AERODYNAMIC DESIGN AND ANALYSIS OF A REUSABLE LAUNCH VEHICLE†

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Abstract

Computational aerodynamics has been used for the design and analysis of the Kistler K-1 reusable launch vehicle. The aerodynamic design methodology for this new vehicle is discussed, and analytical results are compared with wind tunnel test data where possible. The basic computational approach involved the use of all levels of prediction methods from engineering methods to CFD codes. The unique aerodynamic requirements for this innovative launch vehicle configuration dictate the computational methods which can be used, and it was necessary to rely heavily on applied CFD for the aerodynamic characteristics of the K-1 configuration components. The practical and economical uses of computational aerodynamic methods to provide results for a number of challenging and unusual fluid problems are described.

1 Introduction

The need for commercial satellite launches is growing at an unprecedented rate [1]. As a consequence, a number of commercial organizations are developing reusable launch vehicles in an effort to significantly reduce launch costs. The resulting configurations must fly under control through a wide range of Mach numbers, subsonic through hypersonic, at large angles of attack, and with large movement of the cg location. The aerodynamic design and analysis of these unusual configurations is a challenge to the aerodynamicist, particularly under the added constraints of strict schedules and limited funds.

The Kistler Aerospace K-1 RLV has a planned mission profile (Fig. 1) which requires understanding of aerodynamic characteristics of complex configurations over an extensive range of flight conditions [2]. At launch, the booster and orbiter stack is a traditional ground-launch vehicle. At separation, the traditional configuration becomes two independent configurations which are very nontraditional in appearance. The booster stage (Fig. 2a) must fly and maneuver in the wake of the orbiter during the separation phase, it must initiate the return phase to fly back toward the launch site, it must reenter at supersonic speeds with nozzles forward, and it must trim at transonic Mach numbers so that it can transition to the landing phase on parachutes. The orbiter (Fig. 2b) reenters at Mach 25 after it delivers its payload, and it must fly under control and in trim in the hypersonic, supersonic, and transonic flight regimes while maneuvering to return to the launch site for a parachute landing.

Engineering methods, CFD, and wind tunnel testing were used in a coordinated effort to provide the various levels of aerodynamic detail required by the various disciplines involved in the design. The purpose of this paper is to document some experiences using computational aerodynamic methods for the K-1 launch vehicle analyses.

Fig. 1 Kistler K-1 Mission Profile

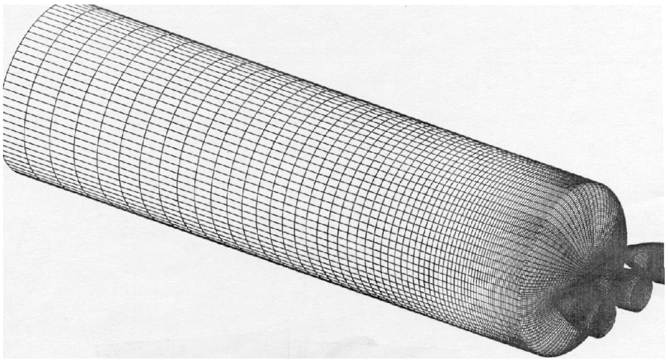

Fig 2 (a) K-1 LAP Booster

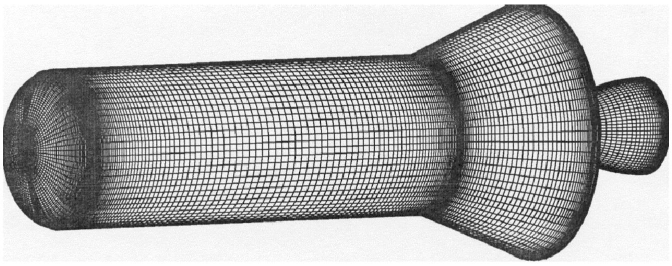

Fig. 2 (b) K-1 OV

2 Background

NEAR has provided aerodynamic support for a variety of commercial launch vehicles [3], including the Kistler K-1 RLV [4], Orbital's Pegasus [5] and Taurus, and the Beal BA-1. Each of these projects required the selection of appropriate prediction methods. Factors of cost and schedule were considered along with accuracy and reliability when selecting the aerodynamic prediction methods. The objective is to minimize uncertainties in the aerodynamics, but the analyst must always consider what solution is adequate for each specific requirement in order to avoid using higher level methods than necessary which could increase the analysis costs.

