Modal Analysis of Supersonic Flow Separation in Nozzles

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Presentation Outline

- Introduction
- Separated Nozzle Flow & Sideloads
- Modal Analysis
- Selected Results
- Implicit Compressible Flow Solver
- Summary

Project Aim

Predict sideloads during startup transients using detailed numerical tools

Investigate the applicability of applying modal decomposition methods to data from numerical simulations of separated nozzle flows

Nozzle Side-loads

Space Shuttle Main Engine.

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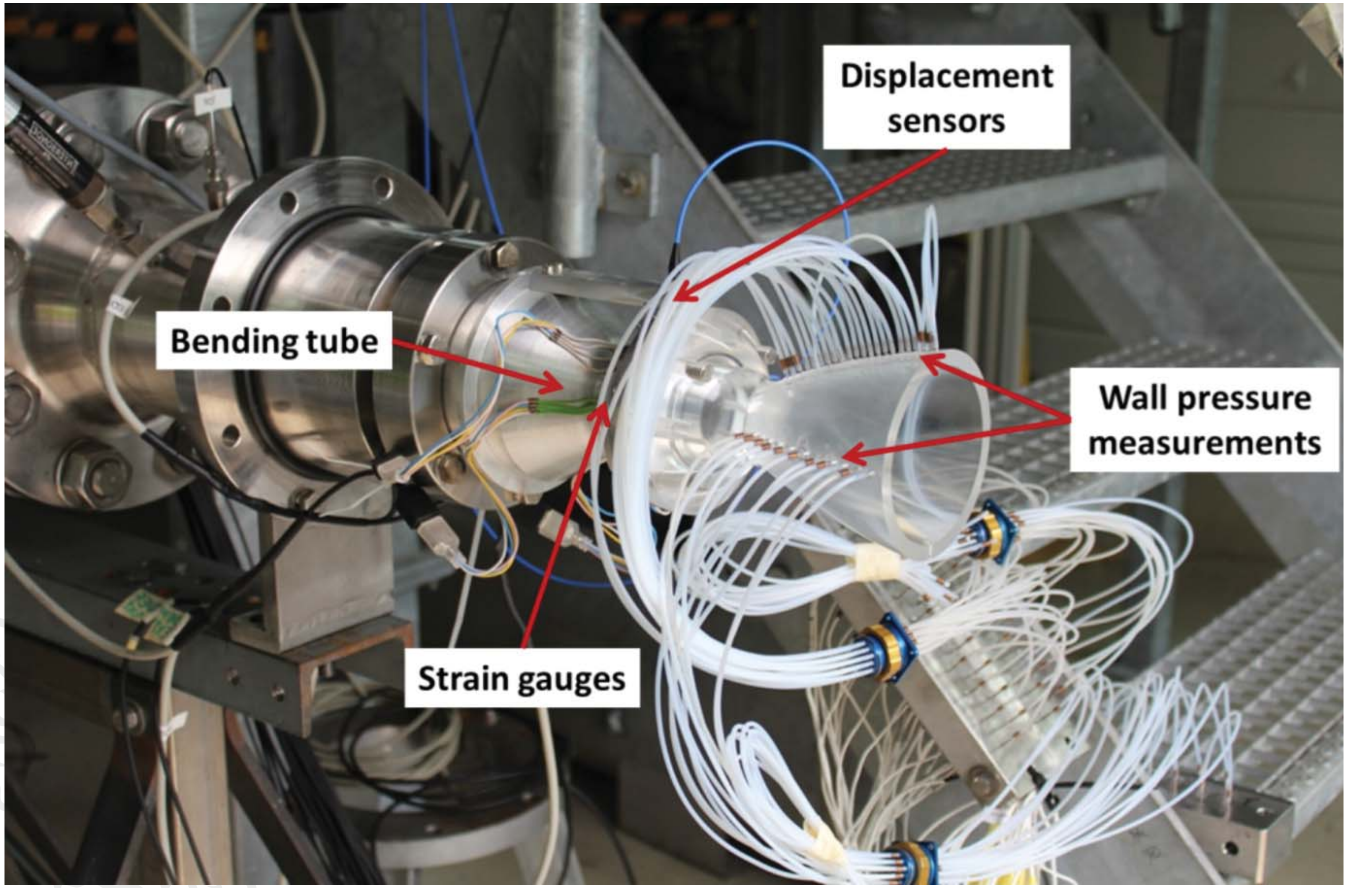
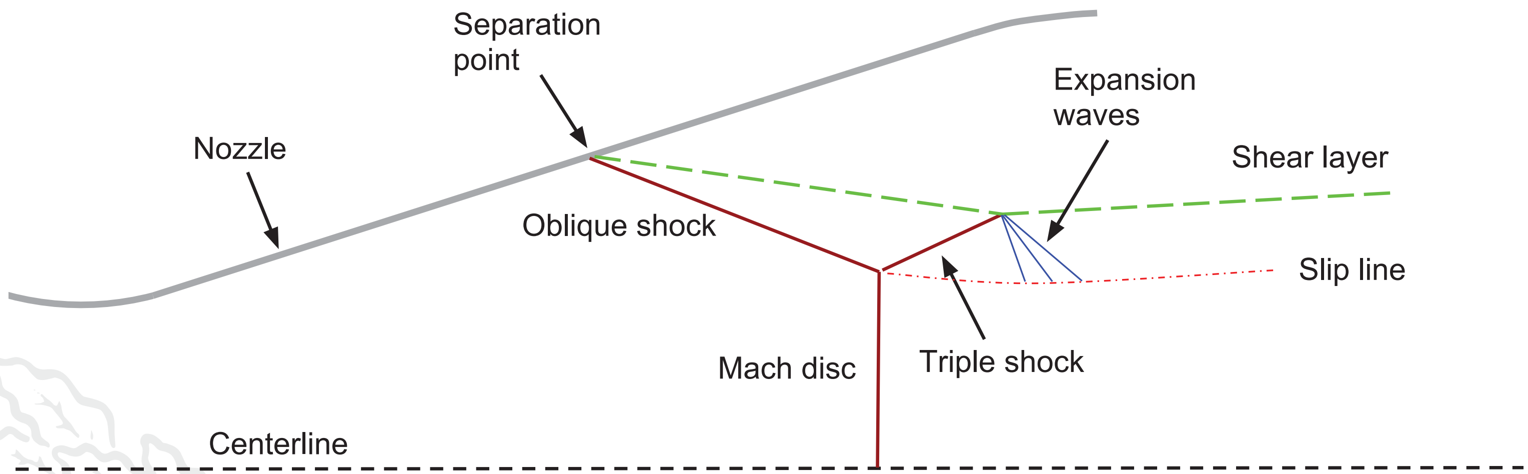
Cold Supersonic Jet

