AERODYNAMIC DATABASE DEVELOPMENT FOR A FUTURE REUSABLE SPACE LAUNCH VEHICLE, THE ORBITAL 500R

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ABSTRACT

The Orbital 500R is a commercial semi-reusable, two-stage launch system under development by Orbital Access. The focus of this paper is a numerical aerodynamic analysis of the reusable first stage spaceplane, capable of powered and glided flight. The vehicle is intended to release expendable upper stage(s) to inject 500-kilogram of payload into low Earth orbit. Ejection of the upper stage(s) is expected to be above 85-kilometres, after which the first stage spaceplane will perform re-entry and landing.

Toolset validation and the establishment of best practice is an integral aspect of assessing and optimising system performance and controllability. Steps have been taken to progress this, related to the use of Fluid Gravity Engineering's Navier-Stokes solver, ANITA. The validation activities were focused around the characterisation of the aerodynamics of two wing-body experimental models, tested across a range of angles of attack at Mach 4.0 and 8.2 respectively. The results have provided a sufficient level of confidence in the use of ANITA to assess the aerodynamic performance of spaceplane wing-body configurations for supersonic and hypersonic flow regimes.

A computational assessment of the vehicle’s aerodynamics has been performed by means of both engineering-based tools and Navier-Stokes CFD computations. Lessons learned from the validation activities fed into the use of ANITA to characterise the vehicle's aerodynamics from Mach 3.0 and above. The lift and drag characteristics of the vehicle were found to be very comparable to those documented for the X-34 reusable launch vehicle from Mach 2.0 up to Mach 6.0. Furthermore, strong code-to-code agreement was observed with the SU2 and ANSYS-Fluent Navier-Stokes solvers for aerodynamic characteristics at Mach 3.0.

Index Terms— Spaceplane, Launch System, Orbital 500R, X-34, Aerodynamics, CFD, Descent Trajectory

1. INTRODUCTION

This paper will present a method for developing an aerodynamic database suitable for early-phase design studies of conventional spaceplane wing-body geometries. The problem is approached by integrating different fidelity analysis methods to populate an aerodynamic database (AEDB) suitable for three degree-of-freedom trajectory simulations. This approach is applied to the Orbital 500R spaceplane, which represents the first stage of a two-stage-to-orbit (TSTO) launch system under development by Orbital Access.

During the early development stages of a launch system, the assessment of the concept's aerodynamic performance is an integral aspect of understanding the feasibility of the system. Furthermore, the increased geometric complexity of spaceplane configurations compared to other spacecraft, such as entry capsules, makes them more susceptible to errors in aerodynamic characterisation. The assessment of the vehicle's aerodynamic behaviour will largely drive the form of the descent trajectory. Lift, drag and pitching moments are the primary aerodynamic parameters to inform on initial estimates of range capability, controllability and thermal protection system (TPS) design requirements in terms of heat fluxes/loads. At these preliminary design stages, the analysis fidelity requirements also need to be balanced against computational power requirements to permit rapid design iteration. As such, the use of validated engineering methods, suitable across a broad flight envelope, is highly desirable.

2. THE ORBITAL 500R

The Orbital 500R is a multi-stage vehicle, using rocket propulsion systems, that will be air-launched from a modified, wide-body carrier aircraft. The main vehicle is a spaceplane that will allow for glided return flight (see Fig. 1).

The second stage is stored within the main body of the spaceplane. This allows for better control of the moments

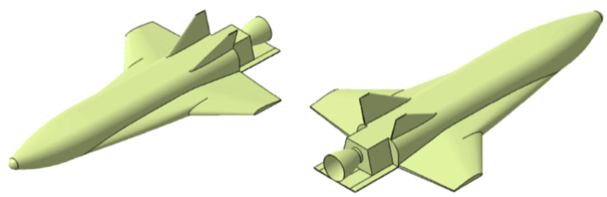


Fig. 1. Orbital 500R spaceplane

induced by the movement of the centre of gravity, however, it introduces complexity and release issues.

The primary mission of the Orbital 500R system is to deliver payloads of 500-kilograms to a 600-kilometre Sun Synchronous Orbit, whether polar or equatorial. The secondary extended mission is to deliver payloads to a maximum altitude of 1,200-kilometres, with payloads up to 150-kilograms. These mission parameters derive from investigations during the previous Future Small Payload Launcher (FSPL) UK study [1], with the goal of establishing the Orbital 500R as a commercial logistics system for in-orbit delivery.

