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USING FLUID STRUCTURE INTERACTION TECHNIQUE TO INVESTIGATE THE EFFECT OF VIBRATION ON BILEAFLET MECHANICAL HEART VALVE DEFORMATION

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ABSTRACT

Fluid-Structure Intraction computer simulation technique is used to study effect of vibration due to blood flow on bileaflet mechanical heart valves structure including the deflection connection in the pin of the valve. This technique is used is to predict the deformation of the bileaflet mechanical heart valve structure, which occurs due to the heart beats. Five heartbeat models were used in this study which is 80, 90, 100, 110, and 120 BPM at variable leaflet angles of 25°, 63° and 85°. To determine the deformation, the equivalent (von-Mises) stress at the connection pin of a bileaflet mechanical heart valve were calculated and compared with the equivalent (von-Mises) stress of the connection pin in the literature. It was found when the heartbeat increased from 80 BPM to 120 BPM, 62 % increase in von-Mises stress values were recorded at the valve connection pin at a fully closed angle of 25°. The increase in heartbeat periodically for the lifetime may weaken the valve's connecting pin and housing, which may cause damage to the bileaflet mechanical heart valve components.

Keywords: fluid structure interaction, stress analysis, bileaflet heart valve, vibration.

INTRODUCTION

A total of 95% of patients using artificial heart valves has been found to exhibit failure in the aortic valve and thus required aortic valve replacement [1]. For bileaflet mechanical heart valve (BMHV), one of the reasons for this failure is the effect of blood flow within the arteries and the subsequent force of the pulsed blood flow, such as blood pressure acting on the arterial walls, generating flow-induced vibration [2]. The blood flow and arterial structure are interactive systems, and their interaction is dynamic. These systems are coupled with the forces exerted on the structure by the blood flow which may deform the heart valve components. As the structure deforms, it changes its orientation, thereby affecting the blood flow characteristics [3]. Danger occurs when the maximum stresses of the connection pin in the BMHV became higher than the allowable stress which may causes damage to valve component. The present study investigates the effects of forced vibration caused by fully developed laminar blood flow to determine all deformations (von-Mises stress and deflection) in the connection pin of the BMHV. The blood flow rate was taken as 9.88 m^3/min [4]. ANSYS software was used to perform the simulation and calculate the von-Mises stress and deflection.

MODELING OF ARTERY WITH BMHV

In this study, Fluid-Structure Interaction (FSI) model using the computational fluid dynamic FLUENT (CFD) coupled with Static Structural was employed. CFD FLUENT and Static Structural software were applied to the 3-D model of the artery with BMHV. The bileaflet valve ring and leaflets from are made of pyrolytic carbon and valve housing is made of titanium. Table-1 lists the properties used in the simulation and included in the model [5].

The induced vibrations that occurred at angles of 25°, 63° and angle 85° were investigated. For patients with BMHV implanted in their heart, the physiological pressure is 120 mm Hg with blood flow rate of 9.88 m^3/min. at variable heartbeat of 80, 90, 100, 110 and 120 BPM. .

Table-1. Material properties [5].

Mechanical properties	Density (Kg/m^3)	Young's Modulus (MPa)	Poisson's ratio
Blood	1060	-	0.2
Artery wall	1060	20	0.45
Valve housing	4500	120×10^3	0.33
Leaflet material properties	2116	30.5×10^3	0.3

MODEL DEVELOPMENT AND BOUNDARY CONDITIONS

The boundary conditions used in this study are no slip conditions with zero velocity existed at the wall boundary, steady - state simulation, flexible support at two ends of the artery were used in the FSI model and blood temperature was 37 °C. The number of elements used in the CFD and Static Structure models are shown in Figure - 1 and listed in Table-2. The cell skewness was 0.72, which was considered acceptable. Given that FSI techniques are used to model the blood flow and study the subsequent vibration generated in the arteries in the presence of a BMHV, such techniques can model the fundamental interaction between the blood flow and the arteries

