BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 59, No. 4, 2011
DOI: 10.2478/v10175-011-0053-7

Noninvasive acoustic blood volume measurement system for the POLVAD prosthesis

Z. OPILSKI[1], G. KONIECZNY[1]*, T. PUSTELNY[1], A. GACEK[2], R. KUSTOSZ[3], and M. GAWLIKOWSKI[3]

[1] Department of Optoelectronics, Silesian University of Technology, 2A Akademicka St., 44-100 Gliwice, Poland
[2] Institute of Medical Technology and Equipment, ITAM, 118 Franklina Roosevelta St., 41-800 Zabrze, Poland
[3] Foundation of Cardiac Surgery Development, Zabrze, Poland 345A Wolności St., 41-800 Zabrze, Poland

Abstract. The following paper presents researches concerning a noninvasive real-time blood volume measurement system applied in POLVAD prosthesis. The system is based on the acoustic Helmholtz resonator principle. The basis of the measurement method, followed by the preliminary tests of the possibility of incorporating the Helmholtz resonance idea into the POLVAD prosthesis is shown. The paper includes the actual measurement system construction and test results, both static and dynamic obtained at the Foundation for Cardiac Surgery Development in Zabrze, Poland. Conclusions and future plans are presented too.

Key words: the heart prosthesis, medical acoustics, the blood volume measurement system.

1. Introduction

An artificial heart is the ultimate goal of many cardiac development programs all over the world. A half-way milestone is an artificial heart-supporting device. There are many approaches to this topic. We can distinguish two main types of such a kind of devices – non-pulsatile and pulsatile ones [1]. The Polish Artificial Heart Program focuses on the latter solution, aiming at the introduction of a fully implantable artificial heart prosthesis. A lot of work has been done in developing the pulsatile prosthesis POLVAD and its automation [2–8]. The Department of Optoelectronics at the Silesian University of Technology in Gliwice has been developing solutions for monitoring the POLVAD prosthesis for this program since the time it started [9–14]. The program is separated into three main stages on the way to its final solution (Fig. 1).

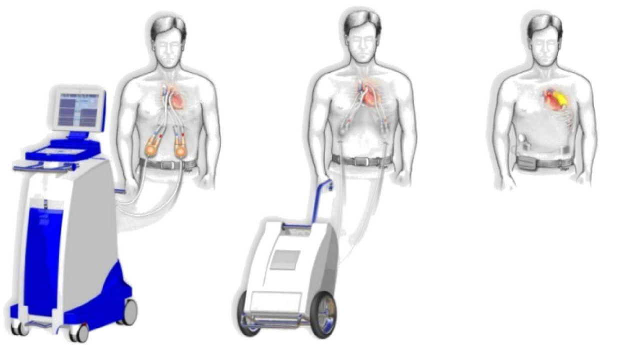

Fig. 1. Stages of the development of heart prosthesis after Ref. [14]

At present the Polish Artificial Heart Program has used the POLish Ventricular Assisting Device POLVAD (Fig. 2) to support the heart process in patients with end-stage heart failure. The prosthesis can work as LVAD (left one) and RVAD (right one), allowing a full heart support when two devices are used. POLVAD is driven by the driving unit POLPDU (Fig. 1 – left).

Fig. 2. Polish heart-supporting device – POLVAD after Ref. [11]

The ultimate goal of the program is to develop a fully implantable internal heart prosthesis. Between the final solution and the current state of the art internal heart supporting devices (Fig. 1 – right) must be developed.

2. The aim of researches

The presented researches focus on the development of the real-time prosthesis blood volume measurement system. The sensor should not be in contact with the environment of the blood. The introduced sensor was developed at the Department of Optoelectronics in Gliwice. The main work focuses on measurements of the air chamber volume. The blood volume is calculated by subtracting the measured air chamber volume from the total prosthesis volume, which is constant. Figure 3 shows a diagram of the POLVAD prosthesis.

*e-mail: grzegorz.konieczny@polsl.pl

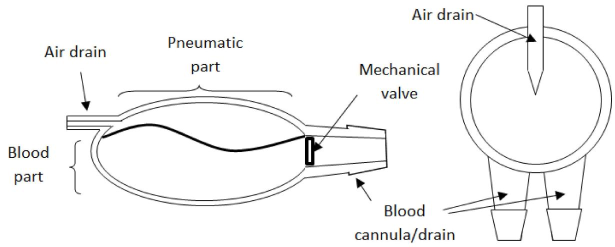

Fig. 3. Polish heart supporting device – POLVAD diagram

The proposed solution is based on acoustic measurements, making use of the acoustic Helmholtz resonance.