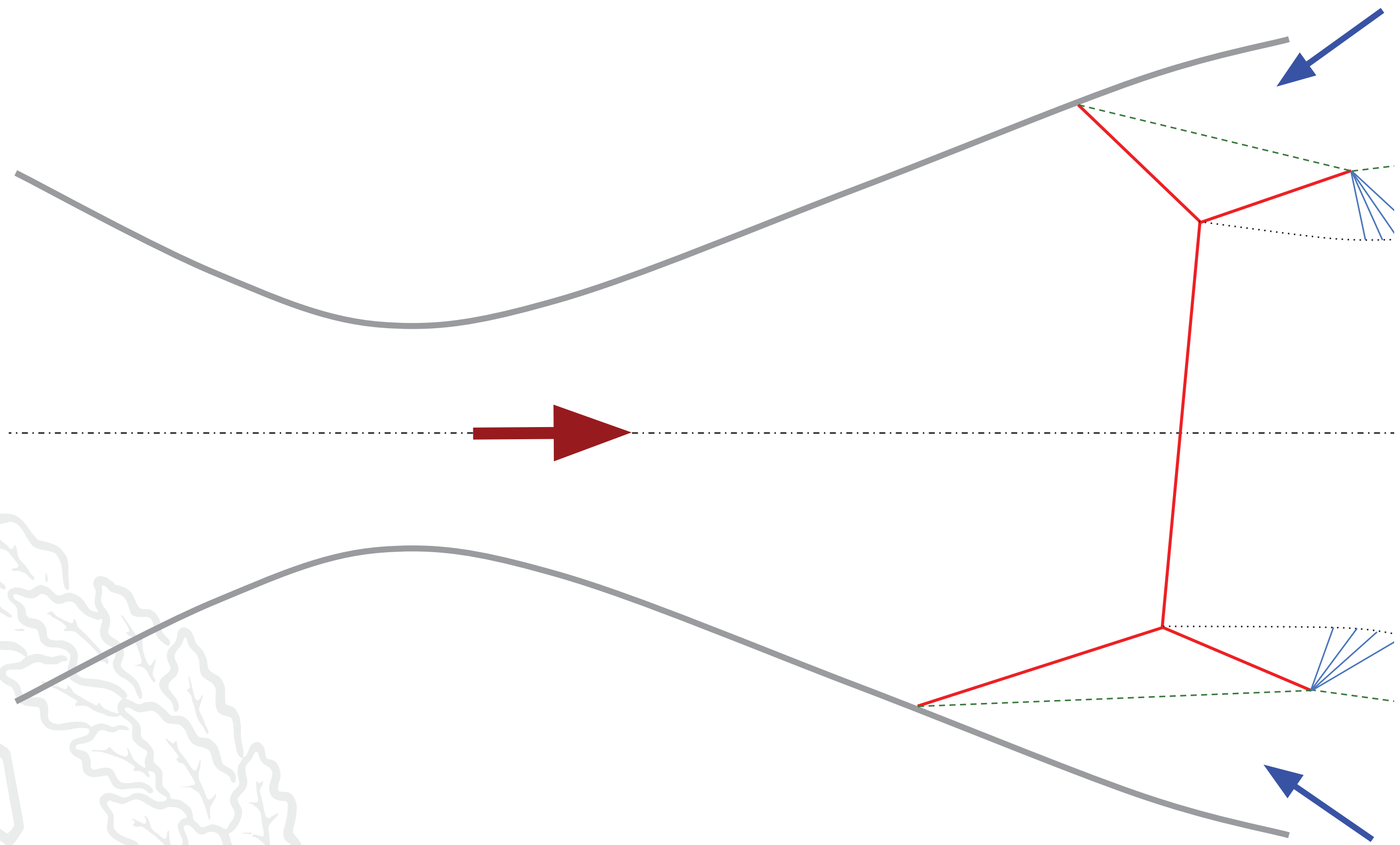


Experimental nozzle at DLR Lampholdshausen. From Génin and Stark 2016.

