Fluid-Structure Interaction Simulation of Artificial Aortic Heart Valves in the Cloud

An UberCloud Experiment for the Living Heart Project

With Support From:

UberCloud Case Study 215

http://www.TheUberCloud.com

May 30, 2019

Welcome!

The UberCloud* Experiment started in July 2012, with a discussion about cloud adoption in technical computing and a list of technical and cloud computing challenges and potential solutions. We decided to explore these challenges further, hands-on, and the idea of the UberCloud Experiment was born, then also due to the excellent support from INTEL generously sponsoring these experiments since the early days!

We found that especially small and medium enterprises in digital manufacturing would strongly benefit from technical computing in HPC centers and in the cloud. By gaining access on demand from their desktop workstations to additional and more powerful compute resources in the cloud, their major benefits became clear: the **agility** gained by shortening product design cycles through shorter simulation times; the superior **quality** achieved by simulating more sophisticated geometries and physics and by running many more iterations to look for the best product design; and the **cost** benefit by only paying for what is really used. These are benefits that obviously increase a company's innovation and competitiveness.

Tangible benefits like these make computing - and more specifically technical computing as a service in the cloud - very attractive. But how far are we from an ideal cloud model for engineers and scientists? At first, we didn't know. We were facing challenges like security, privacy, and trust; traditional software licensing models; slow data transfer; uncertain cost & ROI; lack of standardization, transparency, cloud expertise. However, in the course of this experiment, as we followed each of the 197 teams closely and monitored their challenges and progress, we've got an excellent insight into these roadblocks, how our teams have tackled them, and how we are now able to reduce or even fully resolve them.

This UberCloud Experiment #2015 about "Fluid-Structure Interaction Simulation of Artificial Aortic Heart Valves with Abaqus 2019 in the Cloud" has been performed by enmodes GmbH, a worldwide service provider in the field of medical technology with special expertise in the field of conception, research and development of medical devices. Enmodes has been supported by Dassault Systèmes SIMULIA, Advania Data Centers, and UberCloud, and sponsored by Hewlett Packard Enterprise and Intel. It is based on the development of Dassault's Living Heart Model.

We want to thank all team members for their continuous commitment and contribution to this project. And we want to thank our main sponsors **Hewlett Packard Enterprise** and **INTEL** for generously supporting this #215 UberCloud experiment.

Now, enjoy reading!

Wolfgang Gentzsch and Burak Yenier

**) UberCloud is the online community & marketplace where engineers and scientists discover, try, and buy Computing Power as a Service, on demand. Engineers and scientists can explore and discuss how to use this computing power to solve their demanding problems, and to identify the roadblocks and solutions, with a crowd-sourcing approach, jointly with our engineering and scientific community. Learn more about the UberCloud at: http://www.TheUberCloud.com.*

Team 215

Fluid-Structure Interaction of Artificial Aortic Heart Valves in the Cloud

"We were able to easily access our complex FSI workflow hosted in UberCloud's Abaqus/FlowVision container on sufficient HPC cloud resources to study artificial aortic heart valves in a reasonable amount of time. With our local machines, with just 32 CPU cores, these simulations would have been simply impossible."

MEET THE TEAM

End User – Deepanshu Sodhani, R&D Project Manager for Engineering, Modeling and Design at enmodes GmbH.
Abaqus Software Provider – April Deady, Steve Levine, Karl D'Souza, Dassault Systèmes, providing Abaqus 2019 software and support.
FlowVision Software Provider – Igor Moskalev and Victor Akimov, FlowVision Russia, Sinan Soğancı, Capvidia, providing FlowVision software and support.
Cloud Resource Provider –Aegir Magnusson, Jon Tor Kristinsson, Advania Data Centers, with access and support for the HPC server from HPE.
HPC Cloud Experts – Hilal Zitouni, Ronald Zilkovski, and Ender Guler at the UberCloud In., providing novel HPC container technology for ease of Abaqus and FlowVision cloud access and use.
Project Manager – Reha Senturk and Wolfgang Gentzsch at the UberCloud Inc.
Sponsor – Hewlett Packard Enterprise and Intel, represented by Bill Mannel, and Jean-Luc Assor, HPE.