3. The basis of the measurement method

The proposed sensing system is based on Helmholtz's acoustic resonance principle. The Helmholtz resonator is a closed gas volume with an aperture. In real systems the aperture has a finite length; so it can be treated as a tube with the cross-section area (A) and the length (L). The springiness of the air inside the closed volume causes vibrations of the air inside the tube, the frequency of which depends on the dimensions of the system (Fig. 4).

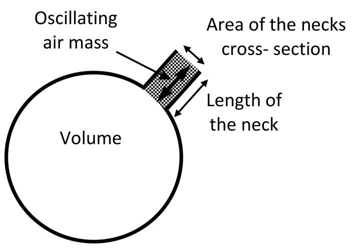

Fig. 4. A simple Helmholtz resonator

When the air mass inside the neck of the area A and the length L is moved inside the closed volume by the distance Δx, it decreases the volume by ΔV, which equals $A\Delta x$. The relation between the dimensions of the resonator necks and the volume is shown in Eq. (1). In this case the volume outside the resonator is indefinite.

$$f = \frac{c}{2\pi}\sqrt{\frac{A}{L \cdot V}}. \tag{1}$$

If the volume outside the resonator is finite, the system is treated as consisting of two resonators, connected by a common neck. Equation (1) assumes a different form, taking into consideration the volume of both connected resonators (Fig. 5).

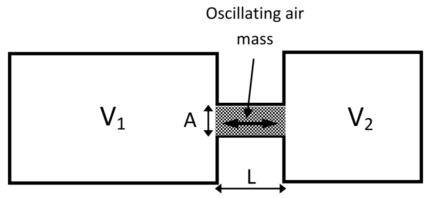

Fig. 5. The two-chamber Helmholtz resonator

In this case pressure changes caused by changes of the volume can be approximated by (2) [15, 16].

$$f \approx \frac{cA}{4\pi}\sqrt{\frac{\pi}{L}\frac{V_1+V_2}{V_1V_2}}. \tag{2}$$

Equation (2) 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 neck and the length. If the parameters of the neck, the volume of one chamber and the gas properties do not change drastically with time, the frequency depends approximately only on the closed volume V_2.

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

In a previous research the acoustic method based on the white noise generation proved to be most promising [9, 10]; thus the new approach was also made in the field of acoustics based on Helmholtz's resonator theory with multiple volumes.

4.1. Preliminary construction of the measurement system in the POLVAD prosthesis. The measurement system consists of an electronic and an acoustic part. The acoustic part includes a transmitter (small loudspeaker) and a receiver (microphone) situated inside the additional acoustic chamber connected with the POLVAD air chamber by a cylindrical neck (Fig. 6a). The electronic part realizes the positive feedback for the acoustic part [15–18]. The signal from the microphone is amplified by a preamplifier, filtered by electronic filters, conditioned by an AGC (automatic gain control circuit) (Fig. 6b).

a) b)

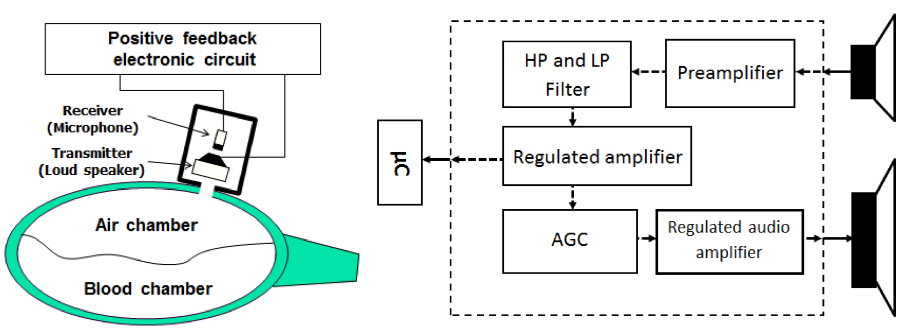

Fig. 6. The overall construction (a) and electronic circuit diagram (b) of the acoustic blood volume measurement system

