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# NUMERICAL INVESTIGATION ON THE EFFECT OF BLOOD FLOW INDUCED VIBRATION ON BILEFLET ARTIFICIAL HEART VALVE BY USING FLUID STRUCTURE INTERACTION TECHNIQUE

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## ABSTRACT

Surgeries for replacement of artificial heart valves became more common and frequently used because of artificial heart valve failure. Determining the reason of the failure and finding suitable solutions require deep knowledge about artificial heart valve behavior and operation. The reasons of valve failure are related to the patient's body and the valve design. The compatibility of the valve to a human body is associated with the dynamics of blood flow and the materials used to manufacture the valve. When blood flows through the arteries and valves, blood exerts forces at the valve components, thereby causing flow-induced vibration, which may damage the valve. In this study, fluid–structure interaction techniques to computational fluid dynamics analysis were used to investigate the effects of vibrations occurring via computer simulation. To obtain the optimal design of shear stress, the shear stress of the connection pin of an artificial heart valve were calculated and compared with the shear stress of the connection pin in the literature. At Reynolds number of 250, the excitation frequencies increased from 94.24 rad/sec to 126.9 rad/sec, which resulted in a 75% increase in shear stress values at the connection pin valve at a fully closed angle of 85°. The increase in frequency may cause resonance phenomenon, which will cause damage to the artificial heart valve components. Consequently, the blood components will also be damaged, thereby causing an increase in blood clogging occurrence downstream of the artificial heart valve.

**Keywords:** fluid structure interaction, artery, artificial heart valve.

## INTRODUCTION

Blood vessels consist of elastic arteries such as the aorta, which branch out to form elastic blood vessels [1]. Previous research showed that many patients with implanted artificial heart valve require surgeries because of artificial heart valve failure [2]. One of the reasons for this damage is the effect of blood flow within the arteries and the subsequent force of the blood flow, such as blood pressure and Coriolis forces acting on the arterial walls, generating flow-induced vibration [3]. 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. The blood force deforms the structure. As the structure deforms, it changes its orientation, thereby affecting the blood flow characteristics [4]. Danger occurs when the natural frequency of the artery without blood flow equates the occurring frequency when the blood flows through the artery causing the resonance phenomenon; such situation results in failure of the artificial heart valve and consequently damages the components. The present study investigates the effects of forced vibration caused by fully developed laminar blood flow at a Reynolds number of 250 in the arterial structure in the presence of an artificial heart valve to determine the shear stress in the connection pin of anartificial heart valve. ANSYS software was used to perform the simulation and calculate the shear stress that occurred in the connection pin of an artificial heart valve.

## Modeling of artery with bileaflet artificial heart valve

In this study, fluid-structure interaction (FSI) techniques were used with ANSYS software. computational fluid dynamics FLUENT (CFD) and static structural software were applied to model the artery with artificial heart valves in 3D. Table-1 lists the properties used in the simulation and included in the model (bileaflet valve ring and leaflets from pyrolytic carbon and valve housing from titanium) [5].

The induced vibrations that occurred at fully open bileaflet heart valve angle of 29.9° and fully closed bileaflet heart valve angle of 85°were both investigated. For patients with artificial valve implanted in the heart, the physiological Reynolds number used in the model was 250 [6].Furthermore, the maximum pressure to support the ventricle while closing the mechanical aortic valve was 80 mmHg [6].

**Table-1.** Material properties.

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

**Model development and boundary conditions**

The following boundary conditions were considered in this study:

1. Walls: No slip conditions with zero velocity existed at the wall boundary.
2. Steady-state simulation.
3. Flexible support at two ends of the artery was used in the FSI model.
4. Blood temperature was 37 °C

The number of cells used in the model was 1,250,088, which was considered acceptable to show the details of the flow as given by [6] (Figure-2). The cell skewness was 0.78, 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 an artificial heart valve, such techniques can model the fundamental interaction between the blood flow and the arteries connected to the artificial heart valve [7].

