# ALE 기법을 기반으로 한 FSI 알고리즘을 이용한 이엽기계식심장판막에서의 혈류유동해석

# Numerical Investigation of Hemodynamics Characteristics in a Bileaflet Mechanical Heart Valve using an Implicit Fluid-Structure Interaction (FSI) Method based on the Arbitrary-Lagrangian-Eulerian (ALE) approach

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## 1. Introduction

Human heart valves diseased by congenital heart defects, rheumatic fever, bacterial infection, cancer may cause stenosis or insufficiency in the valves. Treatment may be with medication but often involves valve repair or replacement (insertion of an artificial heart valve). Bileaflet mechanical heart valves (BMHVs) are widely implanted to replace the diseased heart valves, but still suffer from complications such as hemolysis, platelet activation, tissue overgrowth and device failure. These complications are closely related to both flow characteristics through the valves and leaflet dynamics.

*In vivo* and *in vitro* experimental studies have yielded valuable information on the relationship between hemodynamic stresses and the problems associated with the implants. Recently, Computational Fluid Dynamics (CFD) has emerged as a promising tool, which, alongside experimentation, can yield insights of unprecedented detail into the hemodynamics of prosthetic heart valves. For CFD to realize its full potential, however, it must rely on numerical techniques that can handle the enormous geometrical complexities of prosthetic devices with spatial and temporal resolution sufficiently high to accurately capture all hemodynamically relevant scales of motion. Such algorithms do not exist yet.

The aim of this study is to develop a Fluid-Structure Interaction (FSI) model using the moving-grid method with remeshing techniques, based on the Arbitrary Lagrangian Eulerian (ALE) approach for the physical interactions of MHVs, to investigate flows interacting with moving leaflets and to obtain guidance for further studies. In this study, the physiological flow interacting with the moving leaflets in a bileaflet mechanical heart valve (BMHV) is simulated with a strongly coupled implicit fluid-structure interaction (FSI) method which is newly organized based on the Arbitrary-Lagrangian-Eulerian (ALE) approach and the dynamic mesh method (remeshing) of FLUENT. The simulated results are in good agreement with previous experimental studies. This study shows the applicability of the present FSI model to the complicated physics interacting between fluid flow and moving boundary.

