Optical and Acoustical Methods in Science and Technology 2013

Optical Sensor for Measurements of the Blood Chamber Volume in the POLVAD Prosthesis — Static Measurements

G. Konieczny*, T. Pustelny and P. Marczyński

Department of Optoelectronics, Silesian University of Technology, Akademicka 2A, 44-100 Gliwice, Poland

The paper presents results of extended static measurements of a newly developed optical system for temporary blood chamber volume measurements in the Polish Ventricular Assist Device. The paper additionally introduces a modified measurement stand and improvements of the measurements. Exemplary results acquired with principal components analysis are shown and future development plans of an optical measurement system are stated.

DOI: 10.12693/APhysPolA.124.479

PACS: 42.79.−e, 42.81.−i, 07.07.Df, 47.63.Cb

1. Introduction

The devices used for supporting the heart, available on the market can be divided into two main groups: pulsatile and non-pulsatile ones. In Poland the Polish Ventricular Assist Device (POLVAD) has been successfully used in patients for several years now. The prosthesis is an extracorporeal pneumatic type solution, that is connected with the patient's ventricular system through the skin [1].

The "Polish Artificial Heart Program" started in 2008 has been focused on the introduction of a new family of pulsatile prosthesis and a non-pulsatile solution [2]. Since the very beginning of the Program, the automation of the heart support process became a very important issue. The solution to this problem could vastly improve the treatment of patients with an end-stage heart failure using heart-support devices. In the case of pneumatic devices of such a kind, online blood chamber volume measurements could provide the necessary information for automatizing the heart support process. The article focuses on the blood chamber volume measurement method basing on the optical domain, that might allow to determine the volume with an uncertainty of 10%.

2. State of art

In its actual state, POLVAD prosthesis is not equipped with any kind of monitoring devices. In recent years many researches have been carried out aiming at introducing solutions for monitoring the pressure in the blood and air chambers, the blood oxygen saturation level and the blood chamber volume [3–7]. The problem of measuring the volume of the blood chamber is of great importance with respect to the automation of the heart support process. Currently the problem is partially solved worldwide using blood flow measurements. This method provides satisfying results, but requires periodic controlled full-filling/full-ejection cycles. It also requires noninvasive, ultrasound flow rate meters, which are very expensive. The complex construction of electronic circuits of these devices can hinder the development of miniature versions in near future; thus their usage is restricted to extracorporeal heart support devices.

There were approaches to find solutions that might be integrated in the construction of the POLVAD prosthesis (in future also used in an implantable version of the prosthesis). One of the solutions permitting noninvasive blood chamber volume measurements in the POLVAD prosthesis was an acoustic system based on the Helmholtz resonator [8–10]. This method provided a 10% level of uncertainty, and could be integrated with the prosthesis.

The acoustic system has been successfully developed in the Department of Optoelectronics, Silesian University of Technology in the frames of the "Polish Artificial Heart Program". The acoustic solution requires an additional sensor chamber, which along with the pneumatic chamber, forms a two-chamber Helmholtz resonator. The additional chamber slightly increases the total volume of the prosthesis. Although the acoustic system is capable of temporary blood volume measurements with a satisfying accuracy, the requirement of the additional sensor chamber may hinder the use of such a measurement technique in an implantable version of the prosthesis in the future.

The optical measurement system was proposed to solve the problem of temporary blood chamber volume measurements of the POLVAD prosthesis and to avoid drawbacks of the acoustic method (increase in the total prosthesis volume and susceptibility to acoustic noise) [11].

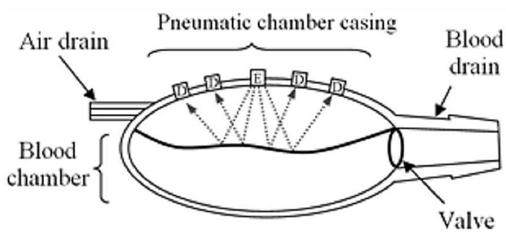

Fig. 1. Idea of the optical measurement method based on reflectance measurements [10].