THE LIVING HEART PROJECT

The Living Heart Project (LHP) is uniting leading cardiovascular researchers, educators, medical device developers, regulatory agencies, and practicing cardiologists around the world on a shared mission to develop and validate highly accurate personalized digital human heart models. These models will establish a unified foundation for cardiovascular in silico medicine and serve as a common technology base for education and training, medical device design, testing, clinical diagnosis and regulatory science —creating an effective path for rapidly translating current and future cutting-edge innovations directly into improved patient care. For more details about the LHP see the LHP Website.

USE CASE

As part of the Living Heart Project (LHP), this cloud experiment has been performed by enmodes GmbH, a worldwide service provider in the field of medical technology with special expertise in the field of conception, research and development of medical devices. In this project, enmodes has been supported by Dassault Systèmes SIMULIA, Capvidia/FlowVision, Advania Data Centers, and UberCloud, and sponsored by Hewlett Packard Enterprise and Intel. It is based on the development of Dassault's Living Heart Model applied to Fluid-Structure Interaction of Artificial Aortic Heart Valves.

Two of the most common and most serious valve disease problems are aortic stenosis and aortic regurgitation, see Figure 1. Aortic Stenosis (AS) is a narrowing of the aortic valve opening. AS restricts the blood flow from the left ventricle to the aorta and may also affect the pressure in the left atrium. Aortic Regurgitation (AR) is the diastolic flow of blood from the aorta into the left ventricle (LV). Regurgitation is due to the incompetence of the aortic valve or any disturbance of the valvular apparatus (e.g., leaflets, the annulus of the aorta) resulting in the diastolic flow of blood into the left ventricular chamber.

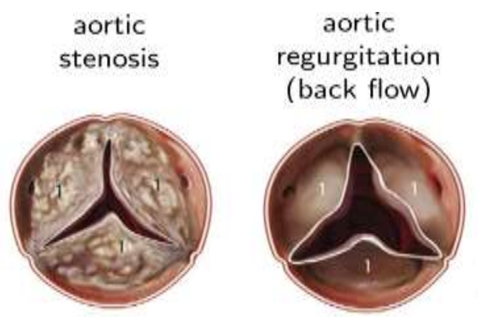

Figure 1: The problem, aortic Stenosis (AS) and aortic regurgitation.

Transcatheter aortic valve replacement (TAVR) was deemed a disruptive medical technology since its first implantation in a patient was performed in 2002. Initially, it was used only in high-risk patient deemed unfit to receive surgical valves (bioprosthetic or mechanical) through open heart surgery. Until recently, TAVR was not routinely recommended for low-risk patients in favour of surgical aortic valve replacement, however, based on recent studies showing it to be non-inferior to surgical aortic valve replacement, it is increasingly being offered to intermediate risk patients. This has resulted in a significant increase in the use of TAVR devices worldwide springing more companies to come up with innovative devices and therapies.

Despite tremendous growth in its usage, the therapy is still expensive and remains elusive in developing countries. This is because the development of these devices is expensive, due to extensive lab tests and animal studies. Adding to this, the success of the device in a patient depends extensively on the experience of the cardiac surgeon. So far, there does not exist any patient-specific approach to assist the surgeons in evaluating the many implants available in clinical use for their structural and hemodynamic compatibility with the patient's anatomy. Although, recent studies have shown that the current generation of devices resolves many hemodynamic issues of these devices like paravalvular leakage, in many cases lead to thrombogenicity. This is primarily attributed to stagnation of blood around the valve, which is, in turn, a result of the prosthesis interaction with the native anatomy.

Advances in anatomical imaging coupled with numerical simulations in the field of cardiovascular medical technology can not only assist the surgeons by evaluating the clinically available devices in virtual native anatomy of the patient, but also reduce the development cycles of these devices. The body of work in this direction is rapidly growing, despite the limitations of the available computational tools and computing power. There does not exist one numerical tool/methodology that can cater to the complex multi-physics problem of fluid-structure interaction of native and prosthetic valves in its entirety. Hence, a combination of different computational fluid and solid solvers are coupled together to tackle such problems. The other contributing factor in the development of numerical tools is the availability of computing power. Growth in on-demand cloud-based computing technologies is significantly assisting in the rapid development of such numerical tools that can assist the surgeons.

