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EFFECT OF TISSUE STIFFNESS ON HEART VALVE LEAFLET FLUTTER

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Abstract. *Calcification is a dysfunction of the bioprotheses heart valves that causes tissue stiffening that prevents the valve leaflets from fully opening, reducing the area that blood has to flow and overload the heart. Among the mechanisms that cause the degradation of leaflet tissues, flutter is considered one of the most harmful. Aiming a better understanding of this phenomenon, the present study compare the effect of different tissue stiffness on leaflet oscillation dynamics during a cardiac cycle. Starting from an aortic valve geometry available on the literature the Finite Element Method analysis leaflets was evaluated throw a cardiac cycle, The transvalvular pressure was applied as physiological boundary condition. In the section results are presented the frequency and amplitude oscillation for each leaflet stiffness modulus. The results obtained show that the flutter oscillation flutter increase with the tissue flexibility, while the amplitude decrease, the tip of flexible leaflets also have a bigger displacement and open quicker. Some of the results obtained differ from those found by researchers who investigated the phenomenon with InVitro studies or fluid structure simulations, indicating that the turbulence caused by blood flow has a predominant effect on the leaflet behavior.*

Keywords: *Bio-engineering, Heart valve, Leaflet Flutter, Finite element method.*

1. INTRODUCTION

The aortic valve is located between the left ventricle and the aorta and is responsible for controlling the unidirectional blood flow (Sacks *et al.*, 2009). During its lifetime, the valve is subject to deterioration that cause the leaflets deterioration (Gould *et al.*, 2013). In that case, how the tissues of the valves do not have the capacity to regenerate and there are no drugs for the treatment of the disease, one of the main strategies adopted is the replacement of the valve by a bioprosthesis (Webb and Wood, 2012; Rabkin-Aikawa *et al.*, 2005). These bioprostheses are commonly made from porcine tissues or bovine pericardium, and they generally have good hemodynamic characteristics and are well accepted by the body. However, these bioprostheses are also subject to the degradation mechanisms and therefore have a lifetime of 10 to 15 years. Understanding these mechanisms that cause tissue degradation is one of the main challenges to propose the design of more durable prostheses that will increase and improve the expectations and lives of patients. Among the phenomena that cause leaflet degradation, flutter is considered one of the most severe according to Ionescu (2014). Observed for the first time by Pinto *et al.* (1978), the researchers conducted a study with the electrocardiogram of 203 patients of varying ages and health conditions, verifying the occurrence of flutter in 17% of the patients. However, despite suggesting that calcified tissues are less susceptible to flutter, they do not quantify this influence.

Singh *et al.* (2008) using Finite Element Method (FEM) with shell elements analyzed the effect of modulus of elasticity and leaflet thickness on valve dynamics. The authors also observed the occurrence of flutter and stress variation on the leaflet. Using purely structural analysis Saleeb *et al.* (2013) conclude that numerical models that consider the hyperelasticity of the material present more reliable results with experimental observations.

One of the main flutter studies in heart valve prostheses was perform by Avelar *et al.* (2017b), where he presents a mathematical model to predict the critical velocity of flutter in porcine and bovine pericardium valves. The analysis show that the internal diameter has a greater impact on the critical velocity, while the thickness of the leaflet is more relevant when considering the critical flow. Both the theoretical study and the experimental validation verified a lower flutter frequency for the pericardial valves. Although the authors suggest that one of the reasons for this difference in flutter frequency caused by the Young Modulus of the material. The study did not show a correlation between these properties.

Using computer simulation and experimental analysis to study the influence of geometry on the dynamics of heart valve bio-prostheses Lee *et al.* (2021) indicated that valves with a smaller internal diameter have higher oscillation frequencies in a range of conditions, and that leaflet thickness is directly related to the oscillation frequency. Despite having characterized the influence of leaflet diameter and thickness on the flutter phenomenon, no correlation was obtained between flutter and leaflet modulus of elasticity.