The basic idea of the optical system based on reflectance measurements is shown in Fig. 1. The proposed

*corresponding author; e-mail: grzegorz.konieczny@polsl.pl

solution can overcome shortcomings of an acoustic sensor: the need of an additional sensor chamber and the susceptibility to acoustic noise (e.g. generated by working valves). The basis of the optical method was described in [11].

3. Advancements in the optical blood volume measurements method

The following article presents researches aimed at increasing the speed and improving the accuracy of the measurement method. So far the optical measurement system is using 12 LED light emitters, and 32 photodiodes as light detectors. The number of optic transducers was chosen to permit a complex examination of the light reflected by the membrane. The working wavelength range of optical elements was selected after measurements of the membrane used in the POLVAD prosthesis had been performed (Fig. 2).

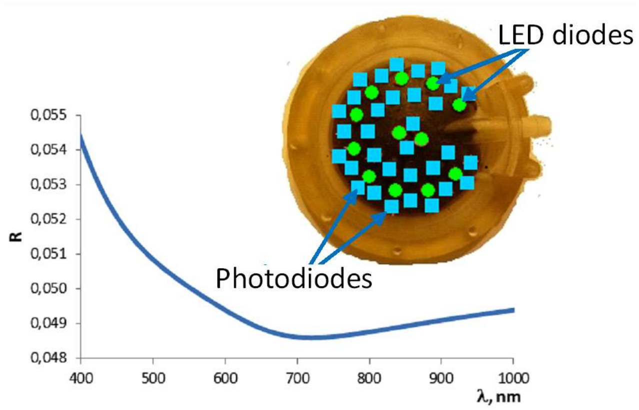

Fig. 2. Membrane reflectance in th 400–1000 nm range and configuration of LED light sources (circles) and photodiodes (squares).

The relation between the energetic reflection coefficient and wavelength in the investigated range of 400–1000 nm shows that the maximum reflectance occurs at near ultraviolet wavelengths. However, the difference of the reflection coefficient in the investigated wavelength range does not exceed 10%. The infrared light range (around 800 nm) was chosen. The wide range of LED diodes and photodiodes available on the market provides a large variety of elements to choose from. Additionally the IR part of the light spectrum allows to use photodiodes with high-pass filters (in the form of a colored casing), which makes the system less susceptible to interferences in the visible light range.

Many advancements have been made since the method was first developed. The acquisition time of data from all 384 configurations was reduced to 1 s by increasing the transmission speed and reducing the time of sampling.

During the tests covering several series of full-filling/full-ejecting of liquid in the blood chamber model, shift in amplitude–volume characteristics was noticed (Fig. 3).

It can be noticed that the characteristics tend to move, showing that more liquid is pumped inside the blood

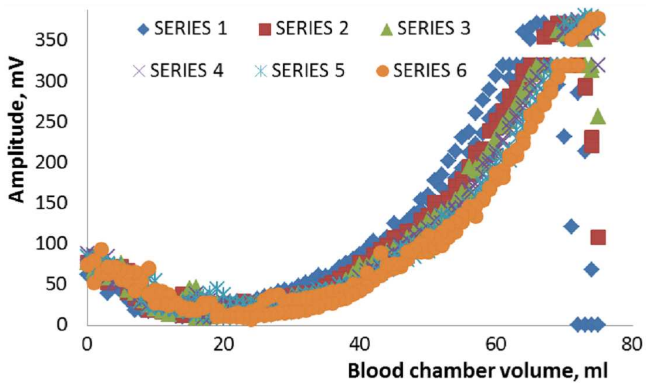

Fig. 3. Six consecutive measurement series of full-filling/full-ejecting.

chamber model during each series than is pumped out. This was caused by the pumping of a blood-like liquid.

In order to solve the problem, the measurement stand was supplied with the camera "0 ml" level calibration system. It was used to compensate the differences in the volume of the liquid pumped in and out of the blood chamber model.