Free Shock Separation

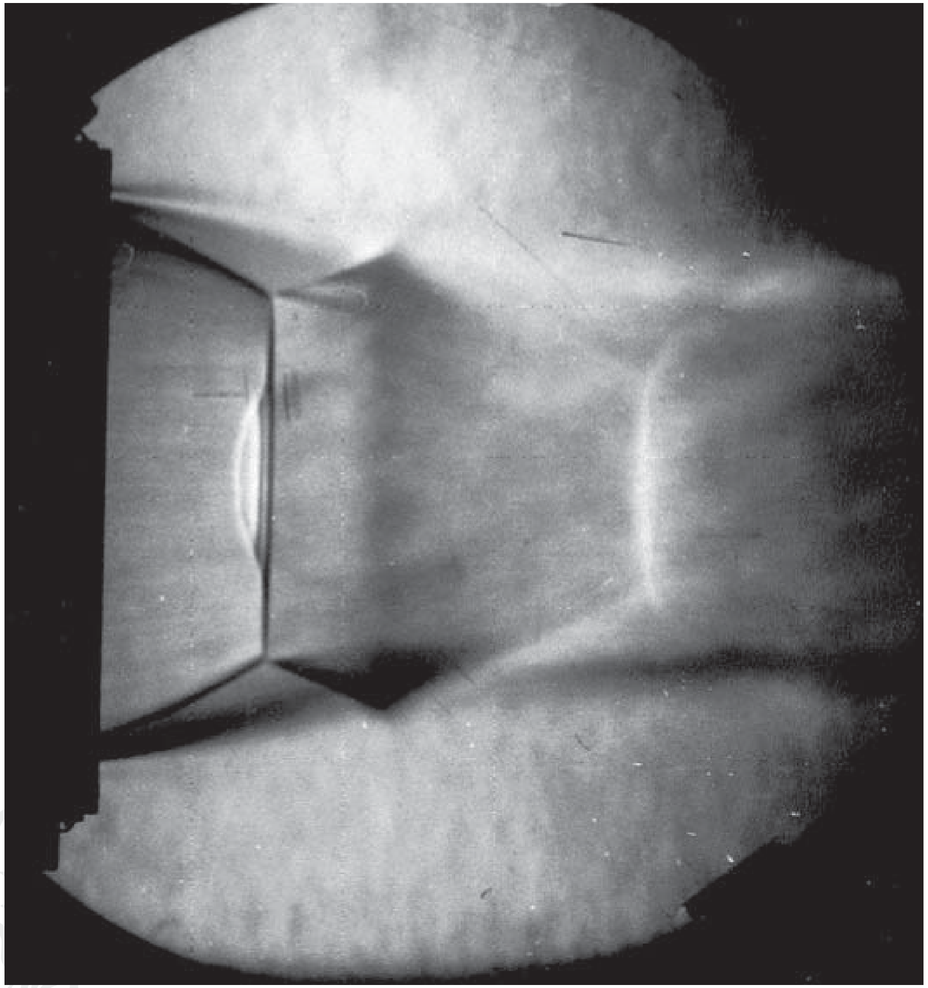


Asymmetric Flow Separation

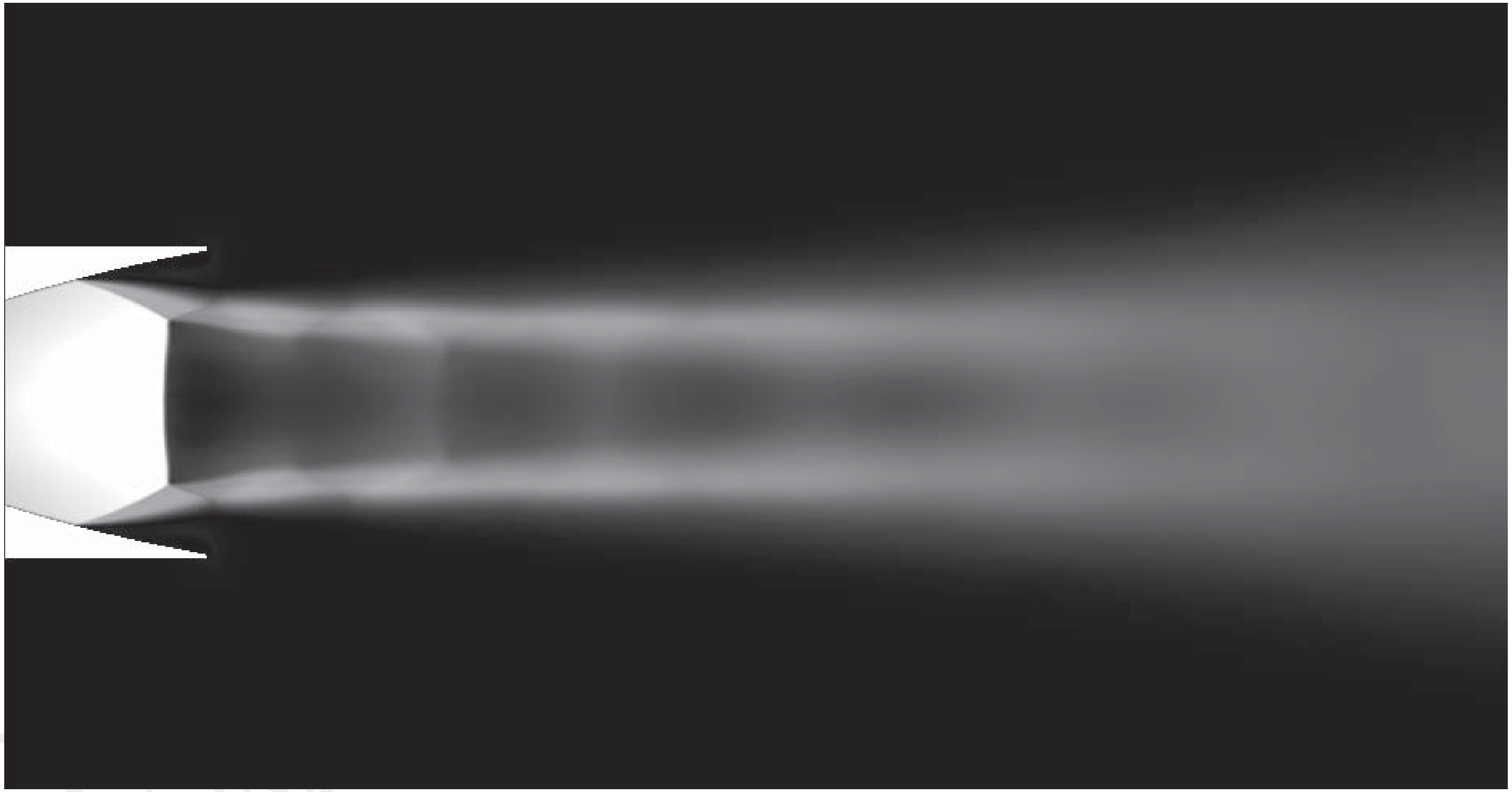


Niklas Andersson

Free Shock Separation - Schlieren Photograph



Free Shock Separation - Numerical Simulation



Average Mach number in a Detached Eddy Simulation (DES).

