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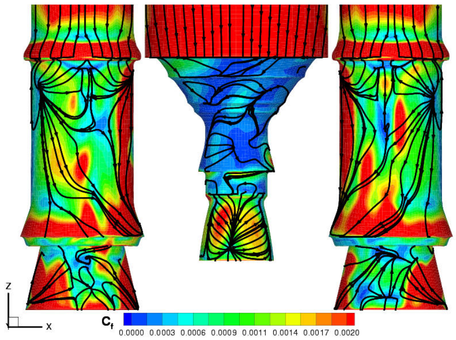
Executive summary

Dynamic load predictions for launchers using eXtra-Large Eddy Simulations (X-LES)



Problem area
Flow-induced unsteady loads can have a strong impact on flight and performance characteristics of aerospace vehicles and therefore play a crucial role in their design and operation. Complementary to costly flight tests and delicate wind-tunnel experiments, unsteady loads can be calculated using time-accurate Computational Fluid Dynamics. A capability to accurately predict the dynamic loads on aerospace structures at flight Reynolds numbers can be of great value for the design and analysis of aerospace vehicles.

Advanced space launchers are subjected to dynamic loads in the base region during atmospheric ascent to space. In particular, the engine and nozzle experience strong low-frequency pressure fluctuations resulting from massive flow separations. Knowledge about the resulting buffet loads is essential for the safe operation of existing launchers and to provide solutions for performance enhancements of future launchers which operate a larger nozzle.

Description of work
A new hybrid URANS-LES turbulence modelling approach termed eXtra-Large Eddy Simulations (X-LES) holds the promise to capture the flow structures associated with massive separations and enables the prediction of the broad-band spectrum of dynamic loads. This type of method has become a focal point, reducing the cost of full LES, driven by the demand for their applicability in an industrial environment.

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Descriptor(s)
massive separated flows
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space launchers
time-accurate CFD
hybrid RANS-LES formulations

This report is based on a paper presented at the 5th European Symposium on Aerothermodynamics for Space Vehicles, Cologne (Germany), 8-11 November 2004.

The industrial feasibility of X-LES simulations is demonstrated by computing the unsteady aerodynamic loads on the main-engine nozzle of a generic space launcher configuration. The potential to calculate the dynamic loads is qualitatively assessed for transonic flow conditions in a comparison to wind-tunnel experiments.

Results and conclusions

Unsteady pressures have been extracted at relevant locations near the nozzle exit. The computed and experimental Power Spectrum Density is plotted against the Strouhal number. It is shown that the computational and experimental results can have comparable frequency content in the selected window. In terms of turn-around-times, X-LES computations are already feasible within time-frames to support the structural design process. The capability will be enhanced by the incorporation higher-order discretisation schemes that improve the turbulent characteristics of the separated flow.

Applicability

Launcher performance adaptations to market needs motivate the incorporation of larger nozzles in their design. The X-LES capability can be utilised to rebuild the effects of base buffeting on the unsteady loads acting on novel nozzles. The results can be exploited for the identification of buffet loads as a structural design load or for the assessment of (unsteady) loads reduction concepts for future launchers.

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Contents

DYNAMIC LOAD PREDICTIONS FOR LAUNCHERS USING EXTRA-LARGE EDDY SIMULATIONS (X-LES)

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ABSTRACT

Flow-induced unsteady loads can have a strong impact on performance and flight characteristics of aerospace vehicles and therefore play a crucial role in their design and operation. Complementary to costly flight tests and delicate wind-tunnel experiments, unsteady loads can be calculated using time-accurate Computational Fluid Dynamics. A capability to accurately predict the dynamic loads on aerospace structures at flight Reynolds numbers can be of great value for the design and analysis of aerospace vehicles.

Advanced space launchers are subject to dynamic loads in the base region during the ascent to space. In particular the engine and nozzle experience aerodynamic pressure fluctuations resulting from massive flow separations. Understanding these phenomena is essential for performance enhancements for future launchers which operate a larger nozzle.
A new hybrid RANS-LES turbulence modelling approach termed eXtra-Large Eddy Simulations (X-LES) holds the promise to capture the flow structures associated with massive separations and enables the prediction of the broad-band spectrum of dynamic loads. This type of method has become a focal point, reducing the cost of full LES, driven by the demand for their applicability in an industrial environment.