Aiming a better understanding of the effect of Leaflet young's module in leaflet flutter Iásbeck *et al.* (2019) evaluate the behavior of leaflets with 5 different stiffness between 3 and 5 Mpa. The author pointed that the transient analysis was consistent with the results observed experimentally and the more stiffened leaflets has a smaller opening area and greater tension at the roots of the leaflets. The authors also evaluate the effect of mesh elements in the results and conclude that first order tetrahedral elements are not suitable for this analysis. Despite observing oscillation frequencies in all analyses, the relationship between flutter and modulus of elasticity was inconclusive.

Although many works have already cited and investigated the flutter phenomenon, there is still no consensus about the influence of leaflet stiffness on the flutter phenomenon, therefore, the present work seeks, through finite element analysis, to evaluate the flutter frequencies for a cardiac prosthesis with different modulus of elasticity.

2. METHODOLOGY

In these study, heart valve prostheses of the same thickness and geometric dimensions were simulated, varying only the modulus of elasticity. As boundary conditions, physiological pressure loads were applied to the ventricular surface of the valve leaflets.

2.1 Valve Geometry

The geometry used in this study was developed according to the methodology suggested by Abbasi and Azadani (2020), where the authors show how the valve geometry was obtained through two 2nd order spline curves and optimized through simulations with physiological boundary conditions. The leaflets were modeled in the SpaceClaim software with a internal diameter of 26 mm and leaflet thickness of 0.3 mm. Figure 1 shows the geometry of the aortic valve.

2.2 Mesh Geometry

To evaluate the sensitivity of mesh results three static simulation was performed considering the boundary conditions similar as shown in 2.3and applying as loading condition a ramp waveform pressure of 400 Pa. Doubling the number of elements in each simulation the convergence criterion was determined that a relative variation smaller than 5% in the leaflet tip displacement was enough to disregard the mesh effects on the results. Considering the mesh test results shown in Table 1 the geometry was discretized into 11,248 first-order quadrilateral elements as shown in Figure 2a. The shell elements were chosen because they demand a lower computational cost and are more efficient in representing thin structures (Carmody *et al.*, 2006).