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Modal Analysis

Objective: To identify oscillating modes of a flow field.

Two different modal decomposition algorithms were used:

- Dynamic Mode Decomposition (DMD)
- Arnoldi algorithm

Linear Flow Dynamics

Assume linear mapping, B, of the flow dynamics such that

$$BQ(t) = Q(t + \Delta t)$$

Where $Q(t)$ is the flow field at time t.

Orthogonal Subspace Projection

An orthogonal vector basis is obtained:

$$V = \{v_0, v_1, ..., v_{m-1}\},$$

We seek a projection of the flow dynamics onto this basis:

$$V^T B V = C_m$$

This is done without direct use of B, which is unknown in its matrix form.

Eigendecomposition

We can then perform an eigendecomposition on the reduced-order matrix C_m

The result is a set of modes, each with a fixed frequency and decay/growth rate and a coherent structure that can be visualized

Arnoldi Algorithm

Uses a linearized flow solver to build a so called Krylov subspace projection basis

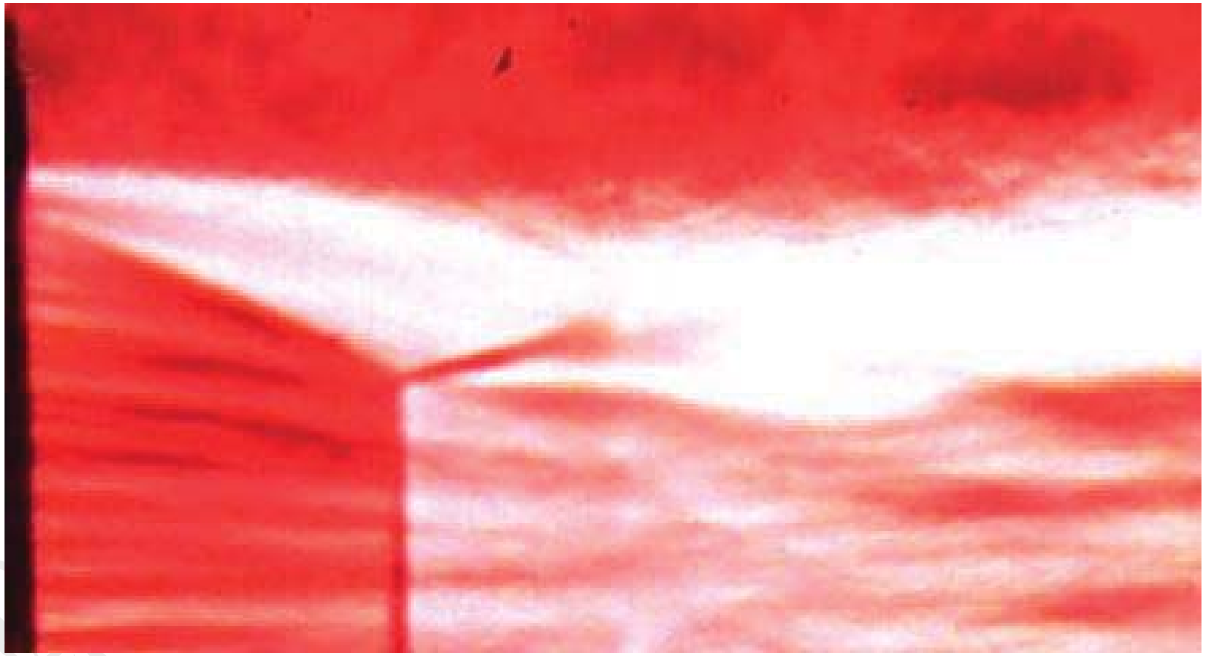
Dynamic Mode Decomposition (DMD)

Uses a sequence of flow field ”snapshot” to construct its projection basis.

The projection basis is comprised of the left singular vectors from a singular value decomposition of the snapshot sequence.

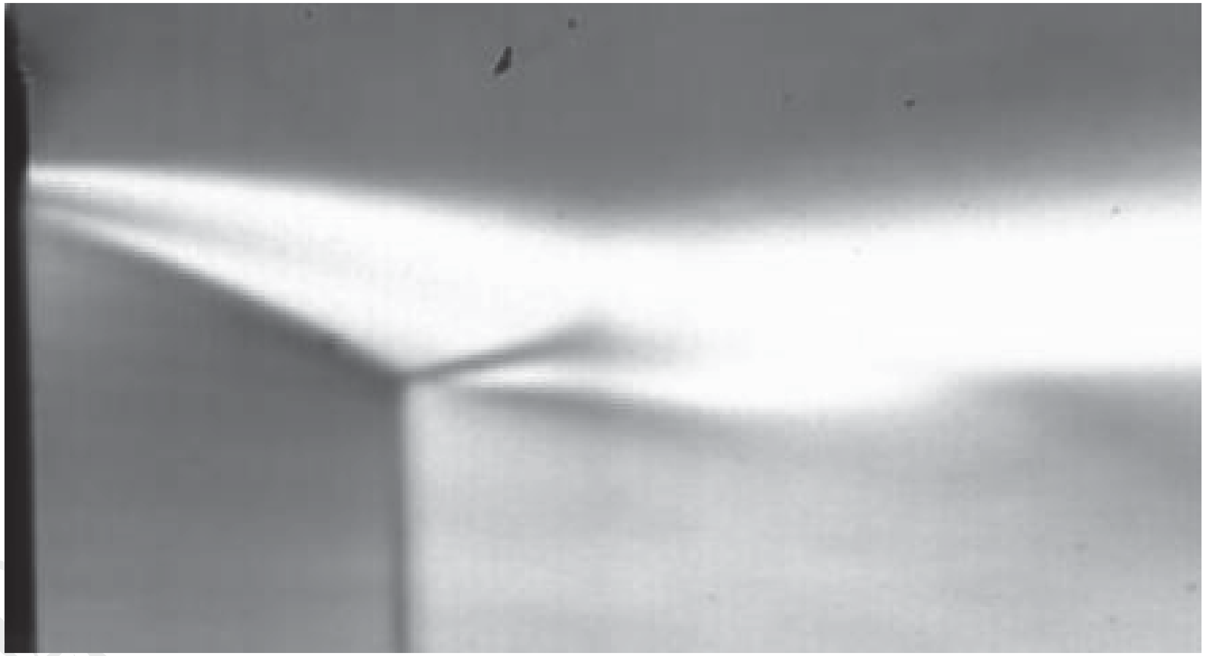
These vectors are also known as Proper Orthogonal Decomposition modes, or POD modes.

