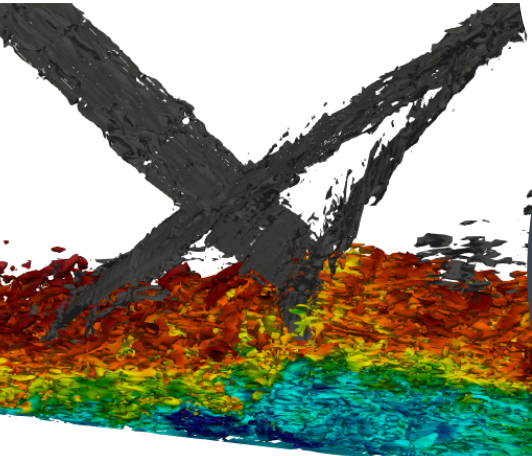
University of Stuttgart
Institute of Aerodynamics
and Gas Dynamics

Min Gao
Daniel Appel
Andrea Beck
Claus-Dieter Munz



Simulation of Shock-wave/ Turbulent Boundary-layer Interaction over an Elastic Panel with a Discontinuous Galerkin Solver

Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, August 3rd, 2023

Motivation

Motivation

- Fluid-structure interaction (FSI) may significantly change the aerodynamic shape of rocket nozzles, especially during start

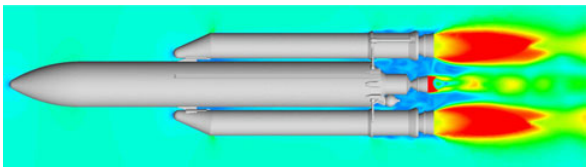


Figure 1: Mach number contour of Ariane-5 [LCF06]

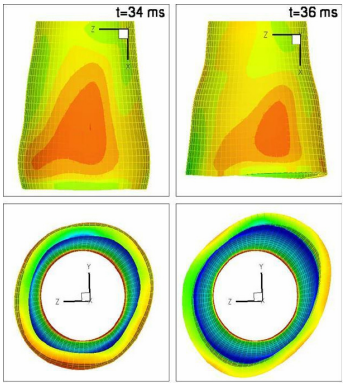


Figure 2: Nozzle deformations [LHH07]

Motivation

- Inside rocket nozzles, shock-wave/turbulent boundary-layer interaction (SWTBLI) is a common flow feature, and hence, an accurate, efficient, and robust FSI framework is built to investigate the effect of elastic panel responses on SWTBLI [GABM23]

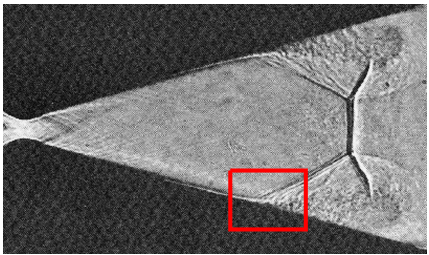
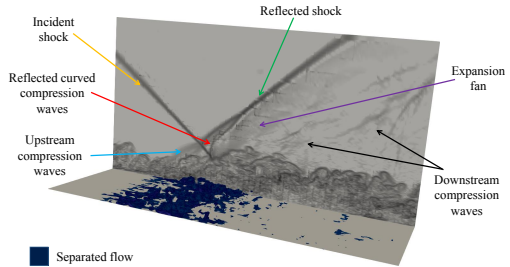


Figure 3: Experimental Schlieren contour of SWTBLI [Ama69]



Outline

Outline

Building blocks

- Fluid solver & Structure solver
- FSI temporal/spatial coupling

FSI solver validation

- Supersonic panel flutter
- Shock impact on deforming panel

Numerical simulations

- Simulation 1 – Supersonic turbulent boundary layer
- Simulation 2 – SWTBLI over a rigid panel
- Simulation 3 – SWTBLI over an elastic panel

Summary & Outlook

Building blocks

Fluid solver & Structure solver

Fluid solver

- Compressible Navier–Stokes equations
- Moving boundaries treatment [MK11]: arbitrary Lagrangian-Eulerian (ALE) formulation
- Non-linear stability: split-form ALE discontinuous Galerkin spectral element method [KSBG20, SKBG20]
- Shock capturing: improve an adaptive filter approach [DW22]
- Time integration: fourth-order five-stage Runge-Kutta scheme [CK94]