2.1. Vehicle configuration

The Orbital 500R spaceplane can be classified as a wing-body. The main body has an overall length of 23.3-metre, from the nose apex to the trailing edge of the body flap. The front fuselage ends with a rounded nose constituted by a quasi-conical shape closed by a 0.6-metre radius hemisphere. The mid-fuselage is characterised by a quasi-constant, rounded-rectangular section while the afterbody ends with a truncated base. The configuration exhibits a double-delta wing configuration with a main 45-degree sweep wing section and an 80-degree sweep strake. To improve lateral stability, the configuration has a dihedral of 3.5-degrees. The overall wing span is 12.6-metres, while the strake root chord is 13.7-metres and the tip chord 2.5-metres. Full span elevons are incorporated at the wing trailing edge. Based on NASA Space Shuttle Orbiter/NASA X-34 concept, a body flap is mounted aft of the fixed fairing and engine housing for pitch control. For directional stability and control, a V-tail solution has been adopted: the two vertical tails have a dihedral angle of 75-degrees, a sweep of 60-degrees and a span of 1.8-metres.

Table 1. Spaceplane configuration comparison

Dimension	Orbital 500R spaceplane	X-34
Length, m	23.3	16.5
Wing span, m	12.6	8.50
MAC, m	6.62	4.43
Wing area, m^2	75.0	33.2

The Orbital 500R spaceplane is comparable in size and planform to the NASA X-34 suborbital vehicle, refer to Table 1. Specifically, it has a double-delta wing with the same sweep angles as the spaceplane. Therefore, the aerodynamic characterisation of the X-34 provides a useful performance reference that will be revisited later in the paper.

3. ANITA VALIDATION

Toolset validation and the establishment of a best practice to evaluate aerodynamic performance is an integral aspect of assessing and optimising the launch system performance and controllability. Steps have been taken to progress this with FGE's Arbitrary Non-equilibrium Implicit Thermochemical Algorithm (ANITA). This is intended to be the workhorse for characterising aerodynamic and aerothermal environments above Mach 3.0 as the Orbital 500R design matures.

ANITA is an arbitrary cell, unstructured mesh, Navier-Stokes solver for gases in thermochemical non-equilibrium. It is designed for the calculation of aerodynamics and aerothermodynamics at hypersonic and supersonic speeds. An example of a past use case of the code in hypersonic flows is provided in Ref. [2].

A set of validation studies were conducted using experimental results from wind tunnel campaigns performed on two wing-body configurations. Fig. 2 provides an example of the ANITA simulations performed on these wing-body models. An overview of cases is given in Table 2.

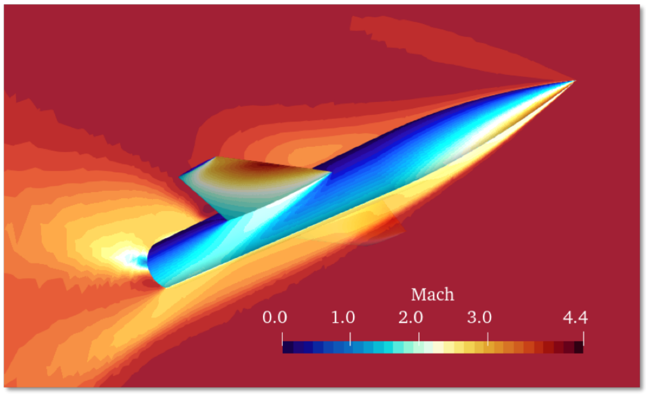
Table 2. ANITA validation cases

Parameter	Singh [3]	Pike [4]
Mach	8.2	4.0
Reynolds no. x10^{-6}	1.65	2.99
Angle of attack, deg	0,3,5,7,10	0,5,10,15,20

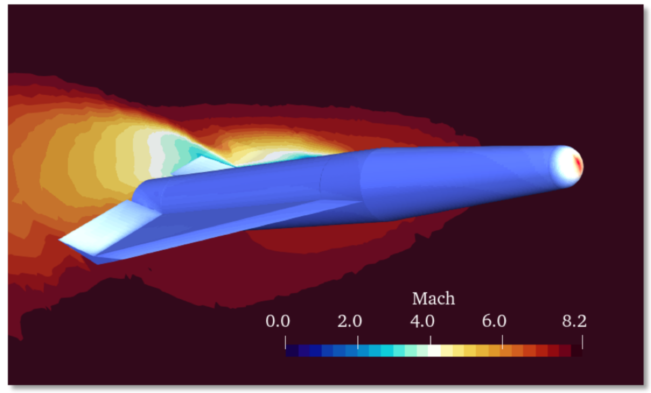
The management of CFD uncertainties is one of the main challenges in the design process. By establishing credible CFD results on relevant test cases, the analysis in this section can be used to inform on the expected level of accuracy achievable from the use of ANITA in the aerodynamic characterisation of the Orbital 500R spaceplane.

