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# Automation of a N-S S&C Database Generation for the Harrier in Ground Effect

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**Abstract**

A method of automating the generation of a time-dependent, Navier-Stokes static S&C database for the Harrier aircraft in ground effect is outlined. Reusable, lightweight components are descsribed which allow different facets of the CFD simulation process to utilize a consistent interface to a remote database. These components also allow changes and customizations to easily be facilitated into the solution process to enhance performance, without relying upon third-party support. An analysis of the multi-level parallel solver OVERFLOW-MLP is presented, and the results indicate that it is feasible to utilize large numbers of processors ($\approx 100$) even with a grid system with relatively small number of cells ($\approx 10^6$). A more detailed discussion of the simulation process, as well as refined data for the scaling of the OVERFLOW-MLP flow solver will be included in the full paper.

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# 1 Introduction

The Harrier is a V/STOL aircraft that can take-off and land vertically, or utilize very short runways, by directing its four exhaust nozzles towards the ground. Transition to forward flight is achieved by rotating these nozzles into a horizontal position. Powered-lift vehicles such as the Harrier have certain advantages over conventional aircraft. Their V/STOL capabilities allow for safer carrier operations, smaller carrier size, and allow for quick reaction time for troop support. They also are not dependent on vulnerable land-based runways. The AV-8A was the first service-version of the Harrier, and the AV-8B was a later redesign for improved payload capacity and range (cf. Siuru [1]). The current work utilizes a version of the AV-8B design. The success and unique capabilities of the Harrier has prompted the design of a powered-lift version of the Joint Strike Fighter (JSF).

The flowfield for the Harrier near the ground during very low-speed or hover flight operations is very complex and time-dependent. A Computational Fluid Dynamics (CFD) simulation of this flowfield is shown in Fig.1. Warm air from the fan is exhausted from the front nozzles, while a hot air/fuel mixture from the engine is exhausted from the rear nozzles. These jets strike the ground and move out radially forming a ground jet-flow. The ambient freestream, due to low-speed forward flight or headwind during hover, opposes the jet-flow. This interaction causes the flow to separate and form a ground vortex which can be unsteady, changing size and position at low frequency. The multiple jets also interact with each other near the ground and form an upwash, or jet fountain, which strikes the underside of the fuselage. If the aircraft is sufficiently close to the ground, the inlet can ingest ground debris and hot gasses from the fountain and ground vortex. This Hot Gas Ingestion (HGI) can cause a sudden loss of thrust (lift), imparing vehicle safety. The high-speed jet flow along the ground can also entrain the ambient flow, resulting in a low pressure region underneath the vehicle, leading to what is referred to as the "suckdown effect".

A number of numerical and experimental investigations have been carried out to better understand the complex time-dependent flows associated with powered-lift vehicles. One approach has been to simplify the geometry to study the basic flow physics. Van Dalsem et.al. [2] performed time-dependent Reynolds-averaged Navier-Stokes (RANS) simulation using a delta wing with two aft mounted thrust-reverser jets in close proximity to the ground plane. These computations captured the loss of lift near the ground associated with the suckdown effect, and the small drop-off of lift at higher locations associated with the conventional ground cushion effect. Preliminary results were also presented for a Harrier YAV-8B forebody and inlet. Chawla and Van Dalsem [3] carried out time-accurate laminar flow simulations using the same delta wing geometry of [2]. Static flow simulations were computed at varying heights above the ground plane, as well as a single maneuver simulation with the delta wing descending towards the ground plane. The static cases showed the expected trends between the lift coefficient and height, including the suckdown and cushion effects. The flows were found to be unsteady, with Strouhal numbers

Figure 1: Harrier jet fountain and ground vortex. Streaklines are colored by temperature.

ranging from 0.015 to 0.03, and certain approximations had to be made in order to reduce the long compute times. Roth [4] also carried out time-dependent RANS flow simulations about a simplified powered-lift geometry, which consisted of a cropped delta wing with a blended fuselage and two circular jets mounted in tandem on the underside of the wing. Laminar and turbulent static flow simulations were computed and compared against experimental data.