Structure solver

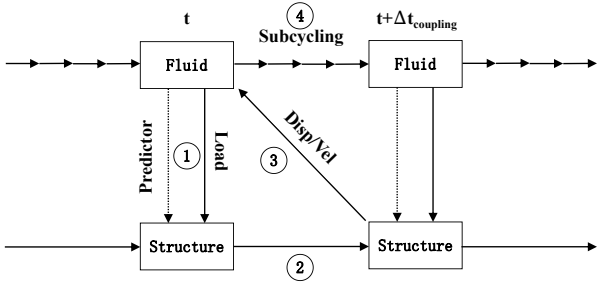
- Dynamic Timoshenko beam
- Spatial discretization: Legendre spectral finite element method [SG08]
- Global matrices: direct stiffness method [Red02] plus homogeneous boundary conditions [Log11]
- Time integration: implicit Newmark method [Cho07]

FSI temporal coupling

- Governing equations of the FSI system

$$\begin{cases} \vec{U}^f_{n+1} = Fluid(\vec{U}^s_n, \vec{U}^s_{n+1}, \vec{U}^f_n) \\ \vec{U}^s_{n+1} = Structure(\vec{U}^f_{n+1}, \vec{U}^s_n) \end{cases} \tag{1}$$

- Work flow of a loosely-coupled FSI approach



FSI spatial coupling

- Principle: ”equivalence of virtual work” on the common interface [dBvZB07]

$$\delta W = \delta \vec{U}^{s^T} \cdot \vec{f}^{\,s} = \delta \vec{U}^{f^T} \cdot \vec{f}^{\,f} \tag{2}$$

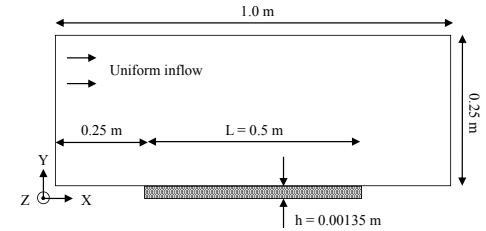
- S $\Longrightarrow$ F (displacement/velocity): $\vec{U}^f = \mathbf{H} \cdot \vec{U}^s$
- F $\Longrightarrow$ S (pressure/viscous load): $\vec{f}^{\,s} = \mathbf{H}^T \cdot \vec{f}^{\,f}$
- For non-conforming meshes, **H** is determined by mesh distribution, mesh resolution, interpolation approach, etc.
- For conforming meshes with the same polynomial degree (**H** is a unit matrix), a high accuracy can be easily achieved in the spatial coupling
- Update the disp/vel inside the interior flow domain: radial basis function approach [DBVdSB07]

$$\begin{bmatrix} \vec{U}^f_{in} \\ 0 \end{bmatrix} = \begin{bmatrix} \underline{\underline{V}}^{in} & \underline{\underline{P}}^{in} \\ \underline{\underline{P}}^{in^T} & \underline{\underline{0}} \end{bmatrix} \begin{bmatrix} \vec{\alpha} \\ \vec{\beta} \end{bmatrix} = \begin{bmatrix} \underline{\underline{V}}^{in} & \underline{\underline{P}}^{in} \\ \underline{\underline{P}}^{in^T} & \underline{\underline{0}} \end{bmatrix} \begin{bmatrix} \underline{\underline{V}} & \underline{\underline{P}} \\ \underline{\underline{P}}^T & \underline{\underline{0}} \end{bmatrix}^{-1} \begin{bmatrix} \vec{U}^f_b \\ 0 \end{bmatrix} \tag{3}$$

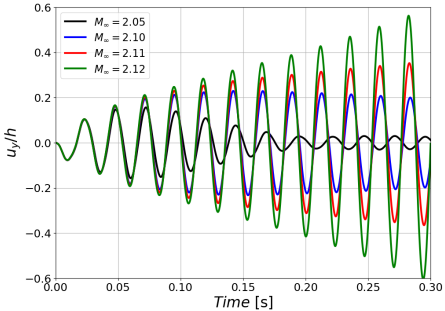
FSI validation

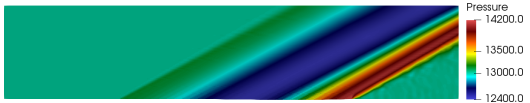
FSI solver validation – Supersonic panel flutter

- The supersonic panel flutter test case by Mouronval et al. [MTHM19]