FLUID-STRUCTURE INTERACTION MODELLING OF ARTIFICIAL VALVES

In this work, we focus our attention on the complex multi-physics fluid-structure interaction (FSI) problem, where the developed simulation model is intended for the better understanding of the dynamic behaviour of the valve and its effect on hemodynamics. A high-fidelity numerical model was used for this purpose. A simplified structural model of the bench test (Figure 2 - where a valve is placed in an ideal tubular aorta in a flow loop replicating the flow conditions from the left ventricle to the aorta) was created for the numerical analysis (Figure 3).

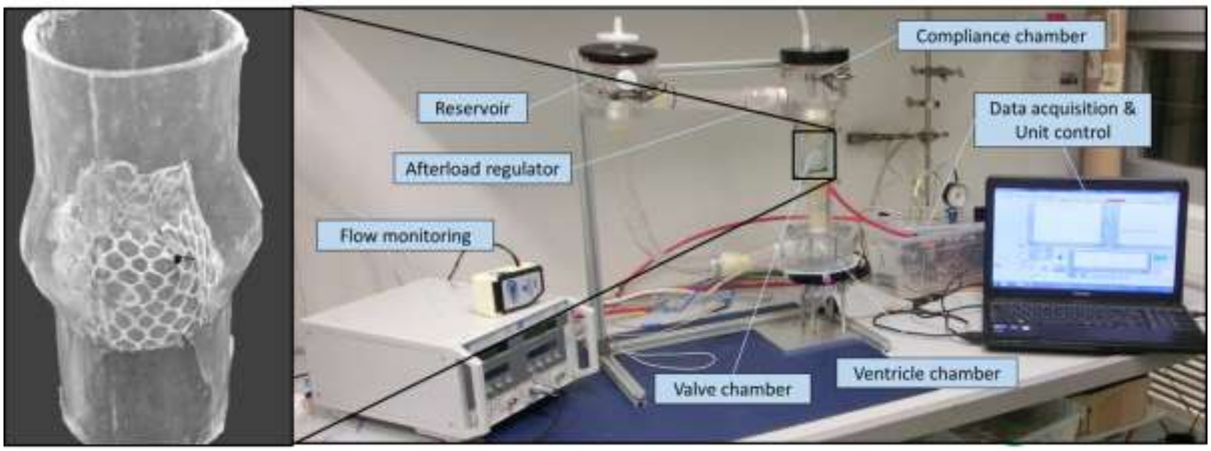

Figure 2: Bench test; flow loop for testing the behaviour of artificial textile reinforced aortic valve in ideal silicone-based aorta.

Bench test boundary conditions were applied. The simulation setup with the structural parts, domain definitions, contact and boundary conditions are shown in Figure 3.

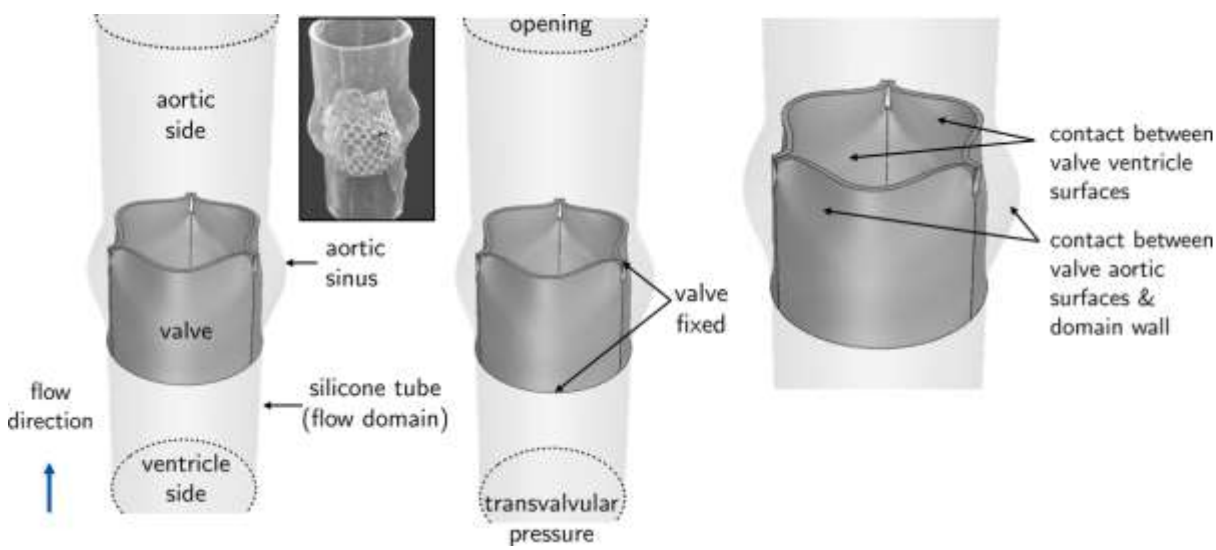

Figure 3: FSI Simulation setup with domain definitions, boundary & contact conditions.