The industrial feasibility of X-LES simulations is demonstrated by computing the unsteady aerodynamic loads on the main-engine nozzle of a generic space launcher configuration. The potential to calculate the dynamic loads is qualitatively assessed for transonic flow conditions in a comparison to wind-tunnel experiments. In terms of turn-around-times, X-LES computations are already feasible within the time-frames of the development process to support the structural design.

Key words: massive separated flows; buffet loads; nozzle vibrations; space launchers; time-accurate CFD; composite RANS-LES formulation.

1. INTRODUCTION

Aerospace vehicles are subjected to significant flow-induced unsteady loads during the launch phase of the flight. To establish the effect of unsteady loads on vehicle design and operation, it is imperative to determine structural responses, internal loads and stresses resulting from time-dependent loads. General time-dependent loads can be categorised in a transient/shock type due to ignition, tie-down release or stage separation and a periodic/random type due to propulsion fluctuations, rocket noise and aerodynamic buffet (NASA-SP-8050). This paper addresses the periodic/random loads that serve as input forces to vibration analysis. Of particular concern are the time-dependent loads exerted on ascent vehicle structures by an unsteady flow, characteristic for buffet and massive flow separations.

The occurrence of buffet during atmospheric ascent depends primarily on the shape of the vehicle. The magnitude of the buffet load depends on the dynamic pressure, the Mach number and the incidence angle (NASA-SP-8001). Unfavourable shape factors include protuberances, and abrupt changes in the vehicles diameter. The vehicle should be designed to minimise buffeting through the use of a favourable geometry. In case this is not achievable, the effect of buffet i.e. oscillating pressures and aero-elastic response must be determined and provided for in the structural design.

Geometry parameters are available for launchers that can be considered as a clean body of revolution that yield nearly buffet free designs. Buffet may still exist in local areas with shock-wave fluctuations like the boat-tail angle of the nose cone and the swelling of the core diameter. Furthermore, adoption of skirts in the base region of the first stage protects the engine and nozzle from pressure fluctuations by reducing the separated wake flow. In contrast, multiple-body launchers that feature a separated wake type of flow in the base region are liable to unsteady aerodynamic interference phenomena and may be considered as buffet prone.

The unsteady loads corresponding to buffet are traditionally determined in delicate wind-tunnel experiments during the design phase and are validated in actual flight. The wind-tunnel measurements provide the buffeting input-forces on rigid scale models (see Figure 1).

Figure 1. Wind tunnel model for buffeting forces measurements

Scaling parameters that have to be satisfied are the Mach number, Reynolds number and reduced frequency. The Mach number and reduced frequency can be satisfied, but generally the Reynolds number is at a sub-scale value. Uncertainties in the scaling laws that provide the extrapolation to flight conditions have not been firmly established with respect to separation phenomena. In order to reduce these uncertainties, there is a clear need for a capability that allows the launcher industry to be able to predict the buffet loads on aerospace vehicles early in the design process at flight Reynolds numbers.

The prediction of buffet loads requires time-accurate turbulent flow simulations. A new hybrid RANS-LES turbulence modelling approach termed eXtra-Large Eddy Simulations (X-LES) holds the promise to capture the flow structures associated with massive separations and enables the prediction of the broad-band spectrum of dynamic loads. Turbulence model validation efforts have indicated an increase in resolved turbulent length scales in building-block applications such as the separated flow over an airfoil and cylinder (Kok 2004).
The observed increase in physical fidelity with respect to massively separated flow modelling has motivated an X-LES simulation effort to demonstrate the calculation of the 3D flow over a complete space launcher with a focus on the base flow in order to assess the buffet forces on the nozzle of the cryogenic engine. The present work contributes to the challenge to accurately predict the dynamic loads on the structural components of a space launcher. Identifying dynamic loads as the actual design loads is critical for performance enhancements for future launchers which, in general, require a larger nozzle.