The logic behind the testcase selection was two-fold. Firstly, it was to target experimental campaigns that investigated flow conditions and geometries relevant to the most important aspects of the Orbital 500R spaceplane and its descent trajectory and, therefore, which exhibited flow fields governed by the same physical phenomena. Secondly, it was to evaluate this experimental data, to identify the sources for which test conditions and geometries were well defined and all experimental measurement accuracies and any post-processing were well described.

Concerning the first selection criterion, the validation activities presented have targeted the high-supersonic/hypersonic portion of the descent trajectory, owing to the dominance of



(a) Symmetry plane Mach number contours of the Pike wing-body at $\alpha = 20$-deg



(b) Mach number contours of the Singh wing-body at $Y = 0.025$-metres at $\alpha = 10$-deg and $\delta_{flap} = 25$-deg

Fig. 2. Wing-body flow fields from ANITA simulations

this regime regarding the duration of flight at these conditions. In addition, potentially large angles of attack may be required under these conditions. The physics of interest relates to the strong bow shocks generated off the nose and leading edges of the lifting surfaces and the resulting shock/vortical interactions, in particular at the wingbody junctions. Capturing the angle at which shock detachment increases significantly at the wing leading edge will also play a pivotal role in how the flow field evolves around the wing.

The challenge of assessing subsonic and transonic aerodynamic performance represents a major milestone in the establishing the controllability of a spaceplane configuration. Vortex-induced effects, leeside separation and the movement of the centre-of-pressure and sonic lines all contribute towards making the transonic regime extremely challenging to model. However, at this stage in the Orbital 500R design and development, neither angle of sideslip nor elevon, aileron or body flap deflection angles have been considered. Therefore, the validation activities were focused on higher speed regimes, where control surface authority was not deemed as critical.

3.1. CFD setup

The following section provides a brief overview of the CFD strategy used on the experimental testcases. A summary of the physical and numerical models employed in ANITA is provided in Table 3.

Pointwise™ was used for grid generation. This offers structured, unstructured, hybrid and overset meshing techniques and a highly automated T-Rex (anisotropic tetrahedral extrusion) technique for boundary layer resolved hybrid meshes. The generation of the volume grids was performed using the orthogonal advancing front marching process to grow tetrahedral cells on the boundary grid. A consistent approach was adopted for the grid development of each model.

Table 3. ANITA setup for validation activities

Physical/numerical model	Description
Viscosity	Sutherland law
Conductivity	Constant Prandtl
Fluid	Calorifically perfect
Turbulence	$k-\omega$ SST
Flux scheme	HLLC or AUSMDV
Flux reconstruction	Second order MUSCL

A grid convergence study was performed on a series of three increasingly refined grids: coarse, intermediate and refined. The computational domains consisted of an adjustable near-field block, encompassed by far-field block. An example of this for the Pike wing-body is depicted in Fig. 3.

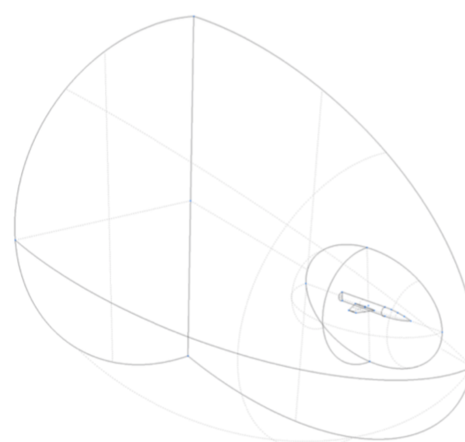


Fig. 3. Pike wing-body computational domain definition: adjustable vehicle and near-field angle

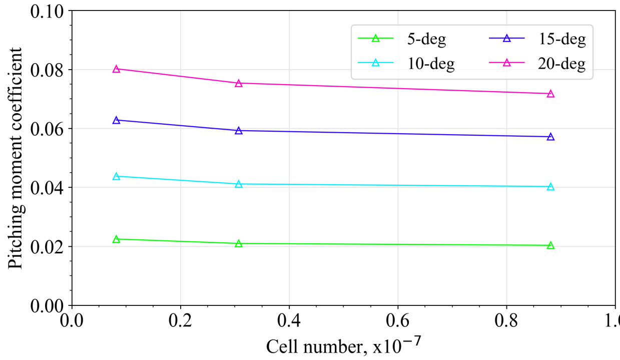


Fig. 4. Pike wing-body grid convergence pitching moment coefficient results

The results of the grid convergence study on the pitching moment for the Pike wing-body are shown in Fig. 4.

