Modal Analysis of Separated Nozzle Flow

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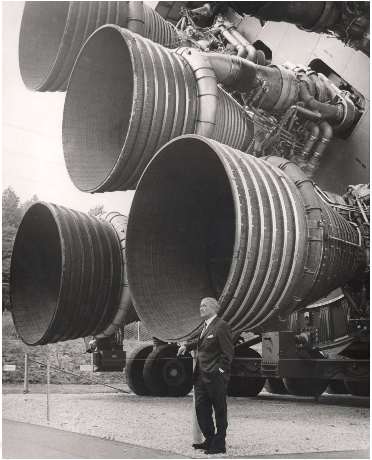
The Convergent-Divergent Nozzle (CD Nozzle)

CD Nozzle - Small Example

Figure: ©Heraeus Group

CD Nozzle - Big Example



Real Rocket Engine Jet

Cold Flow Supersonic Jet

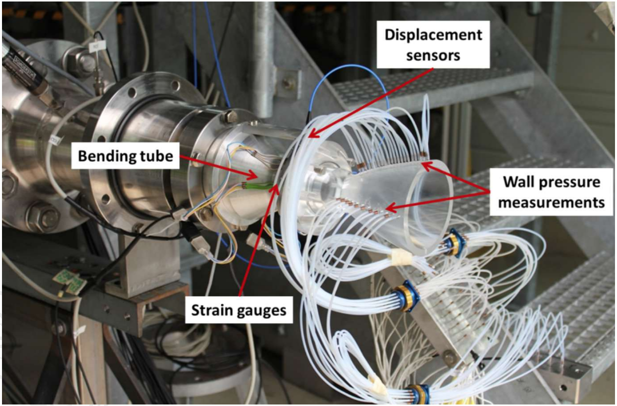
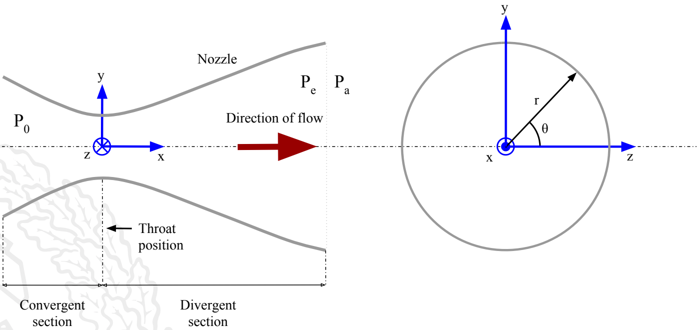
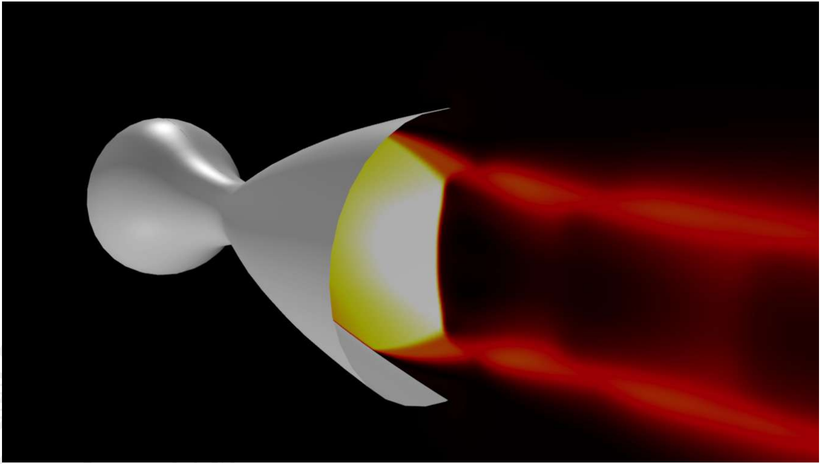


