Visualizing Multiphysics, Fluid-Structure Interaction Phenomena in Intracranial Aneurysms

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Abstract

This work presents recent advances in visualizing multi-physics, fluid-structure interaction (FSI) phenomena in cerebral aneurysms. Realistic FSI simulations produce very large and complex data sets, yielding the need for parallel data processing and visualization. Here we present our efforts to develop an interactive visualization tool which enables the visualization of such FSI simulation data. Specifically, we present a ParaView-NekTar interface that couples the ParaView visualization engine with NekTar's parallel libraries, which are employed for the calculation of derived fields in both the fluid and solid domains with spectral accuracy. This interface allows the flexibility of independently choosing the resolution for visualizing both the volume data and the surface data from each of the solid and fluid domains, which significantly facilitates the visualization of complex structures under large deformations. The animation of the fluid and structure data is synchronized in time, while the ParaView-NekTar interface enables the visualization of different fields to be superimposed, e.g. fluid jet and structural stress, to better understand the interactions in this multi-physics environment. Such visualizations are key towards elucidating important biophysical interactions in health and disease, as well as disseminating the insight gained from our simulations and further engaging the medical community in this effort of bringing computational science to the bedside.

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1. Introduction

The cardiovascular system of the human body is the envy of every engineer. In just one minute the average heart beats about 70 times, pumping the entire blood supply of 5 liters through 62,000 miles of vessels. That is one-fourth the distance between the Moon and the Earth. The brain, in particular, although less than 2% of a human's body weight, receives about 20% of the resting cardiac output of blood and 25% of the body's oxygen supply.

Interactions of blood flow in the human brain occur between different scales, determined by flow features in the large arteries (diameter of 0.5 mm or larger), the smaller arteries and arterioles ($500\mu m$ to $10\mu m$), and the capillaries (mean diameter of $5\mu m$) all being coupled to cellular and sub-cellular biological processes. While many biological aspects have been studied systematically, surprisingly less effort has been put into studying blood flow patterns within the brain; a matter of particular relevance to the clinical evolution of life threatening conditions such as cerebral aneurysms.

Cerebral aneurysms (CAs) [1] occur in up to 5% of the general population, leading to strokes for over 40,000 Americans each year. They are manifested as a pathological dilation of the vascular wall, due to the congenital or acquired structural weakening of the wall media. A potential rupture of a CA can cause subarachnoid hemorrhage, a devastating event that leaves over 60% of the afflicted patients dead or disabled, with less than 50% of survivors being able to return to their former jobs or level of activity.

Currently, there exists no formal framework towards the diagnosis of CAs, and most cerebral aneurysms go unnoticed until they rupture or are detected by brain imaging that may have been obtained for another condition. Moreover, assessing the risk of a potential rupture of a diagnosed CA is mostly empirical as the biomechanics governing the time-evolution of CAs is far from being fully understood. However, it is believed that factors such as location, geometry, blood flow patterns and resulting mechanical stresses within the aneurysm play a prominent role.

Recent advances in computational science now allow for high-fidelity numerical simulations of flow-structure interactions (FSI) in compliant CAs.

The ability to simulate and visualize such cases enables us to study in-detail the flow patterns and the resulting mechanical stress field in the aneurysm, shedding new light on the conditions for its eventual rupture. Here, we demonstrate the potential of this pipeline by presenting visualization results for flow-structure interactions in a patient-specific aneurysm. The aneurysm is located in the cavernous segment of the right internal carotid artery and its detailed geometry was extracted using Magnetic Resonance Imaging (MRI) (see Figure 1).

This paper is structured as follows. In Sec. 2 we briefly describe the multi-physics FSI computational framework. In Sec. 3 we discuss the visualization components that were developed to enable the interactive visual exploration of the resulting FSI data. This comprises a custom ParaView-NekTar plugin for parallel data processing and visualization. ParaView is leveraged for performing standard parallel visualization algorithms and rendering. The key contribution here is reading the NekTar data in its native simulation format, applying transformations for visualizing moving unstructured meshes subject to large displacements and calculating derived quantities of high-order volume data, such as the stress tensor inside solid domains. Finally, in Sec. 4 we present results for a representative case study involving fluid-structure interactions in a patient-specific brain aneurysm.