Depending on the design phase, conceptual, preliminary, or detailed, selection of the level and type of computational method to use is dictated by the type of results needed and the acceptable margins and error bounds for the results. This process has been accomplished at each step of the analysis to maintain control of the analysis costs while providing the best possible results to the disciplines using the aerodynamic characteristics. For example, general aerodynamic forces and moments are required over a wide range of Mach numbers and flow angles for use in performance and trajectory analyses as well as control system design. Detailed pressure distributions are required at a more limited set of flight conditions for structural design and analysis and other studies such as venting and access door loads.

3 Technical Approach

3.1 Design and Analysis Methods

The aerodynamic design and analysis of the K-1 configurations require creative use of analytical methods, CFD, and wind tunnel testing in an integrated design effort. Many different prediction methods are available for application to launch vehicles, ranging from engineering methods to CFD. Those described herein are not unique, but they are the methods that have been validated at NEAR, and there is an experience base to provide some confidence about the accuracy and reliability for specific flow conditions. It is also important to understand the influence of configuration characteristics on the resulting aerodynamics so that the proper code selection is made for the flight conditions of interest. Because of the compressed schedule dictated by the commercial effort, it is important that results be available on a timely basis and that the accuracy of the individual results be assessed. As noted above, it is important that the analytical results be ‘good enough’ without being ‘too good’ because of the additional time and costs associated with using a higher-level prediction method than necessary.

The initial technical approach was to obtain preliminary aerodynamic characteristics with an engineering prediction method. Because of the critical nature of the center of pressure on the orbiter vehicle, it was soon determined that the engineering methods were not adequate to this task. It was determined that Euler [6] solutions were the minimum acceptable level of prediction method which would provide the required accuracy in center of pressure for the range of Mach numbers of interest. Consequently, as the configuration changed during preliminary design, the aerodynamic characteristics were updated through iteration between Euler solutions and wind tunnel tests. As the configuration converged, solutions of the Navier-Stokes equations [6] were used to provide detailed aerodynamic characteristics for those conditions for which viscous effects are important. As part of the CFD effort, grids and solutions from independent sources [7,8] were used to evaluate the quality of the predicted results.

3.1.1 Euler Methods

OVERFLOW [6] is usually run as a Navier-Stokes viscous solver; however, it can also be run in Euler mode for inviscid solutions using a coarser grid. The Euler solutions discussed in the Results section are from this code unless otherwise noted.

3.1.2 Navier-Stokes Methods

OVERFLOW [6] is a Navier-Stokes CFD solver developed at NASA/Ames Research Center. It has become very efficient for large numbers of CFD simulations of different configurations like those discussed in this paper. It is a very flexible CFD tool for launch vehicle design. The central difference scheme with dissipation in space and multigrid in time was used throughout the Kistler project for the K-1 CFD analysis, and all CFD runs were obtained on either SUN or HP workstations.

CFL3D [7] is a Navier-Stokes flow solver for multi-block and structured grids, developed at the NASA/Langley Research Center. It utilizes efficient multigrid and mesh sequencing relaxation schemes for the steady-state solutions. CFL3D provides the most comprehensive list of turbulence models, including 0-equation, 1-equation, and 2-equation models. CFL3D was used as a cross-checking tool for other CFD solutions in the K-1 analysis.

LAURA [8] is a Navier-Stokes code designed for hypersonic viscous flow simulation developed at NASA/Langley Research Center. In particular, LAURA has comprehensive capabilities for both chemical equilibrium and non-equilibrium flow simulations. It was used in the CFD analysis of the K-1 configuration for Mach numbers greater than 6.

