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Dissertation Review

of Ph.D. Candidate, MSc Eng Marcin Nowak

Thesis Title:

Development of numerical model for modeling artificial heart valved for performing virtual therapies

The review has been done according to the letter of the Chairman of the Scientific Council of the Discipline Biomedical Engineering of the Silesian University of Technology, Prof. Marek Gzik, Eng, PhD, DSc. This Letter of June 2, 2022 , No. RDIB. 002.23.2022, contained information about the Decision of the Scientific Council of 19.05. 2022, about the appointment of me as a reviewer of the doctoral dissertation of MSc Eng. Marcin Nowak and it was delivered to me along with the documentation in question on June 6, 2022.

1. Subject of the review

Doctoral dissertation of Ph. D. Candidate: MSc Eng Marcin Nowak: **Development of numerical model for modeling artificial heart valved for performing virtual therapies,** was written in English (186 pgs) and contains the statutory abstracts in English and Polish. Supervisor of the PhD is: Wojciech Adamczyk, PhD, DSc, Assoc. Prof. Co-supervisor: Eduardo Divo, PhD, Prof.

2. Subject, purpose and scope of the work

Valvular heart disease affects over 100 million people worldwide and very often requires the implantation of artificial valves. No one artificial valve is so good as a healthy one, but researches intend to construct the better valve than the diseased one. For this reason, they are intensively studied numerically and experimentally in many research centers. Currently two types of valves are used for implantations: biological and mechanical ones. The mechanical valves of the heart become the most popular, due to its long service life and high efficiency. The greatest difficulty arises, in that there is no material which can truly mimic the inner wall of the circulatory system. This wall is covered with specialized cells – the endothelium. Each of them contains a flow sensor, which senses the shear stress of the flow. The cell orients itself to the flow, it gives a signal – nitric oxide – to the pletelets to calm down and not to adhere. This wondering mechanism is absent when artificial materials is used. The main disadvantage of using artificial valves to replace diseased heart valves is that patients may suffer from implant complications such as platellet aggregation and damage to the morphotic elements of blood. It is caused due to the interaction of the artificial valve leaflets with the blood in living conditions and they are related to the formation of eddies and stresses on the walls of the valve leaflets during heart beats. Such phenomena can lead to undesirable situations, including the destruction of the implant. For patients in an advanced stage, implantation of a prosthesis is the only solution, however, it can lead to numerous complications. Huge potential is seen in the development of an approach combining virtual reality with an advanced numerical model.

The rapid development of computational tools for modeling flows and development of experimental methods in fluid mechanics, and ultrasound systems in medicine brought new research possibilities. This allows for the creation of more accurate numerical models of blood flows by artificial organs in particular aortic valves. There are more and more attempts to use virtual reality, machine learning or artificial intelligence for more accurate prediction and diagnosis.

The subject of the presented dissertation lies in this research area and aims on numerical modeling blood flow throug artifical and anatomical valves. This applies in particular to research related to the development of numerical tools to study the effect of wall calcifications on the function of anatomical and artificial heart valves, previously not investigated in the literature. This requires the development and validation of numerical models enabling this study with the use of computational methods of fluid mechanics and Fluid/Structure interaction. In order to faithfully replicate reality in numerical flow simulations, the emphasis is on time efficiency and stability of algorithms leading to the obtaining of numerical models simulating the elastic / non-deformable valve operation under the influence of the dynamic interaction of blood.

The subject, purpose and scope of the work is very on-time and important both in terms of extending basic knowledge and applicability and lies in the field of biomedical engineering.

3. General evaluation

3.1. The evaluation of the editorial side of the dissertation

The dissertation was edited as a book and consists of 186 numbered pages of a compact text, arranged in 6 numbered chapters containing subsections and three appendixes. The work ends with a list of literature related to the topic of the dissertation (197 items). The actual text of the work is preceded by the Table of contents as well as a list of the Acronyms and Symbols used in the text. The paper contains the abstracts in English and Polish.

In the first part of the dissertation, covering the two initial chapters: INTRODUCTION and MATHEMATICAL MODEL, contains detailed introductory information (48 pages). The current state of knowledge was reviewed, motivations were given, and the purpose and scope of the doctoral dissertation were determined. The basic issues related to the modeling of aortic valve flow and indicators for the aortic valve performance are presented. The fluid mechanics of cardiovascular flow is complex due to the non-linear and non-hoogeneeous rheological properties of the blood and arterial wall, the complex geometry and the pulsatile flow properties and it was underlined in this part.

In the second part of the doctoral dissertation, covering three subsequent chapters: ARTIFICAL VALVE MODELING, EXTENSION OF THE FSI APPROACH FOR THE MECHANICAL VALVE WITH VALIDATION and MODELING ANATOMICAL AND ARTIFICIAL AORTIC VALVE STENOSIS (68 pages), the Author presents his own research results and information on their performance.