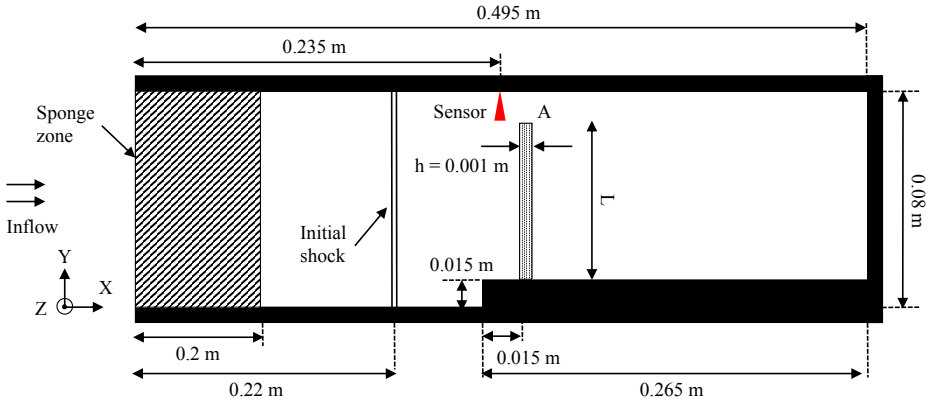






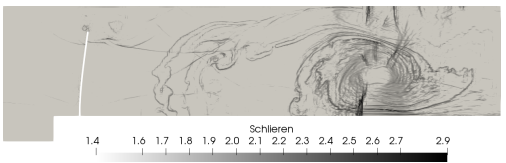
FSI solver validation – Shock impact on deforming panel

- A challenging shock impact on deforming panel test case [SC14, PHÖ+16] is used for further comparison

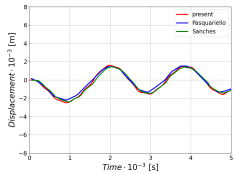


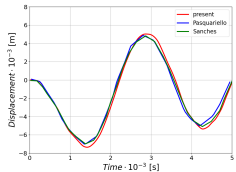
FSI solver validation – Shock impact on deforming panel





- Good agreement on structure and fluid behaviors with references [SC14, PHÖ+16]

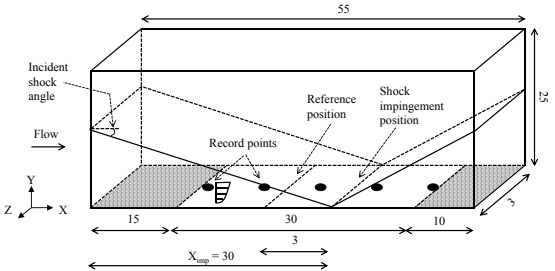




Numerical simulations

Computational setup

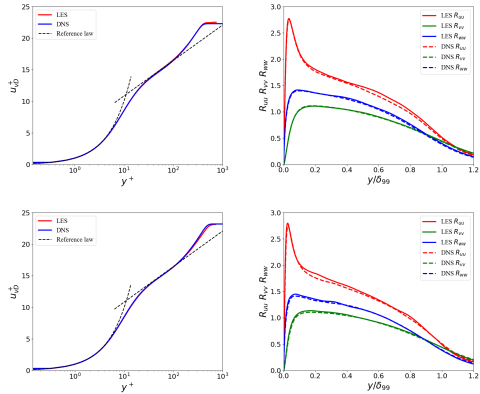
- Free-stream Mach number $Ma = 2.0$, inflow Reynolds number $Re_{\theta_0} = 1270.42$, and incident shock is of an angle $\beta = 37.2°$
- Timoshenko beam width $b = 3.0\delta_r$, thickness $h = 0.26mm$, Young's modulus $E = 77.0GPa$, Poisson ratio $\nu = 0.33$, and density $\rho_s = 10000.0kg/m^3$



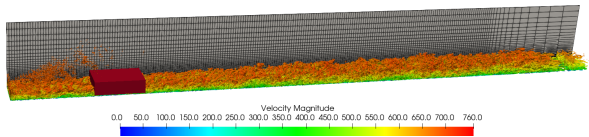
	TBL	static SWTBLI01 [GKM22]	static SWTBLI02	moving SWTBLI
Δx^+	30	30	30	30
Δy^+	1.6	1.6	1.6	1.6
Δz^+	16	16	16	16
Elems	5.2×10^5	2.7×10^5	5.2×10^5	5.2×10^5
N	6	6	6	6
Dofs	1.8×10^8	0.9×10^8	1.8×10^8	1.8×10^8
Cores	16384	16384	16384	16384
Load	10802	5687	10802	10802
PID	$1.74\mu s$	$1.84\mu s$	$2.3\mu s$	$3.26\mu s$
t_{snd}	$0.4ms$	$0.6ms$	$0.7ms$	$0.9ms$
CPUh	1.8×10^5	2.0×10^5	4.2×10^5	8.0×10^5