2. FSI simulation modeling

Fluid-structure interaction phenomena are ubiquitous in nature. Their accurate resolution is of critical importance in applications spanning a broad spectrum of scientific, engineering and medical disciplines, e.g., the fluttering of aircraft wings, the deflection of wind turbines, blood flow dynamics in aneurysms, etc. Simulations of such nonlinear multi-physics interactions require a code-and-model coupling approach that raises a number of challenges, including stable interface conditions, data communication between the coupled solvers, *in-situ* data analytics, etc.

Modeling flow-structure interaction (FSI) in biological systems, where elastic tissues and fluids have almost identical density (low mass ratio problem), is one of the most challenging problems in computational mechanics. One of the major challenges in FSI simulations at low mass ratio is the stability of semi-implicit coupled fluid-structure solvers. Based on recent advances in developing stable numerical algorithms we have developed a solver capable of tackling problems with mass ratios approaching zero, enabling

Figure 1: Flow-structure interactions in an aneurysm. Shown on the left is the patient-specific cranial arterial network where the spectral element equations are solved. Shown in the inset (*top*) is the structure domain representing the elastic tissue of the aneurysm wall. Shown in the inset (*bottom*) is the local stress field in the aneurysm wall due to interactions with recirculating blood flow.

70 high-resolution FSI simulations of biological systems, such as blood flow in
 71 compliant arteries [6, 5].

72 Here, we follow a partitioned strategy in which the FSI solver is based on
 73 coupling the open source parallel codes NekTar [2] and StressNekTar [3, 4],
 74 both of which are based on the spectral/*hp* element method. The fluid do-
 75 main governed by the Navier-Stokes equations is assumed to be incompress-
 76 ible and Newtonian. The response of the solid domain is described by the
 77 elastodynamics equations [6]. To account for moving boundaries we employ
 78 the Arbitrary Lagrangian-Eulerian framework (ALE). The strong coupling
 79 of the two models is achieved by using sub-iterative approach with conver-
 80 gence accelerated by Aitken relaxation [6]. Finally, the formulation is closed
 81 by appropriate boundary, initial and fluid-solid interface coupling conditions
 82 [6, 5].

83 The main challenge here is to tackle cases where the fluid and structure
 84 densities are close and convergence of the coupled solver becomes problematic
 85 due to the so-called added mass effect [5]. The aforementioned modeling
 86 framework has enabled us for the first time to study FSI in a patient-specific
 87 model of brain vasculature, where arterial wall dynamics are simulated at

Figure 2: Illustration of the unstructured surface grid and the polynomial basis employed in NekTar. The solution domain is decomposed into non-overlapping elements. Within each element the solution is approximated by vertex, edge, face and (in 3D) interior modes. The shape functions associated with the vertex, edge and face modes for fourth-order polynomial expansion defined on triangular and quadrilateral elements are shown in color.

very high resolution, and relatively large structural deformations are possible.

Both fluid and solid domains are discretized in space using the spectral/*hp* element method (SEM) [2], according to which, the computational domain Ω is decomposed into a set of polymorphic non-overlapping elements $\Omega^{e_i} \subset \Omega$, $i = 1, \dots, Nel$, as depicted in Figure 2.

Within each element, the solution is approximated as a linear combination of hierarchical, mixed-order, semi-orthogonal Jacobi polynomial expansions. This hierarchical structure consists of separated vertex (linear term), edge, face and interior (or bubble) modes. According to this decomposition, the polynomial representation of a field $u^e(t, \mathbf{x})$ within an element is given by the linear combination of the basis functions multiplied by the corresponding modal amplitudes:

$$u^e(t, \mathbf{x}) = \sum_k \bar{u}_k^e(t) \phi_k^e(\mathbf{x}), \quad (1)$$

where $\bar{u}_k^e$ is an amplitude of the k -th shape function $\phi_k^e(\mathbf{x})$ in the element e .

