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DEVELOPMENT OF A HIGH-SPEED CAMERA-BASED SOFTWARE FOR CHARACTERIZATION OF VIBRATIONAL MOTION IN CARDIAC VALVES

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Abstract. *The flutter effect is an understudied phenomenon that consists of a structural vibration caused in a structural element by the interaction with a fluid flow. This phenomenon occurring in cardiac valves causes oscillations in the cusps, which is associated with regurgitation, calcification and fatigue, reducing even more their lifetime. The lack of technical and scientific knowledge about flutter is one of the obstacles to the development of more durable prosthetic valves and consequent improvement of the life quality of cardiac patients. Within this context, the present work intends to develop a software to be used in the characterization of the vibrational motion of the cardiac valves' leaflets using a high-speed camera. The software will later on be implemented in the analyze of images from an experimental bench that simulates the cardiac flow and the behavior of a porcine and a bovine valve, recorded by a high-speed camera. Computer simulations of the valve vibration were used for the software validation. The results were used to obtain information such as the opening area of the valves, the displacement of the leaflets, and the frequencies and amplitudes of the leaflet vibrations. These values were similar to those found in previous works in the area. Therewith, this work developed a tool that will contribute to studies of the flutter phenomenon in the future, in order to enable the creation of more durable prosthetic valves.*

Keywords: *flutter, cardiac valves, high-speed image processing, computational vision, vibrational motion characterization*

1. INTRODUCTION

Cardiac valves play a fundamental role in controlling the blood flow in the heart, maintaining a unidirectional blood flow from the heart to the lungs and the rest of the body, by opening and closing more than 3 billion times during an individual's lifetime (Peters et al., 2023). Over the course of people's lives, valve dysfunctions can occur, leading to severe cardiac problems, being valvulopathies responsible for approximately 30% of adult cardiac surgeries and 80% of pediatric cardiac surgeries in Brazil (Silva et al., 2009). Due to their uninterrupted work, the valves are constantly subjected to continuous forces due to the interaction between the blood and the cusps. The energy exchanged between the blood flow and the valve leaflet can induce vibration in the cusps, characterizing the phenomenon known as flutter (Avelar et al., 2017b).

Flutter is a physical phenomenon that consists of a structural vibration caused in objects due to interaction with a fluid flow. The oscillations caused in the cusps by this phenomenon are associated with regurgitation, calcification, fatigue, increased thrombus formation and hemolysis, thereby exacerbating the deterioration of cardiac valves (Avelar et al., 2018). Despite this, flutter is a poorly studied phenomenon, with little literature relating the oscillation in the leaflets and their risks to the lifespan of cardiac valves. A specific mechanism leading to flutter in the leaflets has also not been identified (Johnson et al., 2022).

Recent studies have experimentally investigated the frequencies and amplitudes of flutter in biological heart valves, generating a dimensionless curve to predict the onset of oscillations based on the prosthetic tissues, mechanical behaviour and geometrical parameters (Avelar et al., 2017a). Another study creates a mathematical model based on eigenvalues to predict instabilities in the system caused by fluid flow and the onset of vibrations, with results compared to experimental data (Avelar et al., 2018).

Among the main techniques used to estimate the movement of structures, the application of image processing algorithms based on computer vision in a sequence of images such as video frames, stands out. Phase-based Motion Estimation (PME) originates mainly from the theory of displacement in the Fourier transform, which indicates that any motion in the spatial domain results in phase variations in the frequency/wavenumber domain (Li et al., 2023). Vibration analysis requires the selection of physical values at regular intervals to preserve the accuracy of signal processing. In some works, the sampling frequency must be constant and, if possible, customizable to regulate the size of data files, which can occupy a significant amount of memory (Singh and Gupta, 2023).

Given the need for further technical and scientific knowledge regarding flutter, this study aims to develop a software to be used in the characterization of vibrational movement of cardiac valves leaflets, with the intention of providing a tool that will contribute to future studies on the flutter phenomenon. The software will be implemented in the analysis of images from an experimental setup that simulates blood flow and the behavior of cardiac valves, with the images recorded by a high-speed-camera.