Modal Decomposition Example



Video: DLR Lampoldshausen.

Modal Decomposition Example



DMD mode of primary shock oscillation.

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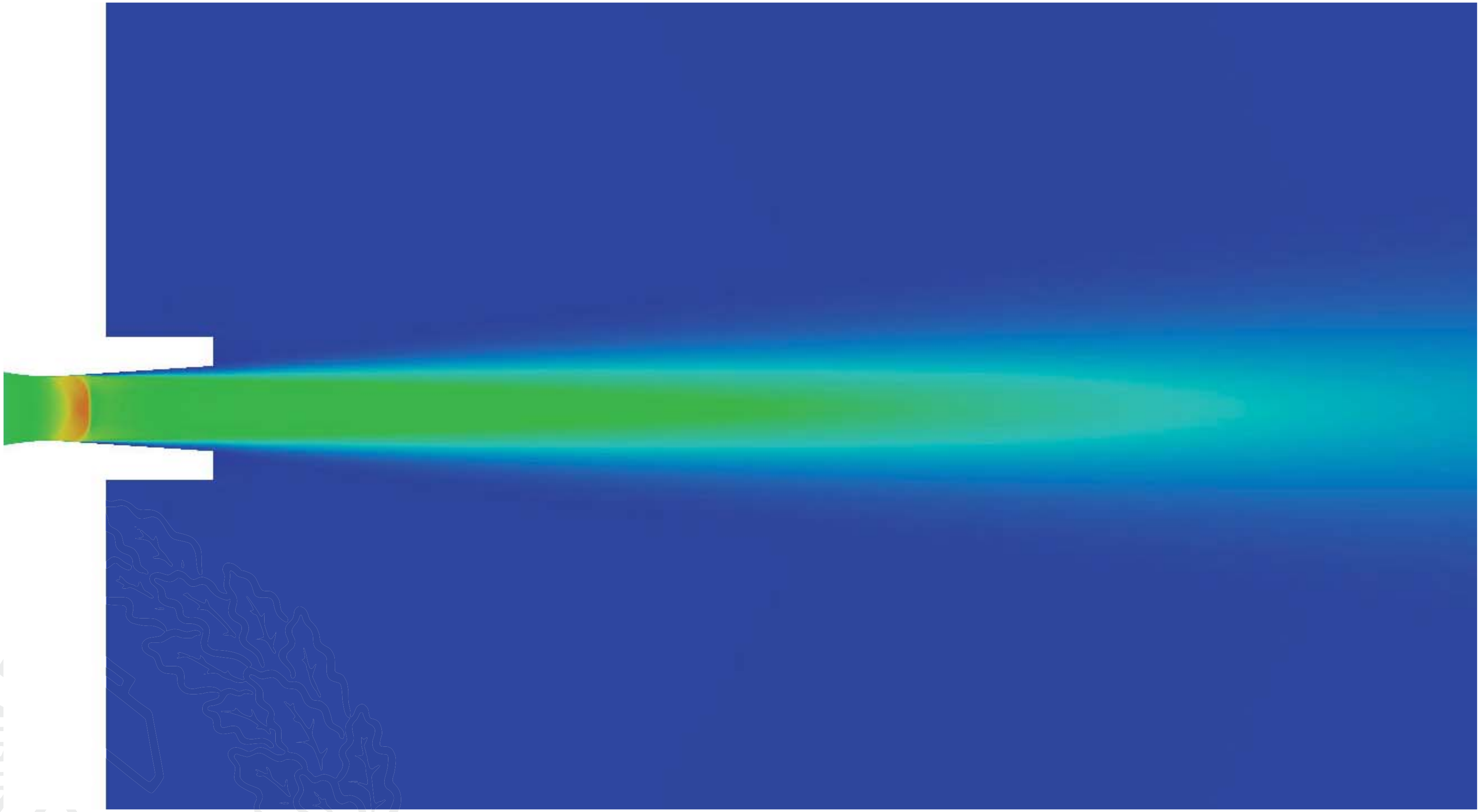
DMD of axisymmetric URANS Simulations