2. COMPUTATIONAL APPROACH

The X-LES turbulence modelling approach can be related to the detached-eddy simulation (DES) for massively separated flows as proposed by Spalart (Spalart 1997). Like DES, X-LES is a hybrid technique which combines the solution of the RANS equations in the attached boundary-layers with the solution of the Large Eddy Simulation (LES) equations in the fully turbulent separated flow regions. However, the X-LES approach consists of a composition of a RANS turbulence model with a well-defined sub-grid scale (SGS) model, while in the DES approach, the RANS turbulence model is only made to behave 'similar' to the Smagorinsky SGS model. Conceptually, the X-LES approach can be considered as consisting of one set of flow equations, obtained by time-filtering of the Navier–Stokes equations (Cock 2004), rather than consisting of separate RANS and LES equations. The sub-grid scale stresses in the time-filtered flow equations are modelled using a single equation for the turbulent (or sub-grid scale) kinetic energy (k) in the complete flow domain. If there is a clear separation between the characteristic turbulence time scales and the time-filter width, then this k equation is formulated as the RANS k–ω model (Kok 1999); if there is no such separation of scales, then the k equation is formulated as the Yoshizawa SGS model (Yoshizawa 1986). The criterion for the separation of scales is based on the turbulence length scale available in the k–ω model, rather than using the distance to the wall (as in the DES approach).

The Reynolds or subgrid-scale stress tensor $\tilde{\tau}$ is modelled using the Boussinesq hypothesis:

$$\tilde{\tau}_{ij} = 2\rho\nu_t \left(S_{ij} - \frac{2}{3} D\delta_{ij} \right) - \frac{2}{3}\rho k \delta_{ij} \qquad (1)$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \qquad (2)$$

$$D = \frac{\partial u_k}{\partial x_k} \qquad (3)$$

where ρ denotes the density, u_i the velocity vector, ν_t the eddy viscosity coefficient, S_{ij} the rate-of-strain tensor, and D the velocity divergence.

Both the RANS model and the SGS model are based on the equation for turbulent kinetic energy k :

$$\frac{\partial \rho k}{\partial t} + \frac{\partial}{\partial x_j}(\rho k u_j) = P_k - \rho\epsilon + \frac{\partial}{\partial x_j}\left(\rho(\nu + \sigma_k \nu_t) \frac{\partial k}{\partial x_j} \right) \qquad (4)$$

where ϵ represents the turbulent kinetic energy dissipation and ν the molecular viscosity coefficient. Note that for the SGS model, k represents only the subgrid-scale kinetic energy. The production term P_k is given by:

$$P_k = \tilde{\tau}_{ij} S_{ij} = \rho\nu_t \tilde{S}^2 - \frac{2}{3}\rho k D \qquad (5)$$

with $\tilde{S}^2 = \tilde{S}_{ij}\tilde{S}_{ij}$ and $\tilde{S}_{ij} = S_{ij} - \frac{1}{3}D$. The difference between the RANS and SGS models lies in the modelling of the eddy viscosity and the dissipation for which different length scales are used;

$$\nu_t = l\sqrt{k} \qquad and \qquad \epsilon = \beta_k \frac{k^{3/2}}{l} \tag{6}$$

for the RANS model, and

$$\nu_t = C_1\Delta\sqrt{k} \qquad and \qquad \epsilon = C_2 \frac{k^{3/2}}{\Delta} \tag{7}$$

for the SGS model. Here, $l = \sqrt{k}/\omega$ being the RANS length scale and Δ being the SGS filter width. For completeness, it is mentioned here that the RANS model is closed by an equation for the specific turbulent dissipation rate ω.

The composite X-LES model is obtained by replacing the length scale in the eddy viscosity and dissipation terms by a composite length scale $\tilde{l}$:

$$\tilde{l} = \min(l, C_1\Delta) \tag{8}$$

The filter width is defined from the computational cell with sizes $(\Delta x, \Delta y, \Delta z)$ as:

$$\Delta = \max(\Delta x, \Delta y, \Delta z) \tag{9}$$

The formulation is closed by the model coefficients given in (Kok 2004).