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connected to the BMHV [5]. In this model, FLUENT (CFD) was first used, and the blood flow rate became an input in the boundary conditions [5]. To account for the generated force caused by heart pulsation, a force was exerted on the model at the artery; this force represents the generated force caused by heart pulsation. The value of the exerted force (F_o) was 0.1 N which was recommended by Mazumdar [7] (Figure-1). From the CFD simulation, the vibration, von-Mises stresses on the BMHV components, including the connection pins, valve housing, and leaflet deformation were all obtained. To investigate the effect of vibration on the blood flow profile, the heartbeat was varied in the CFD model at values of 80, 90, 100, 110, and 120 BPM to obtain the blood velocity vector in the arteries. As mentioned, the CFD modelled was coupled with the Static Structure model to study the effect of varying the heart beats on the valve structure. Considering that vibration occurs because of heart pulsation, the arterial wall velocity will not be equal to zero because of the effect of harmonic force as shown in equation (1)

$$F = F_o . \sin(\omega t) \tag{1}$$

Thus, the harmonic force will cause vibration to the arterial wall.

$$\omega = 2\pi \times HB \tag{2}$$

Where: ω = angular velocity (rad/s) due to pulsation, and HB = heart beat (BPM)

Figure -2, shows the flexibly supported artery conveying blood flow and location of the harmonic forced vibration at different heartbeat.

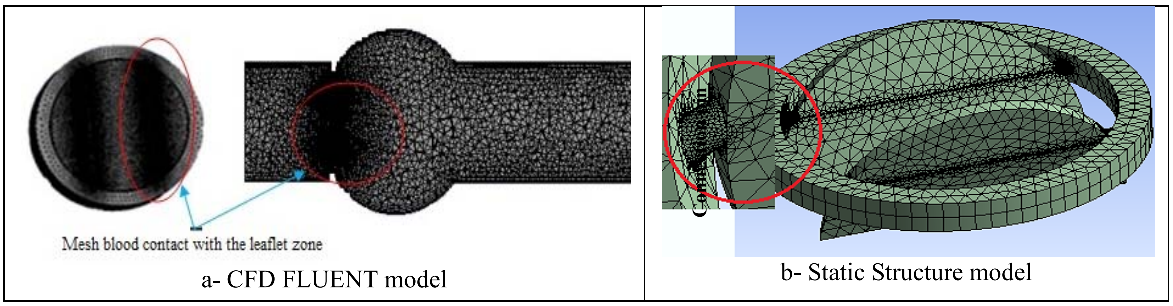


Figure -1. Meshed geometry.

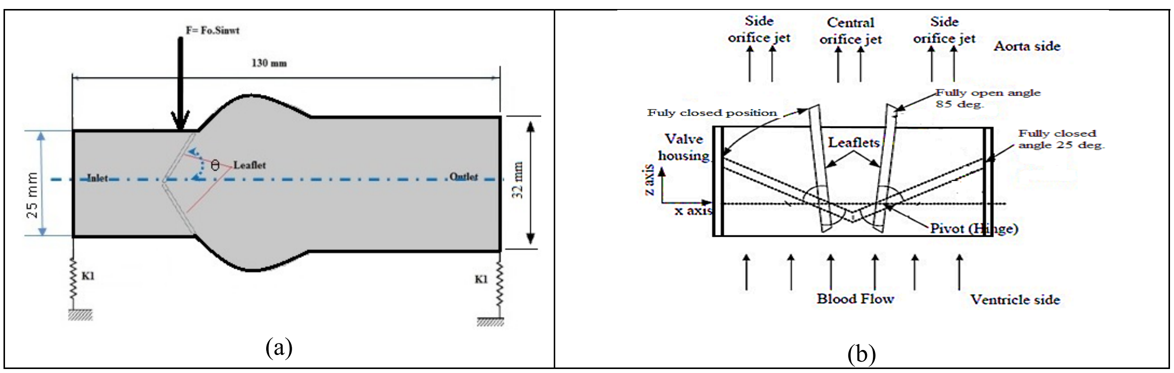


Figure-2. Model of BMHV: (a) location of the harmonic forced vibration and flexibly support (b) kinematics of the BMHV.