Simulation 1 – Supersonic turbulent boundary layer

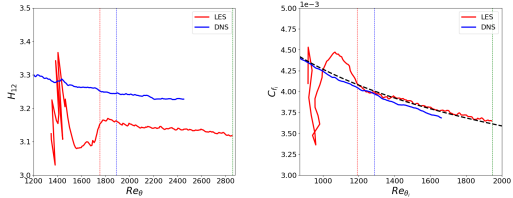
- TBL local statistics at $17\delta_{99r}$ and $35\delta_{99r}$ after the inlet [WSKR18]



- Q-criterion visualization of the TBL

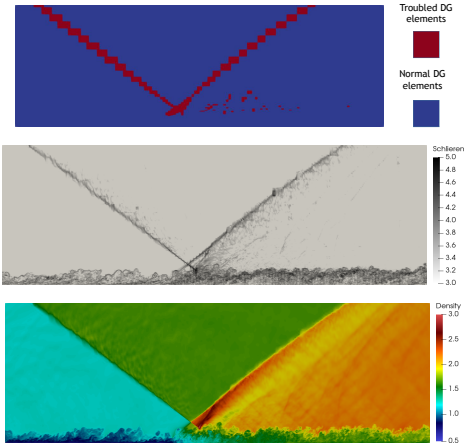


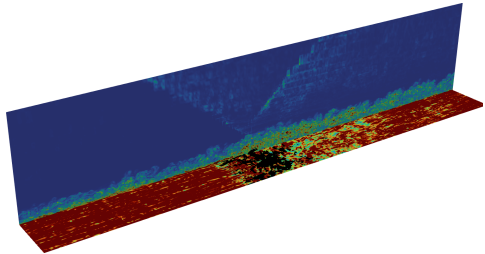
- TBL streamwise statistics



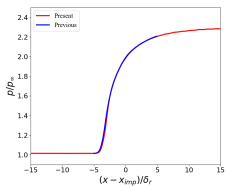
Simulation 2 – SWTBLI over a rigid panel

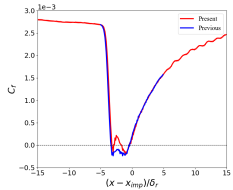
- Instantaneous contours at $t = 0.55ms$





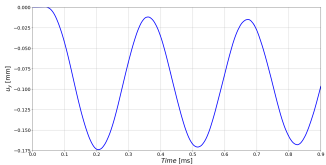
- Mean-flow statistics (different schemes [GKM22, GABM23])

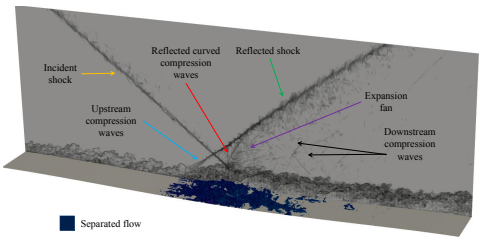




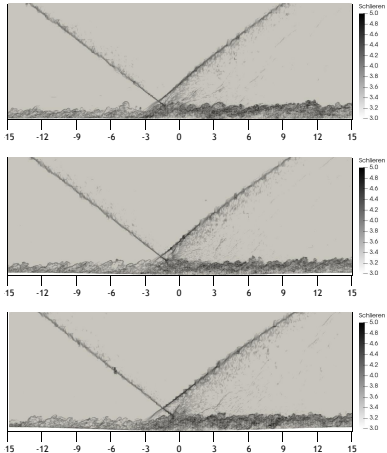
Simulation 3 – SWTBLI over an elastic panel

- Panel response and instantaneous flow features at $t = 0.54ms$



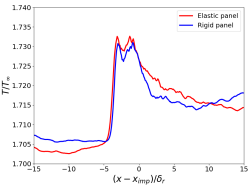


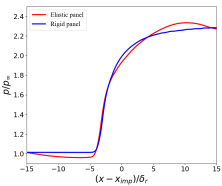
- Instantaneous Schlieren contours at $t = 0.36ms, 0.44ms, 0.51ms$