3.2. Description of validation testcases

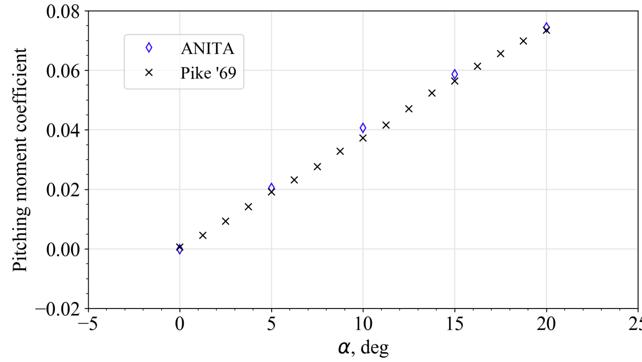
Singh conducted an experimental investigation of the hypersonic flow over a wing-body configuration, for a range of trailing edge flap deflections from 0 to 25-degrees [3]. The present analysis focused on the 25-degree flap deflection case. The tests were conducted in Cranfield University's gun-tunnel. The configuration is characterised by a sphere-cone forebody, followed by a cylindrical fuselage accompanied with a 70-degree sweep delta wing with trailing edge flaps.

Pike conducted a series of tests in the 3x4-foot Tunnel (H.S.S.T.) at R.A.E. Bedford to investigate the forces and flow on a range of wing-body models at Mach 4.0 [4]. The model selected for the validation activity is characterised by a ogive-cylinder body and wings in the plane containing the axis of symmetry of the body. The planform has a lateral plane of symmetry with equal leading and trailing edge sweeps of 26.5-degrees. Boundary layer transition was fixed by a strip of 36 grade Carborundum to 10% chord.

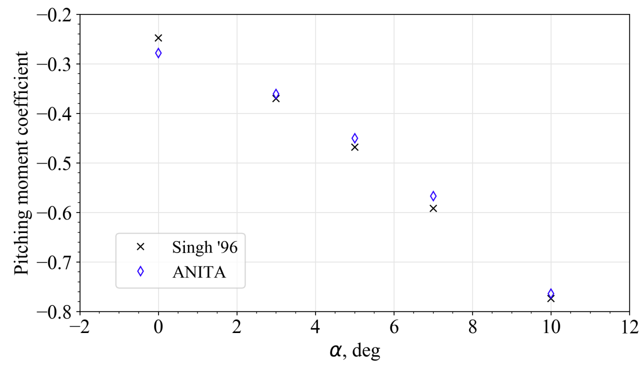
3.3. Validation results

Fig. 5 shows the agreement found using ANITA to calculate the pitching moment coefficients across the range of angles of attack for both wing-body configurations.

The ANITA results show an agreement of within 5% and 10% of Singh's and Pike's experimental pitching moment measurements respectively (excluding the comparisons at 0-degrees). These findings should be interpreted with an understanding of the main sources of uncertainty, believed to arise from experimental error and difficulties with digitising the source material. For Singh's experimental campaign, an error analysis performed by Opatowski [5] showed that the maximum possible error for the three balance channels was: normal force $\pm 3.5\%$, axial force $\pm 6\%$ and pitching moment



(a) Pike wing-body



(b) Singh wing-body

Fig. 5. Wing-body pitching moment characteristics

$\pm 3.5\%$. The measured forces obtained by Pike were corrected for balance interactions, giving an estimated accuracy of: lift coefficient ± 0.003, drag coefficient ± 0.005, pitching moment coefficient ± 0.005. For both campaigns, very good repeatability of the results was reported.

Further uncertainties have inevitably been introduced into the analysis during the digitisation of the experimental results. This will be more significant for the smaller pitching moment coefficients at the lower angles of attack. An uncertainty in the region of several percent is deemed a reasonable approximation to this error.