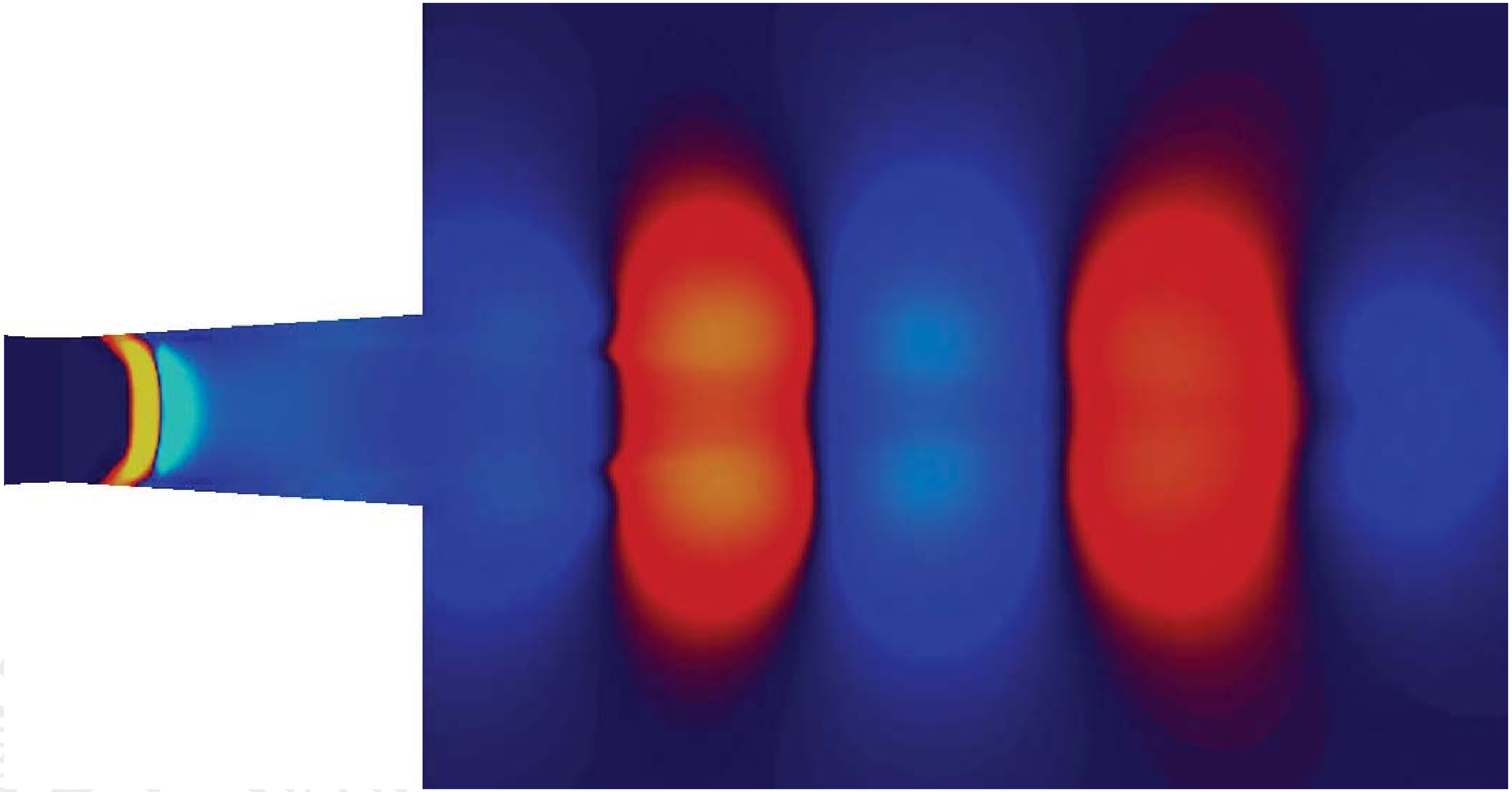
- DMD was applied to axisymmetric URANS simulations
- Compared well with Arnoldi modes in some cases
- Successfully identified so called transonic resonance in a conical nozzle
- Challenges with noise

Axisymmetric URANS



Velocity Magnitude.

