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USING ONE WAY FLUID STRUCTURE INTERACTION COUPLING TO INVESTIGATE THE EFFECT OF BLOOD FLOW ON THE BILEAFLET MECHANICAL HEART VALVE STRUCTURE

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ABSTRACT
A numerical simulation investigation was conducted to investigate the effect of vibration on the structure of bileaflet mechanical heart valve by using one way Fluid Structure Interaction coupling technique. The forces generated due to blood flow and heart pulsation which consequently cause vibrations is investigated numerically. In this model, the heartbeat used is 120 BPM and the bileaflet heart valve leaflet angles where varied 25°, 63° and 85°. The results of the numerical simulation revealed that the blood velocity and von-Mises stress in the connection pin and valve housing at the angle 25° increased by up to 96% and 78% respectively as compared with the blood velocity and von-Mises stresses at fully open angle 85°. The results of the numerical simulation indicated the von Mises stresses values may reach higher values than the allowable stresses of the artificial heart valve especially at the pin connect and valve housing. This may result in the artificial heart valve failure, however, it depends on the valve leaflet position.

Keywords: bileaflet mechanical heart valve, fluid structural interaction, blood flow velocity.

INTRODUCTION
It 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 deforms 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 of blood flow caused by fully developed laminar blood flow to determine all deformations (von-Mises stress and deflection) in the bileaflet heart valve components. The blood flow rate was taken as 2.72 L/min [4].
ANSYS software was used to perform the simulation and calculate the von-Mises stress.

MODELING OF ARTERY WITH BMHV
In this study, Fluid-Structure Interaction (FSI) tehnique 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 valve ring and leaflets are made of pyrolytic carbon and valve housing is made of titanium. Table-1 lists the properties used in the simulation which were included in the model [5]. The induced vibrations that occurred at angles of 25°, 63o 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 2.72 L/min, at heartbeat of 120 BPM.

Table-1. Material properties [5].

Mechanical properties	Density (Kg/m³)	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 cells used in the Static Structure model and CFD FLUENT model was 921,380 and 1,081,125 respectively, which was considered acceptable to show the details of the flow as given by [6] (Figure-2). The cell skewness was 0.72, which was also 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 connected to the BMHV[5].

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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 in the model at the artery; this force represent the generated force caused by heart pulsation. The value of the exerted force (F_o) was 0.1 N which was recommended by Mazumdar [6] (Figure-2). From the FSI simulation, the vibration, von-Mises stresses on the BMHV components, including the connection pins and valve housing were all obtained. To investigate the effect of vibration on the valve connection pin, the heartbeat was taken in the CFD model as 120 BPM to obtain the blood velocities values and von-Mises stress in the valve components. The CFD model was coupled with the Static Structural model to study the effect of the heartbeat on the valve connection pin. 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)

$$F = F_o . \sin(\omega t) \qquad (1)$$

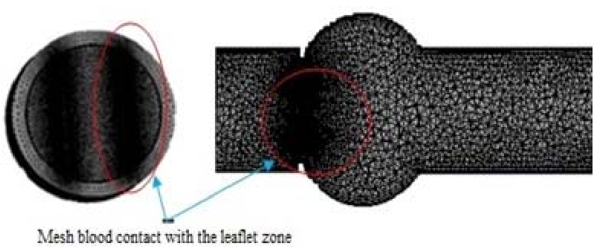
Thus, the harmonic force will cause vibration to the arterial wall.

Where: ω = angular velocity (rad/s) due to pulsation, where

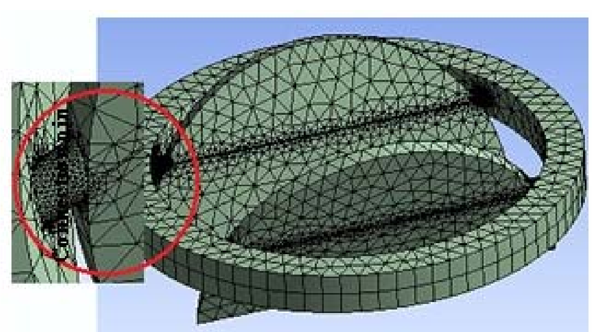
$$\omega = 2\pi \times HB \qquad (2)$$

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.

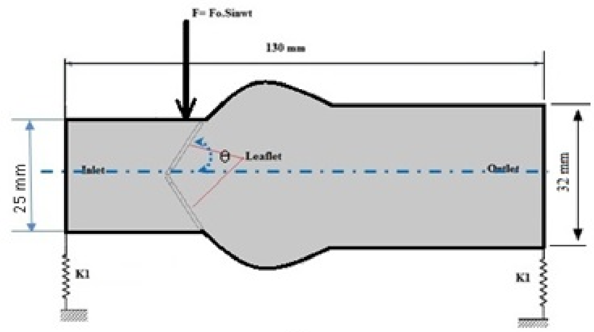


a- CFD FLUENT model

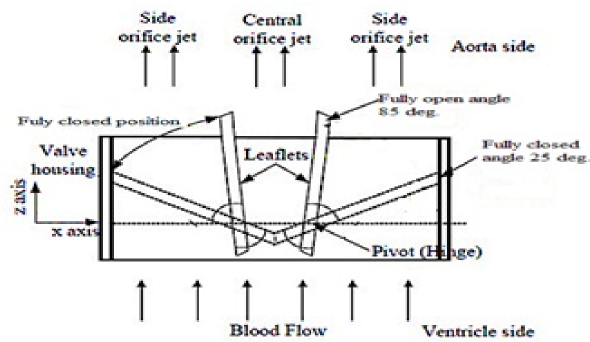


b- Static Structure model

Figure-1. Meshed geometry.



