

A Comparative Study of Hyperelastic Constitutive Models to Characterize the Behaviour of a Biopolymer Material for Diaphragm of Blood Pump Manufacturing

L. V. Belyaev¹, A. V. Zhdanov¹, A. B. Ivanchenko¹, A. V. Stepenkin¹, D. O. Kochetov¹

¹Department of the mechanical engineering, Vladimir State University, Gorky str. 87, Vladimir, 600000, Russia

Abstract. This article presents the results of the stress-strain state modelling of a blood pump diaphragm manufacturing from polyurethane ‘Vitur’ T-1413-85 for pulsatile type Ventricle Assist Device systems. Based on the analysis of the most distributed models of hyperelasticity, a model which most accurately describes the behaviour of the specified material has been determined ($R^2 = 0.9999$ between numerical simulation and experimental uniaxial tensile tests data). Experimental studies have been carried out to determine the displacement of the diaphragm with a thickness of 0.3 mm and 0.5mm under the influence of control pressure. A comparison of the modelling results of the blood pump diaphragm stress-strain state and the conducted experimental studies on the determination of displacements confirmed the adequacy of the chosen model ($R^2 = 0.96$ between numerical simulation and experiment) for both of the studied diaphragm thickness.

Introduction

According to statistical data, every year in Russia are born about 10000 children with congenital heart diseases. For every 1000 newborns, there are 10 children who need heart surgery [1]. The mortality rate for children on the waiting list under the age of 18 is several times higher than for other age groups, which is largely due to the lack of long-term mechanical circulatory support systems. The designing process of paediatric Ventricle Assist Device (VAD) is a more difficult task than directly reducing the existing systems which have a large volume of ejection [2]. A comparative analysis of statistical data about the use of paediatric pulsatile and non-pulsating type VAD systems showed that the negative effects began to appear precisely in pulsatile type VAD systems [3, 4] due to the fact that these systems were not designed for use in paediatrics, but older age groups VAD systems were adapted. Therefore, it is necessary to note the need for a separate development of the VAD system for each age group of patients.

One of the types of systems that are most often used for these purposes are pulsatile type paracorporeal VAD systems with a pneumatic drive [5, 6], which are designed for long-term use and should provide an estimated service life of at least five years or about 200 million cycles of the blood pump works; and contain a blood compartment and an air chamber separated by an elastic diaphragm, creating a pulsatile flow.

Thus, the main element of the blood pump, critically affecting the life of its work, is the diaphragm, which must not only support the above number of work cycles, but also has to provide the required hemodynamic characteristics of its work [7].



Currently, to determine the number of cycles of the blood pump, an approach based on the operation numerical modelling of these systems using virtual experimental stands can be used [4] to predict the performance of the VAD systems at the design stage.

However, for the successful application of this approach, it is necessary to use adequate mathematical models that describe the behaviour of a particular material used to manufacture the blood pump diaphragm.

To considerate the working conditions of the diaphragm special requirements for structural materials are required for their manufacture. They should have a high wearing capacity, the required damping, thermophysical, electrical and elastic properties [8], and a resistance to biological fluids; and provide biocompatibility, a good shape restoration after deformation and not lose them after sterilization [9]. Materials that most fully meet the specified requirements are thermoplastic polyurethanes, which have the indicated properties, the appropriate certificates and are technologically advanced to manufacture [10].

This article presents the results for determining the model of hyperelasticity for the correct mathematical description of the 'Vitur' grade polyurethane behaviour for the further virtual modelling of the blood pump diaphragm behaviour in order to predict the required service life for its work.

Materials and methods

The diaphragm of blood pump is made of polyurethane 'Vitur' T-1413-85 (LLC SPF 'VITUR') [11]. Uniaxial tensile tests were performed, according to the standard test methods (standard ISO 37:2011), on dog-bone specimens ($n = 10$) excised from the diaphragm. Experiments were carried out using a Lloyd tensile test machine (AMETEK TCI, Berwyn, PA) with a load cell of 5 N and a strain rate of 20 mm/min. Air was modelled as an ideal gas with a density of $1.29 \times 10^{-3} \text{ kg/m}^3$.