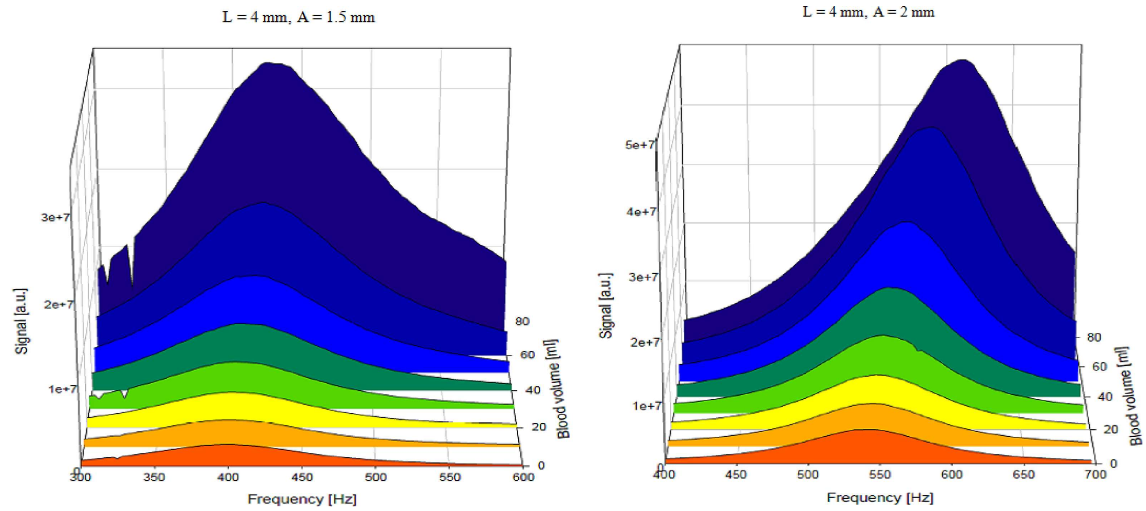

Fig. 7. Frequency characteristics of the Helmholtz resonator measurement system for different air chamber volumes

This signal is sent back to the air chamber by the loudspeaker. It is constantly traveling in a closed loop, and the dominating frequency changes with the changes in the air chamber volume.

Frequency characteristics of two different apertures of the neck connection between the air chamber and the sensor chamber are shown in Fig. 7. It can be seen that the quality of the system is not high (wide frequency peak), but by modifying the diameter of the neck it can be improved (smaller diameter). But the modifications change the frequency characteristics – the frequency-volume changes are smaller. A compromise is required.

If compared with the characteristics of the acoustic method based on the white noise generator, the characteristics in Fig. 7 are more suitable for an analysis. Finding the peak frequency for an actual air chamber volume is relatively easy and does not require any complicated analysis. Simple frequency counting μComputer (μC) can be used (Fig. 6b).

An exemplary static characteristic, showing the relation between the blood chamber volume and the dominant frequency in the measurement system is shown in Fig. 8.

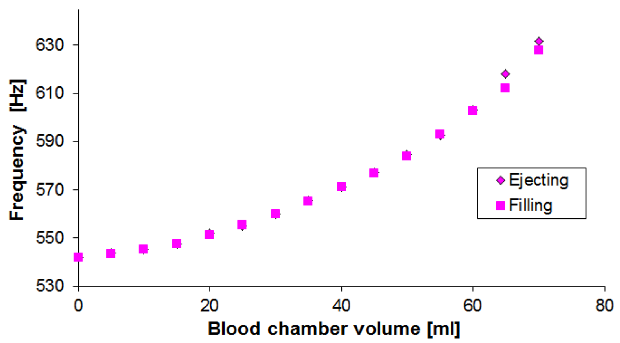

Fig. 8. Static characteristics of the acoustic sensing system

In Fig. 8. the relation is shown between the filling and ejecting liquid (blood-like solution) from the blood chamber. It can be seen that the difference between the filling and ejecting characteristics is minimum. The static characteristic was used as a scaling curve for the measurement system. (The static tests were conducted at the Department of Optoelectronics in Gliwice.) The last 10 ml could not be covered by the acoustic sensor because of an insufficient volume of gas, but the initial research proved that the Helmholtz resonator might be used in the POLVAD prosthesis after some minor modifications in it construction.