The solution computed by NekTar is saved in modal space, i.e., only the values of $\bar{u}_k^e$ being stored for each field variable. The polynomial expansion representing the solution in each spectral element is exploited by the visu-

104 alization software to obtain the solution (or derived quantities) on a given
 105 number of points (vertices) within each spectral element.

106 **3. ParaView - NekTar Interface**

107 Leveraging ParaView’s plug-in interface, and building on previous work
 108 reported in [7], we enable the visualization of fluid-structure interaction data
 109 with high-order spectral accuracy.

110 NekTar’s geometry and solution data are stored separately in MESH and
 111 SOLUTION files, respectively. The MESH file contains the initial coordi-
 112 nates of elements on the continuum mesh, the connectivity of the elements,
 113 boundary condition information, as well as information on the curved bound-
 114 aries. The SOLUTION files contain the calculated values, which can be used
 115 both for restart and also for data analysis. The size of the MESH and SO-
 116 LUTION files depends on the number of elements in the mesh, spectral
 117 resolution and number of field variables considered in the computation, i.e.,
 118 fluid velocity, pressure, mesh displacement, etc. There is a separate MESH
 119 and set of SOLUTION files for each fluid and solid portion of the domain.

120 *3.1. Plugin Overview*

121 Processing of NekTar’s data is accomplished in two steps. In the *first*
 122 *step* the MESH data (a connected list of polymorphic elements) is read and
 123 the computational domain is partitioned across processes (with METIS [8]).

124 The plugin analyzes the SOLUTION file to see what field variables are
 125 included in the data and populates the ParaView GUI based on this informa-
 126 tion. Along with the variables present in the SOLUTION file, interfaces for
 127 calculating derived fields (with high-order accuracy) from the stored variables
 128 are added. These will be specific interfaces for solid and fluid domains.

129 In the *second step* each process reads and stores the solution correspond-
 130 ing to the elements included in its partition. The modal values of the solution
 131 are cached in memory, and are used to transform the solution from modal
 132 to physical space. Using the GUI the user specifies what data should be
 133 made available and at what resolution. The resolution for the continuum
 134 mesh and the boundary surface, which can optionally be extracted from
 135 the fluid continuum mesh, can be set independently. These two steps are
 136 applied to process the data for each domain. The second step is repeated
 137 for each time step. The task of loading field variables, transforming the

Figure 3: This image shows Lambda2 calculated without projection A) and with B).

138 solution from modal to physical space, computing derived properties and in-
 139 terpolating data on vertices of linear elements representing the visualization
 140 mesh is performed independently in each partition, resulting in linear scaling.
 141 Processing of NekTar’s data is performed with the custom reader using the
 142 functionality provided by the NekTar library. To reduce data redundancy
 143 at the interface between elements, duplicate vertices shared by adjacent ele-
 144 ments are removed, using the vtk filter `vtkCleanToGrid`. Finally, the cleaned
 145 `vtkUnstructuredGrid` is passed on to the ParaView pipeline where all of the
 146 standard visualization algorithms can be applied to it.

147 3.2. Processing high-order spectral element data from NekTar

148 In computing derived quantities it is important to take into account that
 149 high spatial resolution achieved by P-refinement (i.e. using higher polynomial
 150 order) allows for the use of relatively large elements, thus using high-order
 151 operators for computing derived quantities is more appropriate.

152 The data computed by NekTar are processed with high-order spectral ac-
 153 curacy, i.e., the interpolation, integration and differentiation are performed
 154 on the quadrature grid consistent with the simulation resolution. The C^0 spa-
 155 tial discretization in NekTar guarantees solution continuity across elements’
 156 boundaries, while it allows discontinuities of the derivatives. To obtain con-
 157 tinuity of derived fields based on solution derivatives (e.g., vorticity, stress
 158 tensor) the user can turn on “high-order projection calculation”. Beneath
 159 the hood of the “projection calculator” is a high-order parallel projection
 160 solver using L-2 projection to transform a discontinuous field into C^0 contin-
 161 uous (See Figure 3). The global projection uses a parallel conjugate gradient
 162 solver, whose scalability has been tuned to tens of thousands processors.