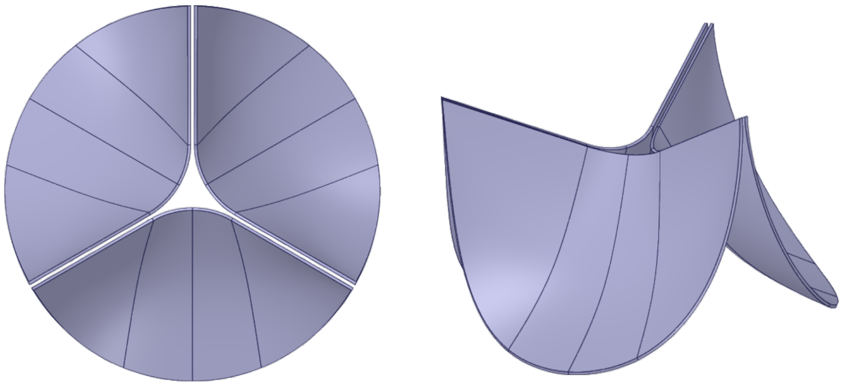


Figure 1. Heart valve geometry

Table 1. Mesh Sensitivity test

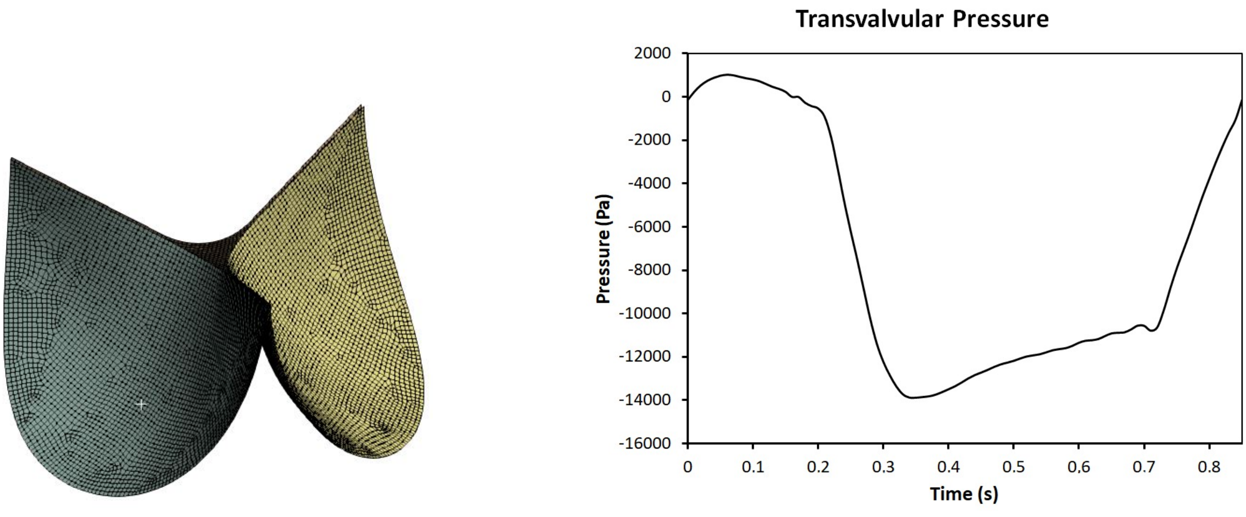
	Mesh 1	Mesh 2	Mesh 3
# Nodes	11628	22641	44826
# Elements	7322	14492	29036
Maximum Skewness	0.57661	0.59859	0.62379
Minimum Ortogonal Quality	0.73005	0.71262	0.69097

Relative Error

	Mesh 1 to mesh 2	Mesh 2 to mesh 3
Displacement (%)	0,47	0,40

2.3 Boundary Conditions

As a boundary condition, the leaflet roots were considered as fixed supports since the stent stiffness is much higher than the leaflet stiffness, so the rotations and displacement on the nodes near the stents could be disregarded (Toninato *et al.*, 2016). As a loading condition, a physiological pressure curve (Figure 2b) was applied to the ventricular side of the leaflets. The contacts between the ventricular faces of the leaflets were modeled as symmetrical and without friction (Iásbeck *et al.*, 2019; Tango *et al.*, 2018). Figure 3 illustrates the boundary conditions applied to the model.



(a) Geometry mesh.

(b) Transvalvular pressure during a cardiac cycle.

Figure 2. Geometry mesh and transvalvular pressure during a cardiac cycle.

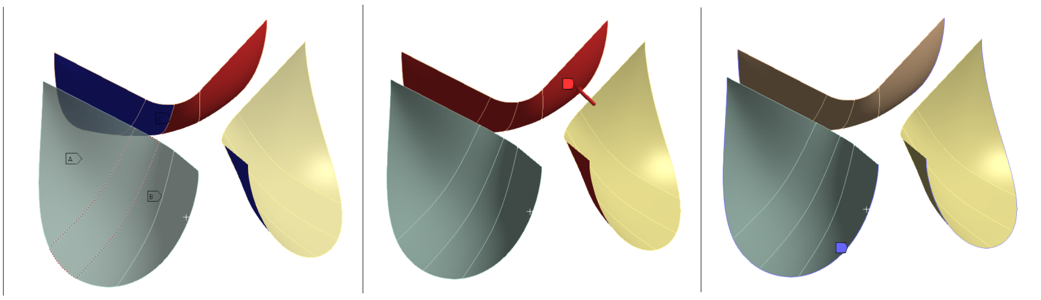


Figure 3. Boundary Conditions.