4 Results

The Kistler K-1 configuration, made up of the launch stack, the first stage launch assist platform (LAP), and the orbiter vehicle (OV), has been studied with wind tunnel tests and a number of computational methods at all levels. The special requirements and unique aerodynamic problems for each component of the vehicle must always be considered when looking at the experimental and computational results. Each component has a flight regime which must be considered, and the specific aerodynamic results required by each discipline differs for each configuration component. Some of the interesting and unique problems addressed by computational and experimental methods are discussed below for each configuration in one of its flight regimes.

4.1 Launch Configuration

The K-1 launch configuration, or stack, consisting of the mated OV and LAP, must be considered from launch to staging, $0 \leq M \leq 4.5$. The angle of attack for the nominal flight conditions is low, typically less than five degrees; therefore, the aerodynamic requirements are not unreasonable. Thrust vectoring provides more than enough control power for stability and control considerations, so reasonable estimates of normal force and center of pressure are needed. Structural analysis and venting studies required pressure distributions which determined the level of prediction capability needed.

As was noted in a previous discussion of prediction methods [4], the blunt nose and flare of this vehicle preclude the use of some of the simpler engineering prediction methods because of the difficulty of producing sufficiently accurate center of pressure results. As a result, Euler solutions were used to create the primary analytical aerodynamic matrix for the entire range of flight conditions ($0.2 \leq M \leq 4.5$; $0 \leq \alpha \leq 15°$). Navier-Stokes viscous solutions were used to supplement the inviscid results for a more limited range of flight conditions ($0.3 \leq M \leq 2.5$; $0 \leq \alpha \leq 5°$) to provide accurate pressure and loading distributions, particularly in the transonic flight regime. Wind tunnel data provided the aerodynamic database required for performance and guidance and control estimates.

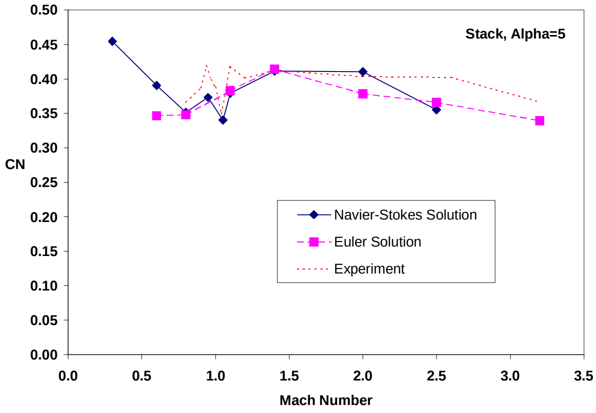

Fig 3 Stack C_N vs M at α=5°

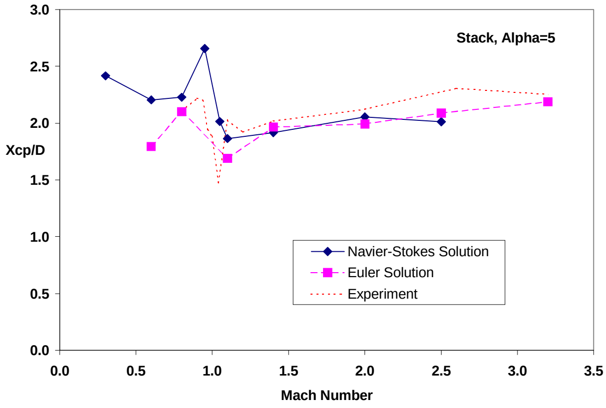

Fig 4 Stack Ccp vs M at α=5°

Comparisons of measured and predicted normal force and center of pressure on the stack configuration at $\alpha = 5°$ are shown in Figs. 3 and 4. Although the viscous solutions follow the trend of the data, there are some differences in the transonic regime where the CFD solutions do not represent the details of the data. The predicted center of pressure is aft of the measurements, thus indicating greater static stability than exhibited in the experiments. It is suspected that flow separation in the nose and flare regions may be influencing the results and causing the observed differences.