(a)



(b)

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

RESULT AND DISCUSSION

Figure-3 shows the comparison between the numerical result for the blood pressure effect on the leaflet and Maximum von-Mises stress. The present finding also supports Kwon [7] study, which concluded that the blood pressure increases from 55 KPa to 500 KPa [7], von-Mises stress also increase on the fully closed angle leaflet 25°. It can be seen clearly that the current numerical result of the angle of the leaflet is good agreement with the Kwon [7] results data, where the error between the current result and Kwon is 8%.

The typical blood flow patterns obtained from the CFD simulation are illustrated in Figure-4b. Equation 2 can be used to calculate the angular velocity due to the pulsation effect on the arteries. Figure-4b, shows the blood flow velocity passes through the region between the bileaflet and the regions between connection pin and the valve housing. For angle 25° and heartbeat 120 BPM, the blood velocity vectors were 1.68 m/s in the connection pin region. Also, the blood flow velocity at angles 63° and 85° the velocity vector were 0.17 and 0.06 m/s respectively. The velocity vector at angle 25° was 89% and 96% higher than at angles 63° and 85° respectively. This percentage of increase in the blood velocity, has resulted in increasing the von-Mises stress.

After the validation of the model was performed, the bileaflet heart valve angle was changed. Figure-4a illustrated the variation of the maximum von-Mises

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stresses values at leaflets angles of 25°, 63° and 85° at heartbeat of 120 BPM. It can be seen from Figure-4a, for angle 25° the von-Mises stress has exceeded the allowable stress for the heartbeat 120 BPM, where the value of von-Mises stress is 37 MPa, which is attributed to high velocities recorded as compared to other angles.

As a result, the von-Mises stress occurring in the connection pin is more than the allowable von-Mises stress 32 MPa [7], which may cause valve failure at the valve connecting pin. Also, for angle 63° and 85° the von-Mises stresses were less than the allowable stress magnitude, where the maximum value of the von-Mises stress is 15 and 8 MPa respectively. The von-Mises stress at angle 63° and 85° was 59% and 78% less than at angle 25°. The increase in von-Mises stress at angle 25° may cause BMHV failure in the connecting pin and valve housing over a long period of time. When the leaflet opens and closes periodically for the long period of time, this may lead to deform the connection pin structure causing a damage between the connection pin and valve housing. Under those circumstances, the stresses became higher than the allowable stresses at 25°, the leaf structure becomes weak and may lead to valve malfunction and failure.

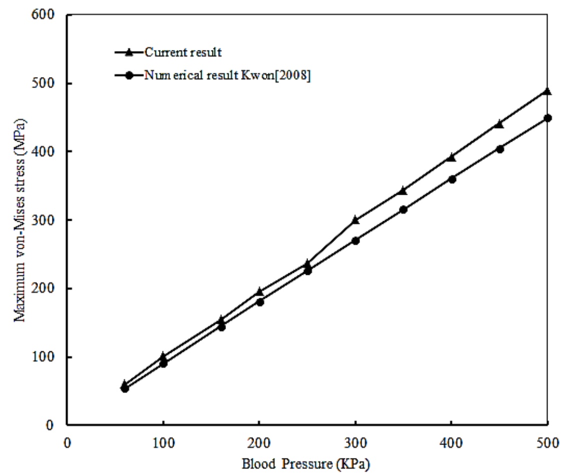
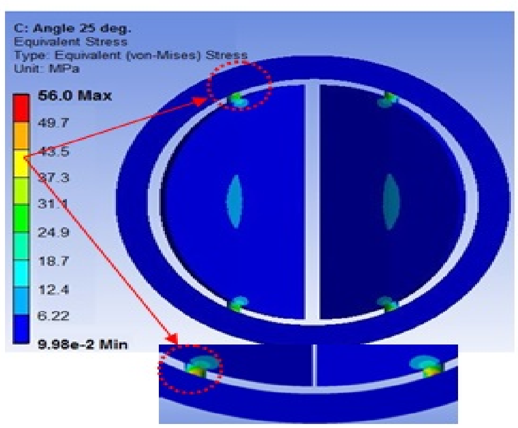
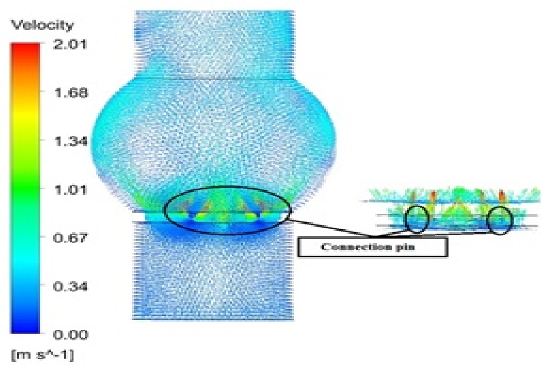


