Time-efficient simulations of weapon bay flows in fighter aircraft

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Introduction

Problem:

- A weapon bay features a highly complex unsteady, separated flow which is characterised by an intense aero-acoustic coupling mechanism.
- Acoustic and flow dynamic interactions inside the cavity lead to a self-sustained oscillation process and presence of Rossiter modes.
- Computation of the Rossiter modes demands a high computational cost.
- Hybrid RANS-LES approach of a weapon bay requires around 1 Million core-h with SuperMUC-NG cluster.

Objectives:

- Understanding the characteristic features of open cavity flows that lead to the resonance phenomena.
- Increasing the computational efficiency and meeting industry standards using appropriate turbulence modelling.
- Formulating best-practices guidelines for simulating weapon bay configurations with the DLR-TAU code.

Rossiter semi-empirical model

The Rossiter model (1) is formulated based on the following mechanism [1]

- Downstream convection of vortices from the shear layer.
- Impingement of vortices at the downstream edge generating acoustic waves.
- Acoustic waves travelling upstream and exciting further disturbances in the shear layer, leading to a self-sustained oscillation process.

$$f = \frac{U_\infty}{L}\frac{m-\alpha}{Ma + 1/\kappa} \quad (1)$$

The table below shows the frequencies at which the modes occur for a transonic flow condition of $Ma = 0.8$ and $Re = 12 \times 10^6$ in a weapon bay.

Table: Modal frequencies based on the semi-empirical Rossiter model

Mode	Theory(Hz)	Exp.(Hz)	CFD (Hz)
1	263	272	266
2	670	755	752
3	1076	1160	1144
4	1484	1600	1622

Numerical approaches

Hybrid RANS-LES approach In this study, SA-IDDES model of Hybrid RANS-LES approach has been used. The Spalart-Allmaras original model with DES capability [2] is based on the standard one-equation Spalart-Allmaras model, which models the transport equation for the eddy viscosity [3]

$$\frac{\partial}{\partial t}(\rho\tilde{\nu}) + \mathbf{u}\cdot\nabla(\rho\tilde{\nu}) = \nabla\cdot\left(\frac{\mu+\rho\tilde{\nu}}{\sigma}\nabla\tilde{\nu}\right) + \rho\frac{c_{b2}}{\sigma}(\nabla\tilde{\nu})^2 + P_\nu - \epsilon_\nu \quad (2)$$

where the production term P_ν and the destruction term ϵ_ν are

$$P_\nu = c_{b1}\rho\tilde{S}\tilde{\nu} \quad \text{and} \quad \epsilon_\nu = c_{w1}f_w\rho\left(\frac{\tilde{\nu}}{\tilde{d}}\right)^2. \quad (3)$$

This model represents the standard SA model, except that the length scale $\tilde{d}$ in the destruction term is modified. In the SA-model, d is the distance to the nearest wall. In the IDDES model, d is replaced with $\tilde{d}$, which is defined as

$$\tilde{d} = d - f_d max(0, d - C_{DES}\Delta) \quad (4)$$

with $\Delta = max(\Delta x, \Delta y, \Delta z)$, $\Delta x, \Delta y$ and Δz represent the grid spacing in x, y and z directions, respectively and f_d is the shielding function desgined to be unity in the LES region and zero elsewhere.

SAS approach In this approach, the RANS based $k-\omega$ SST model has been used with the additional source term Q_{SAS} in the transport equation for the turbulence eddy frequency ω to enable local resolution of the flow structures [4].