In this model, FLUENT (CFD) was first used, and the blood flow velocity became an input in the boundary conditions corresponding to the Reynolds number of 250 [6]. To account for the generated force caused by heart pulsation, a force was exerted on the model at the artery; this force represented the generated force caused by heart pulsation. The value of the exerted force ($F_o$) was 0.1 N (Figure-1), which was recommended by Mazumdar [7].

From the CFD simulation, the vibration, shear stresses at the bileaflet components, including the connection pins and valve housing, and arterial deformation were all obtained. To investigate the effects of vibration on the blood flow profile and velocity, the CFD simulation was coupled with Static Structural to obtain the blood velocity and stream contours in the arteries. 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 [$F = F_o.\sin(\omega t)$]; thus, the harmonic force will cause vibration to the arterial wall. The vibration resulting in harmonic displacement of the arterial wall can be calculated as follows:

$$Y = Y_o.\sin(\omega t) \tag{1}$$

Differentiating equation 1 yields:

$$V = \mp Y_o.\omega.\cos(\omega t) \tag{2}$$

Where:
V: vertical velocity component of the arterial wall, whereas horizontal velocity component of the arterial wall (U) = 0
V: (+)ve at the bottom wall of the artery
V: (−)ve at the top wall of the artery
($Y_o$): deflection at each point along the artery of time (t)

Given the vibration, the arterial wall will move with a displacement. The velocity equation represents a sinusoidal wave. Therefore, the one-time period can be determined as follows:

$$\Omega = 2\pi \times \text{frequency} \tag{3}$$

Since: frequency = 1/time
Hence: time = $2\pi/\Omega$
Where: $\Omega$ = excitation frequency (rad/sec).

Figure-1 shows the flexibly supported artery conveying blood flow and location of the harmonic forced vibration at different excitation frequencies.

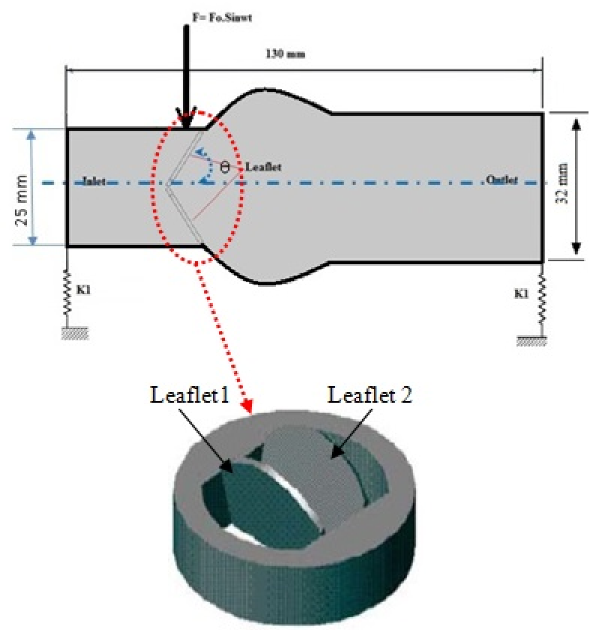


**Figure-1.** Complete computational domain for the simulation of bileaflet mechanical heart valve and the location of the effect of harmonic force.

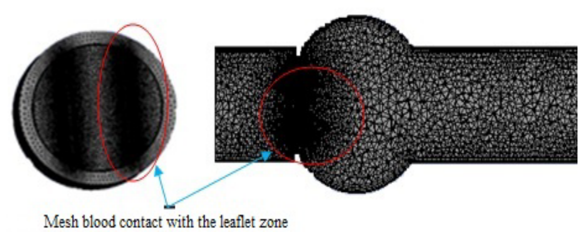


**Figure-2.** Meshed geometry.

## RESULTS AND DISCUSSION

**Vorticity-stream function technique in vibrated arteries connected to an artificial heart valve**

The typical blood flow patterns obtained from the CFD simulation are illustrated in Figure-3. Equation 3 can be used to calculate the excitation frequency on the arteries. For (π/18, 5π/18, and 4π/9), which represent the peak values, Equation 1 is used, and excitation frequencies are found to be (94.24, 120, and 126.9 rad/sec). For closed