Figure: Experimental nozzle at DLR Lampholdshausen. From Génin and Stark 2016

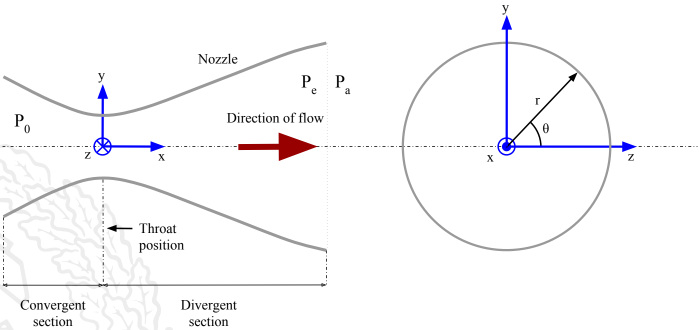
Definition of a CD Nozzle



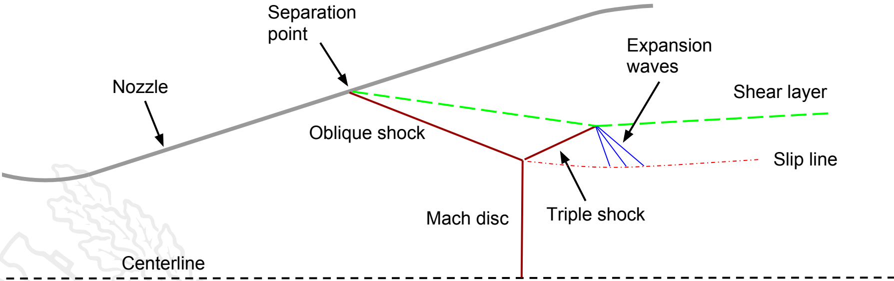
Separated Nozzle Flow



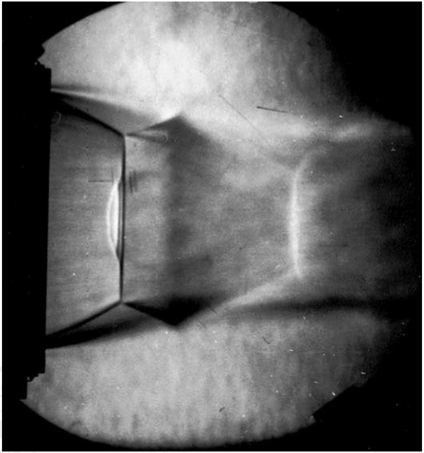
Separated Nozzle Flow



Separated Nozzle Flow - Free Shock Separation



Separated Nozzle Flow - Schlieren Photograph



Nozzle Side-Loads

- Asymmetrical separation inside a supersonic nozzle causes unwanted lateral forces, or side-loads, acting on the nozzle structure
- Semi-empirical side-load models provide only moderate accuracy

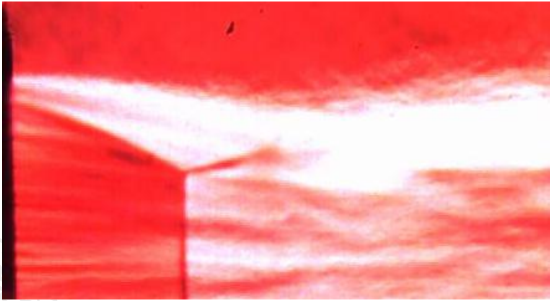
Nozzle Side-Loads

- Computational Fluid Dynamics (CFD) provides a way to directly simulate flow processes that are responsible for the side-loads
- Modal Decomposition of computational and experimental data can provide information about the nature of flow instabilities and their fluctuation frequencies

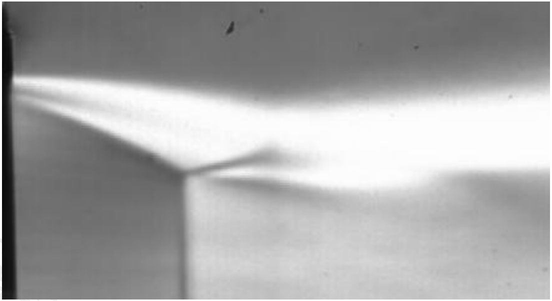
Modal Decomposition

- Identifies fluctuating modes of a unstable flow field, similar to eigenfrequency analysis in structural mechanics.
- In the current project two different modal decomposition algorithms have been applied for the first time to separated nozzle flow. These are the Dynamic Mode Decomposition and the Arnoldi algorithms respectively.

Modal Decomposition Example



Modal Decomposition Example



Computational Fluid Dynamics

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \overline{\rho}\tilde{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \overline{\rho}\tilde{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{\rho}\tilde{u}_i\tilde{u}_j + \overline{p}\delta_{ij} - \tau_{ij}\right) = 0 \tag{2}$$

$$\frac{\partial \overline{\rho}\tilde{e}_0}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{\rho}\tilde{e}_0\tilde{u}_j + \overline{p}\tilde{u}_j - C_p\left(\left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t}\right)\frac{\partial \tilde{T}}{\partial x_j}\right) - \tilde{u}_i\tau_{ij}\right) = 0 \tag{3}$$

$$\tau_{ij} = (\mu + \mu_t)\left(2\tilde{S}_{ij} - \frac{2}{3}\frac{\partial \tilde{u}_k}{\partial x_k}\delta_{ij}\right) - \frac{2}{3}\overline{\rho}\tilde{k}\delta_{ij} \tag{4}$$