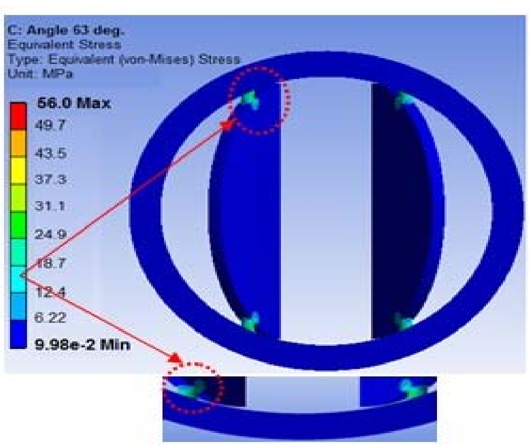
Figure-3. Comparison between the present study and Kwon [7] at fully closed angle 25°.



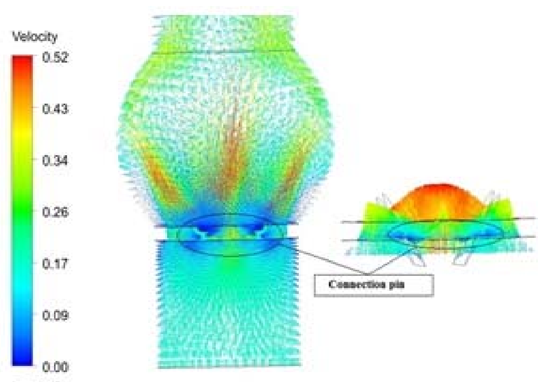
i- Von-Mises stress contour at angle 25°



i- Velocity vectors blood flow at angle 25°



ii- Von-Mises stress contour at angle 63°



ii- Velocity vectors blood flow at angle 63°

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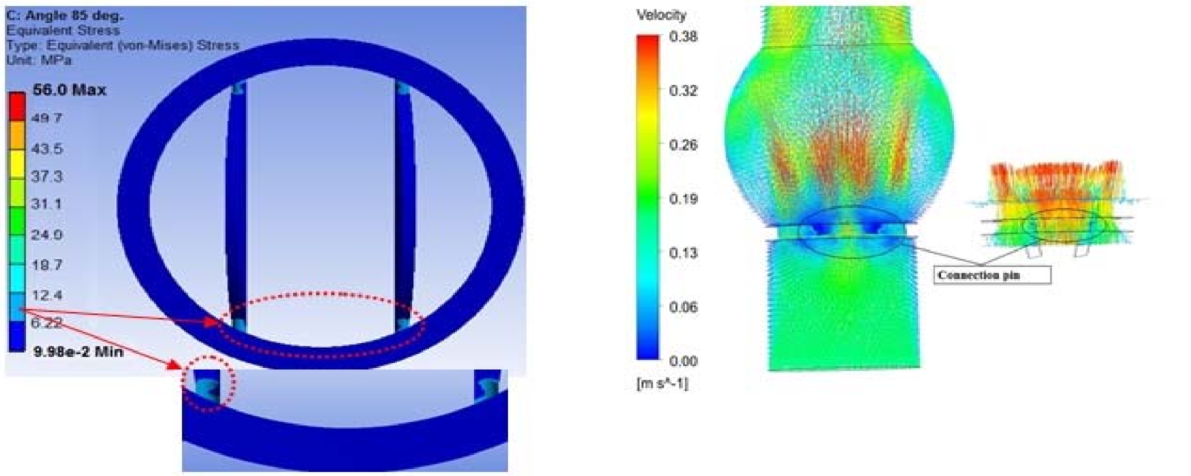

iii- von-Mises stress contour at angle 85°

(a)

iii- Velocity vectors with vibration at angle 85°

(b)

Figure-4. a- Equivalent (von-Mises) stress contour, b- Velocity vectors blood profiles, in the bileaflet heart valve at heartbeat 120 BPM and variable angles.

CONCLUSIONS

The present study studied the effect of blood velocity on the valve connection pin in the BMHV. It was found that at when the open leaflet angle reaches 25°, the von Mises stresses increased by 78% increase as compared with 85° at heartbeat of 120 BPM which is attributed to higher blood velocities values where at 25° angle of the bileaflet heart valve the blood velocities were 89% and 96% higher than at angles 63° and 85° respectively

It was found also that the von-Mises stress values reached 56 MPa, which was higher than the allowable von-Mises stress of the BMHV composite material. This stress value may lead to valve malfunction and failure in the long run.

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