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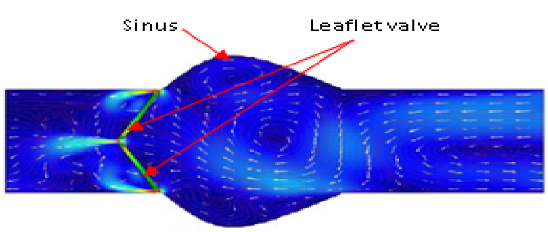
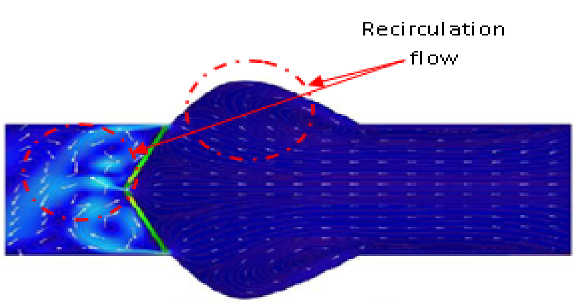
valve angle (85°) and values of 94.24, 120, and 126.9 rad/sec (Figure-3), as the excitation frequency values increased, blood flow vortices and recirculation decreased. Although the recirculation decreased when the excitation frequency increased, this may improve the blood flow uniformity, the shear stressvalue increased when the excitation frequency also increased. This finding is in agreement with the theory of wall vibrations in the arteries.

The increase of excitation frequency of the blood flow caused an increase in the arterial vibration amplitudes. This effect is attributed to the increase in the blood flow velocity (Figure-4), which increased the amount of shear stress. The increase of harmonic force calculated from equation1 increased the value of shear stress in the heart valve connection pin at the valve housing. The results indicated that the shear stress exceeded 235.8 MPa. Notably, the allowable shear stress is 241MPa for the valve composite material [8]. This value indicates that valve failure will occur at the connecting pin region because the shear stress values are higher than the allowable artificial heart valve shear stress.

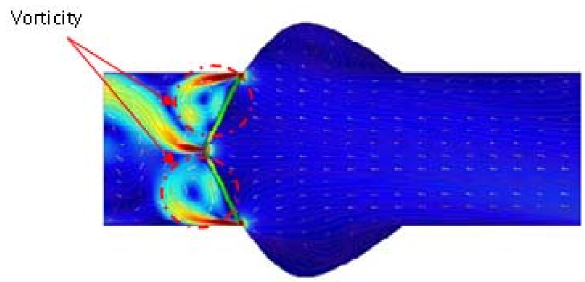
The FSI (Static Structural) results (Figures-5 and 6) showed that the resulting shear stress at 85°angle was ascribed to the induced vibration at the pin connection on the valve housing, which increased from 235.8 MPa at the excitation frequency of 94.24 rad/sec to 1969.9 MPa at excitation frequency 126.9 rad/sec. This finding was attributed to the increase in the shear stress caused by the increase of harmonic force related to the increase of excitation frequency from 94.24 rad/sec to 126.9rad/sec. Figure-6 shows the values of shear stress at fully open angle of 29.9°, which shows that the shear stress magnitude was much less than that of the shear stress allowed at 241 MPa.




(a)Excitation frequency = 94.24 rad/sec.

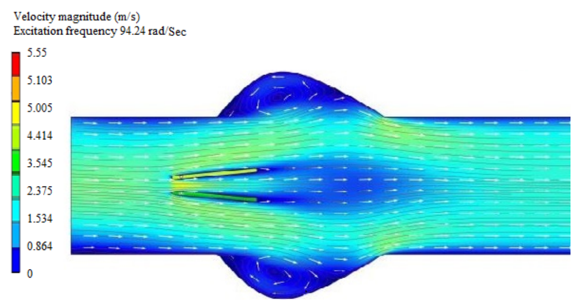



(b)Excitation frequency = 120 rad/sec.