There have been several RANS computations using simplified Harrier geometries. Gea et.al. [5] and Mysko et al. [6] both computed steady transonic flow (out of ground effect) about Harrier wing/fuselage configurations. Smith et al. [7] presented a time-dependent RANS solution about a simplified YAV-8B Harrier in ground effect. To date, this represents the only RANS solution about a fairly complete Harrier aircraft in ground effect. In order to offset the very long compute times, certain simplifications were made to the time-accurate approach.

The purpose of this paper is to describe a process that has enabled 45 time-accurate RANS simulations about a YAV-8B Harrier aircraft in ground effect to be computed. The eventual goal is to compute enough solutions to define a static stability and control (S&C) database. As a first approximation, it's been assumed that the parameters which affect a vehicle in ground effect (to leading order) are the height above the ground plane ($h$), the angle of attack ($\alpha$), and the freestream Mach number ($M_\infty$). The focus of the current work is on the solution process itself, as opposed to the results of the simulations. The results will be described in detail in a companion paper by Chaderjian [8]. In order to compute a S&C database using time-dependent CFD simulations, it's necessary to automate as much of the process as possible, from mesh generation to post processing. This paper describes a strategy that allows this automation, as well as still providing the ability to easily extend and customize the process without relying upon cumbersome software or third-party support. Another focus of the current work is the parallel efficiency of the flow simulation process, as an efficient flow solver is neccessary in order to compute a time-dependent low frequency flowfield. The efficiency of the OVERFLOW-MLP solver, and it's interaction with the runtime environment are examined.

The first section describes the details of the computional mesh that was utilized, and the automatic generation of configurations for the different heights and angles of attack required to fill the S&C database. Next the efficiency of the flow solver and the embarrassingly parallel solution strategy are described, followed by a description of the post-processing tools.

# 2 Computational Mesh

Numerical simulation of the Harrier in ground effect combines the complex geometry of a full-aircraft configuration, and the complex physics of a jet in crossflow impinging on a ground plane. In order to accurately simulate this type of flowfield, Navier-Stokes simulations are required to resolve the viscous jet impingement on the ground plane, the interaction of the jet and ground vortex "fountain" with the aircraft, as well as the features of the jets in crossflow themselves (cf. Fig. 1). An overset grid strategy (cf. [9,10]) was chosen due to the complex geometry and complex physics encountered. Using overset grids allows different regions of the flowfield, which require different levels of physical modeling, to be easily handled, and the relevant features of the geometry can be easily modeled. First an overview of the computational geometry and overset grid system is provided, then the details of the automation process required to generate separate grid systems for each aircraft configuration is presented.

## 2.1 Overset Grid System

The initial definition of the Harrier YAV–8B geometry was obtained from the work of Smith et al. [7]. The definition used in [7] did not include several features of the aircraft, and these were added from the original "lofting-line" data supplied by the then McDonnell Douglas Aircraft Company. Figure 2 shows the computational geometry used in the current study. Most of the major components of the aircraft are modeled, including the wing with leading-edge root extension (LERX), empennage, engine inlet region, and the two engine exhaust nozzles. The engine exhaust nozzles are scheduled 81 degrees from the aft position, again following the work of Smith et al. The engine thrust rating used for all calculations was "short-lift wet". In addition, the positive circulation flaps are also modeled in their fully-deflected position. Due to time constraints, it was not possible to model the fuselage gun pod/lift-improvement devices (LIDS).