4.2. Measurement system with modified construction of the sensor chamber. The proposed mechanical construction of the sensor (Fig. 6a) could not be accepted for use in the final POLVAD prosthesis. The main problem was the shape of the additional sensing chamber. It dramatically increased prosthesis height. The prosthesis should be implantable in the future, therefore it needs to be as compact as possible. During a consultation with the Foundation for Cardiac Surgery Development, a new proposal of the sensor chamber shape emerged. Instead of a single chamber for the acoustic sensor only, a special additional chamber was made on the top of the POLVAD prosthesis, that could also hold the electronic circuits of the other sensors (Fig. 9). This approach made sensor chamber an integral part of the prosthesis, with only minor increase of its height. The new approach provided more compact solution when compared to previous one (4a).

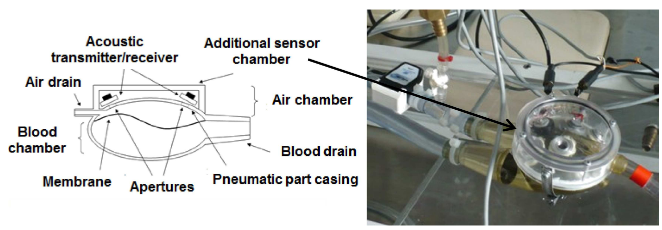

Fig. 9. The POLVAD prosthesis with an additional sensor chamber

The construction of the new sensing chamber required a new approach to the topic. During the testing of the new construction it occurred that adding additional holes between the air chamber and the sensor chamber improves the frequency versus the characteristics of the blood chamber volume. Also the electronic filter construction influenced the static characteristics (Fig. 10). Additional static tests and a final scaling were carried out.

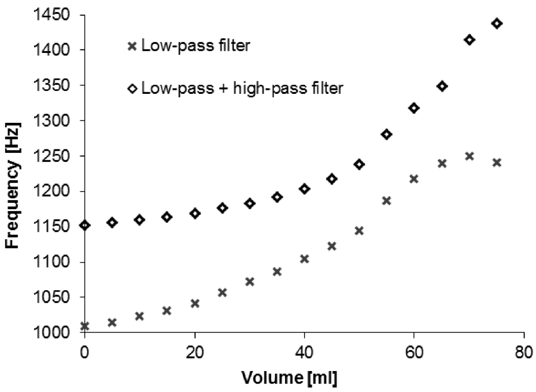

Fig. 10. Static characteristics of a new construction of the sensing system with and without the high-pass filter

It is to be seen that the relation between frequency and the blood chamber volume is different with and without the high-pass filter in the circuit. The frequency difference between the boundary volumes (0 and 80ml) is larger when the HP filter is used, but the frequency changes at lower volumes are unsatisfyingly small, increasing the measurement error of the volume. With the HP filter removed, the static characteristic is almost linear. The latter option was chosen.

The new construction covered the blood chamber volume range of 0–75 ml. In the 0–75 ml range the frequency rises with the blood volume, but in the last 5 ml a frequency drop can be noticed. In order to avoid ambiguous measurement results for > 75 ml blood volume, the acoustic signal amplitude is measured along with the frequency. It allows to discard the wrong signals that occur at a minimum air-chamber volume, where the Helmholtz resonance does not occur.

The new sensor model was subjected to dynamic tests at the Foundation for Cardiac Surgery Development in Zabrze making use of the hybrid human ventricular system model (Fig. 11). The hybrid human ventricular system model allows emulation of cardiovascular system conditions that may occur in the human body. The model allows extensive tests of the proposed blood volume measurement system. Exemplary results are shown in Fig. 12.