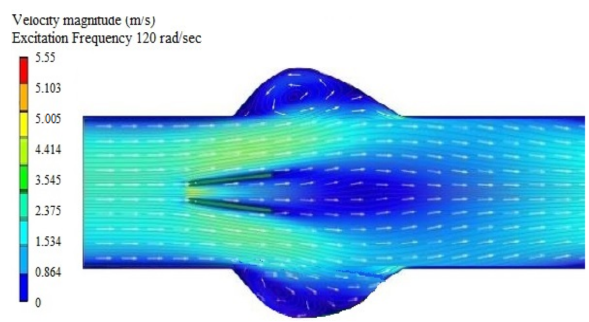



(c)Excitation frequency = 126.9 rad/sec.

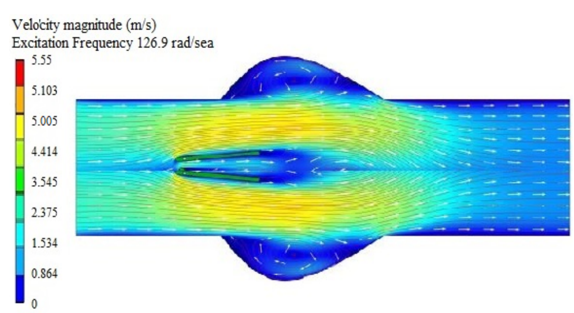
**Figure-3.** Vortices and recirculation at Reynolds number (Re = 250) with variable excitation frequency at a fully closed valve angle (85°).




(a)Velocity contours at the excitation frequency of 94.24rad/sec.




(b)Velocity contours at the excitation frequency of 120 rad/sec.




(c)Velocity contours at the excitation frequency126. 9rad/sec.

**Figure-4.** Velocity contours profiles at Reynolds number (Re = 250) with variable excitation frequency at a fully opener valve angle.

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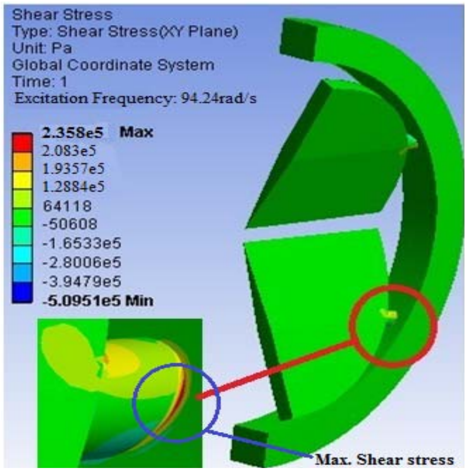
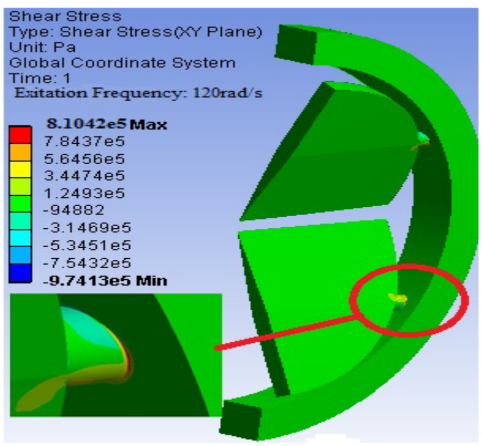
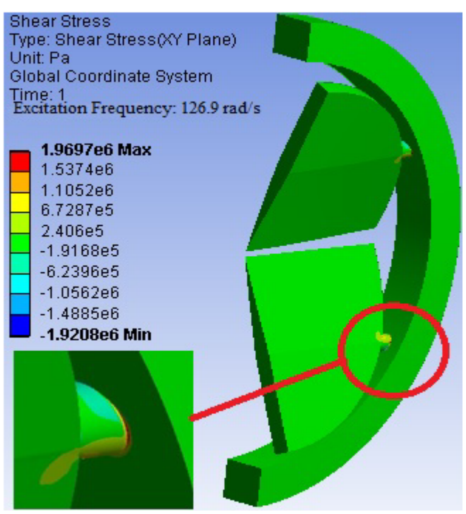



(a)Excitation frequency = 94.24 rad/sec.