All things considered, agreements of 5 to 10% provide sufficient confidence in the use of ANITA for the Orbital 500R spaceplane, when implemented in the configuration detailed above and using lessons learned from the grid development strategies for both wing-body configurations.

4. AERODYNAMIC CHARACTERISATION OF THE ORBITAL 500R SPACEPLANE

The aerodynamic characterisation of the Orbital 500R spaceplane used a design space approach. A multi-dimensional space, defined by Mach number, angle of attack and altitude, was constructed to accommodate all likely operational trajectory dispersions. The results could then be incorporated in trajectory optimisation routines for the spaceplane. The design space was defined by a series of boxes, detailed in Table 4.

Table 4. Definition of the design space

Box	Mach	Angle of attack, deg	Altitude, km
1	0 to 3	-10 to 25	0 to 50
2	3 to 4	-10 to 35	5 to 50
3	4 to 10	-5 to 45	20 to 60
4	6 to 10	-5 to 45	60 to 120

The intention of the chosen analysis approach was to generate a broad assessment of the aerodynamics to a fidelity suitable for early-phase design studies. Engineering methods were used to a greater extent (when compared with CFD) to populate the AEDB. The engineering methods were calibrated to the higher fidelity CFD results. The choice of the CFD cases was made with the intention of targeting regions where rapid changes are expected, to explore the linear or nonlinear dependence of the aerodynamic environments on Mach number, angle of attack and altitude. At this stage in the spaceplane design and development, neither angle of sideslip nor elevon, aileron or body flap deflection angles have been considered.

The design space spans a range of different flow regimes; ranging from free molecular at very high altitudes to continuum deep in the atmosphere. The physical models are different in these regimes. In particular, for slender vehicles at low angles of attack, the free molecular drag will be significantly larger than the continuum level. This is worthy of consideration, owing to the shallow nature of the entry profile because of the vehicle's high $^{L}/_{D}$. Therefore, a considerable period is spent in the higher altitude regime.

A broad overview of the lift and drag characteristics generated across the flight envelope is given in Fig. 6. This is the result of a collaboration between FGE, BAe and the Universities of Glasgow and Strathclyde and each organisations respective analysis toolset and approach. The focus of this paper is to present the application of FGE's methodology and computational tools to flow regimes from Mach 3.0 upwards.

4.1. Panel method analysis

Engineering-level aerodynamic analysis was performed using FGE's ASPEN panel method which computes free molecular and continuum aerodynamics for arbitrary geometries, for high-supersonic/hypersonic speeds. The simplified approach implemented within ASPEN, necessitates an awareness its limitations. These include a lack of capabilities to handle flow separation, real gas effects and flow interaction effects.

The geometry of the vehicle is represented by a system of triangular panels. The only parameter required to calculate the pressure is the impact angle of the free stream flow with the panel. The surface elements that see the oncoming flow directly are said to be in the *impact* region, whilst the elements shielded from the flow are in the *shadow* region. Depending on the region the element falls in along with the nature of its surrounding geometry, an appropriate method can be applied. Accordingly, the spaceplane was divided into separate analysis regions. A description of the panel method implementation is provided in Table 5. All regions of high curvature/bluntness were automatically assessed using the modified Newtonian approach.

Table 5. Local surface inclination methods used for the assessment of the Orbital 500R spaceplane aerodynamics

Component	Impact flow	Shadow flow
Nosecone	Modified Newtonian and Prandtl-Meyer	N/A
Fuselage	Tangent wedge	Prandtl-Meyer
Base	N/A	$p_\infty/3$
Inboard delta	Delta wing empirical	Prandtl-Meyer
Outboard delta	Delta wing empirical	Prandtl-Meyer
V-tail	Delta wing empirical	Prandtl-Meyer
Body flap	Tangent wedge	Prandtl-Meyer

Modified Newtonian, tangent wedge and Prandtl-Meyer methods are well reported in the literature. The 'Delta wing empirical' method, that has been applied to the lifting surfaces, was derived by Gentry et al. [6] who performed experiments on blunt, highly swept delta wings in hypersonic flows. The models showed behavioural characteristics in accordance with tangent wedge theory for angles of attack between 5-degrees and 15-degrees. For angles above 15-degrees, the nature of the flow appears to change such that the tangent cone approximation appears valid up to 40-degrees angle of attack. In accordance with this, Gentry et al. [6] devised an approximate method that was found to perform well on the spaceplane configuration.