Table-2. Finite volume and finite element model data for the BMHV.

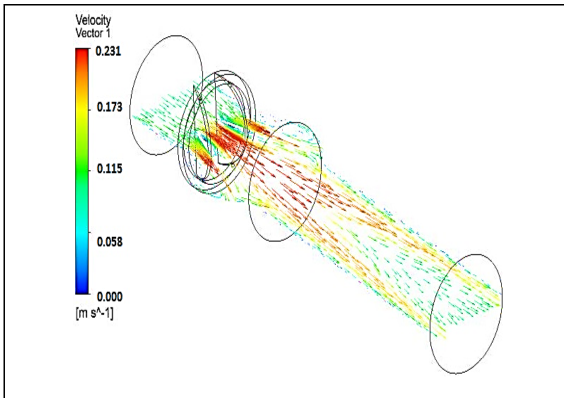
Parameters		Data
Model data (Static Structure)	Element type	Tetrahedrons solid element
	No. of nodes	679424
	No. of element	178426
	Yield stress	407.7 MPa
Model data (CFD FLUENT)	Element type	Quad-tetrahedron fluid element
	No. of nodes	599771
	No. of element	2529870

RESULTS AND DISCUSSIONS

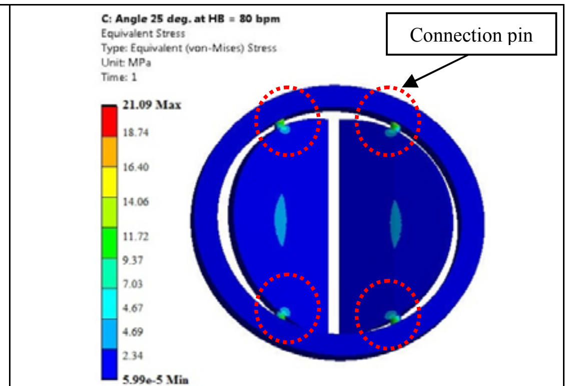
Figure-3a illustrated the CFD simulation of the typical blood flow patterns. For fully open valve angle 85° at heartbeats of 80, 90, 100, 110, and 120 BPM. The increase of heartbeat caused an increase in blood velocities through the heart valve which is consequently resulted in increasing the von-Mises stress and deformation on the leaflet which is attributed to the increase in the arterial vibration amplitudes. Also, when the heartbeat increased from 80 to 120 BPM has resulted in 38% increase in the maximum velocity. Consequently, it resulted in increasing the harmonic force, which increased the values of the von-

Mises stress in the heart valve connection pin by 62%. This leads to increase the deformation in the valve leaflet.

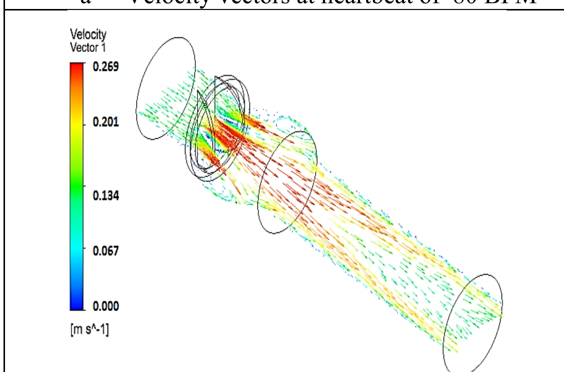
Table-3a shows the variation of the maximum von-Mises stresses values at bileaflet angles of 25°, 63° and 85° at heartbeats of 80, 90, 100, 110 and 120 BPM. The allowable von-Mises stress at the valve pin connection is 32 MPa [6]. It can be seen from Table -3a and Figure -3b, for angle 25° the maximum von-Mises stress is less than 32 MPa with heartbeat 80 and 90 BPM which is below the allowable stress value. However, when heart beat increased to 100, 110 and 120 BPM, The recorded von-Mises stress from the simulation exceeded the allowable stress. This may result in valve failure at the valve connecting pin region. It can be concluded that for all investigated angles, when the heartbeats ranged between 80 and 90 BPM, the stresses were below the aloowable stresses. However, when the heartbeat increased beyond 90 BPM, only 25° angle recorded von-Mises stresses which are higher than the allowable von-Mises stresses, which may lead to valve failure in the valve long run.



