Thickness Effect on the Structural Durability of a Bileaflet Mechanical Heart Valve

Young-Joo Kwon#

Department of Mechano-Informatics & Design Engineering, Hongik University, Choongnam, South Korea

ABSTRACT

This paper discusses about the thickness effects on the structural durability of a bileaflet mechanical heart valve (MHV). In the study on the design and the mechanical characteristics of a bileaflet mechanical heart valve, the fluid mechanics analysis on the blood flow passing through leaflets, the kinetodynamics analysis on the rigid body motion of the leaflet induced by the pulsatile blood flow, and the structural mechanics analysis for the deformed leaflet are required sequentially and simultaneously. Fluid forces computed in the fluid mechanics analysis on the blood flow are used in the kinetodynamics analysis for the leaflet motion. Thereafter, the structural mechanics analysis for the deformed leaflet follows to predict the structural strength variation of the leaflet as the leaflet thickness changes. Analysis results show that structural deformations and stresses increase as the fluid pressure increases and the leaflet thickness decreases. Analysis results also show that the leaflet becomes structurally weaker and weaker as the leaflet becomes thinner and thinner.

Key Words : Bileaflet Mechanical Heart Valve, Fluid Mechanics Analysis, Blood Flow, Kinetoynamics Analysis, Structural Strength, Structural Mechanics Analysis

1. Introduction

This paper addresses the structural analysis required in the structural design of a bileaflet mechanical heart valve. Especially, this paper discusses the thickness effects on the structural strength of a bileaflet mechanical heart valve. Structural optimization techniques, which have evolved integrating engineering design methodologies and computer aided engineering systems and have been applied to save the weight of structures in the fields of mechanical engineering, aeronautical engineering and civil engineering etc., used one numerical expression which defined the objective function, constraint function and design variables together with analysis softwares. However, multidisciplinary analysis and design tec hniques which may integrate design conditions conflicting with each other and manage simultaneously various engineering principles like structural mechanics, fluid dynamics, kinetodynamics, heat transfer and electromagnetics etc., are required to develop products. Multidisciplinary design optimization methodology is an emerging new technology to solve such a complicate structural analysis and design problem with a large number of design variables and constraints (J., Sobieszczanski-Sobieski[1]). Multidisciplinary design optimization methodology is a design automation tool which considers simultaneously various engineering principles and optimizes the structural design. In the classical structural design methodology which separates the complicate structural design problem and treats each separated unit problem, it is very hard to evaluate meanings of optimum design results, because most structural design variables are related to a large number

Manuscript received: August 27, 2002 ;
Accepted: April 30, 2003
Corresponding Author:
Email: yjkwon@wow.hongik.ac.kr
Tel: +82-41-860-2484

of engineering phenomena. And also, all design variables sometimes converge to certain values before they reach optimum design values. Perhaps the first analytical work in structural optimization was done by Maxwell[2] in 1869, followed by the better-known work of Michell[3] in 1904. These works provided theoretical lower bounds on the weight of trusses, and, although highly idealized, offered considerable insight into the structural optimization problem and the design process. Large scale engineering design problems are often characterized by multidisciplinary interactions in which participating disciplines are intrinsically linked to another. Recent interest in the problems associated with multidisciplinary design optimization is evidenced by an increased number of conferences, journals, and publications devoted to the subject. Numerous papers have been published recently which deal specifically with multidisciplinary design optimization applications in such diverse areas as naval structural design, spacecraft design, automobile design, and aircraft design, etc. The intuitive practice of breaking a large task into smaller, more manageable tasks was applied by Sobieszczanski -Sobieski[1]. Two review papers in the field of multidisciplinary synthesis are particularly noteworthy. The requirements and opportun- ities available in multidisciplinary analysis and synthesis applications are reviewed by Tolson[4] (1985). The potentials and achievements of multidisciplinary design optimization are reviewed by Sobieszczanski-Sobieski[5] (1996). Complexities of the geometry models are increasing ; in today's preliminary design environment, it is not unusual for a computer aided design (CAD) model to use over 20,000 curves and surfaces to represent an aircraft. This level of complexity underlines the importance of automation, which enforces the use of computer aided engineering systems like CAD, CAE, Mesh Generator and Solid Modeller, etc. in multidisciplinary design optimization methodology application.