163 Besides calculating vorticity and Lambda2 for the fluid mesh, users can
 164 additionally choose to extract the boundary surface from the continuum mesh

Figure 4: Strong scaling performance of the stress tensor calculation for solid domains in the ParaView-NekTar reader plug-in.

165 and calculate the wall shear stress (WSS). For solid mesh solutions which
 166 contain the solid mesh displacement, the stress tensor can also be calculated.
 167 Scaling performance of this stress tensor calculation can be seen in Figure
 168 4. This quantity is computed at the element resolution of the stored data,
 169 as shown by the `calc_time` line of the graph. This data is then projected
 170 onto the element resolution requested by the user. The graph shows this
 171 interpolation time for element resolutions of two and ten, along with the
 172 total times (`calc_time` plus interpolation time) for the two resolutions. In
 173 both cases linear strong scaling is achieved.

174 At any time the user can choose (through GUI) to change the number of
 175 vertices where data is visualized. Changes in resolution parameters automat-
 176 ically propagate to NekTar's functions, which use the solution data already
 177 cached in memory in its original resolution, to perform interpolation onto a
 178 different set of points and update the *vtkUnstructuredGrid*. Similarly, when
 179 the user animates through time steps of the data set the geometry of the
 180 elements and information on their connectivity are reused, and only the data
 181 from the new SOLUTION file needs to be read from disk, transformed to
 182 physical space and interpolated. As new time steps are read in the cleaned
 183 *vtkUnstructuredGrids* for previous time steps are cached in memory so that

Figure 5: Illustrations of the application of mesh displacement. A) shows the original mesh. B) shows the deformed mesh due to fluid flow. C) shows both meshes together to highlight their differences. In tile D) the values of the displacement have been scaled to accentuate the effect.

184 they don't need to be reread from disk each time they are to be displayed.

185 3.3. Visualizing Fluid-Structure Interactions

186 The FSI calculations we consider here include deformation of the elements
 187 of the mesh over time. These are stored in the SOLUTION files as displace-
 188 ment values for each coordinate of the mesh. If the user chooses to display
 189 the dynamic mesh, via a control on the GUI, the original coordinates of the
 190 mesh are first backed up in memory, so that the original mesh can be restored
 191 without needing to reread it from disk should the user decide to turn off the
 192 dynamic mesh. For each time step the mesh displacement values from the
 193 SOLUTION file are used to update the coordinates of the continuum mesh.

Figure 6: Blood flow in a compliant cerebral aneurysm containing blood flow streamlines (colored by velocity magnitude), and stress tensor magnitude on the walls of the artery. Arrow glyphs along the streamlines indicate the direction of the flow.

194 The coordinates are then interpolated onto the requested element resolution
 195 and used to update the *vtkUnstructuredGrid*. The results of this process can
 196 be seen in Figure 5. Tile A) shows the original mesh while B) shows the
 197 same structure with the deformation applied. In tile C) we display both the
 198 original mesh in white together with the deformed mesh in gold to highlight
 199 the differences.

200 In cases where the displacements are small the user can accentuate the
 201 differences by applying a scaling factor set on the GUI. This is illustrated
 202 in tile D) of Figure 5, where the deformation is exaggerated to illustrate the
 203 effects of the fluid on the structure.

204 4. Aneurysm Case Study

205 We present here visualization results for fluid-structure interactions in the
 206 patient-specific aneurysm introduced earlier. The aneurysm is located in the
 207 cavernous segment of the right internal carotid artery and its detailed geome-
 208 try was extracted using Magnetic Resonance Imaging (MRI). The fluid-solid
 209 mass ratio is 0.5 with the fluid mesh (artery and aneurysm) consisting of

210 42,065 tetrahedral elements, while its solid counter-part (arterial wall) con-
 211 tains 16,912 prismatic elements. The data output of the coupled NekTar
 212 solver comprises of the corresponding solution fields for the fluid and struc-
 213 ture domains. We employed 2^{nd} order accurate time integration schemes and
 214 3^{rd} order polynomial expansions, resulting to about 30 million degrees of free-
 215 dom. The simulation output consists of thousands of files with approximately
 216 100Gb of data, while the computation of two cardiac cycles took about 24hrs
 217 on 1,024 cores of an IBM BG/Q. This is a mid-sized, yet state-of-the-art FSI
 218 problem, with larger more complex simulations planned for the future.