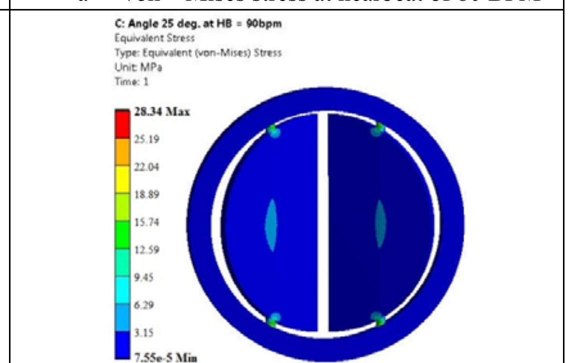
a- Velocity vectors at heartbeat of 80 BPM



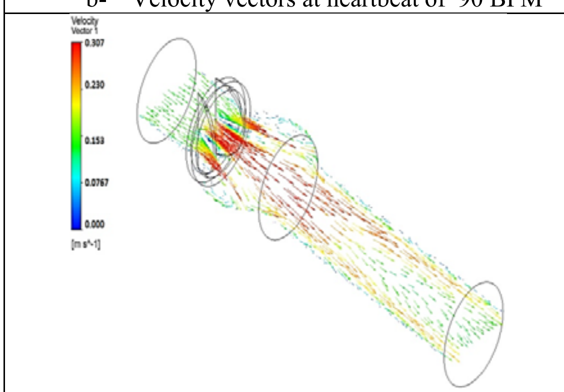
a- von – Mises stress at hearbeat of 80 BPM



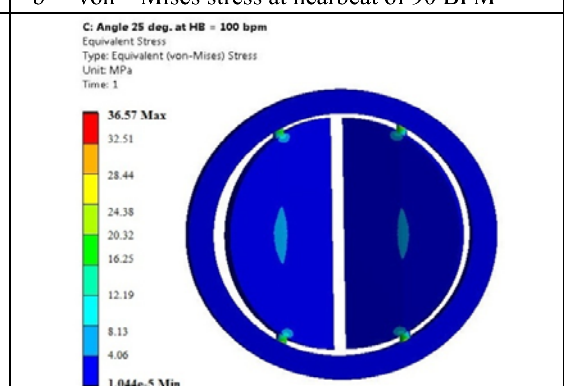
b- Velocity vectors at heartbeat of 90 BPM



b- von – Mises stress at hearbeat of 90 BPM



c- Velocity vectors at heartbeat of 100 BPM



c- von – Mises stress at hearbeat of 100 BPM

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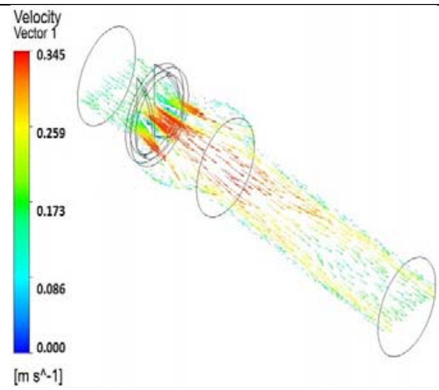
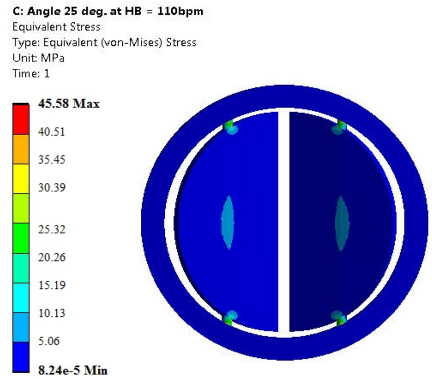
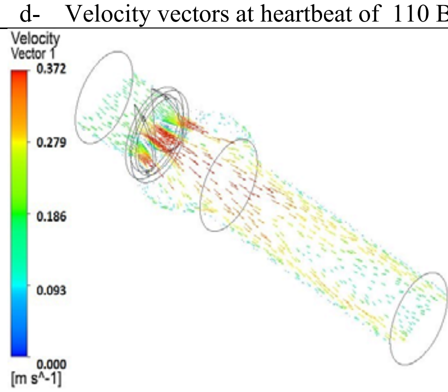