The simulated flow is dynamically divided into RANS regions and LES regions by the X-LES formulation. The availability of the turbulent length scale l in the RANS region allows for a switching to the turbulence resolution length scale $C_1\Delta$ in the LES region. In the flow domain where $l \leq C_1\Delta$ the RANS equations are solved where the original $k-\omega$ turbulence model is applied. In the domain where $l > C_1\Delta$ the LES equations are solved and the k-equation SGS model is applied.
It can be proven that this switching is internally consistent, i.e., the composite length scale $\tilde{l}$ will not switch back and forth between RANS and LES modes at the interface.

The composite length scale $\tilde{l}$ can be interpreted as a composite time scale scale $\tilde{\tau}$ by making use of the Taylor hypothesis: for a fixed location, fluctuations in time are dominated by convection of turbulence by the mean velocity (Cock 2004). Hence, the relevant turbulent time scales follow from $\tau = l/U_{ref}$ with U_{ref} a characteristic mean velocity. In addition, a temporal filter width is introduced by $\Delta_t = \Delta x/U_{ref}$ with Δx representing a characteristic grid size. Depending on the time scale in the flow different turbulence models are used: the RANS type turbulence model is utilised if a separation of time scales exists i.e. $\tau < \Delta_t$ and otherwise the LES type turbulence model is employed. This is an important notice since the frequency range of the flow structures for massively separated flows cannot be discriminated from the turbulence spectrum.

The SGS turbulence model has been implemented in the flow solver ENSOLV, which is part of NLR's flow simulation system ENFLOW (Kok 2000).

3. APPLICATION

The computational geometry based on a 'clean' wind tunnel model is shown in Figure 2.

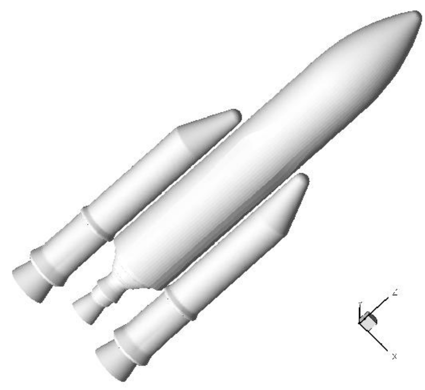

Figure 2. Generic space launcher

Time-dependent flow simulations are performed at transonic conditions: free stream Mach number M_∞=0.73, Reynolds number Re_∞=6 million based on the height of the wind tunnel model. The incidence and side slip angles are set to zero degrees.
The plumes of the central engine and the boosters are modelled by specifying the total pressure and total temperature at exhaust planes inside the nozzles.

The flow calculations are carried out for the full configuration utilising a multi-block grid consisting of 138 blocks containing 4.78 million grid cells. The grid point distribution in the wall normal direction satisfies the requirement of $y^+ \approx 1$ for the considered Reynolds number. It was further verified that the largest vortices in the separated flow region around the nozzle are captured by at least 32 cells, following the rule-of-thumb issued by Spalart (Spalart 2001).

The physical time span that must be calculated is determined by the anticipated lowest dominant frequency for the separated flow in the vicinity of the nozzle. Simulations are performed for a physical time span equal to 6 periodic cycles of the dominant frequency. This should be sufficient to get an impression of whether the relevant flow physics are captured. It is expected that for an accurate computation of statistical data more periodic cycles must be computed. Literature suggests that up to 40 periodic cycles have to be calculated in hybrid LES-RANS simulations.

The computational strategy for the X-LES simulation starts with a steady flow solution based on the RANS equations in which the main flow features are represented. Subsequently, 4 periodic cycles are calculated in X-LES mode with 64 time step per period to damp out the main transient. Finally, 6 periodic cycles are computed in X-LES mode with 256 time steps per period. The resulting time step implies a CFL number of approximately 2 in the separated flow region.

4. UNSTEADY FLOW PHENOMENA

Figure 3 shows integrated skin-friction lines drawn on the surface. The skin-friction coefficient is also included in the plot. The flow detaches from the surface down-stream of the plane defined by the upper conical rings around the booster. The separated flow field is visualised by cross flows on the surface associated to vortices generated by the unsteady shear flow.