To obtain a constitutive model that can reproduce with the maximum possible accuracy the behaviour of the 'Vitur' T-1413-85 material, four classic hyperelastic models (and corresponding submodels) were analysed. It was Mooney–Rivlin (2 and 5 parameters) [12, 13], Neo–Hookean [14], Ogden ($N = 1$, $N = 2$) [15] and Yeoh (3 parameters) [16].

According to the well-known experimental loading curve, the constants in the strain potential energy were determined in the ANSYS program (ANSYS, Inc., USA) using the «Curve Fitting» procedure. To determine the quality of each of the models, the R^2 correlation coefficient was calculated. As a result of the models, a strain energy density curve and a stress–strain curve were obtained. This stress–strain curve will be compared with the actual material curve. The best hyperelastic model will be the one whose average values R^2 (strain energy density and stress) is closer to 1.

After determining the model of hyperelasticity, on the basis of the criterion discussed above, the stress–strain state of the blood pump diaphragm has been simulated on the basis of its 3D model. The diaphragm 3D-model is a cylindrical disk with an outer diameter of 80 mm, a working diameter of 50 mm and 0.5 mm and 0.3 mm of thickness. Due to the diaphragm geometric symmetry and the acting load, its $\frac{1}{4}$ part has been considered. The thickness of the diaphragm was represented by three layers of three-dimensional 8-node finite elements. The diaphragm finite element model contains 77 068 and 20 7884 nodes, 56 409 and 153 744 elements with a thickness equal to 0.5 mm and 0.3 mm, respectively. The boundary conditions corresponded to the membrane fixation conditions of during experimental studies and the selected calculation scheme. The load was set by a linearly increasing pressure for 3 seconds, from 0 to 1.1 atm (10 7873 Pa) spaced at intervals of 0.1 s.

To estimate the accuracy of the simulation results, a comparison of the calculated and experimental data has been carried out. The experimental data were obtained at the test bench, whose diagram is shown in figure 1. The diaphragm made from the 'Vitur' T-1413-85 material with a thickness of 0.5 mm and 0.3 mm is secured between the aluminium base and the clamp with six screws. On the one hand, a pressure gauge is connected to the aluminium base to control the pressure; on the other, the pressure regulator providing the air supply of the required pressure. To measure the displacements (h) of the membrane midpoint in the vertical plane, we used an electro-optical sensor with high sensitivity installed in the arm clamp, and the measurement results have been displayed on the monitor. Five experiments have been carried out for each aperture thickness.

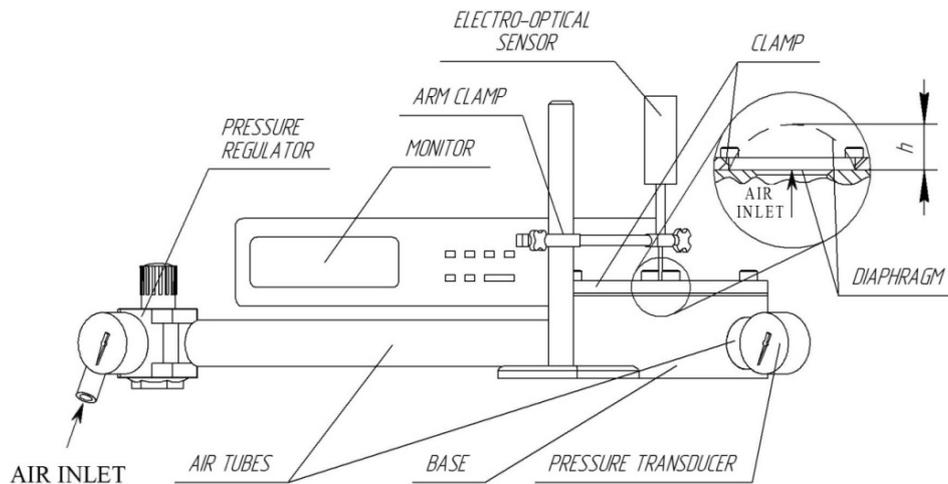


Figure 1. Schematic of experimental setup for diaphragm deformation assessment.