The FSI simulation model was computed on the cloud computing services provided by UberCloud, using Abaqus from Simulia as the structural solver and FlowVision from Capvidia as the fluid solver. The numerical computations were analysed for their scalability in terms of speedup with respect to increase in computing resources. The model was further evaluated to predict the risk parameters to understand the correlation between the level of fidelity and resulting accuracy by carrying out a mesh convergence study over three fluid domain mesh densities. The valve was modelled using approx. 90000 finite elements, whereas the fluid domain, was modelled using approx. 300,000 (mesh 1), 900,000 (mesh 2) and 2,700,000 (mesh 3) finite volume cells.

SIMULATION ENVIRONMENT AND RESULTS

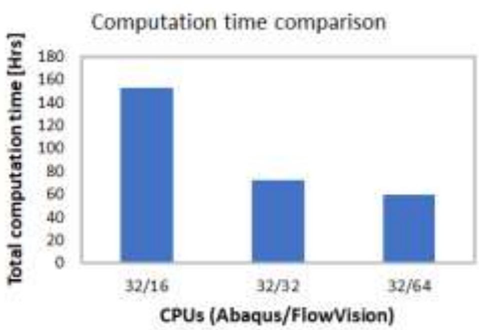

Figure 4: Scalability of FSI simulations.

In the first phase of the project, simulation scalability studies were carried out to evaluate the speed-up in the simulations. The Abaqus explicit structural solver for evaluating the valve was simulated with 32 CPUs and the FlowVision fluid solver for evaluating the hemodynamics with mesh 1 was tested using 16, 32 & 64 CPUs. The scalability of these simulations is reported in Figure 4. Using cloud computing resources, we were able to speed up the simulation for one heartbeat cycles by a factor of 5 (compared to our inhouse resources with a pairing of 16/16 CPUs), which then (still) took approx. 16 hours using a 32/64 CPU cores on Advania's HPC as a Service (HPCaaS) hardware configuration built upon HPE ProLiant servers XL230 Gen9 with 2x Intel Broadwell E5-2683 v4 with Intel OmniPath interconnect. For further evaluation of the simulation method we ran three simulations for analysing the effect of fluid mesh density on the accuracy of the simulation results. These simulations were carried out on 4 nodes with CPU allocation of 24/72 cores for structural and fluid parts. Such high mesh density FSI simulations were made possible in reasonable time due the on-demand availability of cloud computing resources.

Multi-physics simulations of this kind can generate tremendous amount of data. In this work we focus our attention on the hemodynamic performance of the valve, which can be accounted by the three most commonly used parameters namely Average Wall Shear Stress (S_a), Oscillatory Shear Index (OSI) and Retention Time (RT). Wall Shear Stress is represented by the time varying local signal S = S (x, t), exerted by the fluid flow on the valve walls. Leaflet wall-shear stress was computed for both sides of one leaflet (aortic and ventricular). The shear stress exerted by the fluid on the arterial wall, $S(\mathrm{x}, \mathrm{t})$, is defined as the tangential component of the traction vector τ_{f}, $S(\mathrm{x}, \mathrm{t}) = \tau_{\mathrm{f}}.\mathrm{t}_{\mathrm{f}}$, where τ_{f} is the tangent unit vector to the fluid domain in the current configuration and pointing in the mean direction of the fluid. The oscillatory shear index, OSI, characterizes the oscillatory nature or the directionality of the wall-shear stress (OSI = 0: purely unidirectional/pulsatile flow; OSI = 0.5: purely bi-directional/oscillatory flow) whereas S_a represents the average magnitude of the wall-shear stress over one heartbeat. The pulsatility and magnitude of the leaflet wall-shear stress was characterized over one heartbeat (T) of 0.86s. As it can be observed, OSI and S_a are insensitive to the magnitude and direction of the shear stress, respectively. Therefore, alternative indexes have been proposed in the recent literature, trying to extend the predictive power of OSI, e.g. the retention time (RT – equation shown in Figure 5). High values of this indicator is related to the presence of low and retrograde WSS signals and thus linked with the possible deposition and growth of the thrombus.