DMD - Transonic Resonance

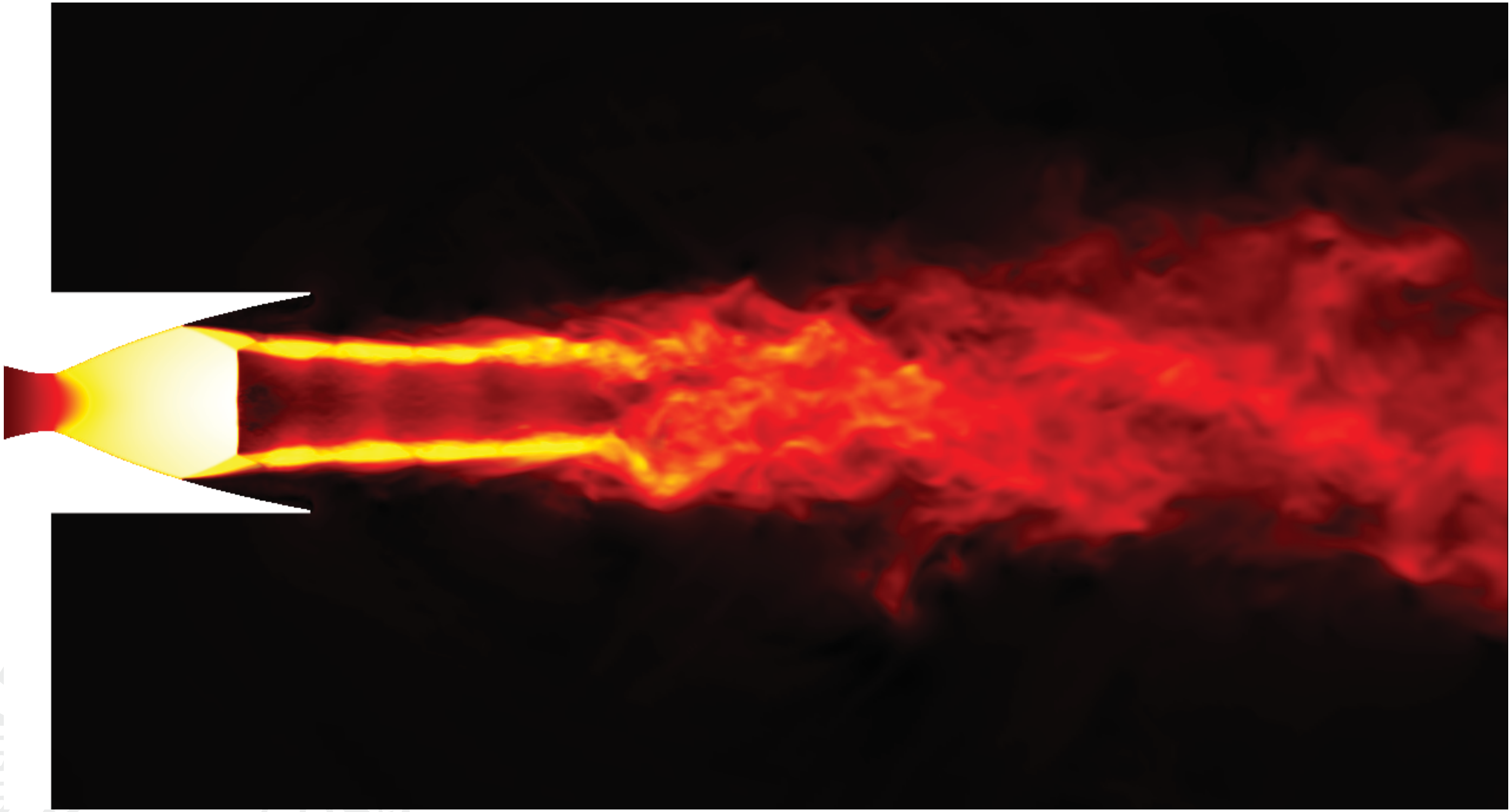


Pressure oscillation field.

Detached Eddy Simulation (DES)

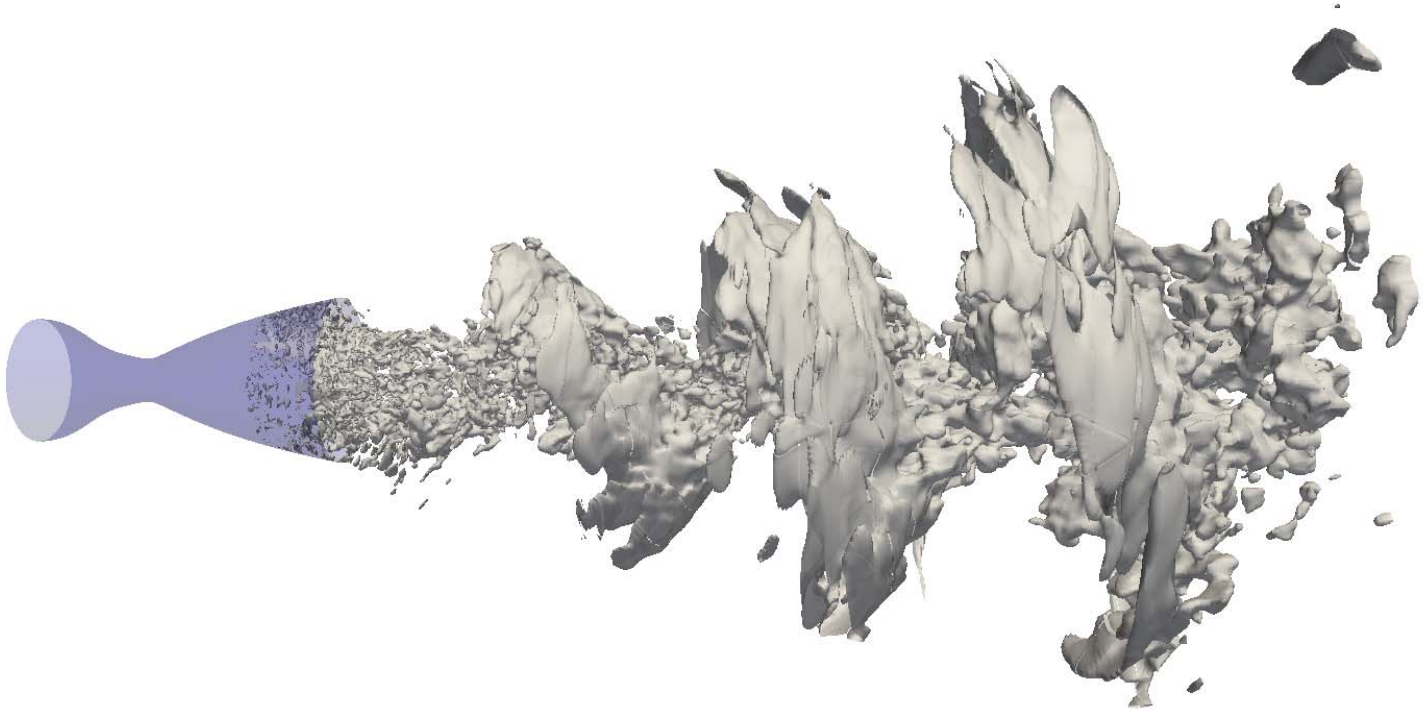
- DES of a separated nozzle flow
- Simulated side-loads were lower than measured side-loads but within uncertainty levels
- DMD Identified modes responsible for side-loads and nozzle ovalization
- Again we had challenges with noise

Detached Eddy Simulation (DES)