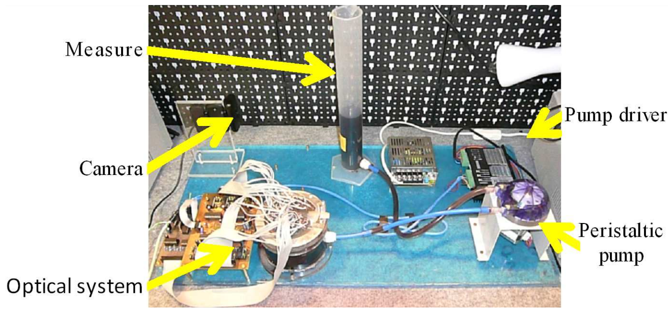

Fig. 4. Measuring stand for static tests of the optical measurement system.

The new measurement stand is shown in Fig. 4. The level of liquid in the measure was detected ("0 ml" level) using a special application at the beginning of the measurements. After each series the liquid level was measured and corrections were made, if necessary (by pumping liquid in/out of the prosthesis) in order to correct the shift in the pumped liquid volume. The correction algorithm solved the problem and allowed long term examinations of the system.

The new model of a blood chamber was also introduced (Fig. 5). Instead of the cylinder, the model based on the actual blood chamber used in the POLVAD prosthesis was applied. The model was constructed in a rapid prototyping process. The volume of the blood chamber of the prosthesis was also modified on the blood chamber side. The modified measurement stand and the method and prosthesis model were tested statically in the Department of Optoelectronics, Silesian University of Technology.

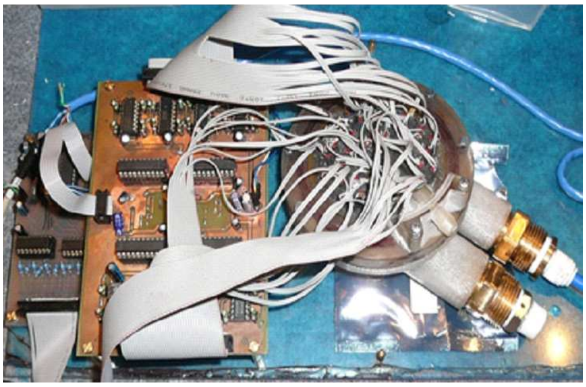

Fig. 5. Modified model of the blood chamber used in the static tests.

4. Results

The main problem in measuring the volume of blood/ liquid inside the POLVAD pulsatile type prosthesis is the flexible membrane, which wrinkles during the pumping process. The idea of using the principal components analysis (PCA) algorithm was proposed and it was expected that by analyzing the signals from many different configurations of optical transmitters/receivers, a pattern might be found. The PCA algorithm, aided by the LRS feature selection, allows to reduce the input parameters (LED-photodiode pairs) needed to assess the proper volume. Extended static tests were performed. 100 series of full filling and full emptying were performed. The data were then used for the numerical analysis using PCA and LRS [12]. The goal of research was to achieve an accurate (10% uncertainty) estimation of the blood chamber volume. Liquid was pumped at a rate of 1 ml/s.

Exemplary results published in [11] indicate the existence of emitter–receiver configurations providing direct information about the blood chamber volume in certain volume ranges.

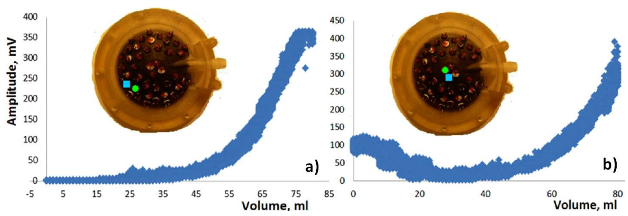

Fig. 6. The average amplitude on the detector vs. the volume of the liquid inside the prosthesis (a) at the example configuration of the emitter–detector pair (b).