Results

In this section, the results obtained for each of the models (and submodels) are presented. The stress–strain curves and strain energy density function curves are shown in figure 2.

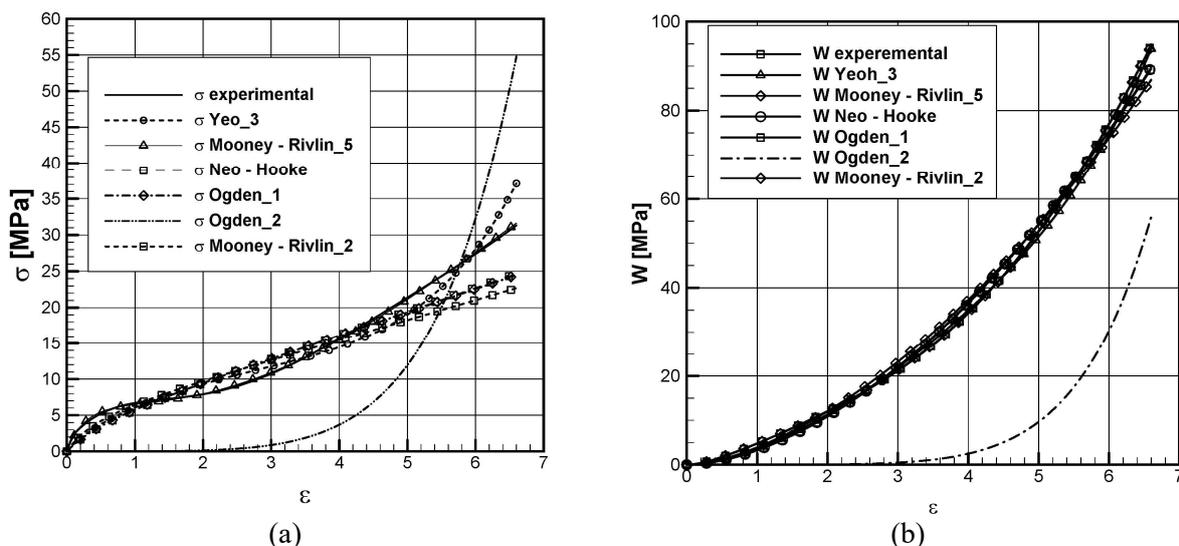


Figure 2. Comparison of experimental and computation data: Stress-strain (a) and Strain energy density - strain (b) plots.

The values of the material constants and R^2 coefficient are shown for each of the studied models in table 1.

The analysis of the data presented in table 1 shows that the behaviour of the material under study can be described by all the considered models of hyperelasticity, except for the Ogden model ($N = 2$), which has a coefficient value of $R^2 < 0,9$. However, the most accurate description is given using the five parametric model Mooney–Rivlin (average value $R^2 = 0.9999$) and it was used to simulate the stress-strain state of the blood pump diaphragm.

As a result of numerical and experimental research, the displacements of the central point of the diaphragm have been obtained (figure 3). The analysis of the graphs shows that the experimental values of the displacements have larger values than those obtained in the modelling process. The large displacements values of the experimental (14.88 mm) and those obtained in the modelling process

(12.6 mm) are characteristic of the smaller aperture thickness: 0.3 mm. The corresponding movements for an aperture thickness of 0.5 mm are: 12.05 mm and 10.09 mm, respectively.

Table 1. The values of the material constants and R^2 coefficient.