2.4 Simulation Setup

To investigate the influence of increased stiffness the leaflet material was modeled as linear elastic with Young's modulus ranging from 1 MPa, 3 Mpa and 5 Mpa, Poisson's coefficient was set to 0.45 for all cases (Tango *et al.*, 2018). The simulations were run in the transient structural Ansys Mechanical software with the "Large deflection" option activated, this consideration is important to account the geometric non linearity due the changes in stiffness caused by the change in the shape of the leaflets during the simulation. The time step should be small enough to capture leaflet oscillations, as the flutter frequency is on the order of 50 to 90 Hz (Lee *et al.*, 2021; Johnson *et al.*, 2022), with some studies pointing to higher frequencies of up to 300Hz (Avelar *et al.*, 2017b; Iásbeck *et al.*, 2019) , a step time of the order of 10-4 seconds was used. As the flutter phenomenon occurs only during the valve opening and due to the high computational cost due to the small time step, only the systole period was simulated. Displacements were obtained in Ansys post-Processing using the probe tool to extract the tip displacement of each leaflet.

2.5 Flutter Analysis

To quantify the frequency and amplitude of leaflet oscillation the Displacement data were treated by selecting only the interval that the valve remained open, the average of the displacements was then calculated and subtracted from the displacement of each point in order to obtain the alternating displacements of the leaflets. After that an frequency domain analysis was performed calculating the Fast Furrier Transform (FFT) in MATLAB software.

3. RESULTS AND DISCUSSION

3.1 Transient Analysis

The opening behavior of the leaflet during the fists 0,02 seconds of the systole are shown in the Figure 5 at equally spaced times of 0.004s.

Observing the figure 5, and the radial displacement of the tip in Figure 4 A is possible to notice that the leaflets with greater flexibility open faster, has greater displacements and remain open for a longer period, while the stiffer leaflet is slower to open and close quicker. The leaflet behavior during the opening is similar to one related by Chen and Luo (2020), however in their study using FSI analysis they observed that stiffened leaflets is also slower to close, leading to higher resistance and a reducing flow rate. Another studies also evaluate the leaflet behavior for valves of different thickness (Johnson *et al.*, 2022; Lee *et al.*, 2021), diameter (Lee *et al.*, 2021) and Young's Modulus (Iásbeck *et al.*, 2019) and variations in opening and closing time were not observed.

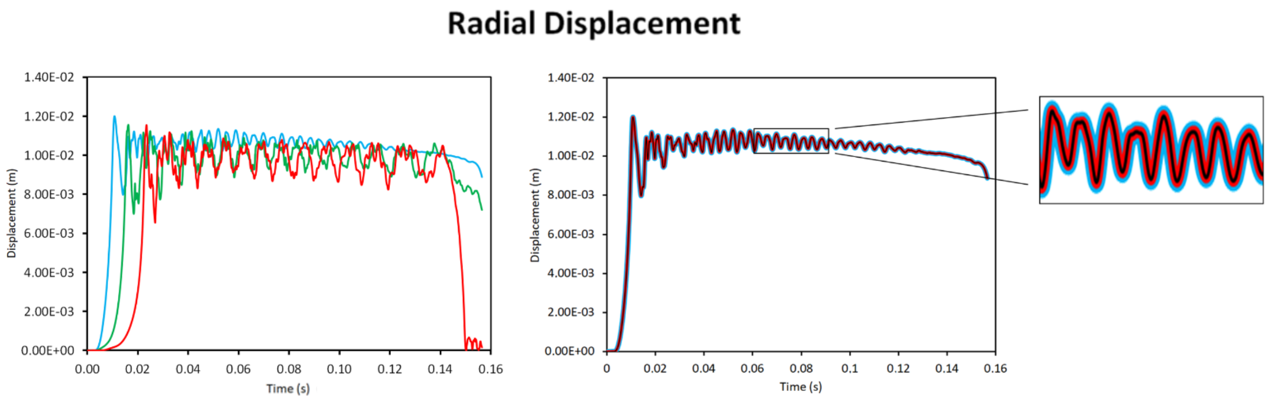


Figure 4. Transient Analisys of leafflet behavior during the systole.