Viscous body-conforming grids were generated about the relevant features of the

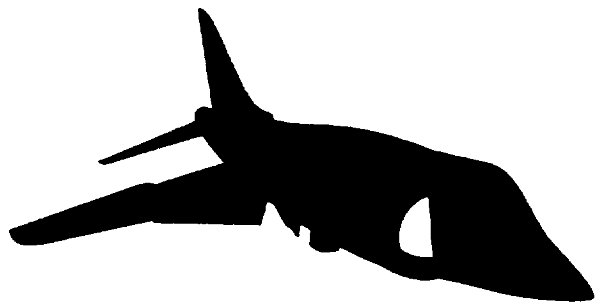


Figure 2: Computational geometry for Harrier YAV–8B

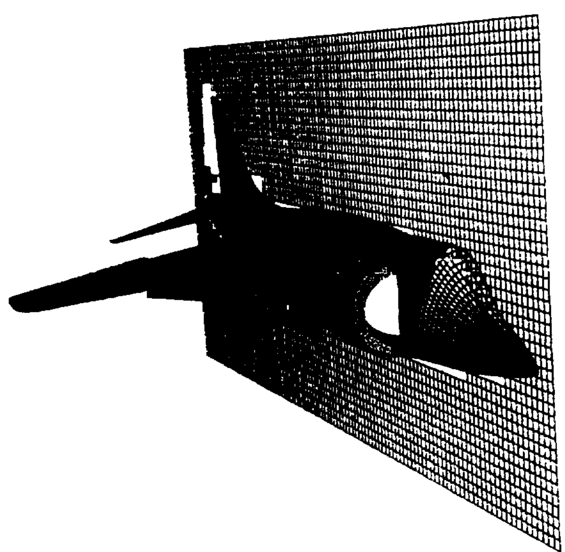
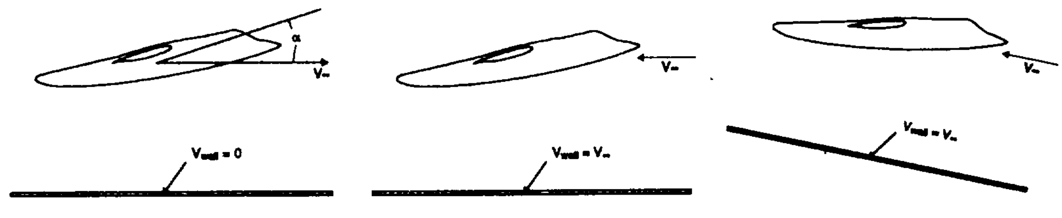


Figure 3: Harrier overset surface mesh definition



(a) (b) (c)

Figure 4: Aircraft frame of reference transformations including ground plane

Harrier geometry, and the overlapping surfaces are shown in Fig. 3. The height of the first cell above the solid surface was specified such that $y^+ \leq 5.0$ in each zone, which was found to be sufficient to resolve the viscous stresses on the surface during a takeoff or landing scenario. The Reynolds number is 12 million, based on the aircraft length. An inviscid Cartesian grid, here called the "near-body Cartesian box", was created to surround the viscous grids with little overlap, and portions of this Cartesian grid which were interior to the solid surface of the aircraft were removed using the overset hole-cutting procedure (cf. Fig. 3). This provided a region surrounding the aircraft which could be placed at any height and orientation relative to a ground plane, without affecting any of the intergrid connectivity between the viscous zones. In other words, the viscous zones and near-body Cartesian box could be processed through the overset connectivity code (Pegasus) once, and then utilized for every configuration without any changes. All of the surface and volume meshes were created using the OVERGRID tool for overset grids developed by Chan [11]. The viscous body-conforming grids, along with the near-body Cartesian box comprise 45 zones and 2.4 million grid points.

## 2.2 Process Automation

Simulating the Harrier in ground effect requires proper treatment of the aircraft/ground plane interaction, which varies from the usual treatment of an aircraft in flight. Fig. 4 shows the reference frame transformations that can be applied to an aircraft in ground effect. Figs. 4b and c would be suitable for a numerical simulation using a fixed grid system, as is used in the current work. Reference frame b) was chosen for this work, so that the flow visualization could take place in a natural frame of reference.

