Numerical simulation of Bileaflet Mechanical Heart Valves using fluid-structure interaction

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I. Introduction

Because of their long life span and durability, Bileaflet Mechanical Heart Valves (BMHV) are preferred for valve replacement. However, current BMHV designs induce calcification and thromboembolism, which is believed due to non-physiological flow and turbulence generated by the valve leaflets. Therefore, numerical flow simulations can provide relevant information for optimization.

When simulating heart valves, the motion of the fluid, the movement of the leaflet walls and their interaction need to be taken into account. This can be done by fluid-structure interaction (FSI). In the past, an FSI algorithm with one degree of freedom was developed, supposing that the two leaflets perform the same motion. In this paper, an algorithm with two degrees of freedom is presented, which allows an asynchronous motion of the two leaflets. The algorithm is extended to perform a correct leaflet movement at closed and opened position. Subsequently, the convergence process is fasted by the use of an adaptive time step size and extrapolation techniques. Finally, the algorithm is tested for two 3D cases and the results are discussed.

II. FSI Algorithm

The FSI algorithm is based on the ALE approach, which implies that the grid follows the motion of the structure and subsequently needs an update. Because this exact motion is a priori unknown, a coupling algorithm is necessary. The flow diagram of the algorithm is visualized in Figure 1. The implementation in FLUENT is done by journal files (to solve the flow problem) and UDFs (to simulate the structural part). They interact with each other and thus perform FSI.

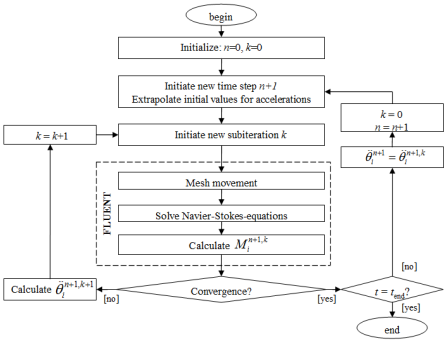

Figure 1: Simplified flowchart.

A bileaflet heart valve can be modeled as a rigid casing wherein two separate rigid leaflets can rotate around their hinges. The position of each leaflet is solely determined by its opening angle, which implies that the bileaflet valve has two degrees of freedom.

The movement of a rigid leaflet i is governed by the equilibrium between the pressure (and viscous) moment M_i around its hinge and the product of its angular acceleration $\ddot{\theta}_i$ with its moment of inertia I_i:

$$\begin{cases} M_1 = I_1 \cdot \ddot{\theta}_1 \\ M_2 = I_2 \cdot \ddot{\theta}_2 \end{cases} \quad (1)$$

In the past, an implicit coupling algorithm was found to be necessary. So for each time step, implicitness between the subiterations is needed to obtain fast convergence. Therefore,

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in each subiteration k+1 of a time step n+1, eq. (1) is linearized, taking into account the mutual interaction between the leaflets:

$$\begin{cases} M_1^{n+1,k} + \frac{dM_1}{d\theta_1}\left(\ddot{\theta}_1^{n+1,k+1} - \ddot{\theta}_1^{n+1,k}\right) + \frac{dM_1}{d\theta_2}\left(\ddot{\theta}_2^{n+1,k+1} - \ddot{\theta}_2^{n+1,k}\right) = I_1 \cdot \ddot{\theta}_1^{n+1,k+1} \\ M_2^{n+1,k} + \frac{dM_2}{d\theta_1}\left(\ddot{\theta}_1^{n+1,k+1} - \ddot{\theta}_1^{n+1,k}\right) + \frac{dM_2}{d\theta_2}\left(\ddot{\theta}_2^{n+1,k+1} - \ddot{\theta}_2^{n+1,k}\right) = I_2 \cdot \ddot{\theta}_2^{n+1,k+1} \end{cases} \quad (2)$$

Because the Jacobian is unknown when using a black box solver, these derivatives will be approximated by finite differences. For doing this, three subiterations are needed within a time step. The first subiteration (k=1) is the reference. In the second and third subiteration (k=2 and k=3) a small perturbation δ is given to one of the angular accelerations. The derivatives can now be estimated. For example:

$$\frac{dM_1}{d\ddot{\theta}_2} \approx \frac{\Delta M_1}{\Delta \ddot{\theta}_2} = \frac{M_1^{n+1,k=3} - M_1^{n+1,k=1}}{\delta} \quad (3)$$

For the subsequent subiterations (k>3) the next angular accelerations are calculated from eq. (2), until convergence is achieved.

The convergence process (within a time step) is speeded up by extrapolation of the accelerations and the Jacobian, taken from previous time steps. This makes that the recalculation of a new Jacobian is not necesarry at every time step. In summary:

- k=0: extrapolation of accelerations
- k=1: accel. from eq.2 with extrapolated Jac.
- k=2: perturbate leaflet 1
- k=3: perturbate leaflet 2
- k>3: accel. from eq.2 with the new Jacobian

Also, the time step size is made dependable of the maximum mesh motion, allowing a larger time step when leaflet motion is small.

III. Results

The algorithm is used to simulate two 3D cases containing an ATS Open Pivot BMHV. One geometry consists of a rigid straight tube. The second geometry is made asymmetrical by placing Valsalva Sinuses downstream of the valve. Blood is used as working fluid. A pressure outlet and a cyclic aortic flow pulse inlet (Figure 3) are applied at the boundaries.

The results are visualised in Figure 2 and 3. It clearly shows that the leaflets in the asymmetrical "Sinuses" geometry perform an asynchronous movement.

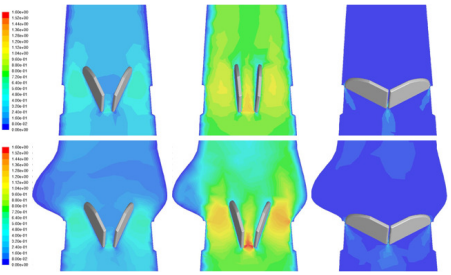

Figure 2: Velocity magnitude contour on longitudinal section (perpendicular on rotation axes), taken at different time. **Up**: Tube; **Down:** Sinuses geometry; **Left**: at 0.03s; **Middle**: at 0.125s; **Right**: at 0.75s.

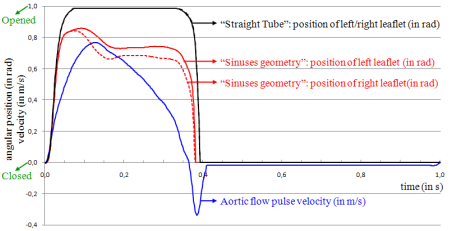

Figure 3: Position of leaflets and aortic flow

IV. Conclusions

An asymmetrical geometry can induce differences in leaflet motion. An algorithm with two degrees of freedom is thus preferred.

The use of an adaptive time step size significantly lowers the number of time steps per time cycle. By extrapolating the accelerations and Jacobian, the number of subiterations per time step can be reduced.

Acknowledgements

Sebastiaan Annerel is funded by a BOF-grant (Special Research Fund) from Ghent University Association.

References

[1] S. Annerel, J. Degroote, J. Vierendeels, *Fluid-Structure Interaction Algorithm for the Simulation of a Bileaflet Prosthetic Heart Valve,* Proceedings of NCTAM2009, 2009.