Direct numerical simulation physiological flows through an idealized aortic heart valve
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Direct Numerical Simulation of physiological flows through an idealized aortic heart valve

Introduction to the physical problem
The aortic heart valve (AHV) ensures unidirectional blood flow from the left ventricle to the aorta during the cardiac cycle (fig. 1), while its proper function is essentially controlled by the surrounding haemodynamic environment (HE). Computational fluid dynamics (CFD) permit the resolution of HE at the microscale, overcoming some of the inherent limitations of experimental techniques [1]. However significant difficulties arise on practical level that usually limit simulations on moderate Reynolds numbers.

Objective of current work
To develop a new, efficient and robust finite element algorithm for the simulation of blood flow in HVs under physiological conditions throughout multiple cardiac cycles.

Physical model
Blood flows through a 2D stented AHV (fig. 2) of width \( w = 24 \text{ mm} \) and total length \( H = 4w \), under physiological conditions (fig. 3), due to a time-varying pressure gradient. It also exhibits non-Newtonian behavior that is described with the Carreau-Yasuda model [2], while its density is constant \( \rho_f = 10^3 \text{ kg/m}^3 \). Leaflets are assumed to behave as incompressible Neo-Hookean solids, with \( \rho_s = 1.2 \times 10^3 \text{ kg/m}^3 \), \( G = 3 \times 10^5 \text{ N/m}^2 \).

Numerical approximation
New numerical techniques (fig. 4) are introduced in the TFEM package [3] to alleviate reported difficulties [1,4], associated with accuracy and stability of calculations at high Reynolds numbers: \( Re_{\text{peak}} = \rho_f U_{\text{peak}} (w/2)/\eta_f \approx 4,000 \). A high resolution approximation with \( h = \delta_{\text{min}} = 0.05 \text{ mm} \) is used (fig. 2) to accurately capture the Taylor microscales \( \delta_{\chi_t} = w(10/Re_{\text{peak}})^{1/2} = 1.2 \text{ mm} \) and approach to the Kolmogorov ones \( \delta_{\chi_k} = w Re_{\text{peak}}^{-3/4} = 0.05 \text{ mm} \).

Results
The instantaneous flow fields downstream of the leaflets exhibit very rich dynamics (fig. 5). During the acceleration phase, flow is dominated by large-scale, coherent instabilities and organised unsteadiness associated with the roll up of the valve shear layer into the aortic sinus.

Work in Progress
• Extension of the proposed methodology to 3D
• Introduction an XFEM approximation for the coupling of the fluid and the elastic solid

Conclusions
We have developed a new algorithm for the direct numerical simulation (DNS) of pulsatile flows through an AHV at very high Reynolds number \( (Re_{\text{peak}} \approx 4,000) \), which is able to predict the deformation of the leaflets even during the closure stage.

References