4.1.1. Viscous bridging

ASPEN has an in-built capability to compute the approximate viscous contribution based on flat plate theory with compressibility corrections. The local skin friction coefficient, c_f, for incompressible laminar and turbulent flows over a flat plate is given by Eq. (1) and Eq. (2) respectively.

$$c_{f,lam} = \frac{0.664}{\sqrt{Re_x}} \quad (1) \qquad c_{f,turb} = \frac{0.0592}{Re_x^{0.2}} \quad (2)$$

where Re_x is the running-length Reynolds number based on boundary layer edge properties. The compressibility corrections have been applied to Eq. (1) and Eq. (2) using the

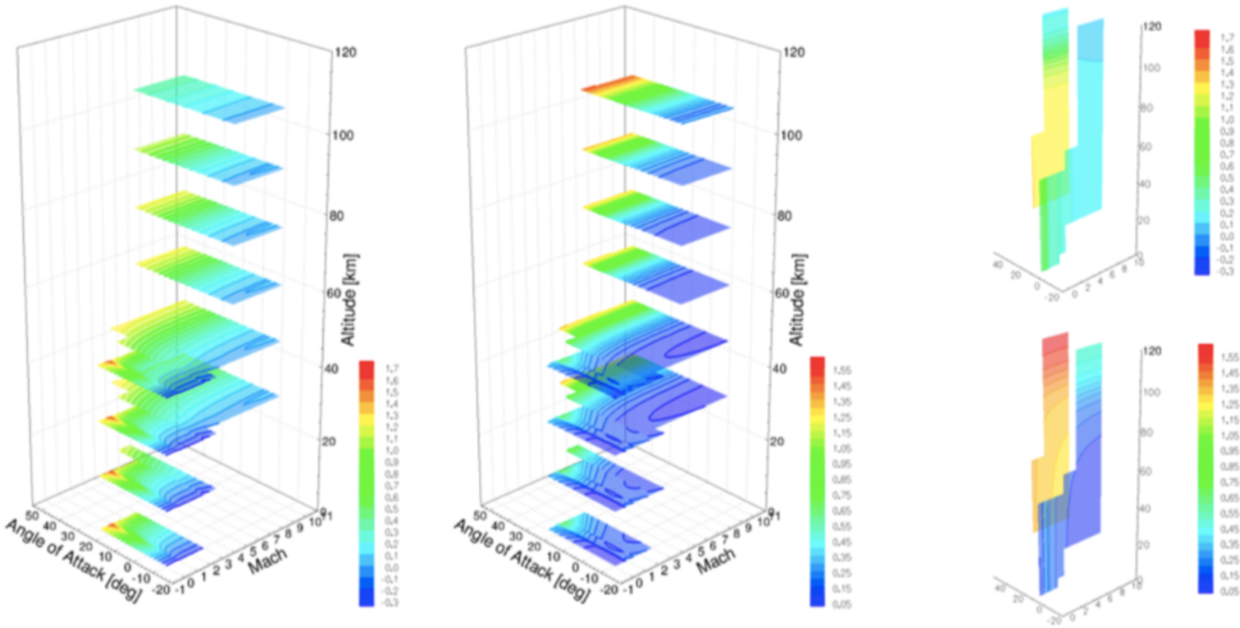


Fig. 6. Lift (left) and drag (centre) coefficients, values at selected altitudes. C_L (right-top) and C_D (right-bottom) variations with altitude at 0-deg and 20-deg

Eckert reference temperature and Van Driest II methods respectively. Summation of the panels' local shear stresses, resolved in the vector defined by the appropriate stagnation point to the panel centre, permits an estimation of the global shear stress. This model was subsequently calibrated to viscous Navier-Stokes solutions from ANITA at a series of trajectory points.

4.1.2. Free-molecular bridging

For initial scoping studies, as applicable to the current stage of development of the Orbital 500R spaceplane, 'bridging methods have been used. These methods implement empirically derived expressions to cover the transitional flow regime, linking continuum to free molecular flow regimes. Consequently, both the continuum and free molecular aerodynamic databases are required to generate the intermediate transitional data. The calculation of aerodynamics in free molecular flow has been conducted using the pressure and shear equations developed by Schaaf [7].

The main attraction of using bridging functions to characterise the vehicle force, moment and heat transfer levels is their relative simplicity and ease with which they can be applied to determine the vehicle aerodynamic loads. However, they are known to be highly geometry dependant.