When the aortic valve in a human body is in malfunction, a mechanical heart valve (MHV) can be installed. Downstream of the MHV, elastic artery wall with sinus is located. In blood flow[6-10] passing through the leaflets of a mechanical heart valve and elastic artery, hemolysis and platelet activation causing thrombus formation[11-12] can be seen owing to the shear stress in the blood. Also, fracture and deformation of the leaflets can occur depending on the shape and material properties of the MHV. Therefore, a comprehensive study is needed on the motion of leaflets associated with the blood flow and on the hemodynamics associated with the behaviour of leaflets and elastic artery wall in terms of fluid-solid interaction problem for the design of the MHV. In the present study, the characteristics of the behavior of leaflets in conjunction with the blood flow is to be investigated in the light of structural analysis. Here, a numerical analysis of deformation and stress in the leaflet is to be carried out in association with reaction force at the hinge, leading to the establishment of design optimization for a MHV. Intrinsically, the design problem of a bileaflet mechanical heart valve is characterized by multidisciplinary interactions in which fluid mechanics, kinetodynamics, and structural mechanics are linked to another. The interdependency of these discipline analysis modules in such application contributes to difficulties in successfully implementing a holistic design synthesis strategy to require the multidisciplinary design optimization methodology. Furthermore, such integrated implementation is also subject to complexities introduced as a result of an increased number of design variables and constraints. Hence, the computer aided engineering systems like CAD, CAE, Mesh Generator, and Solid Modeller etc. should be used for the structural analysis.

Recently, the multidisciplinary design optimization methodology using computer aided engineering systems, is efficiently applied to solve a complicate large scale structural design problem (Giesing, Agrawal, and Bharadvaj[13]; Charmis[14]; Rowell, Braun, Olds, and Unal[15]; Jameson[16]). Consequently, computer aided engineering systems are used in the present study. They are CFD-ACE for fluid mechanics analysis of blood flow, ADAMS for kinetodynamics analysis of the leaflet motion, and NISA for the structural mechanics analysis of deformed leaflets.

2. Blood fluid force applied on the leaflet of a bileaflet MHV

In this section the fluid mechanics analysis results of the blood flow passing through the leaflet of a bileaflet mechanical heart valve are presented to calculate the fluid force applied on the leaflet surface.

The mechanical heart valve used for the analysis is the St. Jude Medical bileaflet mechanical heart valve(see Fig. 1). The diameter of the mechanical heart valve is

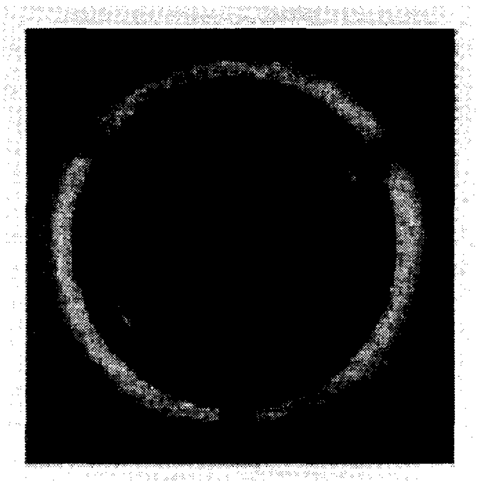


Fig. 1 Model of a bileaflet mechanical heart valve used in the analysis

22.5 mm and the thickness of the leaflet is 0.65 mm. The maximum opening angle of the valve is 85° and the closing angle of the valve is 25° . The material of the valve is pyrolytic carbon over graphite substrate for housing and leaflets. The leaflets are flat and impregnated with tungsten for radio-opacity. The two semicircular leaflets open to 85° , resulting in a central, near laminar flow. Leaflets are orifice oriented and closing forces are supported by the pivot system. The pivot guards are raised above the housing, and leaflet motion is performed by rotation. Relatively high velocity blood jets and approximately 10-15 percent regurgitant flow wash the pivot recesses. The St. Jude Medical bileaflet heart valve has been designed to rotate within the housing and to radio-opacify the annular rotating mechanism.