The obtained numerical results from performed simulations were presented and their very detailed analysis was carried out. This allowed for the formulation of conclusions presented in the chapter 6.: DISCUSION AND CONCLUSIONS (6 pages) and for setting directions for further research. The appendices present the algorithms for data extraction writen in Phyton source codes (A, B) and materials supplementing the methodology of numerical calculations used by Author moving mesh (C).

The writing of the entire manuscript is clear and perfect, the new methods are described in detail, the introduction and discussion are consistent and necessary, the drawings are very careful and illustrate the text well.

3.2. Specific comments

The thesis concerns research aimed at creating numerical models capable to simulate work of artificial and anatomical human heart valves for performing virtual therapies.

A comprehensive analysis of accurate, reliable, stable, and time-efficient calculations was carried out, which included the choice of an efficient computational strategy, the development of an internal model for modeling the fluid-structure interaction, and the appropriate time step size for the geometry, network, and solution. This is a key topic for the simulating of work of human artificial and anatomical valves.

The in- house model is constructed to accurately control the time step of the transient model for efficient and reliable use of the moving mesh modules.

The numerical models, including the bileaflet valve, were validated experimentaly using a dedicated LabView application. The experimental design is convincing and adequately carried out. New algorithms were developed to process data from a high-speed camera, to determine the angle of inclination of the lobes and the degree of valve opening. In addition to the measurements, the results of numerical calculations were validated by patient study data available in the literature, which included echocardiography, PIV, flow and pressure measurements, flap shape, and it was concluded that the developed models showed physiological values and were very well tolerated. measured on a special test bench

The influence of atherosclerotic plaque accumulation on the functioning of the anatomical and artificial valve was examined in detail. The effect of progressive calcification on valve performance has been studied for both the anatomical and the mechanical valve. It has been shown, inter alia, that calcification of the human aortic valve changes its kinematics more in the range of maximum opening than maximum closure, and that the gradient of transvalvular pressure increases as a result of valve calcification. The results can be considered a pioneering step towards understanding this proces.

In the numerical study the fluid /structure interaction was model used. The blood flow were descibed with the Navier-Stokes equations where the Windkessel model for the boundary condition was applied (created on the basis of an electrical analogy) and the Carreau model was used to decribe rheology of the blood. The k-epsilon model of blood flow turbulence was applied. To determine the valve structure deformation time variables solid mechanical equations were used. For non-deformable bodies, an own model was implemented to determine their movement due to fluid movement. A two-sided solid-fluid interaction model was used to model the anatomical valve using a new method of realizing a movable mesh. The novelty of the current research is focusing on the development of very accurate numerical methods and their validation so that the numerical simulation of valve operation best reflects reality.

The work of the artificial valve was analyzed with its virtual implantation into the real geometry of the patient's vessels. An own model was implemented to define the movement of the artificial valve. The study may open novel therapeutic windows in medicine for further research that include possible implantation interventions predictions on disased valve.

I consider the work to be very valuable both from a cognitive and utilitarian point of view.

The research problem is clearly defined and topical. Results are new and important. Conclusions and observations presented at the end of the dissertation are correct. My substantive evaluation of the work is very high.

4. Summary and general conclusions

I state that dissertation subject matter is innovative and up-to-date, the scope of the research conducted is very extensive and meets the statutory requirements for doctoral dissertations. It presents a solution to a very complex problem and presents original and valuable results in the field of biomechanical engineering. It relates well to the state of the art and brings new content to it, which indicates the research maturity of the PhD student.

The main goals of this thesis were ambituos, but have been achieved.

The results are original and makes a significant contribution to the knowledge of numerical modeling heart valves blood flows, both artificial and natural valves. Work in particular in the context of carried out numerical simulation sheds new light on the effect valvular and aortic calcification. Moreover indicates on potential of using Virtual Reality in predicting walve implantations. The author showed also have a good knowledge of measurement methods, he designed a stand for testing the flow through the valve. This is undoubtedly an achievement of great value practical. The manuscript represents an interesting advancement in the field of biomedical egineering. My overall grade for the dissertation is very high.

I believe that in connection with the achievements indicated above, this doctoral dissertation should be awarded and I apply to the High Discipline Council of Biomedical Engineering of the Silesian University of Technology for its distinction.

5. Final evaluation statement

In the dissertation thesis **Development of numerical model for modeling artificial heart valved for performing virtual therapies** very interesting results were obtained in the framework of a consistent numerical study. I realy appreciate the candidate expertise in the field of CFD and biomedical engineering. The research is described of the international standard. The thesis fulfill all criteria for a PhD Dissertation set out in the Article 187 of the Act of July 20, 2018 – Journal Laws of the Republic of Poland (Dziennik Ustaw of 2020, item 85, as amended) and I propose to admit it for public oral defense.