The bridging function was selected as appropriate to recreate the data within the Knudsen range 0.003 to 10, which encompasses all of the altitudes above and including 80-kilometres, up through to the highest altitude considered of 120-kilometres. Fig. 7 shows the classical, expected 's-shape' profiles exhibited by the lift and drag coefficients with Knudsen number, Kn. Note that the characteristic length is taken as the base height of 1.8-metres. This will be sensitive to body size and will be significantly lower in altitude for smaller, more detailed geometric regions. The form of the bridging relation used in this study, in the case of the lift coefficient, is:

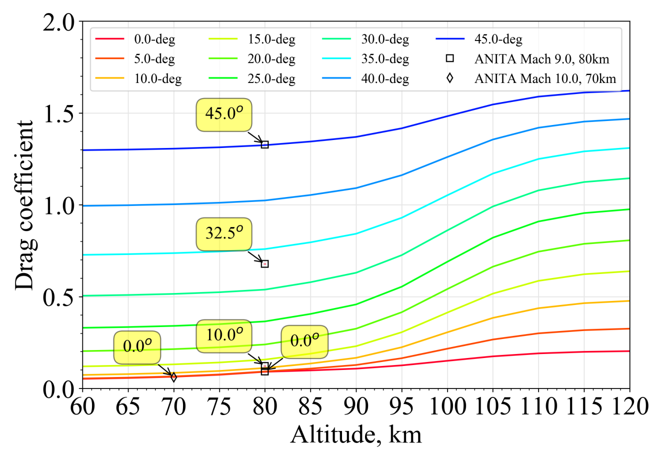


Fig. 7. High altitude lift and drag characteristics of the Orbital 500R spaceplane generated using calibrated engineering methods with a free molecular bridging function incorporated

$$C_L = C_{L,cont} + \phi(C_{L,fm} - C_{L,cont}) \tag{3}$$

Where $cont$ denotes continuum coefficients, fm stands for free molecular and $\phi = {}^{Kn^n}/_{Kn^n+k}$. Values of $n = 1$ and $k = 0.1$ have been used. Exactly the same approach described by Eq.(3) was used to determine the drag coefficient. This is what is termed a global bridging approach (i.e. the coefficients are bridged directly, not the local pressures/skin frictions).

4.2. CFD analysis

The lessons learned during the validation activities, presented in Sec. 3, were used to inform on the strategy chosen to perform the ANITA simulations on the Orbital 500R spaceplane.

Pointwise™ was used for grid generation, to take advantage of its hybrid meshing technique, discussed in Sec. 3.1. The wall cell spacings ensured a y^+ value of less than one. A similar grid convergence procedure to that outlined in Sec. 3.1 was performed, with the use of inviscid simulations at the outset to determine the shock shape and guide the further development of the viscous grids. The final computational grids are composed of about 2.5 million cells for the Eulerian versions and 4.2 million cells for the viscous ones. The computational grid, in the vicinity of the vehicle, used for the symmetric, half body computations is shown in Fig. 8.

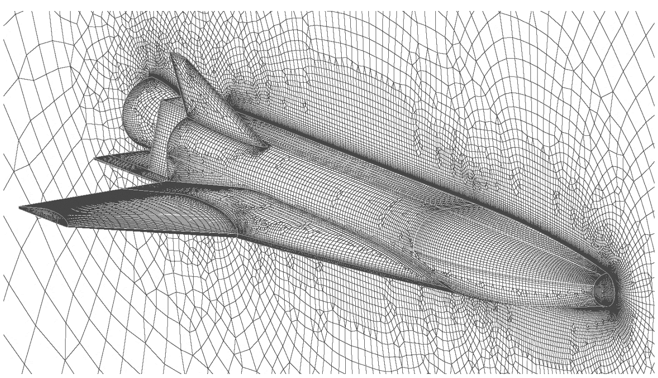


Fig. 8. Orbital 500R spaceplane computational grid

At high-supersonic/hypersonic speeds, the flow field is dominated by strong bow shocks generated off the nose and leading edges of the lifting surfaces and the resulting shock/vortical interactions, in particular at the wing- body junctions. As such, aerodynamic efficiency is affected to a much greater extent by surface conditions of the windward rather than leeward regions of components because of the stark differences in pressures. Geometrical entities with small curvature radii inherently result in steep pressure gradients. The aforementioned reasoning motivated the approach towards refining the resolution in specific regions of the vehicle to sufficiently capture the flow physics. The windward surface resolution was particularly important to accurately compute the pitching moments.