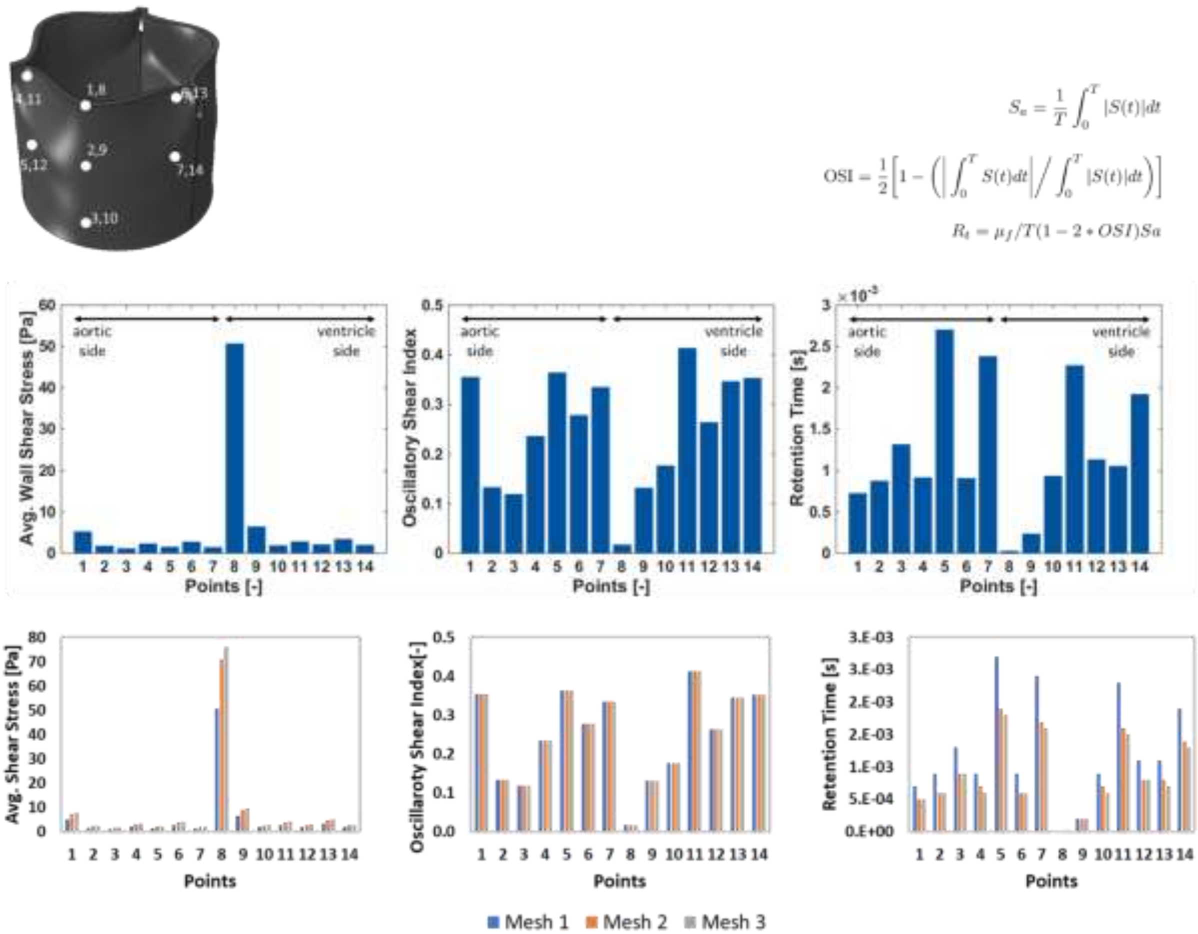

Figure 5: Zones for evaluation of the performance parameters; definition of the parameters; values of the parameters for mesh 1; comparison of the values for different meshes.