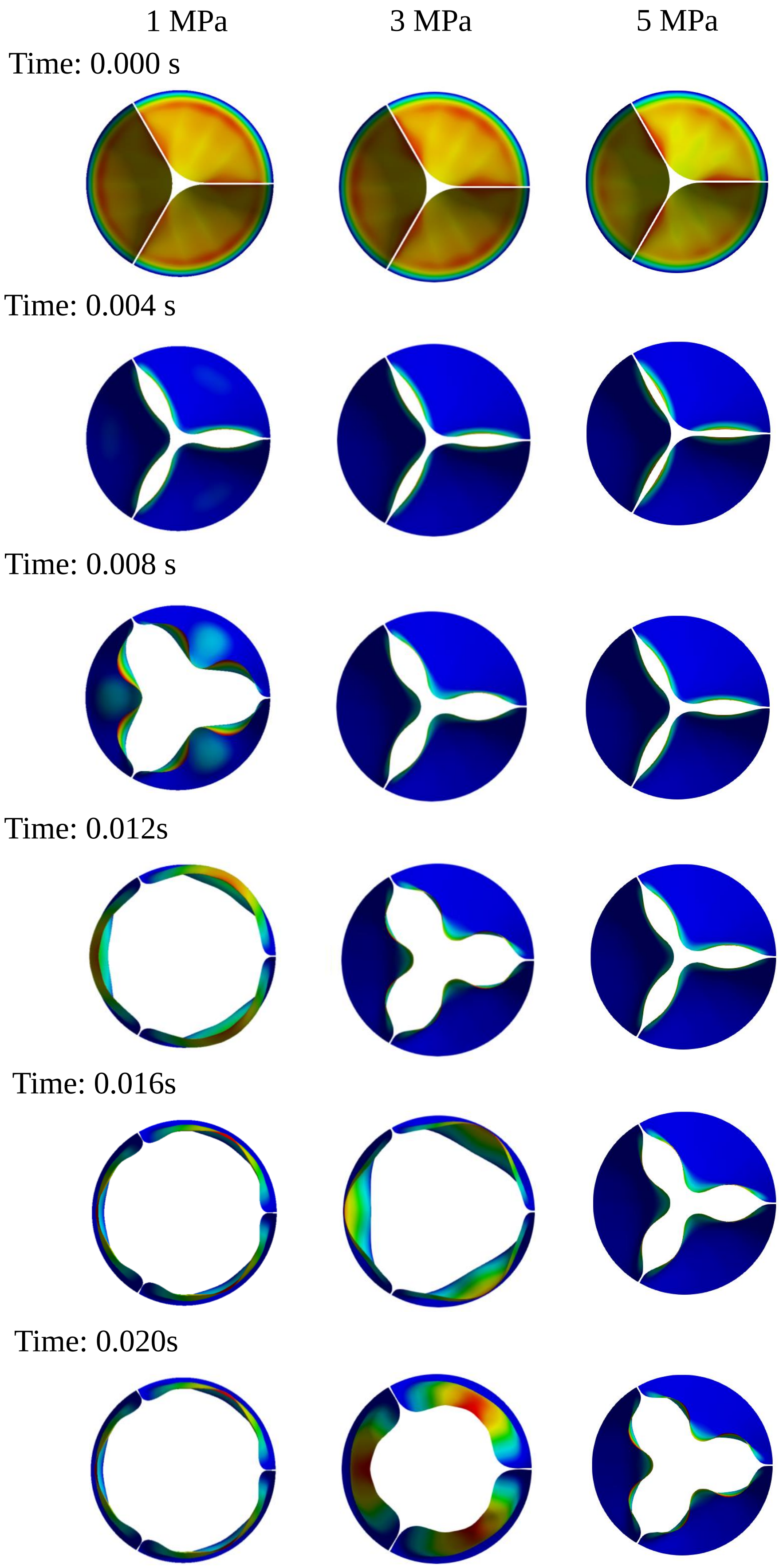


Figure 5. Transient Analisys of leafflet behavior during the systole

Another important observation is shown in the Figure 4 (B) where the symmetrical displacement of there leaflets are shown. That symmetry on the leaflet behavior is divergent of the ones shown by Zhu *et al.* (2023) and Johnson *et al.* (2022), where the authors using In Vitro experiments and fluid structure simulation (FSI), respectively, reported lagged oscillation between the leaflets. One of the possible reasons for the differences in the results observed between these studies may be related to the chosen analysis method. Flutter is an effect caused by the interaction of the structure with the flow, with the purely structural analysis not considering the effects of flow and turbulence on the leaflets, producing different results from those obtained in experimental analyzes or fluid-structure interaction analyses.