The developed program uses computational methods to measure the valve's opening radius frame by frame, for the calculation of various degrees of freedom in each cusp. The algorithm was written in Python, as it is a high-level programming language and, therefore, more suitable for software development. Additionally, Python also includes OpenCV, a widely used library for computer vision codes.

2. MATERIALS AND METHODS

2.1 Data processing

The software was developed aiming to track the contour of the cardiac valve's cusps in each frame of the videos generated by the simulation. Python programming language was used to create the code. Among the main libraries used for the project development, NumPy, OpenCV, and Pandas can be mentioned. NumPy is a fundamental library for scientific computing in Python. It is used for efficient manipulation and processing of numerical data, particularly useful for calculations involving large datasets, matrices, and advanced mathematical operations. OpenCV is a popular library for computer vision and images, offering a wide range of functions and algorithms for capturing, processing and analyzing images and videos. Lastly, Pandas is a data analysis library that provides data structures to facilitate organization, filtering, aggregation, and analysis of data.

The general approach of the code consists of delimiting the annular diameter of the valve and marking its center. Then, the image was processed with filters so that the program could detect edges in the valve image. Extracting edges effectively to reduce noise is crucial for image processing, which can significantly reduce the calculations to be performed (Singh and Gupta, 2023). The program delimited each of the three leaflets of the valve, and in each delimited region, lines of equal spacing were drawn, connecting the center of the circle to the nearest edge. The lines were of different colors for each region. The program also allows the user to choose the number of lines they want to be drawn for each leaflet. This allowed us to obtain organized information about the various degrees of freedom of each cusp for further analysis. The number of lines and the spacing angle between the lines were determined by the program based on this choice and then drawn on the frames when the video was displayed. The Figure 1 shows a flowchart of the created code.

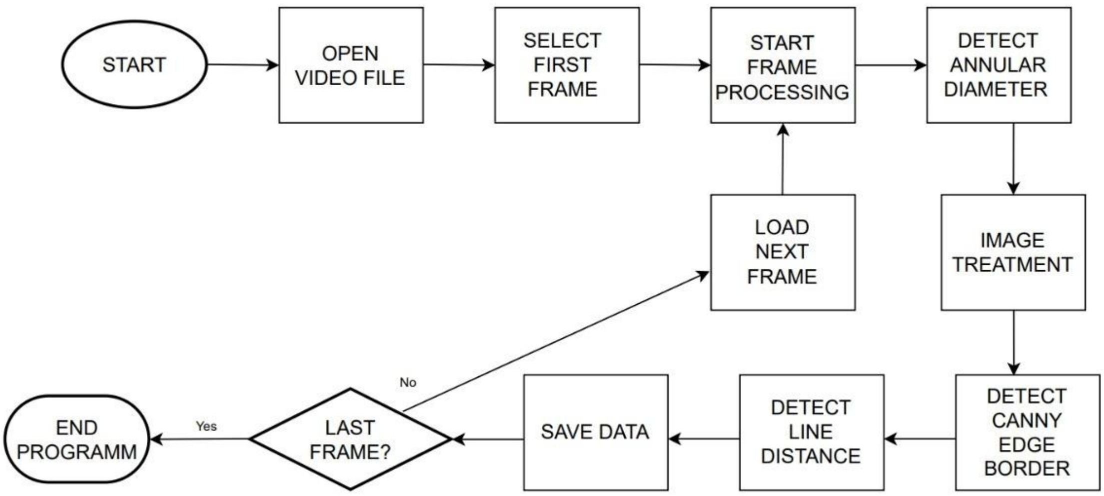

Figure 1. Workflow of the algorithm used for the program

2.2 Image treatment

Each frame of the simulation video underwent a series of filters and image manipulations. Firstly, a specific region of interest (ROI) was delimited using an elliptical mask with a 1-degree amplitude and a radius proportional to the valve's radius. A cropping was done for each number of lines stipulated by the user. Next, the cropped region was color-filtered to obtain only the red tones in the image, which corresponded to the coloration of the leaflet edges in the simulation for identification by the software. Image segmentation represents a fundamental process in computer vision and medical image analysis, and image segmentation algorithms, specifically edge detection algorithms, have been widely used in various applications in the past decade to extract features from images (Milavonic et al., 2019).