The parameters are evaluated on both aortic (P1-P7) and ventricular side of the valve (P8-P14) (see top left in Figure 5). Time-averaged wall shear stress (S_a) values within the seven distinct regions are reported in Figure 5. The high shear stresses (higher at P8 than at P1) are due to the high fluid velocities experienced by the centre points of leaflet edge due to incomplete closure of the valve. Also, the wall-shear stress magnitude predicted along the ventricle side is consistently higher than that computed along the aortic side. As expected, the leaflets experience the flow transitioning from unidirectional/pulsatile at the base to oscillating/recirculating at the belly and edge on the aortic side.

This is due to the presence of sinus of Valsalva in the computations, which assist in flow recirculation. Also, as the outlets from the sinus of Valsalva into the coronary arteries was not considered, the recirculation of the fluid persists for the entire duration of diastole. Contrary to this, the ventricle side mostly experiences a unidirectional flow which transitions into recirculating zones close to the stitch areas of the leaflets. But, as the retention time of the fluid is in the order of 10^{-3} s, risk of deposition and growth of thrombus are rather low, suggesting a good valve performance.

From the mesh convergence study, it can be further observed that on refining the mesh, the time averaged shear stress values are increasing at all the evaluation points on the valve, while the retention time decreases. These results suggest that even with almost 2.7 million elements, the simulation has still not reached a converged solution. Even though the inference of the results does not change with mesh refinement, further investigations on mesh density is needed to achieve a converged solution.

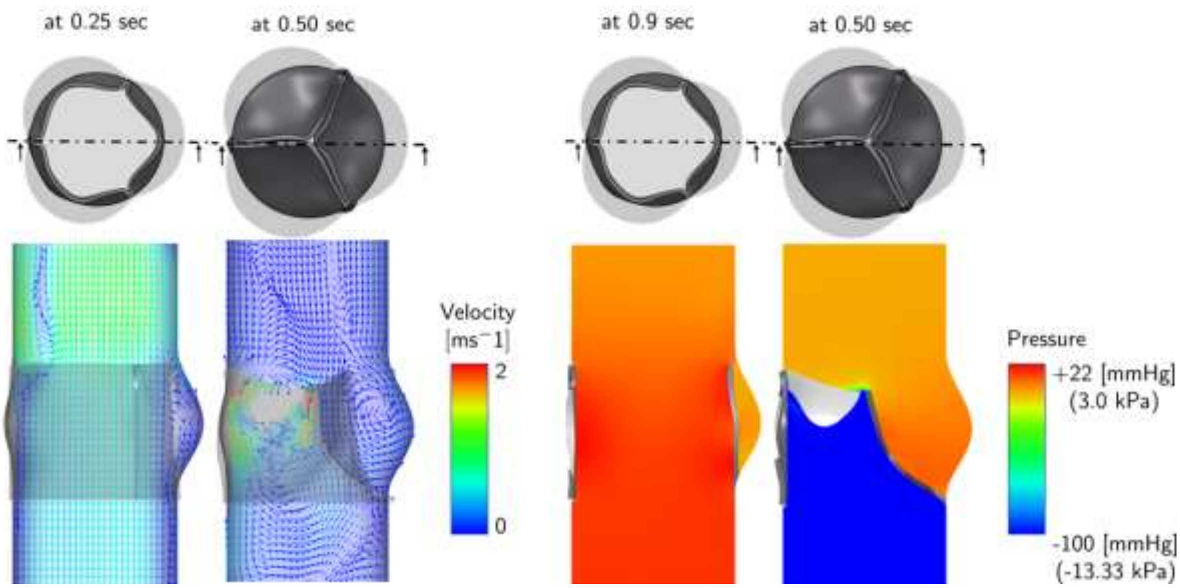

Figure 6: Velocity and pressure distribution around the valve.

One can also determine various useful indicators such as pressures & velocity fields (Figure 6), where areas of abnormal recirculation, vortices and leakages can be observed. One can also evaluate the valve kinematics/kinetics (Figure 7) like leaflet motion, stresses and strains, etc. to evaluate the valve performance. E.g., by evaluating the geometric orifice area (GOA), i.e. the anatomical area of the aortic valve orifice. These indicators could help in improving the valve design cycle.