The viscous body-conforming region was combined with the automated script system developed for the High Wing Transport [12], in order to develop a system which could automatically generate the complete system for the aircraft and ground

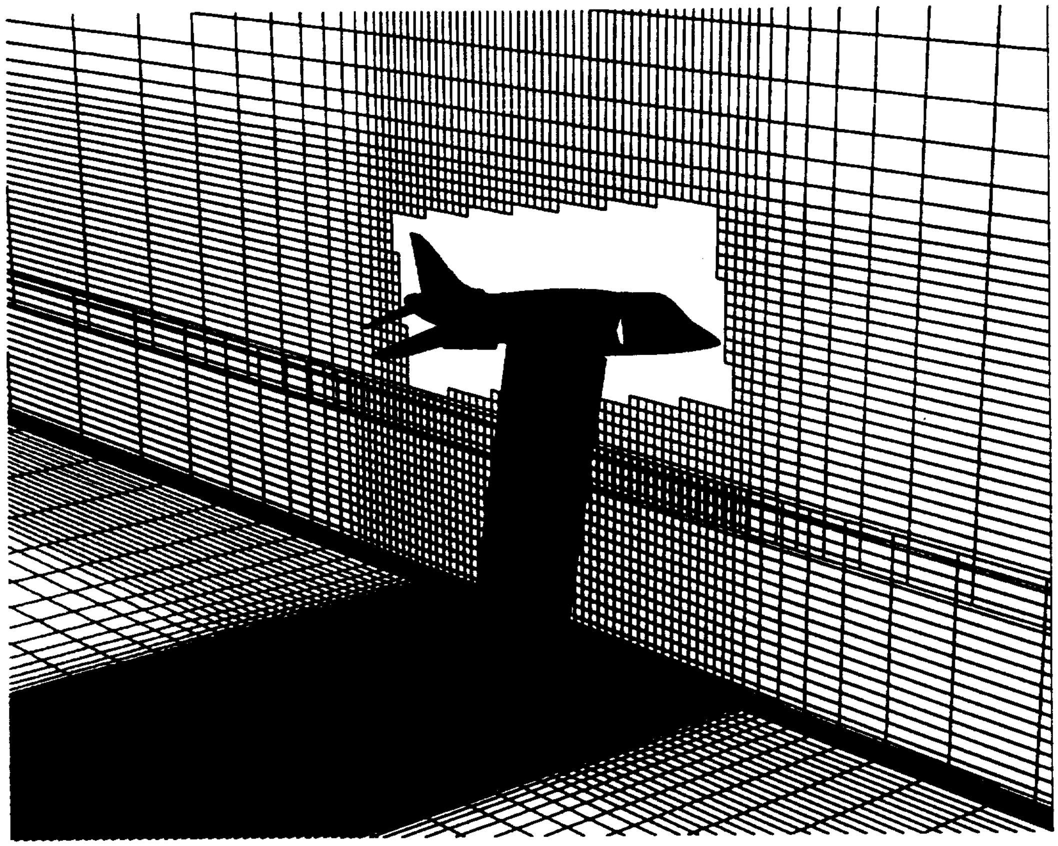


Figure 5: Viscous ground plane and inviscid outer field zones

plane in combination. The script system allowed the processing to be performed in two steps; first the aircraft was placed at the desired height and orientation and the viscous intergrid connectivity was established, then the ground plane and farfield grids were placed around the aircraft, and the complete connectivity was determined. An example complete grid system is shown in Fig. 5. The jet exhaust region was modeled using viscous Cartesian zones which are generated specifically for each height and angle of attack. The viscous ground plane is broken into three regions to allow higher resolution directly under the aircraft where the jet impingement creates large gradients. The final grid system consists of 52 zones, and 3.6 million grid points for the configuration with the aircraft at 30 feet above the ground plane. The number of grid points changes with height, due to the generation of specific grids for the jet region at each height, as will be discussed below. The system has been validated by computations and comparisons to the previous computational results of Smith et al. [7]. These comparisons with previous computational work and other flight-test data will be included in the complete paper.

In order to avoid generating field grids specifically for each configuration, a general set of field grids were created and an overset hole-cutting procedure was used to eliminate portions of the grids which weren't necessary, depending upon the aircraft height. For example, the green inviscid grid in Fig. 5 actually extends above the aircraft, however that portion is removed by the red grid which surrounds the aircraft box. Similarly, depending upon the height and angle of attack, the red outer zone and jet grids may extend below the viscous ground plane, so a cutting plane is established to remove them if necessary. In this manner, some points aren't utilized due to the hole cutting procedure, but there is no need to generate separate field grids for each configuration. The exception to this strategy is the viscous zones which model the jet convection to the ground plane. These zones are computed using a complete Navier-Stokes algorithm, as opposed to the thin-layer Navier-Stokes approximation which is used for the body-conforming viscous zones. Hence these jet grids are both dense and expensive to compute. Instead of removing portions of the jet grids using an overset hole-cutting procedure, which would lead to expensive computations essentially being thrown away due to the iblank logic, these grids were generated specifically for each height and then rotated into position relative to the aircraft based on the angle of attack.

