise based acoustic method (Fig. 5). Finding the peak frequency for the given air chamber volume is relatively easy and does not require complicated analysis. A simple frequency counting element may be used. In the proposed measurement system a microcontroller is used for this purpose. It also realizes the translation of the resonant frequency to the volume of the blood chamber and transmits data to the PC application written in the LabView environment.

The measurement system underwent static measurements in the Department of Optoelectronics, Gliwice, Poland. The exemplary static characteristic showing the relation between the blood chamber volume and the dominant frequency in the measurement system are shown in Fig. 10.
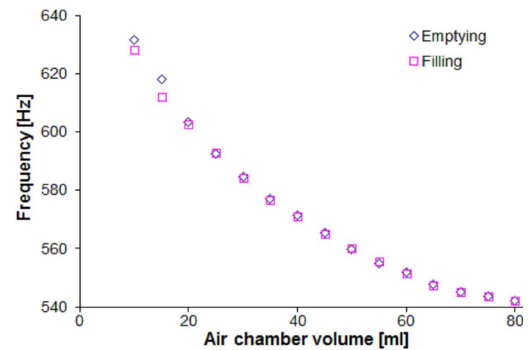

Fig. 10. Static characteristics of the sensing system for filling and ejecting.

Both filling and ejecting static characteristics are shown. It can be seen that there is a small difference between both characteristics at lower blood chamber volumes. This may be caused by the shape of the air chamber, when the membrane is almost touching the upper casing of the POLVAD prosthesis.

During the initial researches a few problems arose with the acoustic sensor system that needs to be solved in the future sensor development:

- adjusting the measurement system for dynamic measurements,

- conditioning the amplitude of the acoustic measurement signal,

- covering the 0–10 ml blood chamber volume range,

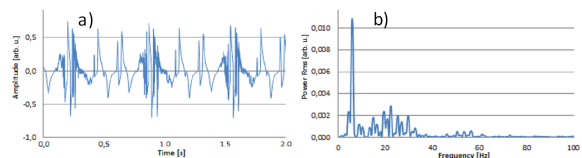- filtration of the noise caused by the POLVAD prosthesis (Fig. 11).

Fig. 11. Acoustic noise generated by the working POLVAD device (a) and the FFT of the noise signal (b).

The acoustic noise generated by the working prosthesis can be seen in Fig. 11a. The noise signal amplitude is high enough to interfere an operation of the measurement system. Fortunately the noise frequencies are within the range < 100 Hz, which is far from the resonant frequencies of the proposed system (> 540 Hz). It should be possible to filter the noise by means of the electronic filters.

5. Conclusions

The conducted researches prove that the blood chamber volume can be measured by means of the system based on the acoustic Helmholtz resonator principle. The static measurements are promising, and show that it is possible to estimate the blood chamber volume with a measurement error $< 10\%$. Frequency characteristics are relatively easy to analyze — a microcontroller is used for collecting the data, presenting and sending them to a specially written application in the LabView environment. Next stage of the researches includes adjusting the measurement system for dynamic tests. At this point effective filtering must be implemented in order to avoid the influence of the noise of the working prosthesis. Dynamic tests will be realized at the Foundation for Cardiac Surgery Development in Zabrze, Poland.

Acknowledgments

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