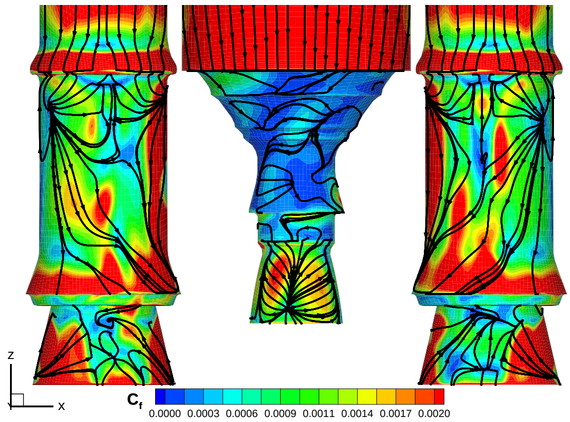

Figure 3. Numerical oil-flow pattern and skin friction distribution

Figure 4 shows the stream-lines in the base flow region projected onto the X-Z symmetry plane of the configuration. Here, the distribution of the total pressure loss coefficient is included in the plot to detect the cores of vortical flow structures. The figure shows a snapshot of the generation and decay of vortical structures that impinge on the nozzle, engine thermal protection and main-stage thermal protection.

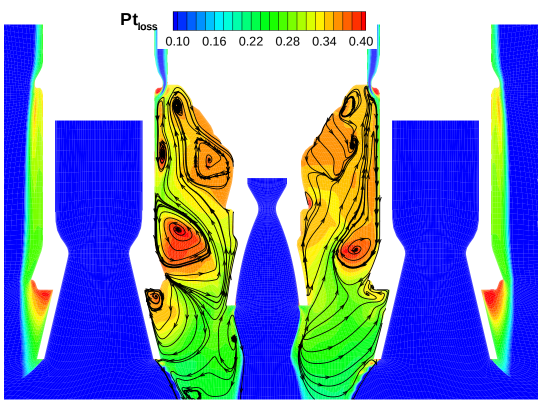

Figure 4. Stream-line and total pressure distribution

5. NOZZLE LOADS

The evolution with time of the interactions among the vortices in the base regions is reflected in a variation in the static pressure. As the interactions are inherently three-dimensional of nature, the pressure forces acting on the nozzle wall are non-symmetrical and result in a side-load.

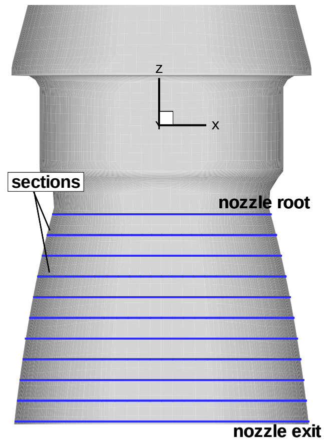

Figure 5. Shear force evaluation sections

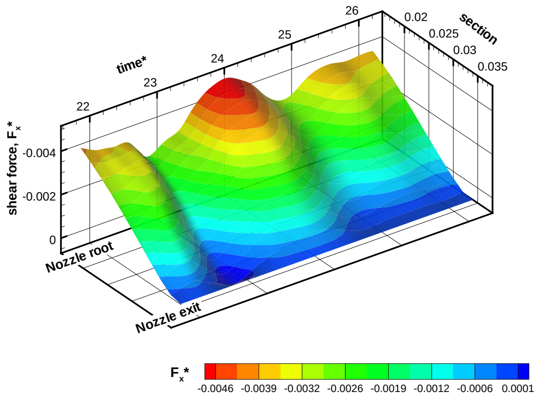

Figure 6. Time response for nozzle shear-force

A perspective to assess the side-loads on the nozzle is given by considering the nozzle as a cantilever beam. Figure 5 depicts the nozzle sections over which the sectional shear force is evaluated. Figure 6 shows the load on the nozzle as a time response in terms of the non-dimensionalised shear-force in the x-direction, F_x. The amplitude of the integrated shear force fluctuation is a significant portion of the mean value during the considered time period of the dominant frequency.

6. SPECTRAL ANALYSIS

In order to get an appreciation of the computed dynamics, the Power Spectral Density (PSD) of the buffet pressure is evaluated for a single location on the nozzle. These numerical results are compared to experimental results. It is emphasised that the experimental data is used only for a qualitative assessment, as there exist essential differences between the computational and experimental configuration. For a meaningful comparison, the PSD's should be computed for the same (non-dimensional) time span. As the X-LES computation spans only a fraction of the time span in the experiment, the presented PSD's are based on the time span of the computation.