The wallclock time required to generate a single overset grid system, including storing the files on a remote database, was approximately 10 minutes. The processing system was a 2-CPU desktop workstation, and Pegasus 4.1 [13] was used as the overset grid processing software.

# 3 Remote Database Interface

Computing an S&C database involves performing a parametric study of the forces and moments on the aircraft. In this work, the parameters of interest were chosen to be the height of the vehicle above the ground plane, the angle of attack, and the freestream Mach number ($h$, $\alpha$, and $M_\infty$). Working with such a parameter space, it's desirable to automate as much of the solution process as possible - from mesh generation to post-processing of the computed results. This automation speeds the overall process and minimizes human errors. To this end, a modular script system was developed that allowed different facets of the solution process to utilize a consistent interface and set of tools.

This script system was implemented using the Perl language. Perl was chosen because it is an object-oriented language which encourages the re-use of components, and it's a powerful interpreted language which can fulfill all of the needs of the script system without resorting to creating specialized compiled binaries, or mixing scripting languages. One of the requirements on the script system for the current work was to manage a heterogeneous, specialized computing environment. In this environment, each computer (or group of computers) has a specific dedicated task - one machine is dedicated to archival storage, one machine is dedicated to high-performance computing, one machine is dedicated to post-processing and flow visualization.

The backbone of the script system is an interface to an S&C database stored on a

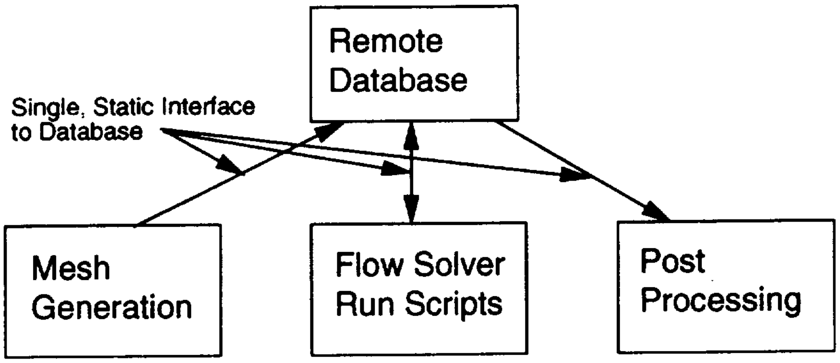



Figure 6: Schematic of remote database interface concept.

remote archival storage system. All interaction with the database utilizes this same interface (cf. Fig. 6). The interface to the remote database is implemented using a Perl module (object). In an object-oriented fashion, the interface is considered static and is the means by which clients (the application scripts in this instance) interact with the database. The actual implementation details behind the interface are hidden from clients and hence can be changed at any time, provided that the interface remains static. This allows the design to evolve with the needs and abilities of the rest of the system. For example, currently the database is implemented simply using a UNIX file and directory structure. If this was replaced with a more sophisticated database software tool, none of the application scripts would need to be changed. The application scripts are not even aware that the data is stored remotely. The interface currently supports several low-level methods, such as "copy-to", "copy-from", etc. from which higher-level tools can be developed. In practice, an application script would issue a command and provide the current parameter values ($M_\infty$, $\alpha$, $h$), and the Perl implementation stores the file in the proper location within the database. All files are stored in the database as read-only to prevent multiple users or runaway processes from overwriting entries in the database.

Using the remote database module, scripts were developed to generate the overset grid system, run the flow solver, and post-process the results through a GUI (written using Perl-Tk). In this manner, not only is there considerable software re-use among the various scripts, but an entirely new database can be accessed simply by creating a new specific instance of the remote database module, i.e. the higher-level scripts do not need to change to compute a new database. The scripts which run the flow solver are briefly described in Sec. 4, while the post-processing tools are discussed in Sec. 5.