$$\tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) \tag{5}$$

$$\frac{\partial \overline{\rho}\tilde{k}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{\rho}\tilde{k}\tilde{u}_j - \left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial \tilde{k}}{\partial x_j}\right) = P_k - \overline{\rho}\tilde{\varepsilon} \tag{6}$$

$$\frac{\partial \overline{\rho}\tilde{\varepsilon}}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{\rho}\tilde{\varepsilon}\tilde{u}_j - \left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \tilde{\varepsilon}}{\partial x_j}\right) = \left(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\overline{\rho}\tilde{\varepsilon}\right)\frac{\tilde{\varepsilon}}{\tilde{k}} \tag{7}$$

$$P_k = \left(\mu_t\left(2\tilde{S}_{ij} - \frac{2}{3}\frac{\partial \tilde{u}_k}{\partial x_k}\delta_{ij}\right) - \frac{2}{3}\overline{\rho}\tilde{k}\delta_{ij}\right)\frac{\partial \tilde{u}_i}{\partial x_j} \tag{8}$$

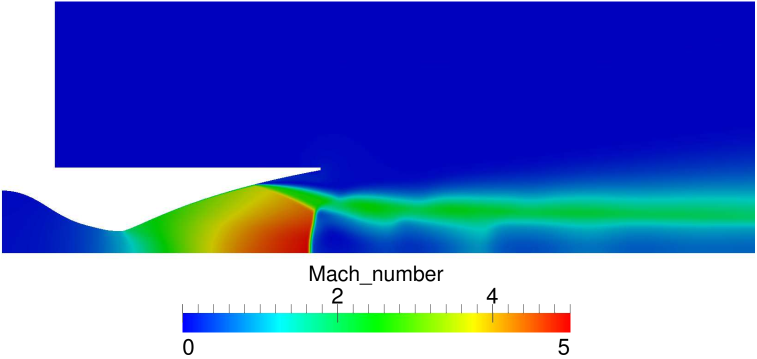
$$\mu_t = \min\left(C_\mu\overline{\rho}\frac{\tilde{k}^2}{\tilde{\varepsilon}}, \frac{C_r\overline{\rho}\tilde{k}}{\sqrt{\tilde{S}_{ij}\tilde{S}_{ij}}}\right) \tag{9}$$

G3D::FLOW

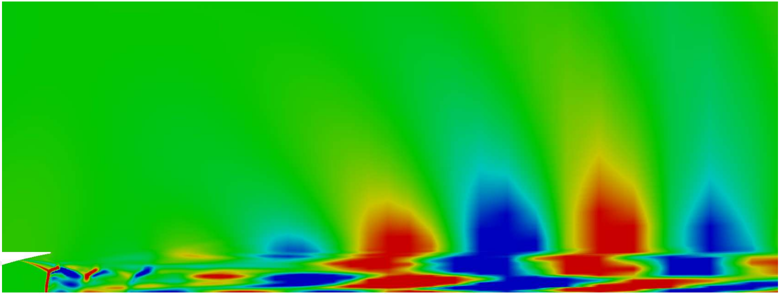
An explicit compressible Navier-Stokes equation solver.

Jointly developed at GKN Aerospace Sweden AB and Chalmers University of Technology.

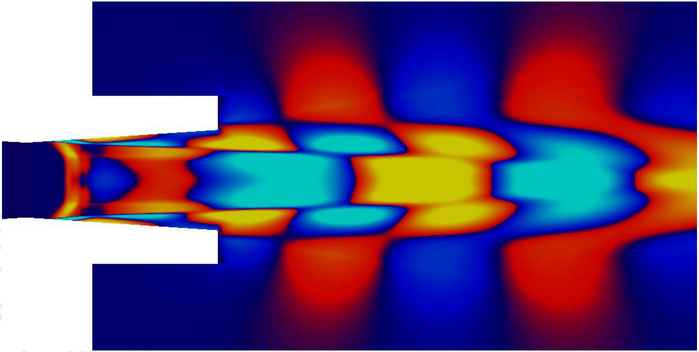
Separated Nozzle Flow - Steady State Flow Field



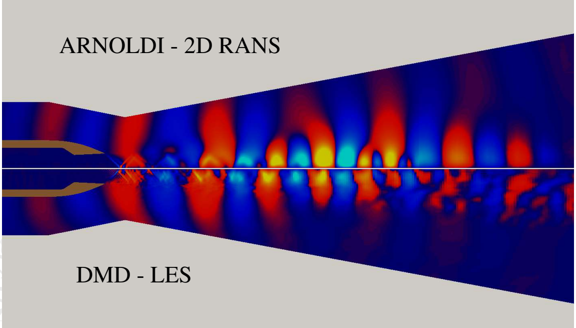
Separated Nozzle Flow - Arnoldi Mode Example