Downstream of the mechanical heart valve, an elastic artery wall with sinus is located. The artery wall is assumed to be a circular tube with 25.0 mm diameter. The blood flow is assumed to be an incompressible steady pulsatile laminar two-dimensional flow. The fluid dynamics analysis for the blood flow is performed using the computational fluid mechanics analysis code, CFD-ACE. The geometry of the mechanical heart valve and the artery wall used in this calculation is shown in Fig. 2. Also the coordinate system used in the analysis is shown in Fig. 2. Fluid forces and other constraint conditions needed in the kinetodynamics analysis and the structural mechanics analysis stages are computed through the present fluid mechanics analysis.

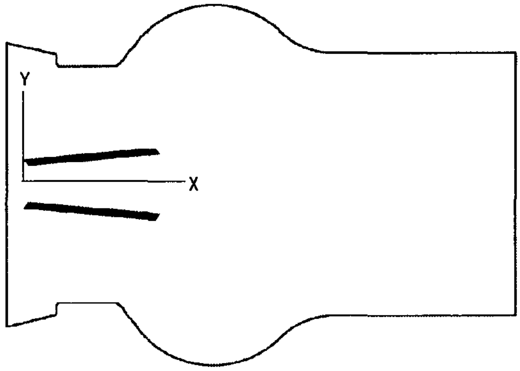


Fig. 2 Geometry of the mechanical heart valve and the artery wall, and coordinate system used for the analysis

2.1 Blodd material properties and boundary conditions for blood flow

The replaced mechanical heart valve is opened periodically by the pulsatile blood flow generated by the heart beating. The density of blood is assumed to be 1,000 kg/m^3, and the viscosity coefficient is assumed to be 4.0×10^{-6} m^2/sec. The pressure profile measured for each time through in vitro experiment is used as the boundary condition in the ventricle and the aortic valve. The number of heart beating is 75 beats/min. The blood velocity on the aortic valve wall is zero. The blood velocity on the interface between the valve and the blood is as same as the valve velocity. The valve movement is divided into four stages, i.e., the opening stage, the completely opened stage, the closing stage and the completely closed stage. In this research, three valve movement stages, i.e., the opening stage, the completely opened stage and the closing stage are studied.

2.2 Hemodynamic analysis results and discussions

As the heart ventricle shrinks, the valve starts to open and the opening angle of the valve becomes the maximum value of 85° when the time reaches t=0.056 seconds. The maximum opening angle of 85° is maintained between t=0.0565 seconds and t=0.145 seconds. The closing stage of valve starts from t=0.145 seconds. After t=2 seconds the valve closes rapidly. The valve movement in the closing stage is faster as twice as that in the opening stage. Time variation of the Y direction force applied on the top surface of the leaflet of a

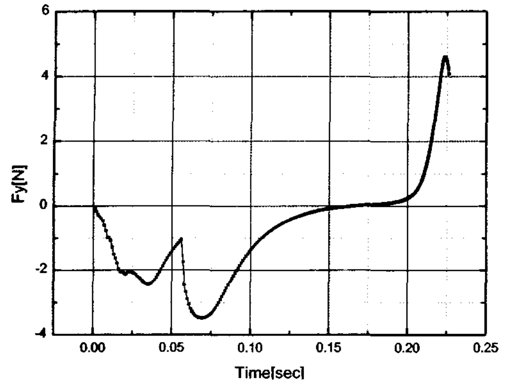


Fig. 3 Transient variation in the Y direction force

mechanical heart valve is shown in Fig. 3. The force is negative during opening and opened stages of valve movement. After the time reaches t=0.144 seconds, the force increases into positive value and the valve starts to close. Forces and moments computed in this section are used as the constraint condition in the next kinetodynamics analysis and the structural mechanics analysis.