# 4 Simulation Process

## 4.1 OVERFLOW-MLP Solver

One of the goals of the current project is to utilize large-scale parallel computers, such as the NASA Ames 512-processor R12000 SGI Origin 2000 (O2K) machine, to compute the S&C database. The SGI O2K is a shared-memory, multi-processor (SMP) machine. A version of the OVERFLOW solver [14], called OVERFLOW-MLP (for "multi-level parallelism"), has been developed by Taft [15] for use on these types of architectures. The OVERFLOW-MLP solver utilizes two levels of parallelism - domain decomposition, and procedural (or loop-level) parallelism. The domain decomposition scheme is implemented on top of the "production" version of the parallel OVERFLOW solver.

As the OVERFLOW-MLP solver uses two methods of parallelization, there are combinations of parameters that can be varied to effect performance of the code. The main parameters are the number of processors per domain (which can vary from one domain to the next), the number of domains, and the total number of processors utilized. As a large number of cases are required to fill the S&C database, some experimentation was performed to determine an optimum configuration of the OVERFLOW-MLP control parameters for the current problem configuration.

Initially it was found that the OVERFLOW-MLP solver did not provide good a good load balance when used as a pure domain decomposition parallel solver. This was caused by the load-balancing routine ignoring the type of scheme used in a particular overset zone (e.g. inviscid vs. viscous), and simply using the total number of grid points in an overset zone to determine the weighting strategy. In many cases this strategy is effective, however in the current work the jet grids are both large and contain the full viscous terms. This makes these grids much more computationally expensive than the Euler or thin-layer N-S grids, and hence caused problems for the simplistic load-balancing algorithm. A weighting based upon the type of scheme used in each zone was added to the load-balancing algorithm, and this improved the performance of the pure domain decomposition scheme. Even with this modest improvement, the load-balancing algorithm is still not performing as desired, and a new scheme will likely be developed. The details and performance of this new scheme will be detailed in the full paper.

Using the OVERFLOW-MLP code essentially as a pure domain-decomposition scheme (i.e. using 1 CPU per domain), it was efficient to compute using 16 CPUs for the current Harrier application. This was suitable for computing a database using the embarrassingly-parallel approach to be discussed in the next section, however it is still desirable to utilize large numbers of CPUs in order to explore database-fill methods other than the brute force approach, and for future work simulating vehicle maneuvers. Figure 7 shows the parallel speedup when computing the Harrier configuration for 500 physical timesteps, using a variety of domain sizes and CPUs. The ideal time was chosen as the 16 CPU pure domain decomposition configuration,

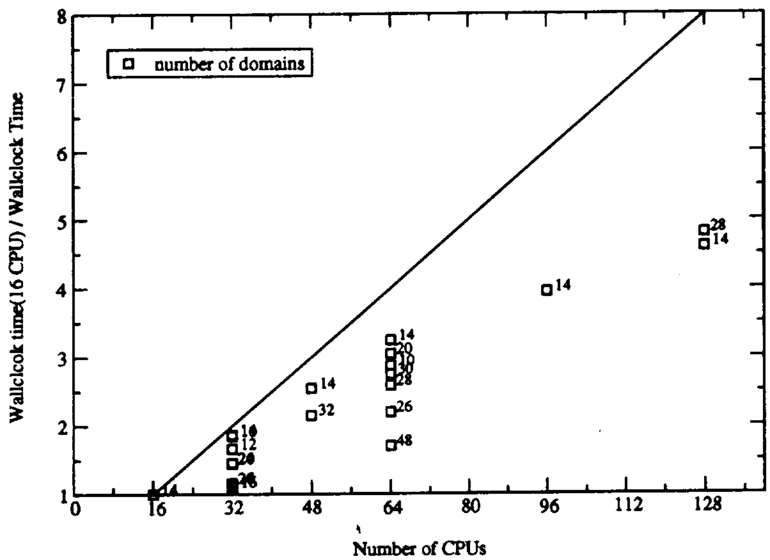



Figure 7: Parallel speedup for the OVERFLOW-MLP code computing the Harrier configuration (SGI R12000 O2K).

so that all data could be referenced to a single value making a comparison meaningful. All of the timings were obtained when the machine was under normal load, so some variability in the timings is expected. It's seen that while some configurations can provide reasonable performance using 32 CPUs, none of the options performs well using more processors.