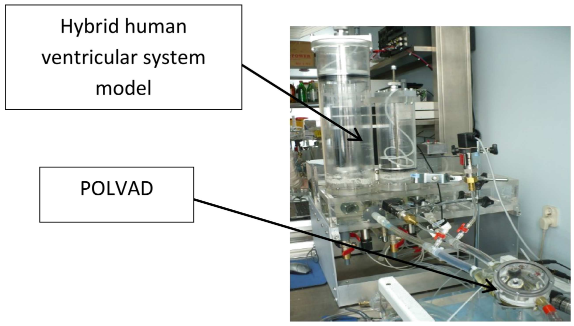

Fig. 11. Hybrid human ventricular system model for testing the POLVAD prosthesis

The measurement system was tested at different heart support speeds and different driving air pressures (SDP –systolic drive pressure [mmHg], DDP – diastolic drive pressure [mmHg], AHR – average heart rate). It made the POLVAD prosthesis work in different states – full rejection/partial filling (Fig. 12a), full filling/partial rejection (Fig. 12b) and step by step filling/rejection (Fig. 12c). It can be seen that the acoustic blood volume sensor provides real time results, providing not only information about the boundary blood volumes per a cycle, but also information about the work of the prosthesis – by analyzing the graph; problems concerning valves and blood flow can be determined. The sensor was successfully tested with driving speeds up to 180 cycles/minute. Additionally, in order to verify the results of the acoustic method, the pressures inside the air and the blood chamber of the POLVAD prosthesis were measured (Fig. 13). By analyzing Fig. 13, it can be seen that changes of the driving pressure make the membrane move, so that the liquid is being pumped.

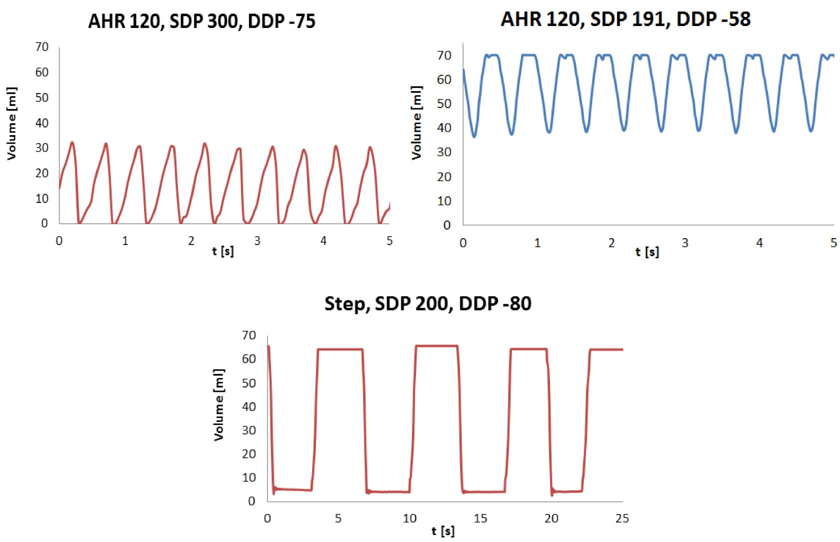

Fig. 12. Exemplary results of dynamics tests conducted at the Foundation for Cardiac Surgery Development in Zabrze

This proves that the blood volume measurement system provides results without any noticeable delay (the measured membrane movement occurs immediately after the driving air pressure has changed). The delay of measurements caused by estimating the frequency equals 10 ms. Figure 13 shows that at the beginning of the filling process is the moment, when the output valve is not completely closed, letting some of the liquid flow through (it can be noticed at the bottom Fig. 13).

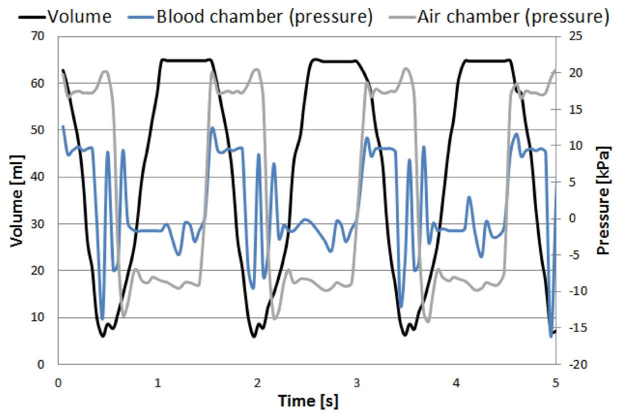

Fig. 13. The results of measurements of the acoustic sensor vs. the pressures inside the prosthesis

5. Conclusions

The presented acoustic blood measurement system provides a reliable solution to blood volume sensing. Both static and dynamic tests are shown. Research shows that the measuring device can work at all the possible driving speeds and pressures of the POLVAD prosthesis. All tests were conducted with the use of a blood-like solution (water with glycerin). The system measures the blood volume with a negligible delay. The noninvasiveness is ensured by measuring the air chamber volume, thus an additional separation from the blood environment is not necessary. The sensor requires individual calibration for each prosthesis. The results are encouraging and provide a firm foundation for a fully functioning prototype construction.