3. Kinetodynamics analysis of the leaflet motion

In this section, the velocity and acceleration of the leaflet of St. Jude Medical bileaflet mechanical heart valve are computed, and also reaction forces at joints are computed to understand the dynamic characteristics of the bileaflet MHV. The kinetodynamics analysis for the leaflet motion of a bileaflet MHV is executed using ADAMS.

3.1 Kinematic model of the leaflet

The mechanical heart valve consists of three parts, i.e., the leaflet which controls the blood flow, the orifice ring which supports the leaflets and the sewing cuff which attaches and fixes the orifice ring to the tissue of the heart muscle. The kinetodynamics analysis for the leaflet motion of a mechanical heart valve is performed under the condition that the opening angle of the valve is between 25° and 85° to get the reaction force at each joint. The kinematic model of the mechanical heart valve consists of three links and four joints. And the mobility of the valve movement is two. The kinematic diagram of the leaflet is shown in Fig. 4.

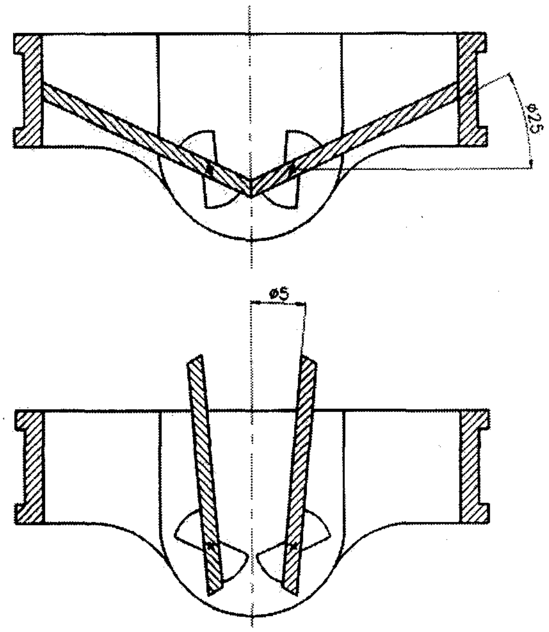


Fig. 4 Kinematic diagram of St. Jude Medical bileaflet mechanical heart valve

3.2 Kinematic analysis results and discussions

Velocity and acceleration of the leaflet, and reaction forces at joints should be computed to understand the dynamic characteristics of the mechanical heart valve. For this purpose, the kinematics analysis for the mechanical heart valve movement induced by the fluid force of the blood flow should be executed. Fluid forces computed in the previous section 2 are applied and the kinetodynamics analysis follows under the opening angle and closing angle. The velocity and the acceleration of the leaflet tip are zero between t=0.056 seconds and t=0.145 seconds. And velocity and acceleration of the leaflet tip change rapidly after t=0.2 seconds when the valve starts to close rapidly. The reaction force during 0.056 seconds between the beginning opening angle 25° and the maximum opening angle 85° changes very roughly. The reaction force at the joint increases rapidly after t=0.2 seconds when the valve starts to close. The structural deformation at the leaflet is expected at the closing position of the valve where the maximum reaction force occurs at the joint. These constraint conditions may be used for the structural mechanics analysis of the mechanical heart valve in the next section.

4. Structural stress analysis for the deformed leaflet

The position of the leaflet and the fluid force applied on the leaflet at the position where the structural deformation of the leaflet is expected to occur should be known in order to execute the structural mechanics analysis of the leaflet. In this section, the interactive relations between the result of fluid mechanics analysis and of kinetodynamics analysis executed in the previous sections are considered.