After the image manipulations, only white points were obtained, representing the edges of the leaflets found by the software. Figure 2a shows a frame of the valve simulation with its edges colored in red by the ANSYS software. Figure 2b illustrates one of the angular cuts made in the frame, and Figure 2c depicts the frame displayed after the program execution for one of the simulation videos used to validate the software.

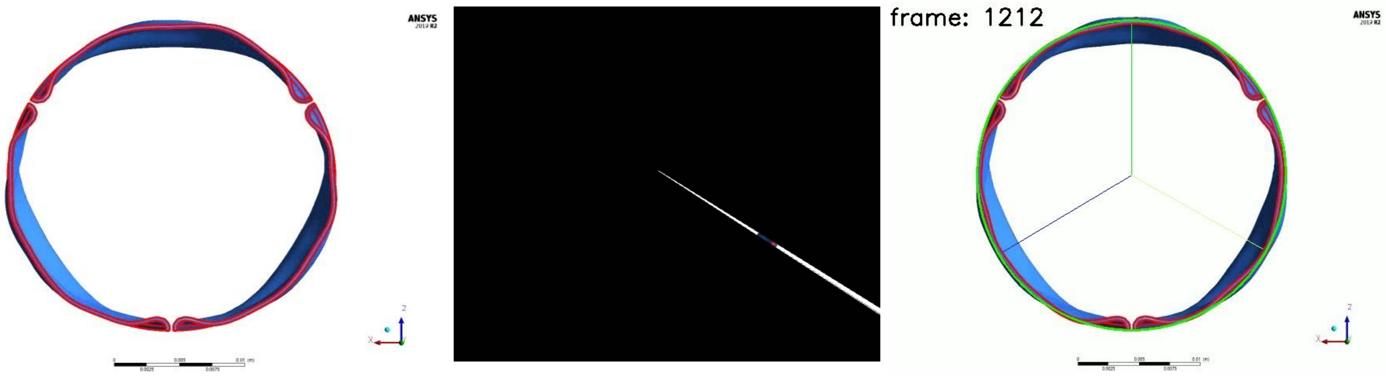

Figure 2. (a) Frame of the valve simulation. (b) 1-degree angular cut of one of the valve leaflets performed by the software. (c) Frame of the result after the program execution. The green, blue and yellow lines represent the distance between the center of the valve and the edge of each leaflet.

2.3 Software validation

In the initial software validation process, simulations were performed to obtain the radial displacements of the leaflet's tips using the Ansys Mechanical Software. All data were extracted from videos generated by these simulations, where the edges of the leaflets were highlighted in red to be used as a detection point for the program.

The geometry of the aortic valve used in this study was developed based on a geometry available in the literature in the work of Abbasi and Azadani (2020), which describes the step-by-step process for its acquisition. Figure 3 illustrates the developed geometry, considering an internal diameter of 25 mm, a protrusion height of 13 mm, and a leaflet thickness of 0.3 mm (Chen and Luo, 2020; Lee et al., 2020).