219 The results loaded into ParaView contain the fluid velocity and pressure,
 220 as well as the mesh displacement, velocity and acceleration in each of the do-
 221 mains. Using the ParaView-NekTar interface we compute the fluid vorticity,
 222 wall shear stress on the arterial wall boundary surface, and the full volume
 223 representation of the stress tensor in the arterial wall.

224 Visualization of the blood flow streamlines and vorticity iso-contours can
 225 reveal the complex flow patterns in the aneurysm, while rendering the stress
 226 tensor on the arterial walls highlights the local stresses in the aneurysm due
 227 to the multi-physics, flow-structure interactions. Looping through animation
 228 frames offers invaluable information of the evolving dynamics in a global
 229 setting, such as tracing and tracking possible hydrodynamic instabilities, de-
 230 tecting oscillatory responses, and identifying the effective dimensionality of
 231 the system. Furthermore, in a local setting, visualization allows researchers
 232 to zoom in and extract high-resolution spatio-temporal analytics of the flow
 233 field and derived quantities that may be of vital importance to the medical
 234 practitioner. For instance, visual identification and monitoring of the loca-
 235 tion of maximum wall shear stress within the aneurysm sack during a full
 236 heartbeat could ultimately provide clearcut evidence towards the assessment
 237 of a potential treatment.

238 Although visualization offers a flexible platform for debugging, post-
 239 processing, and data analytics, its true power lies in the fact that it can
 240 often transform a perplexing simulation into a lucid story, accessible by a
 241 very broad audience. In the particular case of studying CAs, visualization
 242 can deliver content of both educational and practical value, with the audience
 243 ranging from aspiring biomedical engineers to seasoned neurosurgeons.

244 A manifestation of the capabilities and functionality of the ParaView-
 245 NekTar plugin is presented in Figures 6 and 7. Figure 6 depicts the blood
 246 streamlines at the systolic peak of the cardiac cycle. These velocity stream-
 247 lines are colored by the velocity magnitude and include arrow glyphs which

Figure 7: Blood flow in a compliant cerebral aneurysm containing blood flow streamlines (colored by velocity magnitude), and stress tensor magnitude on the walls of the artery. Isocontours of the vorticity magnitude, which indicate areas of swirling flow, are colored by the pressure.

248 indicate the direction of the flow. Figure 7 contains vorticity isocontours
 249 that are colored by pressure, the gradient of which is the driving force of
 250 the flow. Swirling flow inside the aneurysm sack induces deformation of the
 251 arterial wall due to mechanical stress. By rendering the derived stress tensor
 252 data, visible on the wall of the artery in both Figures, we can provide a clear
 253 visual identification of the regions of high stress, hence the regions of sus-
 254 ceptible rupture. The visualizations clearly establish the correlation between
 255 complex flow patterns and stress on the vascular wall and provide insight on
 256 this fundamental biomechanical interplay.

257 5. Discussion

258 Computational resources follow an ever-increasing path, while develop-
 259 ments in sophisticated models and algorithms create new directions to eluci-
 260 dating the mechanisms that drive many physical and biological systems. This
 261 promising loop has been increasingly drawing the interest of scientists and
 262 engineers across a broad range of disciplines, leading to an unprecedented

263 volume of simulation data output. Designing efficient, application-driven
264 tools for accurately analyzing, visualizing and interacting with these com-
265 plex datasets is of crucial importance for gaining a better understanding of
266 the underlying processes [9, 10].

267 Here, we presented visualization results using a new NekTar reader plug-
268 in designed to process and visualize fluid-structure interaction data computed
269 by a coupled high-order spectral/*hp* element solver. The software was used to
270 study the interaction between unsteady blood flow and the resulting stresses
271 in the elastic tissue of a brain aneurysm, revealing the intricate interactions
272 within this pathology. The generated spatio-temporal visualizations provide
273 a key enabling technology towards not only revealing elucidating aspects of
274 the underlying physics, but also potentially providing invaluable input on
275 whether and how a clinical practitioner should intervene.

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