$$Q_{SAS} = max\left[\rho\zeta_2 S^2\left(\frac{L}{L_{vK}}\right)^2 - F_{SAS}\frac{2\rho k}{\sigma_\phi}max\left(\frac{1}{k^2}\frac{\partial k}{\partial x_j}\frac{\partial k}{\partial x_j}, \frac{1}{\omega^2}\frac{\partial\omega}{\partial x_j}\frac{\partial\omega}{\partial x_j}\right), 0\right] \quad (5)$$

with von Karman length scale $L_{\nu K}$ given by

$$L_{\nu K} = \kappa\frac{U'}{|U''|}; \quad U'' = \sqrt{\frac{\partial U_i}{\partial x_k^2}\frac{\partial U_i}{\partial x_j^2}}; \quad U' = \sqrt{2\cdot S_{ij}S_{ij}} \quad (6)$$

Mesh distribution

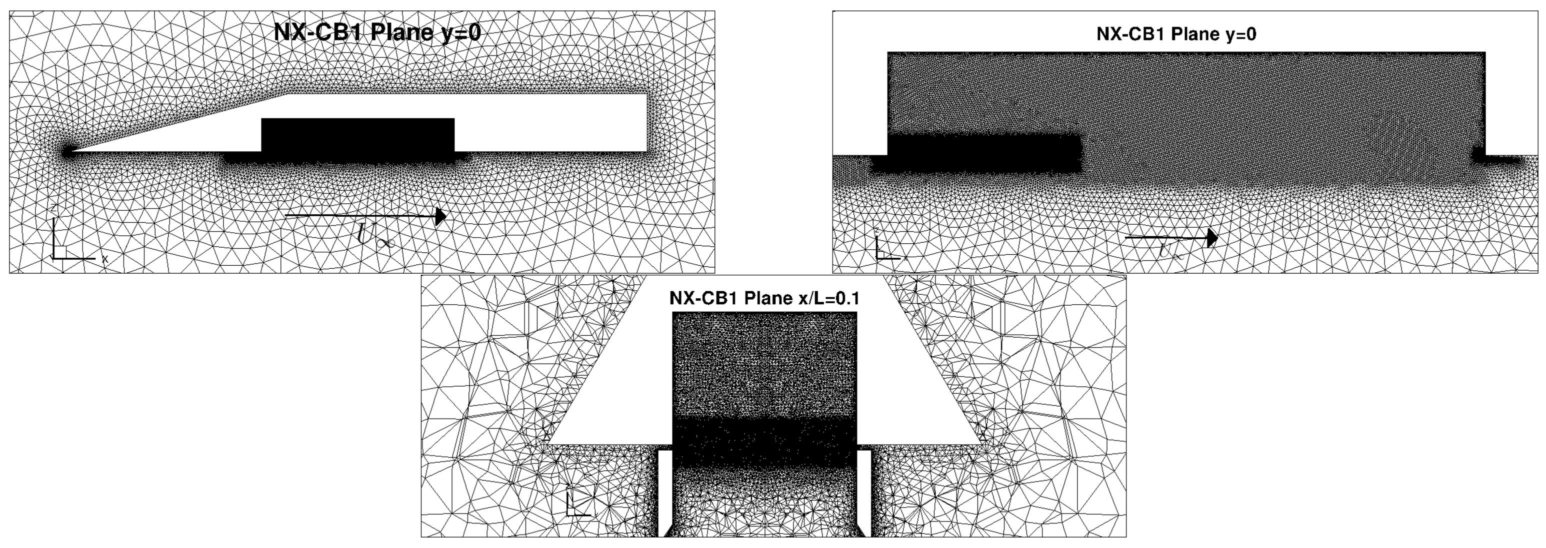

Figure 1: Mesh distribution showing fine resolution of crucial regions

Results of Hybrid RANS-LES and SAS approaches

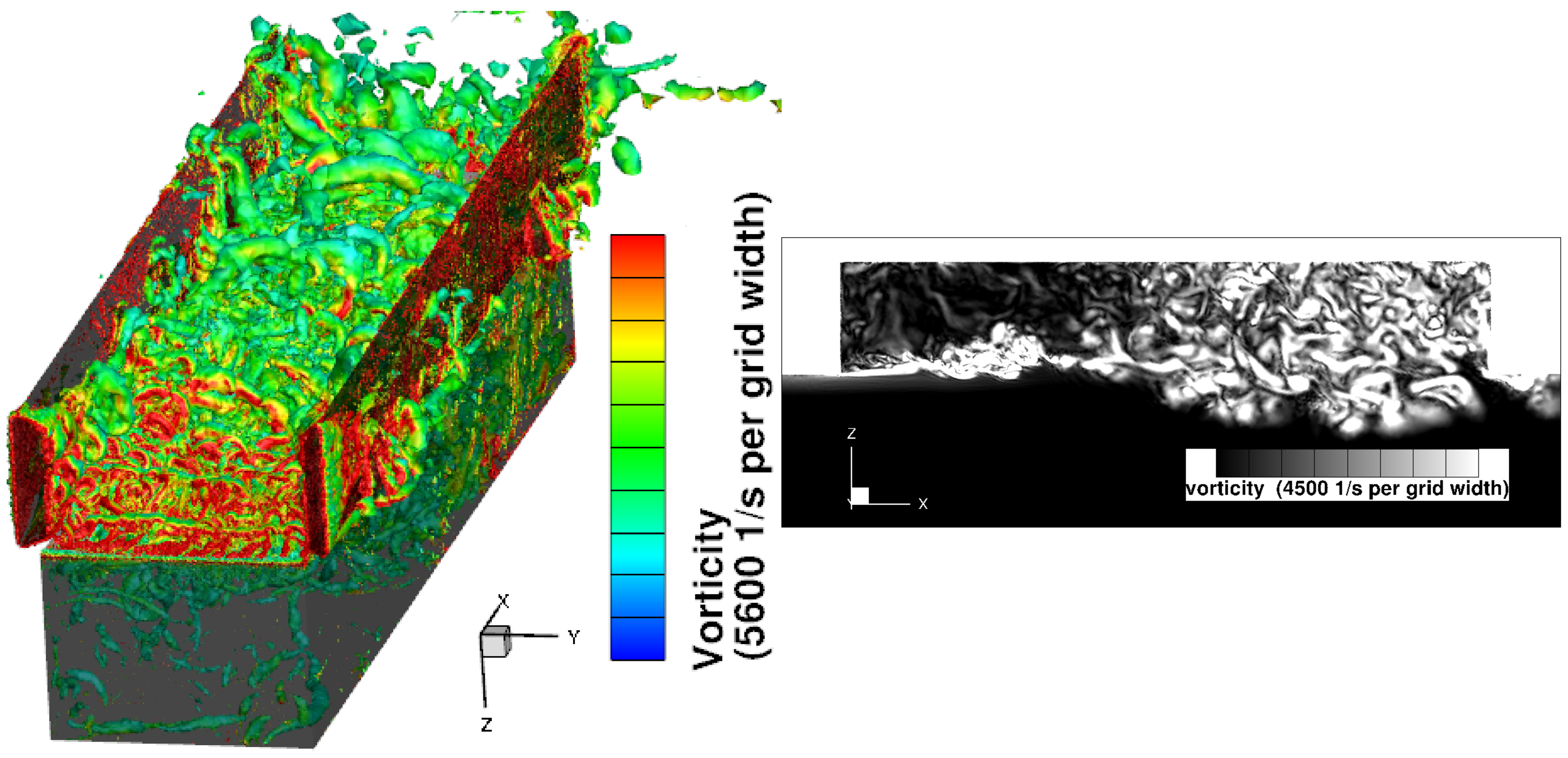

Figure 2: Shear layer instability (left) growing in its width seen in the streamwise direction(right)