d- Velocity vectors at heartbeat of 110 BPM

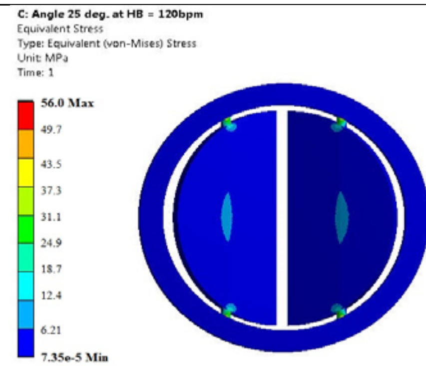


d- von – Mises stress at hearbeat of 110 BPM



e- Velocity vectors at heartbeat of 120 BPM

(a)



e- von – Mises stress at hearbeat of 120 BPM

(b)

Figure- 3. a-Velocity vectors profiles at flow rate 9.88 m^3/min with variable heartbeat at angle 85°, b- Von - Mises stress canture at flow rate 9.88 m^3/min with variable hearbeat at angle 25°

Table-3b, shows the values of maximum deformation with angles 25°, 63°, and 85° respectively, which shows that the maximum deformation magnitude was much less than that of the deformation allowed at 4.89×10^{-6} m [6]. As seen, when the leaflet opens and closes periodically for long time it may lead to a change of the leaflet structure causing damage between the connection pin and valve housing.

Table-3. a-Maximum von-Mises stress occurring in flate leaflet of the BMHV.

Heartbeat BPM	**Max. von - Mises stress at angle 25°** (MPa)	**Max. von –Mises stress at angle 63°** (MPa)	**Max. von – Mises stress at angle 85°** (MPa)
80	21.09	12.03	6.82
90	28.34	15.97	8.38
100	36.57	17.06	12.00
110	45.58	25.04	14.85
120	56.00	31.00	18.13

Table-4. b-Maximum deformation occurring in flate leaflet of the BMHV.

Heartbeat BPM	Max. Deformation at angle 25° (m)	Max. Deformation at angle 63° (m)	Max. Deformation at angle 85° (m)
80	3.02×10^{-7}	1.68×10^{-7}	9.8×10^{-8}
90	4.08×10^{-7}	2.26×10^{-7}	1.33×10^{-7}
100	5.27×10^{-7}	2.39×10^{-7}	1.71×10^{-7}
110	6.56×10^{-7}	3.54×10^{-7}	2.13×10^{-7}
120	7.99×10^{-7}	4.29×10^{-7}	2.56×10^{-7}

CONCLUSIONS

The purpose of the current study was to determine the von-Mises stress and deformation effect on the connection pin and leaflet in the BMHV and compare with allowable von-Mises stress in literature. These findings suggest that in general an increase in heartbeat of 80 to 120 BPM resulted in a 62 % increase in the von-Mises stress values at angle 25°. The results also showed that for all investigated valve leaflet angles when the heat beats equal or less than 90 BPM, the recoded stresses were below the allowable von-Mises stress of the valve pin connect. However, when the heart beat increased above 90 BPM, only 25° recorded stresses which were above the allowable von-Mises stress of the pin connect of the BMHV composite material. This may lead to valve malfunction and failure in the long run.

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