4.2 LAP Return Configuration

After separation from the orbiter vehicle, the first stage booster (LAP) must fly in the wake of the OV for a short period of time before it returns to the launch site. During this short part of the ascent trajectory, the LAP is flying, cavity forward, through a large angle of attack range in the wake of the OV. To further complicate the aerodynamics, it must fly through the shock wave of the OV on its return flight. It was decided that this portion of the return flight was best considered with wind tunnel testing. CFD analysis was considered, but the number of calculations required would be very expensive, and there was an element of uncertainty which would be very difficult to estimate. The wind tunnel data provided interesting results which proved useful in the estimates of the OV wake characteristics described in a later section.

The latter portion of the LAP return flight is interesting because of the unique configuration. The LAP must fly with the three rocket nozzles facing into the flow, and because of the characteristics of the vehicle, the LAP may be flying at moderately high angles of attack at supersonic and transonic speeds. This configuration was considered with both Euler and Navier-Stokes solutions as well as experimentally. The Euler solutions were obtained on a grid which did not include the three nozzles. The Navier-Stokes solutions were obtained on a grid which included the nozzles. The wind tunnel tests were run with and without nozzles.

A representative comparison of the CFD results and the wind tunnel data on the LAP at Mach 2 is presented in Figs. 5 and 6. The comparison of normal force coefficients in Fig. 5 illustrates the small effect of the nozzles and the capability of the CFD solutions. Both viscous and inviscid solutions are in good agreement with the measured normal force characteristics at moderate angles of attack.

The comparisons for center of pressure shown in Fig. 6 are not as encouraging. The viscous solution and the measurements exhibit similar trends, but the CFD results are approximately five feet aft of the data. This error is about 10% of the LAP length, and the predicted results indicate greater static stability than the data. As expected, the nozzles move the center of pressure forward, and this is shown by both the CFD solutions and the data. However, the predicted influence of the nozzles appears to be slightly greater than that measured, but this is because the result without nozzles was obtained from an Euler solution, and the result with nozzles was obtained from a Navier-Stokes solution.

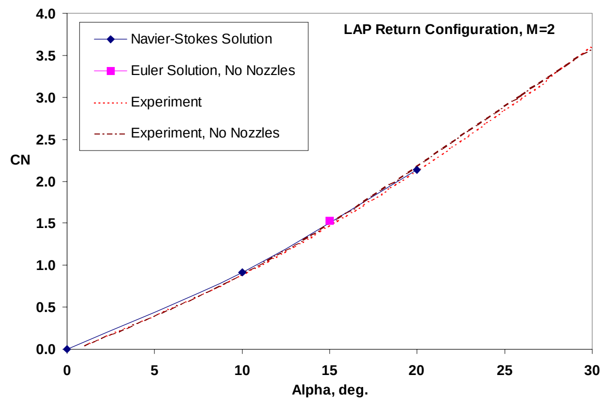

Fig 5 LAP C_N vs Alpha, M=2

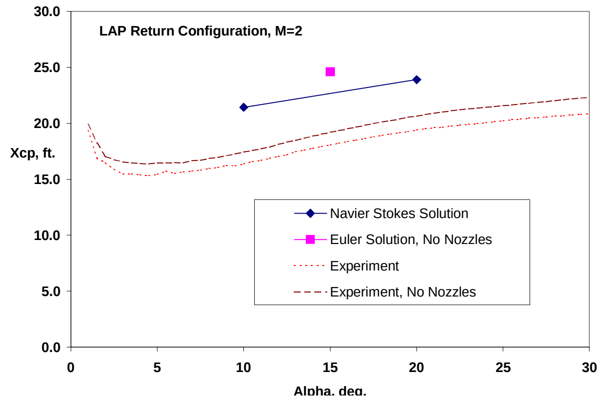

Fig 6 LAP Xcp vs Alpha, M=2

The measured and predicted longitudinal aerodynamic characteristics of the LAP at $\alpha = 20°$ are shown for a range of Mach numbers in Figs. 7 and 8. The viscous solutions are compared with wind tunnel data for the configuration with nozzles in these figures. The normal force coefficients are in good agreement, and the CFD solutions illustrate the trend in the data in Figure 7. As observed previously, the center of pressure comparison in Fig. 8 is not in as good agreement, and the CFD results again indicate greater static stability than the measurements. It is possible that the details of the interference of the nozzles on the flow field around the body of the LAP is not being computed correctly.