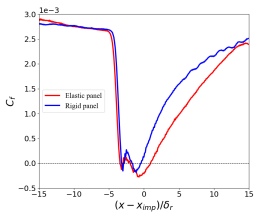


Simulation 3 – SWTBLI over an elastic panel

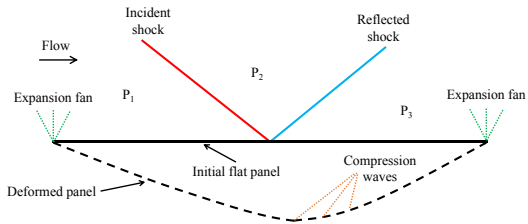
- Mean-flow statistics [WGE13, HBM22]





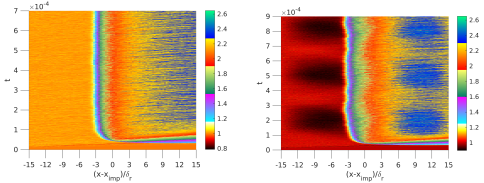


- Effect of the panel response can be demonstrated by a downwards deformed panel

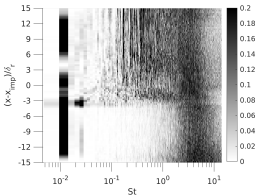


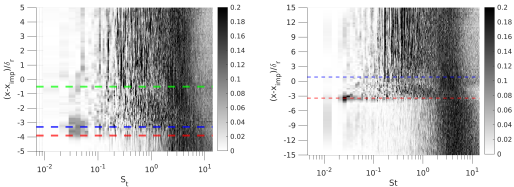
Spectral analysis 2 & 3

- An extra flow unsteadiness due to panel vibration [PHA^{+}15, HBM22]



- Similar magnitude and location of separation-induced unsteadiness [GKM22, GABM23]





Summary & Outlook

Summary & Outlook

Summary

- First partitioned FSI simulation using high-order schemes in both structural and fluid solvers
- An adaptive filter is improved to maintain the overall high accuracy, efficiency and flexibility of our FSI solver
- A comparison with a simulation of SWTBLI over a rigid panel reveals the significance of FSI effects
- For further details, see our paper "*A high-order fluid–structure interaction framework with application to shock-wave/turbulent boundary-layer interaction over an elastic panel*" (link temporarily valid) **https://authors.elsevier.com/a/1hRla3AMrTGrfW**

Outlook

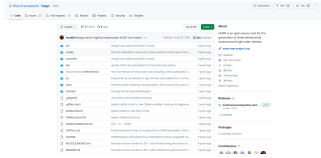
- Extending the FSI solver to employ more efficient LES schemes [HBM22] and to incorporate structural non-linearity [SMG22]

Acknowledgments

- Support from the China Scholarship Council (**CSC**)–201906020172, the Deutsche Forschungsgemeinschaft (**DFG**) through the project GRK 2160/2 'Droplet Interaction Technologies' (**DROPIT**), the German Research Foundation (**DFG**) through **Germany's Excellence Strategy**-EXC 2075—390740016
- Discussion with **Marcel Blind**, funded by Deutsche Forschungsgemeinschaft (**DFG**) FOR2895, on SWTBLI and LES
- The computing time on the HPE APOLLO (**HAWK**) provided by the HLRS through the project '**hpcdg**'
- **FLEXI** [KBB$^+$21] has been developed, tested and applied by a number of people, both from the **Numerics Research Group** at the University of Stuttgart and elsewhere

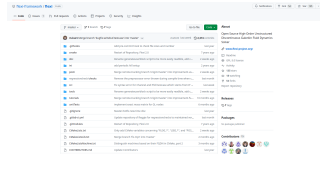
Open source code HOPR & FLEXI

- **HOPR github**
  `https://github.com/flexi-framework/hopr`
- **HOPR website**
  `www.hopr-project.org`





- **FLEXI github**
  `https://github.com/flexi-framework/flexi`
- **FLEXI website**
  `www.flexi-project.org`





Universität Stuttgart

Thanks for your attention! Any questions?



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Telephone: +86 15911060751
RG: https://www.researchgate.net/profile/Min-Gao-29

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[KBB+21] Nico Krais, Andrea Beck, Thomas Bolemann, Hannes Frank, David Flad, Gregor Gassner, Florian Hindenlang, Malte Hoffmann, Thomas Kuhn, Matthias Sonntag, et al., *Flexi: A high order discontinuous galerkin framework for hyperbolic–parabolic conservation laws*, Computers & Mathematics with Applications **81** (2021), 186–219.

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