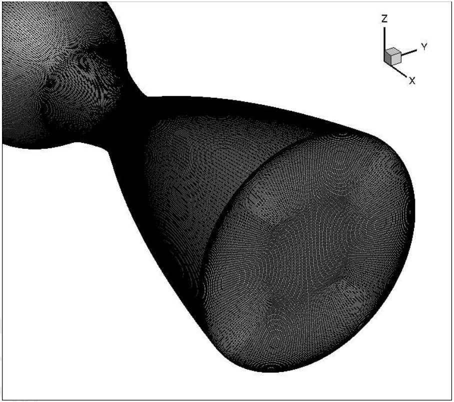
Transonic Resonance - DMD Mode Exmaple



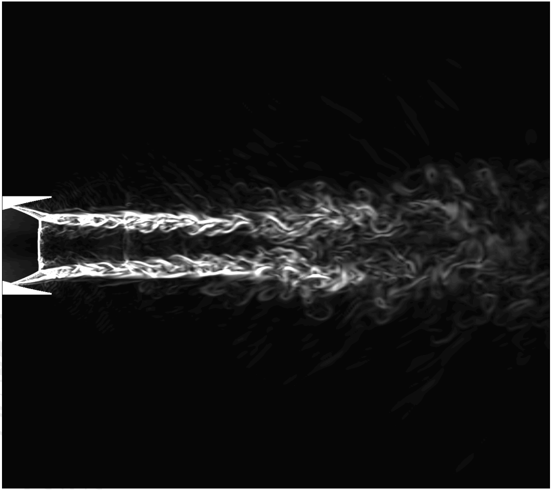
High Cost vs. Low Cost Modal Decomposition



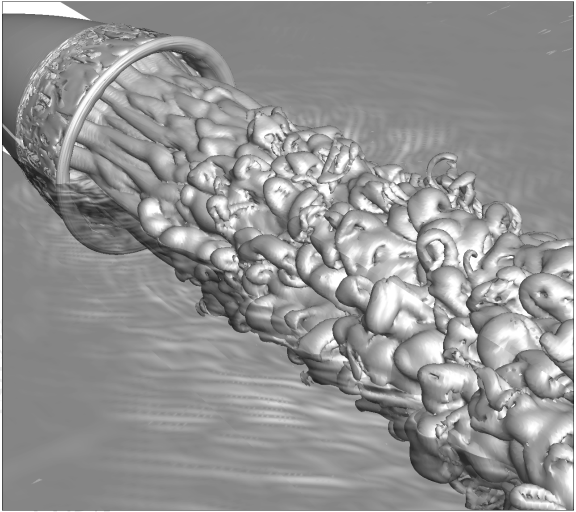
High Fidelity CFD



High Fidelity CFD - Density Gradient Magnitude



High Fidelity CFD - Vorticity Magnitude Iso-surface



High Fidelity CFD - Simulated vs. Measured Side-Load

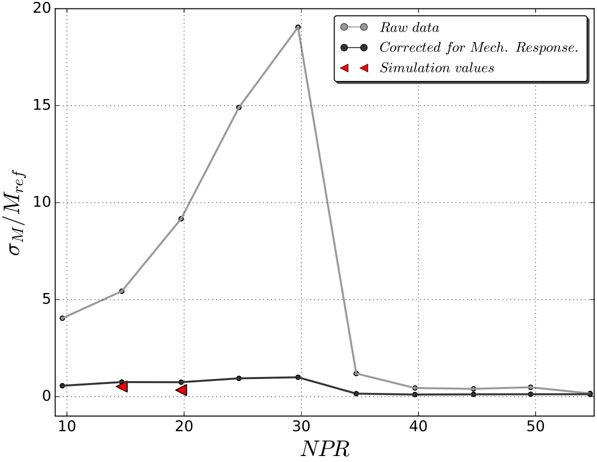
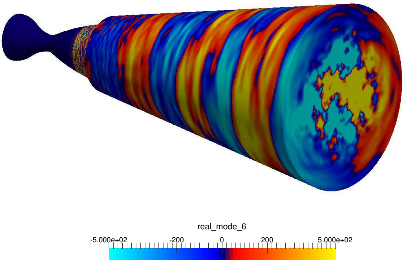


Figure: Raw and corrected measured σ_M side-load vs. simulated values.

High Fidelity CFD - DMD Mode Example



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