The position of the leaflet where the blood fluid force applied on the leaflet becomes maximum was computed to be the closing angle of the leaflet through the previous fluid mechanics analysis and the kinetodynamics analysis. Hence, the structural mechanics analysis of the leaflet is carried out at the closing angle of the leaflet according to the leaflet thickness variation to get the thickness effects on the structural strength of the leaflet. NISA, a commercial finite element code, is used for the structural mechanics analysis.

4.1 Structural model and boundary conditions

The finite element model for the structural mechanics analysis of the leaflet is shown in Fig. 5. The half of the leaflet is modelled due to the symmetric geometry of the leaflet. The model consists of the eight node hexahedron elements. Finer finite element meshes will give more accurate analysis results. Hence, eight elements along the leaflet thickness are used in the analysis model. The orifice ring is neglected in the analysis, because it does not affect the analysis results. The orifice ring is assumed as a rigid body. Three degrees of freedom (u_x,u_y,u_z) are constrained at the hinge point and on the outer surface of the leaflet which contacts the rigid orifice ring. The symmetric boundary condition (u_z=0) is applied on the symmetric surface (z=0) of the half model. Also the symmetric boundary condition (u_y=0) is applied on the symmetric surface (y=0), since both two leaflets contact on this symmetric surface. The fluid force which is the external force applied on the leaflet is exerted as normal uniform pressure onto the leaflet surface. The material of the leaflet is assumed to be Si-Alloyed PyC. The total number of elements and the total number of nodes generated in the model are 72,446 and 81,526, respectively. The Young's modulus, the Poisson's ratio and the density of the material used are 30.5GPa, 0.3 and 2,116Kg/m^3, respectively.

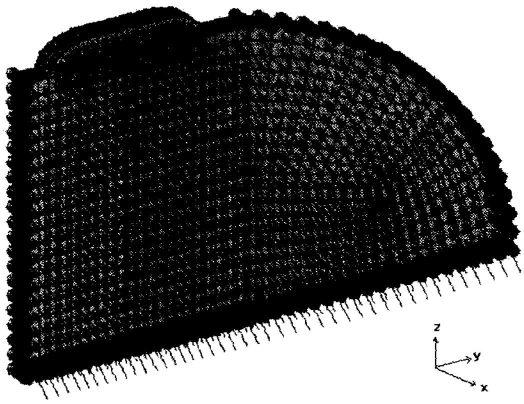


Fig. 5 F.E. model and constraint conditions for the leaflet (half model, thickness = 0.65 mm)

4.2 Structural stress analysis results and discussions

The structural deformation and stress distribution results which are obtained from the structural mechanics analysis of the leaflet are shown in Fig. 6 and Fig. 7. The maximum deformation occurs at the lower central part of the leaflet and the maximum stress occurs at the upper central part of the symmetric plane (y=0) of the leaflet. And a large stress also occurs at the hinge and the lower part of the leaflet end surface. Figure 8 indicates relationships between the maximum deformation and the maximum stress as the leaflet thickness increases from the 0.5 mm to 0.75 mm.

As indicated in the figure, the maximum stress are smaller than the yield stress 407.7 MPa of the material. Hence, the leaflet is structurally safe, but the internal stress and deformation values increase as the leaflet thickness decreases. Therefore, the structural strength of the leaflet decreases as the leaflet thickness decreases. According to figure 8, as the pressure increases, the stress and the deformation also increases for all leaflet thicknesses. However, the stress and deformation becomes much larger and larger as the pressure increases when the thickness becomes smaller and smaller. This phenomenon suggests that the leaflet structure becomes unstable and unsafe when the leaflet becomes thinner and thinner.