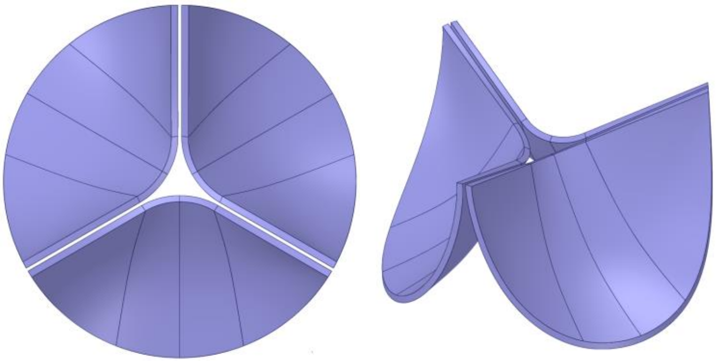

Figure 3. Developed geometry for the simulations

The numerical calculations were performed using the ANSYS-Mechanical® software (ANSYS-Mechanical Inc., Lebanon, NH, USA). Transient simulations were conducted with a time step of 1x10-4, as this time step is suficiente for evaluating the flutter of the leaflets (Ìasbeck, 2019). For the constitutive behaviour was considered the strain energy function following the first-order Ogden model, Equation (1).

$$W = \frac{\mu}{\alpha}(\lambda_1^{\alpha} + \lambda_2^{\alpha} + \lambda_3^{\alpha} - 1) + \frac{1}{2}K(J-1)^2, \quad (1)$$

where W is the strain energy function, λ_1, λ_2 and λ_3 are the principal stretches of the Cauchy-Green tensor, K is the Bulk modulus, $J = \lambda_1\lambda_2\lambda_3$ and μ and α are model constants. The values $\mu = 59{,}782.4$ and $\alpha = 12.97$, $J \approx 1$ and a density of 1100 kg/m3 were used (Joda et al., 2016, Borowski et al., 2022). The frictionless contact was defined between the leaflet's surfaces facing the left ventricle between the leaflets (Pasta et al., 2020, Emendi et al., 2020), and the Augmented Lagrange method with a normal stifness of 0.1 was chosen, which is recommended for problems where bending is dominant (Ansys, 2022). Fixed supports were applied on the sides of the leaflets, and a constant pressure of 1020 Pa was applied on the surfaces facing the left ventricule, corresponding to the systolic peak transvalvular pressure from the work of Tang et al. (2018). The Newmark method was selected for temporal discretization, and the Newton-Raphson method was used to linearize and solve the linearized equations.

For the mesh convergence test, static structural simulations were performed on three different meshes, and the chosen mesh had 11628 nodes and 7322 elements since the displacements at the leaflet tips ant the maximum principal stress in the computational domain had a relative error less than 5% between the finest meshes.

3. RESULTS AND DISCUSSION

As discussed, after the software development, it was validated using computational simulation videos generated by the ANSYS software. A graph was plotted comparing the leaflet opening radius obtained by the simulation program and measured by the developed software. Figure 4a illustrates this comparison for the line tracking the leaflet movement at 60 degrees. By comparing the simulation and the results, a relative error to the simulation of 0.0525% was obtained, considering the comparison of approximately 6000 points. Since the relative error is too small to be visualized, an approximation on the main peaks of the leaflet displacement plot was performed and can be visualized in Figure 4b. Figure 4c shows the discrepancy beetween the edges detected by the programm and the actual edges, which causes the relative error mentioned. Since the simulation is performed with a three-dimensional valve, the error is generated by a rear part of the valve that is mistakenly detected by the program as an edge. Once the software is used to analyse the frames of the videos recorded by the high-speed camera on the experimental bench, it is expected that this error will no longer be observed, since the image captured by the camera will show the valve as a two-dimensional object.