Two sample configurations of such a type can be seen in Fig. 6. Additional graphic information about the location of the emitter and detector for each characteristic is included. More comprehensive researches show that these configurations provide a repeatable response during long term tests. The characteristics in Fig. 6 show results concerning 100 series.

Static tests were used to improve the PCA algorithm. The first 50 series were used for learning process. Other 50 series were used for testing the algorithm. The results of the recognition process using the PCA algorithm can be seen in Fig. 7.

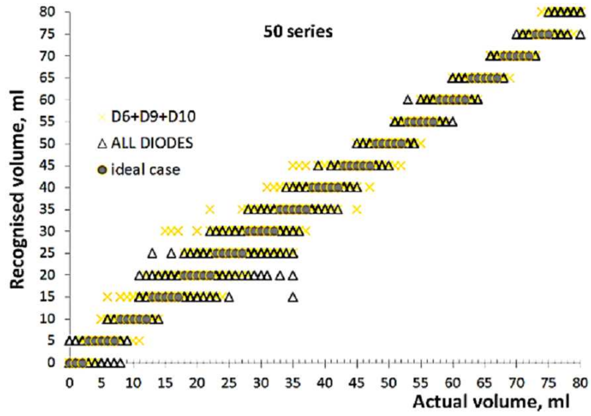

Fig. 7. Blood chamber volume estimated using the PCA algorithm compared with the actual volume.

Two different learning paths were taken into account. In the first approach all possible parameters (transmitter–emitter combinations) were used in the PCA learning process. The second approach considered only combinations of three LED diodes and all photodiodes. Reducing the number of LED diodes from 12 to 3 significantly decreased the time of acquisition. The algorithm has chosen a combination of diodes 6, 9, and 10 as providing the best recognition results. It can be seen that the suggested algorithm provides better results for border volumes of the blood chamber (0–15 ml and 45–80 ml). In this case the uncertainty of recognition does not exceed 5 ml. Both approaches provide similar results in that range.

In the range of 15–45 ml the method is less accurate. This can be due to the "wrinkling" of the membrane in this range of the blood chamber volumes. Some volumes in this range are better recognized by the system using all possible diodes and other volumes are better estimated with the use of only 3 diodes. This indicates that the results acquired using the PCA algorithm supported by the LRS function are highly dependent on the input parameters; therefore a proper selection of the input data (parameters) is crucial for the success of a total recognition.

5. Conclusions

The measurement circuit described earlier in [11] was modified. The stability of the optical system was improved. Additional modifications of the measurement stand permitted long term measurements conducted in the Department of Optoelectronics. The results acquired in 100 series of full-filling/full-ejecting show that the amplitude–volume characteristics for the selected LED--photodiode configurations are repeatable in certain volume ranges. The conducted measurements were obtained under relatively stable pumping conditions. At this point there is no information on how the membrane will behave in conditions of dynamic measurements. However, it is unlikely that the membrane did not wrinkle in a random way during 100 filling/ejecting of liquid series. It seems that using wide angle LED diodes and wide angle photodiodes permits a partial compensation of the "wrinkling" effect of membrane. Future dynamic researches should prove if that assumption is correct and if the circuit can be used for temporary blood chamber volume measurements in the POLVAD prosthesis.

The volume estimation using the PCA algorithm allowed to estimate the volume of the blood chamber with 10 ml uncertainty in the range of middle volumes. 5 ml uncertainty was achieved in the lower and higher volumes range. The method requires improvements in the field of the feature selection process, which should ensure a more accurate estimation of the volume.

The optical system has been prepared for semi--dynamic tests which will be conducted at the modified measurement stand in the Department of Optoelectronics, Silesian University of Technology.

Acknowledgments

The research was partially financed by the Polish National Centre of Science NCN (Cracow, Poland), within the grant No. 4896/B/TO2/2011/40.

M.Sc. Grzegorz Konieczny is a beneficiary of the "SWIFT (Scholarships Supporting Innovative Technology Forum)" project POKL.08.02.01-24-005/10 co--financed by the European Union within the European Social Fund.

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