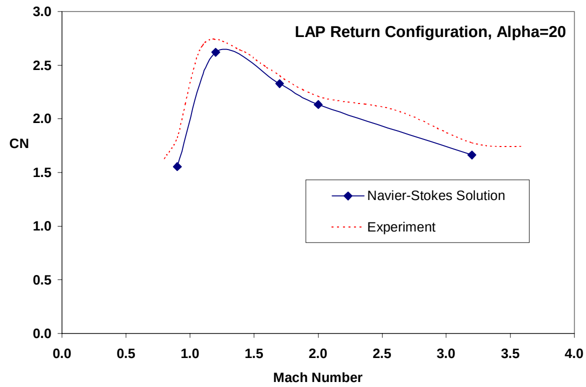

Fig 7 LAP C_N vs M, α=20°

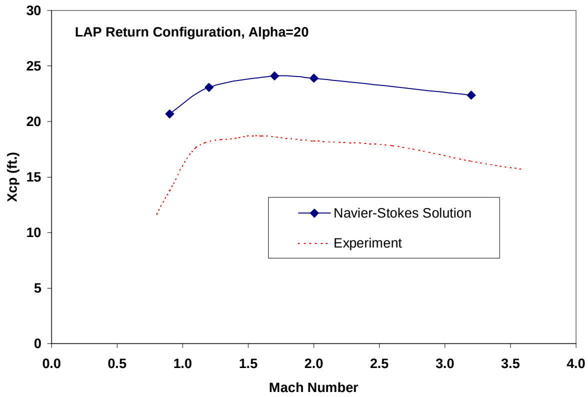

Fig 8 LAP Xcp vs M, α=20°

4.3 OV Return Configuration

The OV has a number of interesting flight conditions for which analysis is required. It must return from orbit, be stable through the hypersonic and supersonic Mach regimes, and maintain reasonable trim characteristics until the stabilization and landing parachutes are deployed. The K-1 OV configuration with its blunt nose, long cylindrical body, and aft flare proved to be a challenge for all the prediction methods investigated [3]. Since OV forces and moments have been discussed elsewhere [3,4], another interesting aspect of the use of computational analyses is described.

The stabilization parachutes are critical for OV stability during the deceleration and landing phase of the flight; thus detailed information about the wake of the OV at low supersonic Mach numbers is needed for parachute design and analysis. Since wake flow measurements in this regime are very expensive to obtain, CFD was used to provide the detailed flow information needed. However, data for CFD validation purposes are not available at the Mach numbers of interest. Wake data are available at a higher Mach number from the separation studies; therefore, validation of the computations was conducted at a higher supersonic Mach number to build confidence in the solutions at the lower Mach numbers. These results are shown in Figs. 9-11.

In Figs. 9 and 10, the predicted variation of local Mach number and pressure on the centerline of the OV is compared with measurements in the wake of a similar flared body [9]. Although the data measurements are sparse, the agreement with the viscous solutions is quite reasonable.