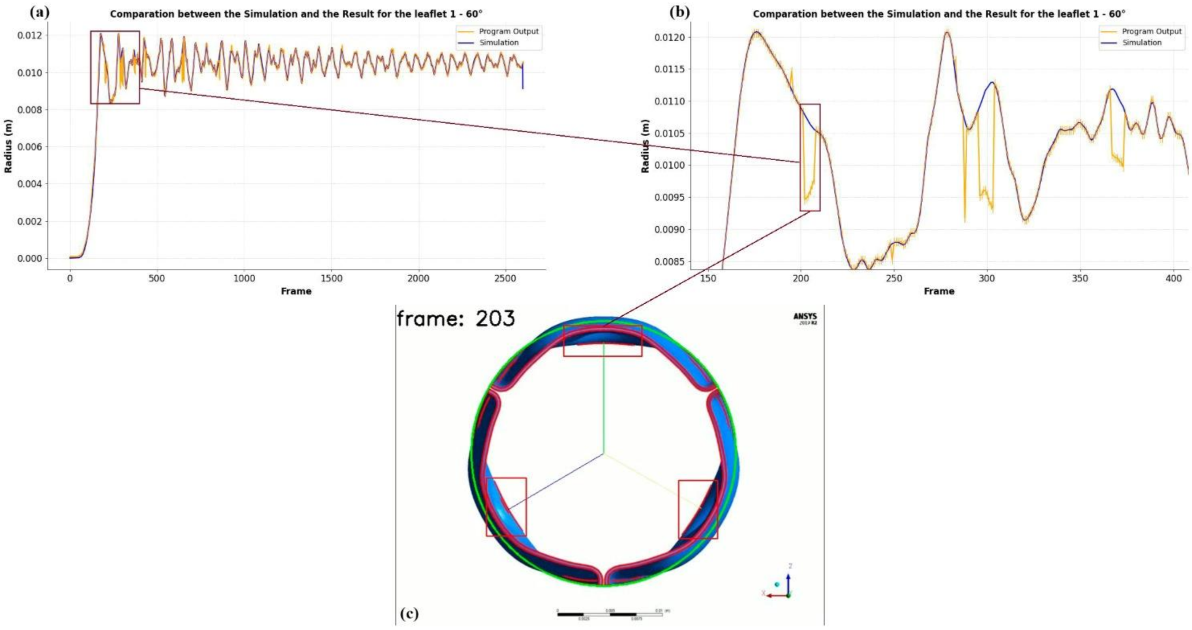

Figure 4. (a) Comparison of the leaflet opening radius at 60 degrees. (b) Main peaks of discrepancy between the software analysis and the simulation. (c) Error in the edge detection

The data obtained by the program from the simulation was processed using a code that utilizes Fast Fourier Transform (FFT), capable of extracting the frequencies from a given signal to identify the dominant frequencies. The displacement signal during systole (valve open) was selected (Iásbeck, 2019). FFT graphs were plotted for each leaflet of the valve, and through the transform, it was possible to obtain the predominant frequencies of the system, along with their respective amplitudes. The values obtained by the program were compared to those generated by the simulation itself, which was used for software validation.

Figure 5a presents the results obtained from the software for the analysis of the first leaflet, delimited between 0 and 120 degrees. The three most significant frequencies found were 237.08Hz, 368.01Hz and 530.69 Hz, with peak amplitudes of 0.00010m, 0.00047m and 0.00019m, respectively. In sequency, Figure 5b presents the results obtained for the analysis of the second leaflet, delimited between 120 and 240 degrees. The three most significant frequencies found were 239.29Hz, 367.82Hz and 530.18Hz, with peak amplitudes of 0.00015m, 0.00047m and 0.00015m, respectively. Finally, Figure 5c presents the results obtained for the analysis of the third leaflet, delimited between 0 and 120 degrees. The three most significant frequencies found were 237.99Hz, 367.22 Hz and 531.03Hz, with peak amplitudes of 0.00013m, 0.00045m and 0.00021m, respectively.