The main contributing factor to the poor parallel efficiency with large numbers of processors is the scalability of the underlying procedural parallelism in the production OVERFLOW code. For a multi-level parallelism scheme, such as the OVERFLOW-MLP code, the total parallel efficiency ($\eta_T$) can be viewed as a multiplicative product of the domain-based efficiency ($\eta_D$), and the procedural efficiency ($\eta_P$)

$$\eta_T = \eta_D \cdot \eta_P = \frac{wt_1}{wt_N \cdot N} \tag{1}$$

where $wt_N$ is the walltime using N CPUs. Since $\eta_T$ and $\eta_D$ can be measured directly, the procedural efficiency can be calculated. Reducing the data in Fig. 7 using Eqn. 1 (using the timing on 16 CPUs as a reference instead of a single CPU), leads to a procedural efficiency curve for the underlying algorithm for the Harrier application (cf. Fig. 8). Note that the average number of CPUs per domain is utilized as the abscissa. It's seen that all of the computations are collapsing to the same curve, to within the variability of the timing data. Further, the procedural efficiency reduces quickly, so that with 4 CPUs/domain the procedural efficiency has already dropped to about 80% for this application. This means that if the load balancing is only 80% efficient, the overall efficiency of the code will only be 64%, and it is this multiplicative factor which leads to the degraded performance with large numbers of CPUs seen in Fig. 7.

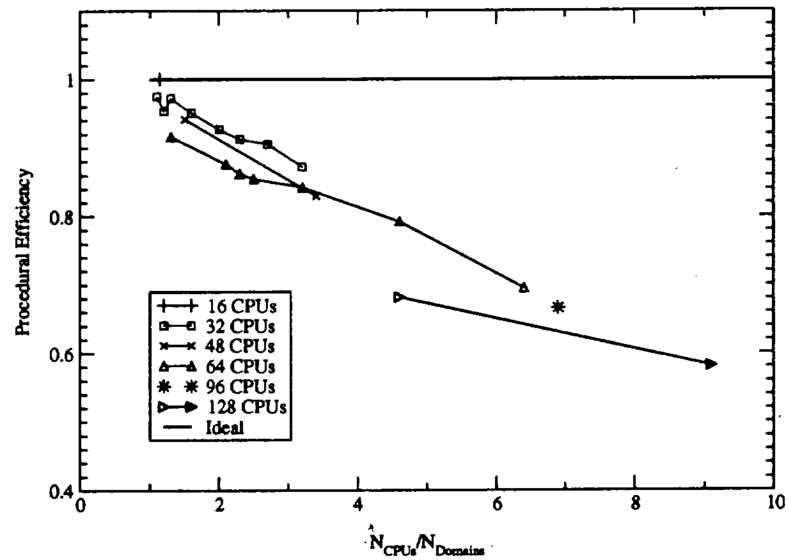



Figure 8: Procedural efficiency for the OVERFLOW-MLP code computing the Harrier configuration (SGI R12000 O2K).

Following the above analysis, in order to utilize larger numbers of processors efficiently (approaching 128 CPUs) without requiring major changes to the OVERFLOW-MLP code, it's seen as necessary to increase the number of overset zones by splitting existing large zones, and then utilize a low number of processors per zone. This will provide a combination of good load balancing and good loop-level parallelism that is required for the multi-level parallel code. Preliminary results using this approach have been successful at utilizing more processors efficiently for the Harrier application, and a discussion of the complete results will be included in the full paper.

## 4.2 Script System

In order to compute an S&C database, it's desirable to take advantage of the "embarrassingly parallel" nature of the problem. In other words, since each configuration is essentially an identical problem with varying inputs, it's possible to compute several database parameters together in parallel and hence reduce the total wallclock time required to compute the entire database. For the Harrier application, the parameters of interest are height, angle of attack, and Mach number (cf. Sec. 1).