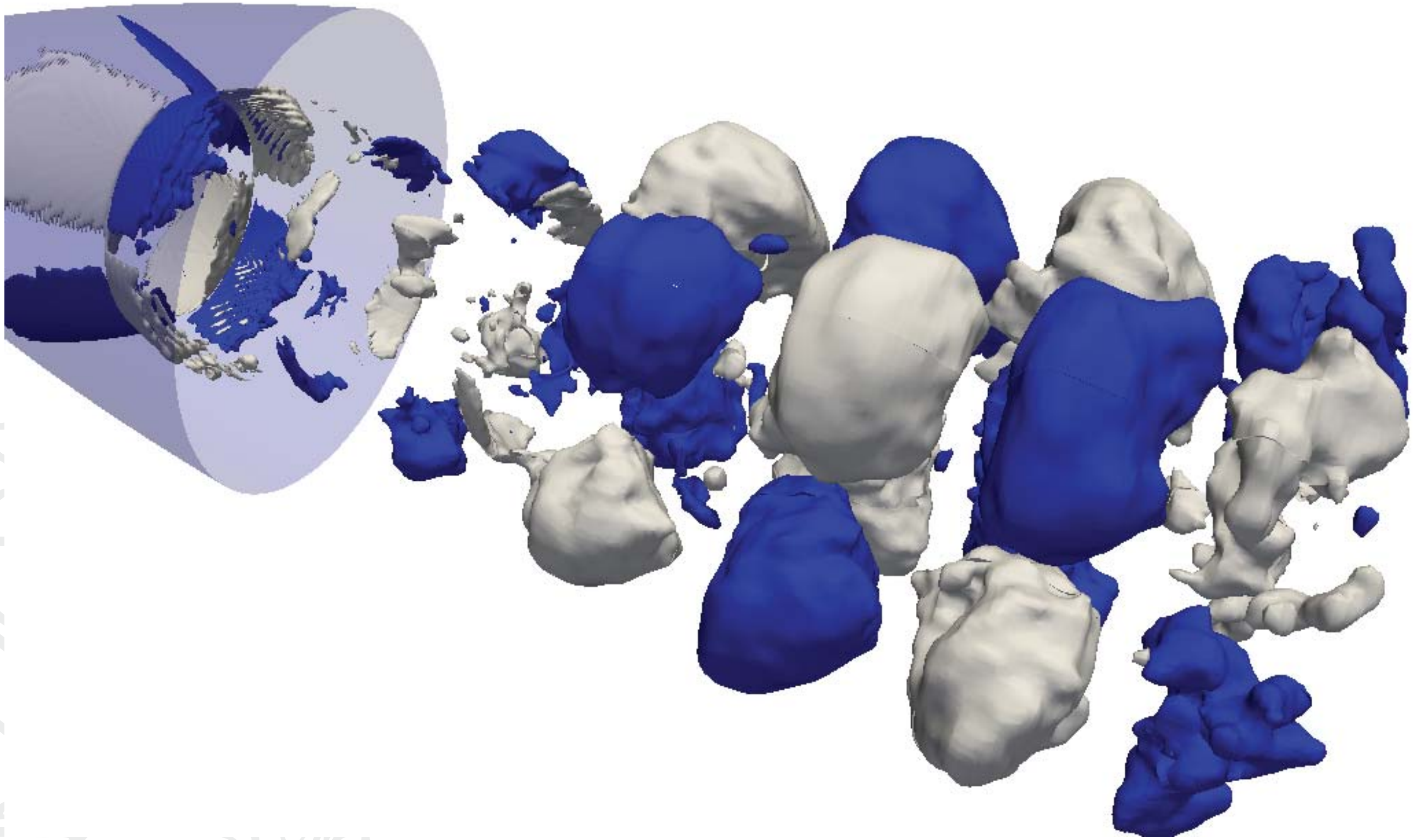
Velocity Magnitude.

DMD - Helical Mode



Isosurface of pressure oscillation filed.

DMD - Ovalization



Isosurface of pressure oscillation filed.

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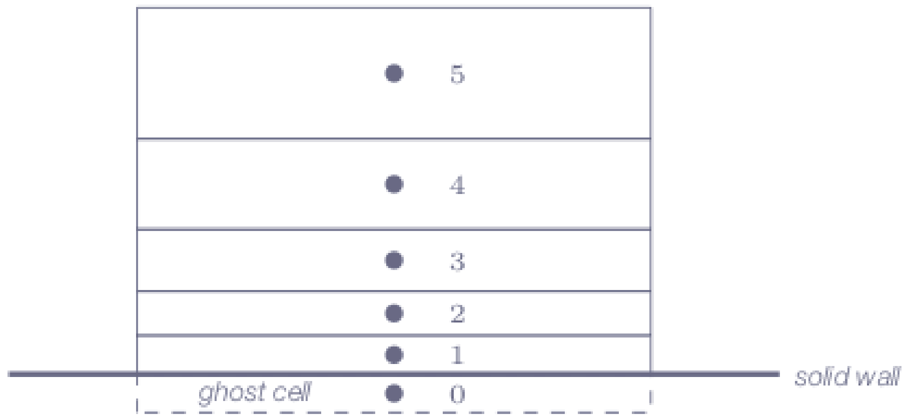
Implicit Compressible Flow Solver

- Semi-implicit Solver
- Implicit Residual Smoothing
- Dual Time Stepping
- Fully Implicit Solver

Semi-implicit Solver

- Local implicit problem in the wall-normal direction



Implicit Residual Smoothing

- Preconditioning
- Increases the stability margin of the explicit time marching method
- Possible to increase CFL number

Dual Time Stepping

- Reformulation of the explicit time stepping algorithm
- Each time step is solved iteratively using sub-iterations
- Dual Time Stepping combined with Implicit Residual Smoothing results in a solver speed-up factor of 10-80 (depending on case)

Fully Implicit Solver

- Global implicit formulation
- Fully coupled problem leads to very large matrices
- Matrix coefficient calculation
  - analytic formulations
  - automatic differentiation
- Matrix solver based on the solvers and data storage structures in PETSc

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Summary

- The Arnoldi and the DMD methods can be used to identify important oscillating modes
- These modes could potentially lock onto structural eigenmodes
- Future challenges are:
  - to eliminate the effect from noise in DMD modes
  - to further develop side-load resolving simulation methods

Publications and Collaborations

- one PhD student (Lic 2014, PhD 2017)
- 6 conference papers
- one journal publication (one additionally under review)
- exchange with DLR Lampoldshaussen (ongoing discussions about future project)
- joint publication on DMD with INSA Rouen (future exchange)