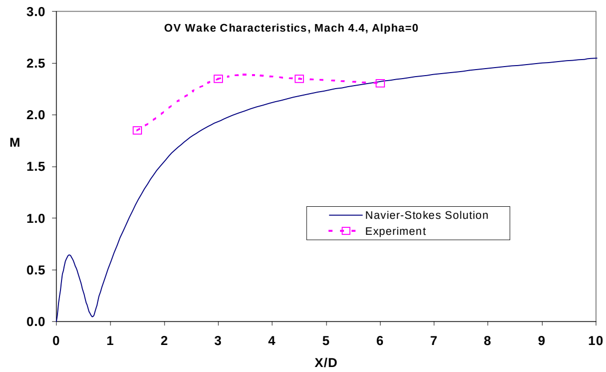

Fig 9 OV Wake Mach Number

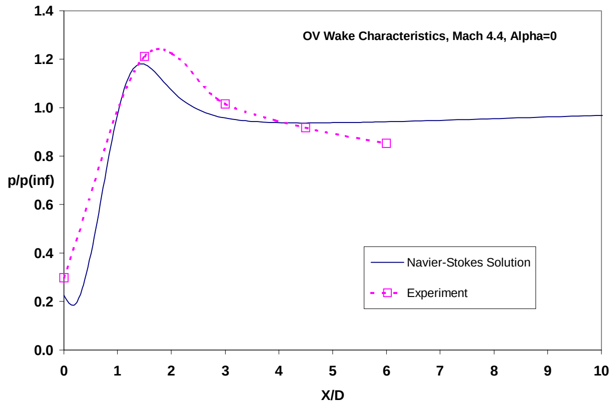

Fig 10 OV Wake Pressure Ratio

In Fig. 11, the predicted dynamic pressure profiles across the OV wake are shown at six diameters downstream of the flare base. The wind tunnel measurements were obtained from measurements of the axial force on the LAP as it was traversed through the wake. The dynamic pressure ratio was assumed to be the ratio of the axial force on the LAP submerged in the wake to the axial force in the free stream. The predicted details of the wake are in very good agreement with the experiments, including the location of the bow and flare shocks. The locations of these shocks were also validated with shadowgraph measurements (Fig. 12) during the wind tunnel test. This picture is made up of a superposition of several photographs taken as the OV model traversed the length of the test section. The shock waves have been enhanced for better visibility.

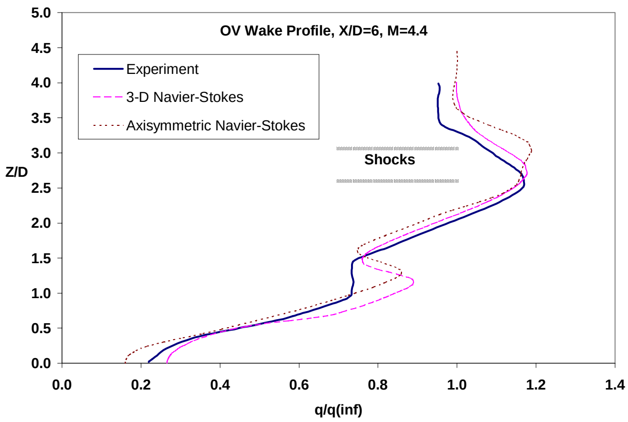

Fig 11 OV Wake Dynamic Pressure Profile, M=4.4, X/D=6

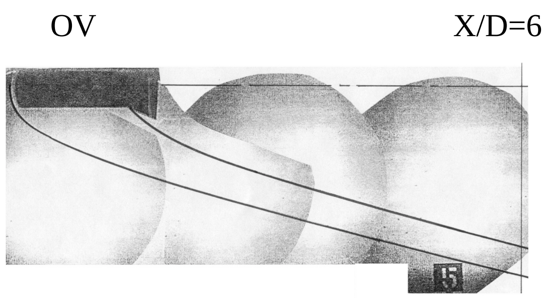

Fig 12 OV Shadowgraph, M=4.4

5 Conclusions

Applied CFD has been used extensively during the preliminary design of the Kistler K-1 reusable launch vehicle. Euler solutions have proved to be useful as a practical design method, and Navier-Stokes solutions have been used for selected conditions for which high accuracy and detailed flowfield results were needed. Wind tunnel data were used to validate the analytical results and assess the aerodynamic uncertainties.

One of the lessons learned in the aerodynamic design and analysis effort is that advanced CFD methods can be used routinely for the prediction of aerodynamic characteristics on unusual and unconventional flight vehicles. It was shown that these methods can provide aerodynamic information on a timely basis while keeping to the cost and schedule of a commercial program.

A number of different aerodynamic tools are required for the successful computational aerodynamic design and analysis of advanced launch vehicles. Some care must be applied before using the results, particularly if test data are not available for validation, and the user must understand the limits and uncertainties involved with the different methods and approaches.

Wind tunnel tests are important in the validation of prediction methods, but if they are not available, the aerodynamics analyst should consider the use of multiple independent codes to test the results for consistency. However, even if this is accomplished, the analyst must have a basic understanding of the applicability of the different levels of computational methods before accepting the predicted aerodynamic characteristics.

6 Acknowledgements

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