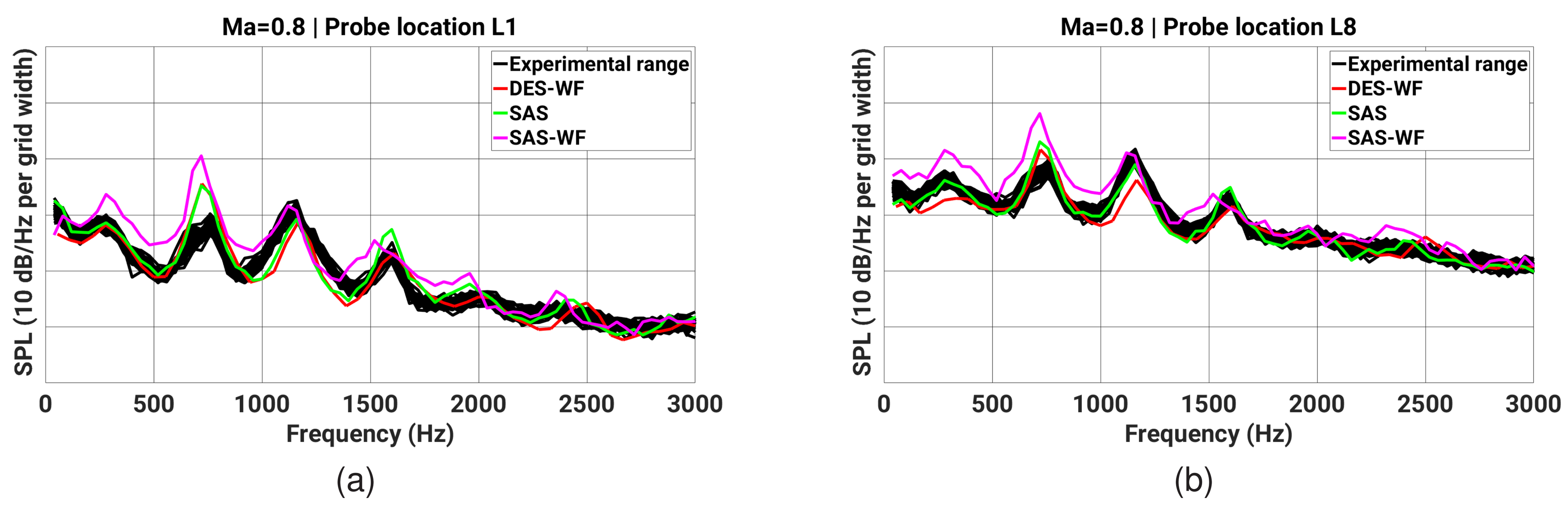

Figure 3: Spectral analysis of the pressure signal - hybrid RANS-LES and SAS approaches

Computational efficiency The DES-WF (SA-IDDES model with wall function) simulation is estimated to be around 50% computationally cheaper than the DES simulation (SA-IDDES model with wall integration) [5], whereas the SAS simulation is estimated to be 90% computationally efficient than DES simulations and the SAS-WF simulation is twice as fast as the SAS simulation.

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References

[1] J.E. Rossiter. Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds, 1964.
[2] P. R. Spalart, W. H. Jou, M. Strelets, and S. R. Allmaras. Comments on the feasibility of LES for wings and on a hybrid RANS/LES approach. Advances in DNS/LES, 1(January):48, 1997.
[3] P. R. Spalart and S. R. Allmaras. A one-equation turbulence model for aerodynamic flows. La Recherche aerospatiale, (1):521, 1994.
[4] F. R. Menter, A. Garbaruk, P. Smirnov, D. Cokljat, and F. Mathey. Scale-adaptive simulation with artificial forcing. Notes on Numerical Fluid Mechanics and Multidisciplinary Design, 111(January):235246, 2010.
[5] K. Rajkumar, E. Tangermann, M. Klein, S. Ketterl, and A. Winkler. DES of weapon bay in fighter aircraft under high-subsonic and supersonic conditions. Notes on Numerical Fluid Mechanics and Multidisciplinary Design, 151:656665, 2021.