Despite the previously mentioned divergences, it is possible to notice that the dynamic behavior of the leaflets is similar to those presented by Avelar *et al.* (2017a) in their experimental analysis. Although purely structural finite element analysis of leaflets is not sufficient to represent valve behavior in detail, this method is simpler and less costly than InVitro experiments and fluid-structure interaction analyses. Thus, it can be a more economical alternative to provide qualitative data on the behavior of the valve.

3.2 Flutter Analysis

Analyzing the movement of the leaflets in the frequency domain we observed three main oscillations frequencies in all leaflets, noticing that the stiffened leaflet has higher frequency and lower amplitude of oscillation, while the more flexible leaflets shown lower frequencies and higher amplitudes. However, as shown by Iásbeck *et al.* (2019) this is not a direct correlation, with the intermediate stiffness leaflet (3 Mpa) presenting amplitudes and flutter frequencies very similar to the stiffened leaflet. The flutter frequencies and leaflet amplitude obtained via FFT (Fast Fourier Transformer) are summarised in the Table 2.

Table 2. frequency and amplitude of oscillation

E	Frequency (Hz)	Amplitude (mm)
1 MPa	28	0.2
3 MPa	13.4	0.44
5 MPa	12	0.5

Although flutter is a recurrent phenomenon, there is still no consensus about its causes, the present work sought to understand the correlation between oscillation frequencies and amplitudes with leaflet stiffness. The results found are similar to the flutter frequencies observed by Johnson *et al.* (2022), however the behavior The symmetric pattern of leaflets observed in this study differs from the observations made by Zhu *et al.* (2023) e Johnson *et al.* (2022) who found a lagged movement between the flyers. It is believed that this difference in behavior dynamic of the valve is due to the purely structural analysis methodology that disregards the effects of flow about the leaflets. This study also observed a decreasing relationship between the frequency of oscillation and the stiffness of the leaflets, unlike the results obtained by Lee *et al.* (2021) who pointed out in their study higher frequencies of oscillation for thicker leaflets.

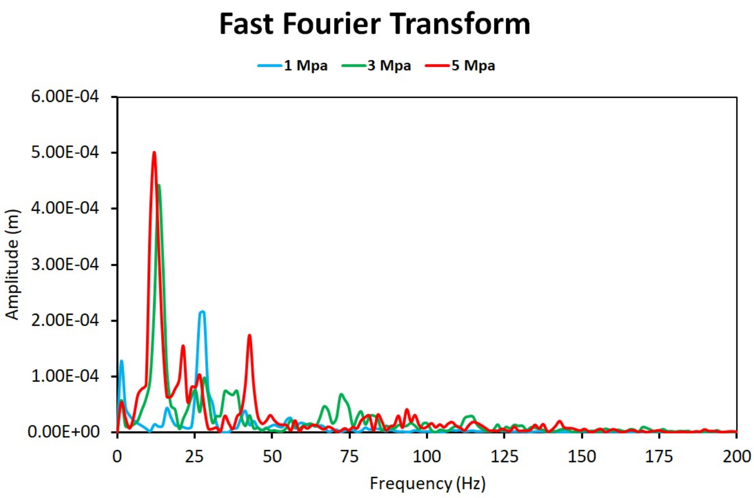


Figure 6. Leaflet flutter Analysis in Frequency Domain.

4. CONCLUSION

The present work investigates the flutter phenomenon in heart valves. Performing structural simulations using the finite element method, the effect of stiffening of leaflet tissues on the frequencies and oscillations of cardiac bio-prostheses was investigated. The results obtained indicate that more flexible leaflet valves open more easily and remain open for longer. Flutter frequencies were observed in all simulated leaflets, however the results obtained differ from other studies presented in the literature and it was not possible to establish a direct correlation between flutter and leaflet stiffness.

5. ACKNOWLEDGEMENTS

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