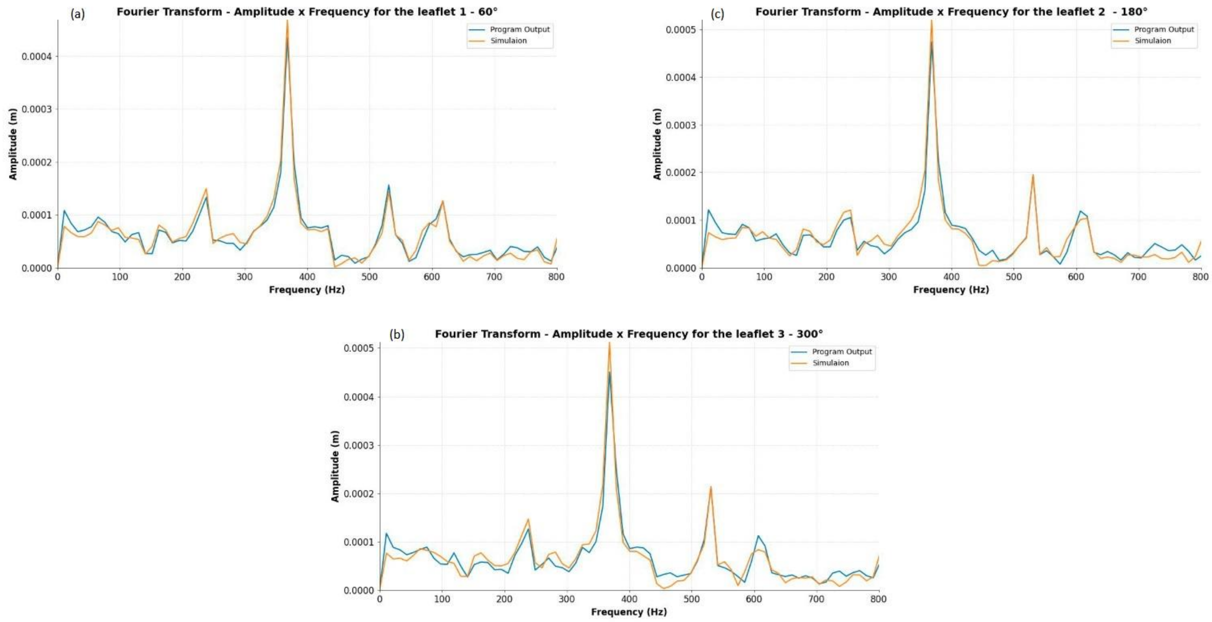

Figure 5. (a) FFT for the first leaflet, at degree 60. (b) FFT for the second leaflet, at degree 180. (c) FFT for the third leaflet, at degree 300.

The Table 1 shows the comparison of the 3 predominant frequencies and their respective amplitudes found by both the software and the computational simulation, for each of the 3 leaflets. The values found by the software are very close with the values taken from the simulation itself in ANSYS, as it can be seen in Table 1. These values are also similar to those found in previous works on the area, such as that of Iásbeck (2019) in the analysis of flutter in cardiac valves.

Table 1. Comparison between the simulation and the software results

Leaflet	Frequencies (Hz) (Simulation in ANSYS)	Amplitude (m) (Simulation in ANSYS)	Frequencies (Hz) (Software)	Amplitude (m) (Software)
First leaflet, at degree 60	238.41	0.00015	237.41	0.00013
	368.30	0.00047	368.20	0.00043
	530.47	0.00014	530.07	0.00016
Second leaflet, at degree 180	232.41	0.00019	238.05	0.0001
	368.18	0.00052	368.43	0.00047
	530.47	0.00014	530.13	0.00019
Third leaflet, at degree 300	238.88	0.00014	237.44	0.00013
	368.16	0.00051	367.63	0.00045
	531.17	0.00021	530.83	0.00021

For further analysis, the mean absolute percentage error (MAPE) was calculated for each leaflet, as presented in Table 2. Then an arithmetic average of the three values was taken as the mean absolute percentage error for the entire valve, and a value equal to 0.57% was found.

Table 2. Mean Absolute Percentage Error (MAPE)

Leaflet	Mean Absolute Percentage Error (%)
First leaflet, at degree 60	0,37
Second leaflet, at degree 180	0,72
Third leaflet, at degree 300	0,61

4. CONCLUSION

Meeting the objectives of the work, it was possible to develop a program in Python for parameterization of high-speed filming images of cardiac valve leaflets, with a mean absolute percentage error of 0,57% for the entire valve. Since the validated software is intendent to be further applied in the analysis of the video frames obtained from an experimental bench, it is expected that the software will provide accurate data, especially since the valve filmed on the bench will be analyzed as a bidimensional object. One way to improve the software in the future would be to develop other ways for the user to interact with the program to make other desired measurements and calculations, for instance the opening area of the valve.

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