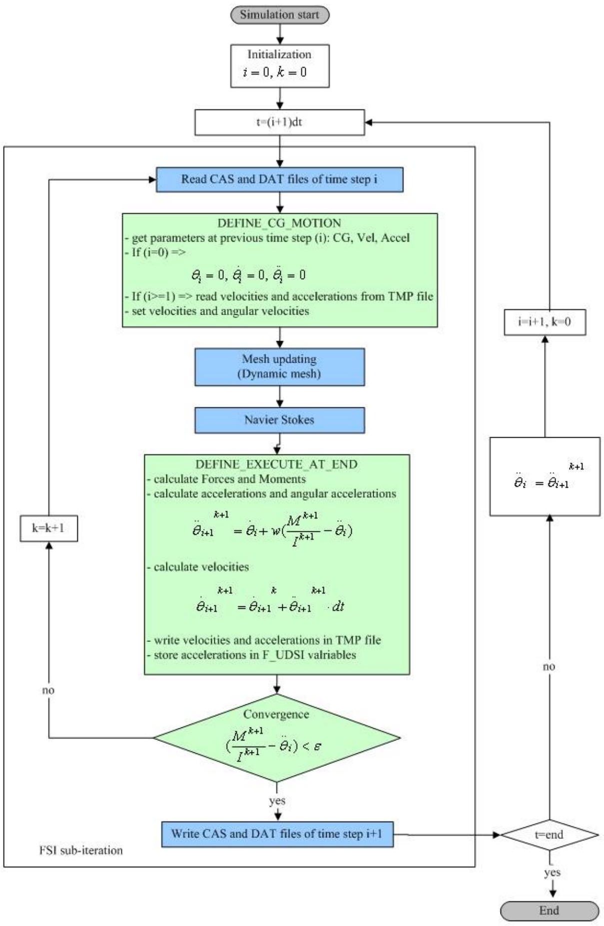

Fig. 1 Implicit coupling scheme of the fluid-structure interaction

## 2. Methods

The scheme of the coupling procedure of fluid-structure interaction employed in this study is shown in Fig. 1. As mentioned above, the fluid domain is solved using the finite volume method computational code Fluent (Ansys Inc., USA), which provides a number of features well suited to handle the specific problem of rotating boundaries. We will use a spring-based moving, deforming mesh module, which allows a robust mesh deformation handling by assuming that the mesh element edges behave like an idealized network of interconnected springs. In order to maximize the influence of the boundary node displacements on the motion of the interior nodes, no damping was applied to the springs. To preserve the quality of the mesh during the valve motion, the maximum admissible skewness of the computational cells is set. The Fluent remeshing algorithm is adopted to properly treat degenerated cells, which agglomerates cells that violate the skewness criterion, and locally remeshes the agglomerated cells. If the new cells satisfy the skewness criterion, the mesh is locally updated with the new cells (with the solution interpolated from the old cells); otherwise, the new cells are discarded (FLUENT Users Manual, 2007).

The moving deforming mesh module is used in conjunction with two user-defined subroutines, named DEFINE _EXECUTE_AT_END (moving body dynamics; MBD) and DEFINE_CG_ MOTION (center of gravity motion; CGM), respectively; at the beginning of each step the first one calculates and updates the kinematics of the leaflets on the basis of the moment applied to the leaflet, which is calculated by the second subroutine at the end of the time step, once the time step convergence has been achieved. An iterative call to the fluid solver is performed by an external subroutine in order to update the solution of the fluid dynamic field and achieve the convergence of the FSI cycle, until the difference between the external momentum divided by the inertia of the fluid (calculated by MBD) and the angular acceleration (imposed by CGM) is not below a threshold value. More in detail, since the valve leaflet is rigid body in rotation on a fixed pivot, the angular position is the only degree of freedom and leaflet dynamics can be calculated using:

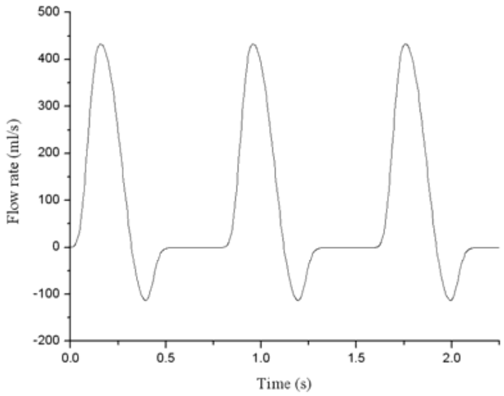

Fig. 2 Flow rate at the inlet

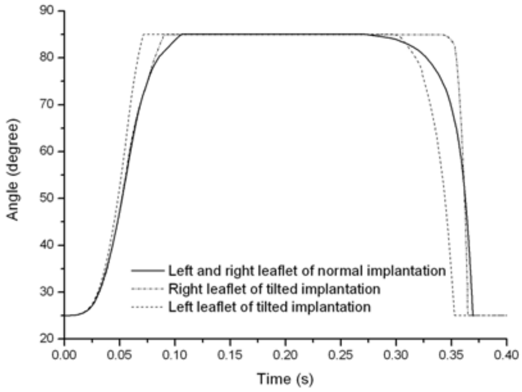

Fig. 3 Transient open angle

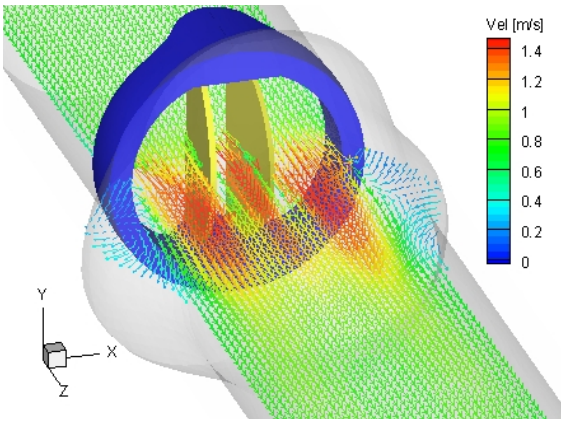

Fig. 4 Velocity field of the normal implantation at the peak flow rate

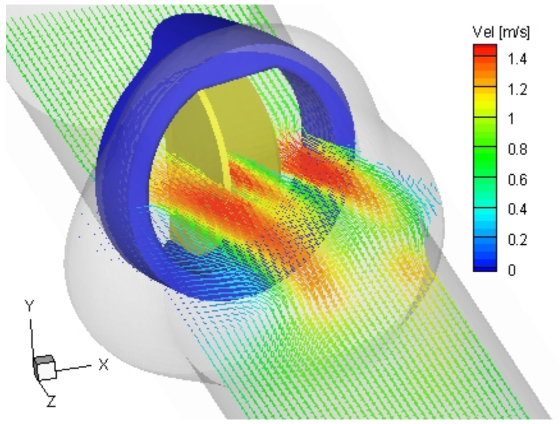

Fig. 5 Velocity field of the tilted implantation at the peak flow rate

$$I\ddot{\theta} = M_p + M_s \quad (1)$$

where I is the angular inertia, $\ddot{\theta}$ the angular acceleration of the leaflet, $M_p$ the torque applied on the leaflet external surface by the pressure field, and $M_s$ is the moment generated by shear stresses.

The acceleration value for the subsequent iteration within the generic time step i is updated through an under-relaxation scheme as

$$\ddot{\theta}_{i+1}^{k+1} = \dot{\theta}_i^{k} + w\left(\frac{M_p^{k+1} + M_s^{k+1}}{I^{k+1}} - \ddot{\theta}_i^{k}\right) \quad (2)$$

where k is the iteration index and w is the under-relaxation factor, which plays the role of damping changes in the acceleration produced during each iteration. Starting from the acceleration obtained in Eq. (2), the velocity and the displacement of the leaflet are calculated using the Newmark method.

## 3. Analysis model

The analysis model includes a BMHV and three sinuses. Ventricular and aortic vessels are assumed to be straight tracts. A three-dimensional model is made based on a 25 mm aortic BMHV of St. Jude Medical. The normal implantation ($0^o$) and tilted implantation ($20^o$) of the bileaflet MHVs are considered in the present study.

Blood is assumed to be an incompressible Newtonian fluid with a density of 1,000 kg/m$^3$ . The volume flow rate (Fig. 2) measured in *vitro* study (3) is imposed as the inlet condition (the ventricular side) and the pressure in the outlet is set to 0 mmHg. No-slip conditions are imposed for the walls. At the beginning of the calculation (t=0 s), the flow is assumed to be at rest and the valve is closed. The calculation is carried out over three cardiac cycles to confirm cyclic independence and this paper presents results from the third cycle.

## 4. Results and discussions

The leaflet behavior can be divided into four phases: opening, fully open, closing and fully closed phases (Fig. 3). Opening velocity quickly increases then decreases until the valve opens fully. Closing velocity exponentially increases in the opposite direction.
It is observed that, in the normal implantation the left and right leaflets behave symmetrically, while in the tilted implantation the left and right leaflets behave asymmetrically and, more specifically, the motion of the left leaflet precedes that of the right leaflet in the opening phase as well as in the closing phase.

The flow field shows symmetric flows and is divided into three streams: one central and two side streams. During the fully open phase, three jet-like streams are clearly observed because the leaflets functions as fixed obstacles (Fig. 4). Vortices formed in the sinus. In the tilted implantation, the blood flows is deflected to the right sinus and the blood flows through the right orifice much more than through the other orifices (Fig. 5).

## 5. Conclusions

A numerical simulation of three-dimensional, physiological flow interacting with the moving leaflets of the BMHV has successfully carried out. The predicted results have been in good agreement with available results in the literature. The applicability of the present FSI model in the complicated physics of the BMHV has been validated. The results are important for identifying approaches to further improve BMHV design and performance, and to provide guidelines for further studies.

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