Acknowledgements. The work is financed by the Polish National Centre of Science NCN within the grant No06/WK/PO1/0001/SPB-PSS/2008.

REFERENCES

[1] H.M. Reu and A. Akdis, "Blood pumps for circulatory support", *Perfusion* 15, 295–311 (2000).

[2] M. Gawlikowski, T. Pustelny, and R. Kustosz, "The physical parameters estimation of physiologically worked heard prosthesis", *Journal de Physique* IV 137, 73–78 (2006).

[3] T. Pustelny, P. Struk, Z. Nawrót, and M. Gawlikowski, "Design and numerical analyses of the human greater circulatory system", *Eur. Physical J. Special Topics* 154 (1), 171–174 (2008).

[4] M. Gawlikowski, T. Pustelny, and R. Kustosz, "Selected problems of mechanical heart supporting automation", *Eur. Physical J. Special Topics* 154 (1), 65–69 (2008).

[5] M. Gawlikowski, T. Pustelny, R. Kustosz, and P. Struk, "The methods of physical parameters measurement regarding the heart supporting automation", *Eur. Physical J. Special Topics* 154 (1), 71–76 (2008).

[6] M. Gawlikowski, T. Pustelny, B. Przywara-Chowaniec, and P. Struk, "The anatomic structure of pulmonary arterie as a source of unreliability in thermodilution cardiac output measurement", *Acta Phys. Pol.* A 114 (6-A), 81–89 (2008).

[7] B. Przywara-Chowaniec, L. Polonski, M. Gawlikowski, and T. Pustelny, "Clinical studies of rheocardiography application to hemodynamic monitoring of patients with dilated cardiomyopathy", *Acta Phys. Pol.* A 116 (3), 380–382 (2009).

[8] M. Gawlikowski, T. Pustelny, B. Przywara-Chowaniec, and J. Nowak-Gawlikowska, "Model study of cardiac output measurement by thermodilution in thermal instability", *Acta Phys. Pol.* A 118 (6), 1124–1026 (2010).

[9] M. Gawlikowski, M. Darłak, T. Pustelny, and R. Kustosz, "Preliminary investigations regarding the possibility of acoustic resonant application for blood volume measurement in pneumatic ventricular assist device", *Molecular and Quantum Acoustics* 27, 89–96 (2006).

[10] M. Darlak, Z. Opilski, M. Gawlikowski, R. Kustosz, and T. Pustelny, "Acoustic method of noninvasive blood volume monitoring in POLVAD pump", *Artificial Organs* 31 (10), A50 (2007).

[11] G. Konieczny, Z. Opilski, T. Pustelny, and E. Maciak, "State of the work diagram of the artificial heart", *Acta Phys. Pol.* A 116 (3), 344–347 (2009).

[12] G. Konieczny, Z. Opilski, T. Pustelny, A. Gacek, P. Gibinski, and R. Kustosz, "Results of experiments with fiber pressure sensor applied in the polish artificial heart prosthesis", *Acta Phys. Pol.* A 118 (6), 1183–1185 (2010).

[13] G. Konieczny, Z. Opilski, T. Pustelny, and E. Maciak, "Measurement methods used in the artificial heart of the type POLVAD", *Electrical Review* R 86 (10), 53–56 (2010), (in Polish).

[14] *Foundation of Cardiac Surgery Development*, http://www.frk.pl/index/ (2010).

[15] N.C. Fernelius, "Helmholtz resonance effect in photoacoustic cells", *Appl. Opt.* 18, 1784–1787 (1979).

[16] T. Kaczorek, "Stability and stabilization of positive fractional linear systems by state-feedbacks", *Bull. Pol. Ac.: Tech.* 58 (4), 537–554 (2010).

[17] L. Klonowski, Z. Kulas, E. Beres-Pawlik, M. Rząca, R. Czarnecki, and Z. Grzebieniak, "Point investigation method for cancer changed tissues", *Acta Phys. Pol.* A 118 (6), 1174–1176 (2010).

[18] Z. Zaczkiewicz, "Representation of solutions for fractional differential-algebraic systems with delays", *Bull. Pol. Ac.: Tech.* 58 (4), 607–612 (2010).