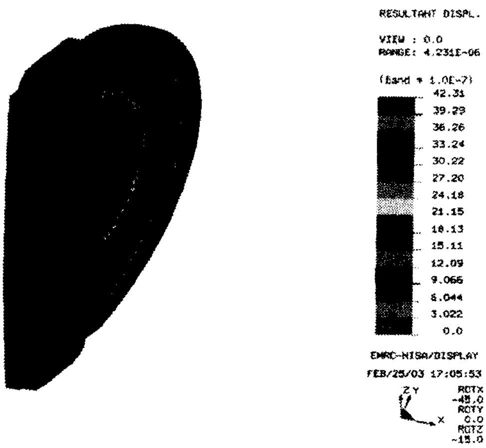
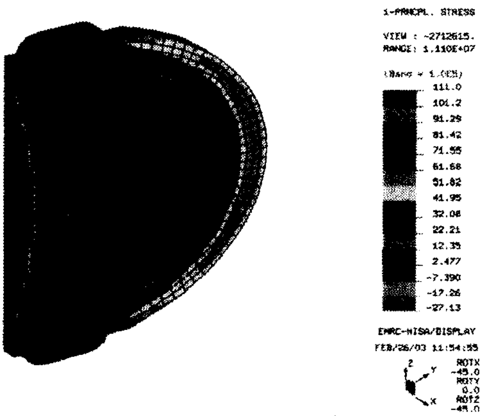
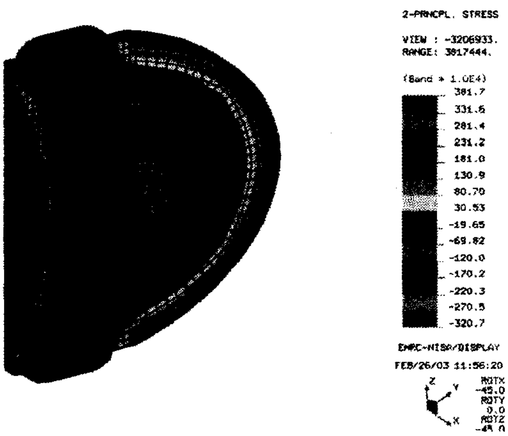


Fig. 6 Resultant displacement and deformed shape of the leaflet (thickness = 0.65 mm)

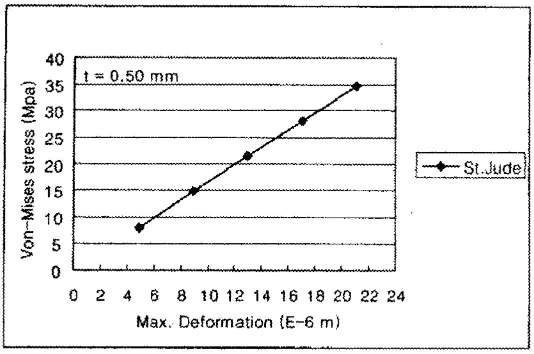


(a) first principal stress

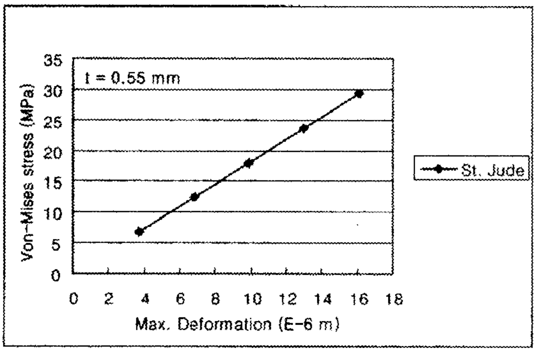


(b) second principal stress

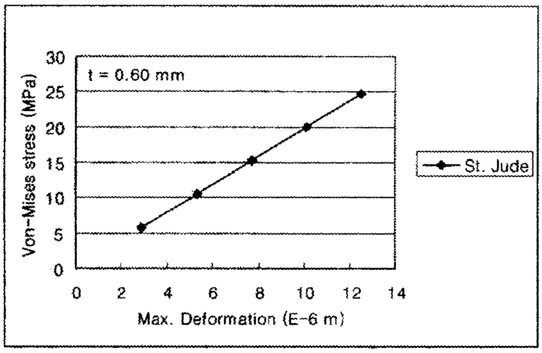
Fig. 7 Stress distribution in the leaflet (thickness = 0.65 mm)