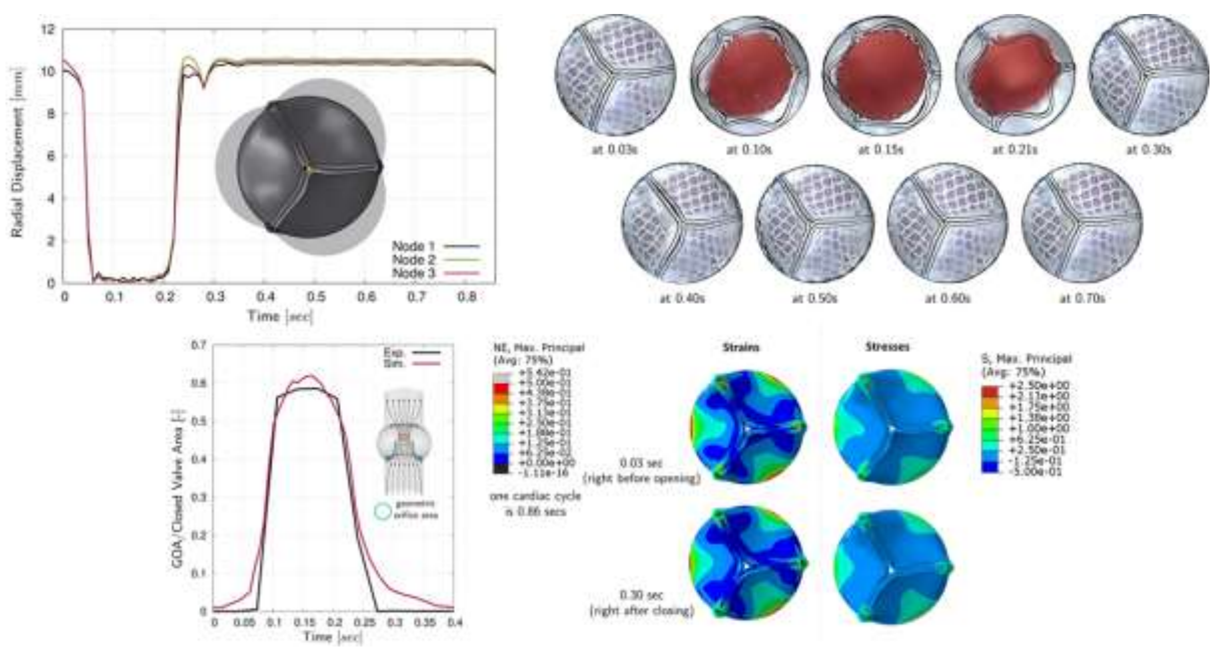

Figure 7: Clockwise from top left: leaflet kinematics, visual comparison of leaflet open and close phases with experimental setup, stresses and strains on the valve and comparison between numerical and experimental values for the ratio of GOA to Closed Valve Area.

CHALLENGES AND BENEFITS

Some of the challenges that we faced during the project were:

- Initial hiccups of setting up and testing the highly complex fluid-structure-interaction containers and the time management for the projects.

Some of the benefits that we experienced:

- Gaining easy and intuitive access to enough HPC resources enabled us to study the valve behaviour, and speeding up the design iteration process. With our local machines, with just 32 CPU cores, these simulations would have been impossible.
- As we had a dedicated 4-node HPC cluster in the cloud, it was easy to run post-processing scripts, without the need of submitting a second job in the queue, which would be the typical procedure of a shared HPC resource.
- Since all project partners had access to the same Abaqus/FlowVision container on the HPC server, it was easy to jointly debug and solve problems as a team. Also, sharing models and results among the team members was straight-forward.
- **The partnership with UberCloud would further allow us to perform such complex multi-physics simulations using realistic human heart models. For us, UberCloud's high-performance cloud computing environment and the close collaboration with HPE, Dassault, Capvidia and Advania, will be critical to speed-up our simulations not only for valve design iterations but also patient specific studies and services**.

Case Study Author – Deepanshu Sodhani, enmodes GmbH, and Team 215.

Join the UberCloud Experiment or Contact Us for Your Proof of Concept

If you, as an **end-user**, would like to participate in this Experiment to explore hands-on the end-to-end process of on-demand Technical Computing as a Service, in the Cloud, for your business then please register at: http://www.theubercloud.com/hpc-experiment/

If you, as a **service provider**, are interested in promoting your services through the UberCloud then please send us a message at https://www.theubercloud.com/help/

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