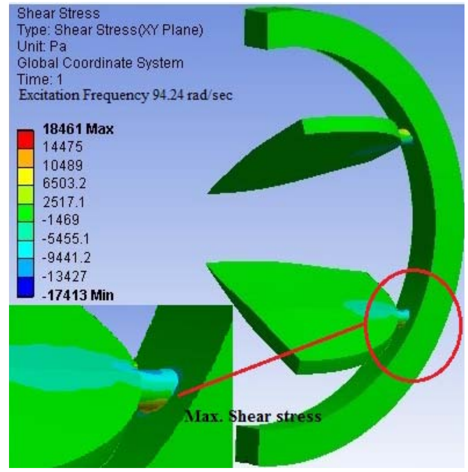



(b)Excitation frequency = 120 rad/sec.

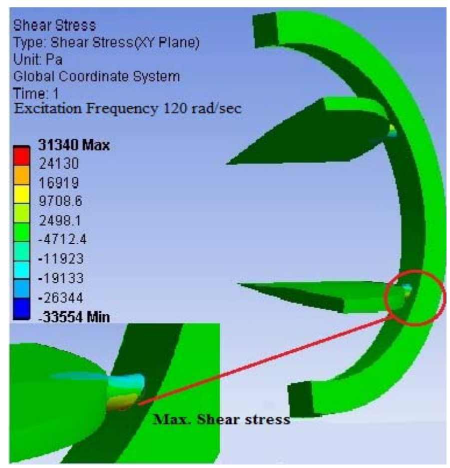



(c)Excitation frequency = 126.9 rad/sec.

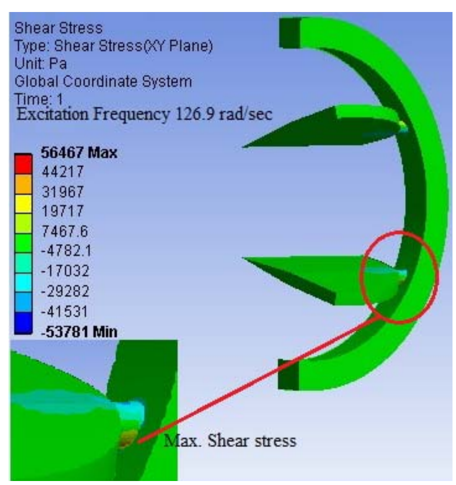
**Figure-5.** Shear stress at Reynolds number (Re = 250) with variable excitation frequency at fully closed bileaflet heart valve angle.




(a)Excitation frequency = 94.24 rad/sec.




(b)Excitation frequency = 120 rad/sec.




(c)Excitation frequency = 126.9 rad/sec.

**Figure-6.** Shear stress at Reynolds number (Re = 250) with variable excitation frequency at fully open bileaflet heart valve angle.

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## CONCLUSIONS

The cardiovascular artery in the presence of the bileaflet artificial heart valve was modeled and simulated by using CFD and Static Structural techniques to model the blood flow and the resultant induced vibration. The excitation frequencies increased from 94.24 rad/sec to 126.9 rad/sec, which resulted in a 75 % increase in shear stress values at the connection pin valve at a fully closed angle of 85°. Furthermore, the shear stress values reached 1969.7 MPa, which was higher than the allowable shear stress of the artificial heart valve composite material. This stress value will lead to valve malfunction and failure.

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