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Review on the doctoral thesis "Fluid-structure interaction" by Adam Kosík

Overview

The thesis is on the description of a computational model for fluid-structure interactions, coupling the compressible Navier-Stokes equations with different hyperelastic materials models. For discretization, the author chooses the discontinuous Galerkin (DG) method, both in the fluid and the solid domain. Temporal discretization is by means of the BDF scheme considering different degrees. The coupling is realized by means of a strongly coupled iteration. Aim of the work is an application to vocal fold dynamics.

Fluid structure interactions is a very topical subject with a lot of different contributions within the last years. The new aspect of the present thesis by Admin Kosík is the consequent use of DG methods in space, also for the structural part. Here, this is mainly motivated by implementational aspects and to get a uniform environment, as DG is well suited compressible flows.

Summary

The first chapter is devoted to the modeling of nonlinear elasticity. The author gives a basic introduction to the concepts of coordinate systems, strain, stress and hyperelasticity. In the second chapter, Kosík introduces the discretization scheme for the elasticity problem. He utilizes the discontinuous Galerkin method with different forms of penalization of the inter-element jumps. For the linear elasticity problem a detailed component-wise description of the variational formulation is given. For the general nonlinear formulation, only the incomplete interior penalty formulation is considered. Furthermore, Kosík derives the detailed set of directional derivatives to assemble the Jacobian in a Newton iteration including nonlinear models like the St. Venant-Kirchhoff or the Neo-Hookean material. Time discretization is accomplished with the backward difference formulas of different degrees.

Chapter 3 is devoted to the numerical realization of the DG method for elasticity. Here, various benchmark problems (defined by Hron & Turek) are analyzed and discussed. The author starts by presenting two static problems, where an elastic beam is deflected by a gravity force. Quantity of interest is the horizontal and vertical deflection in the tip of the beam. Kosík presents mesh convergence results for DG methods up to polynomial degree 3. Considering linear elasticity, the author finds reasonable results that indicate proper convergence. Using third order polynomials, the results do not show perfect robustness. The three variants of the interior penalty method show similar performance. Considering the nonlinear St. Venant-Kirchhoff material this findings are confirmed. In the succession, a dynamic elasticity problem with an oscillating beam is considered. Comparison of the different time-discretization schemes shows, that BDF 1 is not appropriate, while the second order method gives good results. Next, Kosík studies the effect and the proper choice of the DG penalization parameter enforcing continuity of the solution. Experimentally, he shows a relation of the optimal (minimal) parameter to the structural parameters. Further, a very short comparison between the DG and continuous finite element method is given for the linear elasticity test-case.

In view of the vocal folds application, Kosík studies non-homogeneous materials, where the Lamé coefficients jump within the domain. He presents a simple modification of the original benchmark problems and replaces the homogeneous beam by a model with three different layers. Finally, he presents a complex numerical model for vocal folds, that includes four different structural regimes.

Chapter 4 introduces the compressible Navier-Stokes equations and transformation of these equations to the ALE coordinates. Spatial discretization is accomplished with the DG method, temporal discretization with backward difference formulas.

In Chapter 5, Kosík treats the complete fluid-structure interaction problem. Coupling is realized by a Dirichlet – Neumann iteration, where the solid problem is driven by the fluid stresses on a Neumann boundary and the fluid-problem and the ALE deformation problem by the structural motion in form of Dirichlet data. A strongly coupled iteration is presented, which is appropriate for vocal folds, as densities vary a lot. The interface conditions are controlled by means of relative and absolute variations in the interface displacement. The ALE mapping is defined by a pseudo-elasticity problem with locally adjusted coefficients. For testing the complete framework, a simplified vocal folds model problem is introduced. The variants of the DG and BDF formulas show good agreement on different mesh- and time-step sizes. Finally, a more complex geometry of a idealized vocal tract is analyzed.

In Chapter 6, details on the elaborate implementation of the numerical methods are given.

Assessment

The thesis of Kosík gives a good and detailed view on the various steps necessary to model and simulate the complex problems of vocal folds dynamics. The chosen numerical methods are appropriate for the problem under consideration. The highlight and most important part of the thesis is the description of the DG method for the elasticity problem. Here, Kosík gives details and a thorough numerical analysis of the robustness and accuracy of the implemented techniques. There are some points, where the thesis does not fully discuss or answer all relevant questions:

- The investigation of non-homogeneous materials is very interesting. Here I was surprised, that the meshes are non-matching. For such an *interface-problem* this will result in non-optimal convergence rates. Unfortunately, no insight analysis is given.

- The author gives detailed tests on the elasticity problem, but no real validation of the fully coupled fsi problem. The vocal fold examples are very specific and the results are not compared to other literature values. It would have been very reasonable to consider the fsi-benchmark problems by Hron and Turek and take the chance to define a compressible version of this test-case.

The field of fluid-structure interactions is still emerging and contributions are very welcome and highly appreciated by the community. Although there are some open points which would have been worthwhile to investigate, I fully recommend to accept this thesis for a dissertation. After a successful defence, Adam Kosík should be awarded the title PhD.

With best regards,

Thomas Richter