Model	Material parameter	Value	$R^2(\sigma)$	$R^2(W)$	Average [$R^2(\sigma);R^2(W)$]
Mooney–Rivlin 2 parameters	C_{10}	1 373 972.9308 Pa	0.9619	0.9967	0.9793
	C_{01}	926 605.6951 Pa			
	C_{01}	4 262 541.1172 Pa			
Mooney–Rivlin 5 parameters	C_{02}	-552 059.6224 Pa	0.9997	1.0000	0.9999
	C_{10}	-139 000.0739 Pa			
	C_{11}	277 624.5084 Pa			
	C_{20}	-17 835.0520 Pa			
Neo-Hookean	μ	3 260 238.7247 Pa	0.9683	0.9980	0.9832
Ogden N = 1	α_1	1.9837	0.9671	0.9979	0.9825
	μ_1	3 336 940.0532 Pa			
	α_1	7.4353			
Ogden N = 2	α_2	7.4372	0.8910	0.8964	0.8937
	μ_1	58.6609 Pa			
	μ_2	58.6610 Pa			
	α_2	7.4372			
Yeoh 3 parameters	C_{10}	1 800 959.9809 Pa	0.9809	0.9994	0.9902
	C_{20}	-16 902.1001 Pa			
	C_{30}	275.9376 Pa			

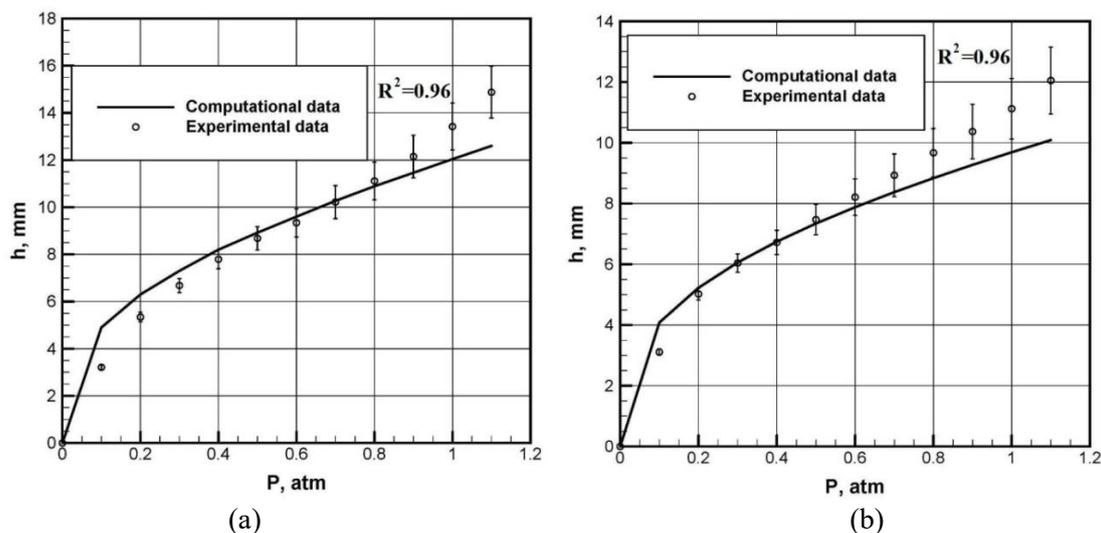


Figure 3. Comparison of experimental and computation data of diaphragm inflation with different thickness: 0.3 mm (a) and 0.5 mm (b).

Conclusions

The results showed that a better accuracy provides a description of the material behaviour using the five parametric Mooney–Rivlin model. A comparison of the modelling results of the blood pump diaphragm stress-strain state and the conducted experimental studies on the determination of displacements confirmed the adequacy of the chosen model ($R^2 = 0.96$ between numerical simulation and experiment) for both of the studied diaphragm thickness, which allows us to talk about its potential use for a further behaviour virtual modelling of the blood pump diaphragm made of the polyurethane brand ‘VITUR’ in order to predict the required resource for its performance.

Acknowledgments

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