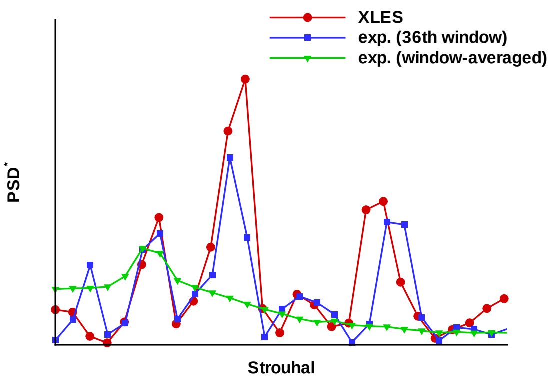

Figure 7. Computational and experimental spectra

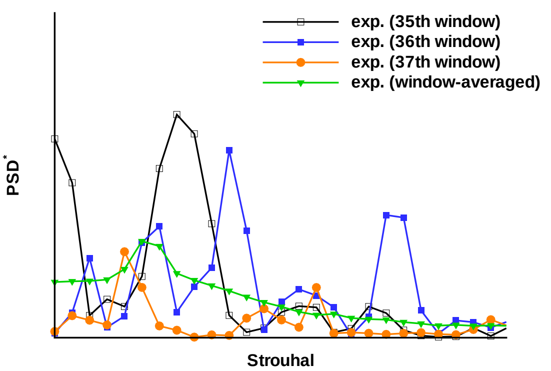

Figure 8. Window-wise variation of experimental spectra

Figure 7 compared the PSD of the X-LES computation with the PSD of the 36^{th} window of the experiment, which is found to give a minimum deviation between the two. This shows that the computational and experimental results can have comparable frequency contents in the selected window. To stress this point, figure 8 shows a window-to-window variation which is significant. Nonetheless, there is a strong indication that the numerical algorithm is capable of capturing typical dynamic flow physics observed in the experiment.

7. COMPUTATIONAL TURN-AROUND TIME OUTLOOK

The computation of a single time step requires 3.3 Tflop for the full grid. The computations are carried out on the NLR NEC-SX5/8 computer with an effective single processor performance for the ENFLOW algorithm of 1 Gflop/s which implies that a single time step requires 55 minutes CPU time on one processor. Thus, the total computational turn-around time for 6 periods (with 256 time steps per period) amounted to 340 wall-clock hours while employing 4 processors.

To present an outlook for future X-LES simulations for realistic ARIANE 5 type of configurations, estimated turn-around times are presented in table 1.

Table 1. Estimated turn-around times for X-LES simulations

	8 Gflop/s	60 Gflop/s	403 Gflop/s
6 periods	170 hr	22 hr	3.4 hr
40 periods	1200 hr	160 hr	23 hr

The current computation of 6 periods is considered as well as the prolongated computation of 40 periods. For a NEC SX5, turn-around times are given when using 8 processors. Also included is the estimated turn-around time based on the Linpack performance benchmark for the NEC SX-5 and the current Top 500 supercomputer. If a present day Top 500 supercomputer could be used, the extended X-LES computation can be performed within the industrially relevant time-frame of a single day.

8. CONCLUSIONS

The industrial feasibility of X-LES simulations is demonstrated by computing the unsteady aerodynamic loads on the main-engine nozzle of a generic space launcher configuration. The potential to calculate the dynamic loads is qualitatively assessed for transonic flow conditions in a comparison to wind-tunnel experiments. Unsteady pressures have been extracted at a location near the nozzle exit. The computed and experimental Power Spectrum Density is plotted against the Strouhal number. It is shown that the computational and experimental results can have comparable frequency content in the selected window. In terms of turn-around-times, X-LES computations are already feasible within time-frames to support the structural design process. Future work is directed towards more detailed investigations of a 4^{th}-order spatial discretisation for the entire flow domain. First results are encouraging for the decay of homogeneous turbulence and the separated flow over a cylinder.

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