4.3. Code-to-code validation

A code-to-code validation was performed at Mach 3.0, 20-kilometres altitude across a range of angles of attack. In addition to ANITA, the Navier-Stokes simulations were performed by BAe using the ANSYS-Fluent solver and by the University of Strathclyde using Stanford University's SU2 solver. Independently generated computational grids were used. Fig. 11 shows examples of the flow fields from the SU2 simulations. A variation of less than 1% was found for the lift and drag coefficients. Similarly, Fig. 9 highlights an excellent alignment of the pitching moment coefficients (referenced around an estimated CoG).

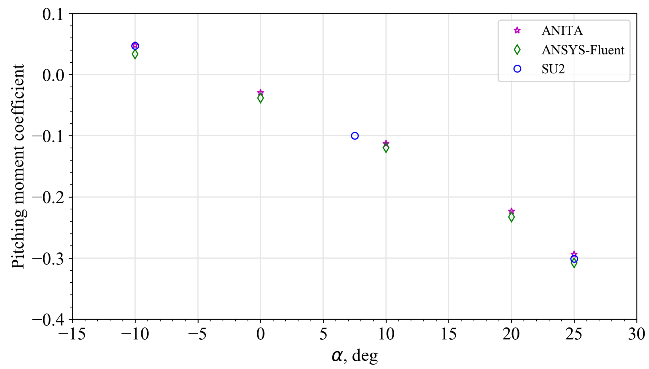


Fig. 9. Pitching moment coefficient code-to-code comparison referenced around a realistic CoG location

4.4. NASA X-34 comparison

Similarities between the X-34 and the Orbital 500R spaceplane, as outlined in Sec. 2.1, mean that it offers a valuable validation case in the supersonic and hypersonic flow regimes. A remarkably good alignment of lift and drag coefficients was found from Mach 2.0 up to Mach 6.0, to Brauckmann's published results [8]. The comparison at Mach 6 is shown in Fig. 10.

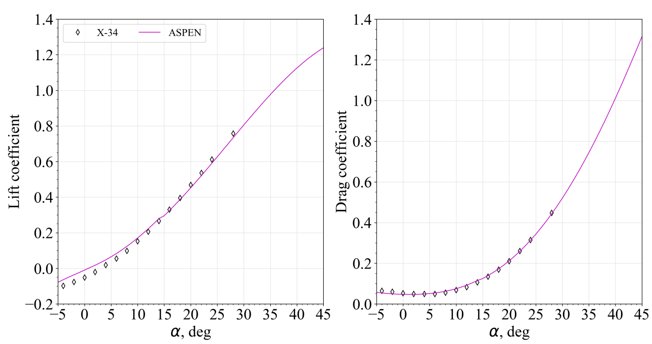


Fig. 10. Comparison between the Orbital 500R spaceplane and the X-34 lift and drag characteristics

Fig. 11. Mach 3.0 contours for $\alpha = -10$-deg (left), $\alpha = 7.5$-deg (centre), $\alpha = 25$-deg (right) for $Y = 4.263$-metres

5. CONCLUSION

This paper has presented the appraisal of the Orbital 500R spaceplane's aerodynamics in a computationally inexpensive manner. This has been achieved through the effective implementation engineering methods calibrated with validated Navier-Stokes computations for a calorifically perfect gas in both laminar and turbulent conditions. Bridging relations have enabled a characterisation of the aerodynamics from the continuum up to the free molecular regime. The vehicle's configuration exhibits notable similarities to NASA's X-34 reusable launch vehicle, therefore, it provided a useful validation case. The lift and drag characteristics of the Orbital 500R spaceplane were found to be very comparable to those published for the X-34 from Mach 2.0 up to Mach 6.0. Furthermore, strong code-to-code agreement with ANITA was observed with the ANSYS-Fluent and SU2 Navier-Stokes solvers for aerodynamic characteristics at Mach 3.0.

Validation of FGE's Navier-Stokes solver ANITA, that was used for the Orbital 500R AEDB CFD computations for Mach 3.0 upwards, has been performed on two simple wing-body configurations at Mach numbers of 8.2 and 4.0 respectively. Extremely good alignment of the aerodynamic coefficients was observed throughout. In particular, pitching moment coefficient agreements within 10% were observed across the range of angles of attack considered, with the primary uncertainty drivers being experimental error and inaccuracies associated with the data digitisation. This has provided a sufficient level of confidence in the use of ANITA to assess the aerodynamic performance of spaceplane wing-body configurations in supersonic and hypersonic flows.

6. ACKNOWLEDGMENTS

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