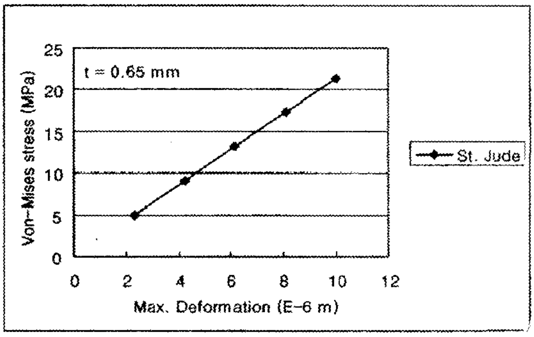
(a) thickness = 0.50 mm



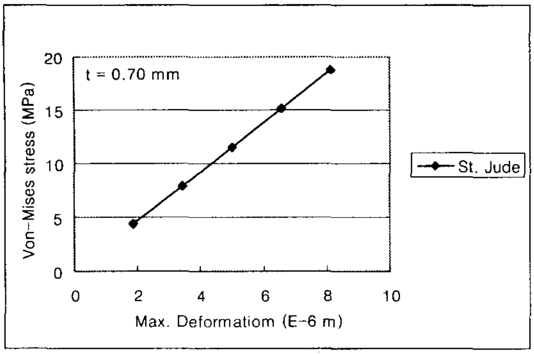
(b) thickness = 0.55 mm



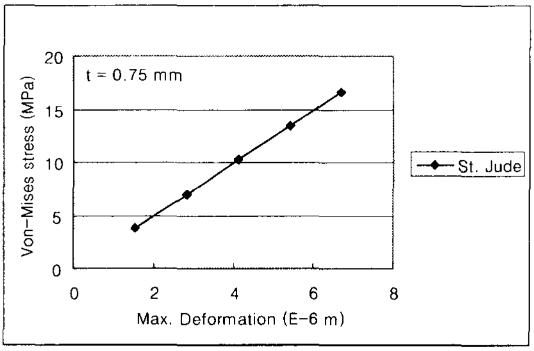
(c) thickness = 0.60 mm



(d) thickness = 0.65 mm



(e) thickness = 0.70 mm



(f) thickness= 0.75 mm

Fig. 8 Relationships between the von Mises stress and the maximum displacement in the leaflet of the St. Jude Medical mechanical heart valve according to the leaflet thickness change (t=leaflet thickness)

5. Conclusions

In this paper the structural analysis required in the design of a bileaflet mechanical heart valve is executed. The structural analysis requires the complicate several analyses like the fluid mechanics analysis, the kineto-dynamics analysis, and the structural mechanics analysis. The blood fluid pressure forces which are calculated using the fluid mechanics analysis of the blood flow passing through the leaflet of a bileaflet mechanical heart valve are used as the external load constraint for the kineto-dynamics analysis of the leaflet motion of a bileaflet mechanical heart valve to get the reaction force at the hinge of leaflet. The angular position of the leaflet where the reaction force at the hinge is maximum is identified through the kinetodynamics analysis. The closing angle of the leaflet is identified as the right time when the reaction force becomes maximum. Hence, the leaflet in the closing angle 25° is used for the structural mechanics analysis to get deformation and stress which occur in the leaflet on which the blood fluid force is applying. The structural mechanics analysis is performed as the leaflet thickness increases from 0.5 mm to 0.75 mm. The analysis result shows that the leaflet becomes structurally weaker as the thickness decreases.

References

1. Sobieszczanski-Sobieski, J., "Multidisciplinary Design Optimization : An Emerging New Engineering Dis-cipline," Advances in Structural Optimization, edited by J. Herskovitz, Kluwer, Dordrecht, The Netherlands, pp. 483-496, 1995.
2. Maxwell, C., Scientific Papers, Dover Publications, pp. 175-177, 1952.
3. Michell, A. G. M., "The Limits of Economy of Material in Frame Structures," Philosophical Magazine, Series 6, Vol. 8, No. 47, pp. 589-597, 1904.
4. Tolson, R. H. and Sobieszczanski-Sobieski, J., "Multidisciplinary Analysis and Synthesis : Needs and Opportunities," AIAA Paper No. 85-0584, pp. 275-292, 1985.
5. Sobieszczanski-Sobieski, J. and Hafta, R., "Multidisciplinary Aerospace Design Optimization : Survey of Recent Developments," AIAA Papers 96-0711, pp. 235-247, Jan. 1996.
6. Yoganathan, A. P., Corcoran, W. H. and Harrison, E. C., "In Vitro Velocity Measurements in the Vicinity of Aortic Prostheses," J. Biomechanics, Vol. 12, pp. 135-152., 1979.
7. Chandran, K. M., Khalighi, B. and Chen, C. J., "Experimental Study of Physiological Pulsatile Flow Past Valve Prostheses in a Model of Human Aorta-II. Tilting Disc Valves and the Effects of Orientation," J. Biomechanics, Vol. 18, No. 10, pp. 773-778, 1985.
8. Farahifar, D., Cassot, F. and Bodard, H., "Velocity Profiles in the Weak of Two Prosthetic Heart Valves Using a New Cardiovascular Simulator," J. Biomechanics, Vol. 18, No. 10, pp. 789-802, 1985.
9. Gross, J. M., Shermer, C. D. and Hwang, N. H. C., "Vortex Shedding in Bileaflet Heart Valve Prostheses," Trans. Am. Soc. Artif. Intern. Organs, Vol. 34, pp. 845-860, 1988.

10. Fatermi, R. S. and Chandran, K. B., "An in Vitro Study of the St. Jude Medical and Edwards Duromedics Bileaflet Valve Using Laser Anemometry," J. Biomech. Eng., Vol. 111, pp. 298-302, 1989.
11. Yoganathan, A. P., Corcoran, W. H., Harrison, E. C. and Cari, J. R., "The Bjork-Shiley aortic prosthesis : Flow characteristics, thrombus formation and tissue over-growth," Circulation, Vol. 58, pp. 70-76, 1978.
12. Pantalos, G. M., Everrett, S. D., Mohammad, S. F. Burns, G. L., Solen, K. A., Reynolds, L. O. and Olsen, D. B., "Quantification of perivalvular thrombus formation in blood pumps by coordinate mapping," Artificial Organs, Vol. 14, No. 5, pp. 348-354, 1990.
13. Giesing, J. P., Agrawal, S. and Bharadvaj, B. K., "The Role of Computational Fluid Dynamics in Multidisciplinary Design Optimization of Transport Aircraft," Proceedings of the 6th International Symposium on Computational Fluid Dynamics, Technology and Operations Congress (Lake Tahoe, CA), 1995.
14. Charmis, C. C., "Coupled Multidisciplinary Optimization of Engine Structural Performance," Journal of Aircraft, Vol. 36, No. 1, pp. 190-199, 1999.
15. Rowell, L. F., Braun, R. D., Olds, J. R. and Unal, R., "Multidisciplinary Conceptual Design Optimization of Space Transportation Systems," Journal of Aircraft, Vol. 36, No. 1, pp. 218-226, 1999.
16. Jameson, A., "Re-Engineering the Design Process Through Computation," Journal of Aircraft, Vol. 36, No. 1, pp. 36-50, 1999.