Two scripts were written to control the flow solver; the first runs the flow solver for a single set of parameters, while the second runs multiple concurrent sessions of the flow solver, each with a different set of parameters. The script for running a single job* manages retrieving the latest flow solution from the remote database, setting up the input files, running the flow solver, checking if the flow solver executed properly, and then storing the new flow solution to the remote database. Since the flowfield in

*A job is a particular set of parameters, with a specific input file, flow solver, etc.

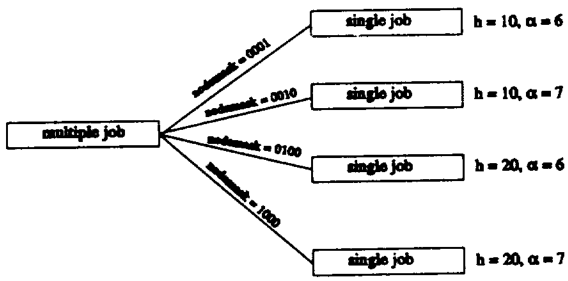



Figure 9: Schematic of running multiple concurrent jobs

the current work is unsteady, this process must be iterated many times in succession. The locations of the various files (both remotely and on the local high-performance computing machine) and the flow solver inputs, are all determined based upon the parameters within the database matrix.

The script which runs multiple concurrent jobs leverages the work of the script which runs a single job. The multiple job script sets up a matrix of jobs to run, and then "launches" (literally forks()) an instance of the single job script for each set of parameters (cf. Fig. 9). The multiple job script then waits for the single instances to finish, and when one does another job can be launched. When all of the jobs have finished the script exits.

When working on an SMP architecture it can be difficult to run multiple instances of the same executable concurrently on a dedicated set of processors without the multiple instances interfering with each other and greatly reducing the efficiency of the parallel flow solver. The initial database computations (performed in March-April, 1999) had no way to account for processor interference, and hence the "embarrassingly-parallel efficiency" was not 100%. Rather, the average wallclock time required for a single database point when multiple concurrent computations were performed was roughly 1.3 times that required for a single computation in isolation.

On the NASA Ames O2K machines running the portable batch system (PBS), a "nodemask" variable is supplied to each batch job. This nodemask variable specifies the subset of the machines processors which the current batch session can access. The recent versions of the OVERFLOW-MLP code use the nodemask variable to execute a pin-to-node strategy, whereby the domain decomposition assigns domains to specific processors for the duration of the flow solver execution, rather than allowing the OS to dynamically balance the CPU usage. When running multiple concurrent versions of the OVERFLOW-MLP executable, it's thus necessary to apply another mask to the nodemask variable that PBS provides - a so-called "job mask" which specifies the processors which each specific job should utilize. In other words, if 16 processors are supplied by PBS, and it's desired to run 4 concurrent jobs, the job mask would mask portions of the original 16 processors so that 4 distinct processors are available to each job. This was done by creating a Perl module which stores the original PBS nodemask variable, and then portions it out to each job that is launched so that no two jobs can access the same processor (cf. Fig. 9). In this manner, concurrent versions of the same executable can be run without processor interference, and without requiring modification of the flow solver code. Using the job nodemask and the pin-to-node strategy, the embarrassingly-parallel efficiency when running multiple concurrent cases was indistinguishable from the theoretical maximum of 100%.

# 5 Post Processing

As with the mesh generation and flow simulation processes, when analyzing hundreds (or more) of CFD simulations it's desirable to automate much of the post-processing analysis. This automation can also be used to "mine" the database for interesting or critical points, as well as obtain general structures. As was discussed in Sec. 3, a GUI tool was built upon the remote database interface using Perl-Tk and utilized to perform post-processing analysis of the S&C database.

The GUI tool, referred to as "DBview", has two main modes of operation; interactive and batch processing. In interactive mode DBview is itself in some sense simply a layer between the remote database and analysis application software residing on the engineers desktop machine. For example, DBview does not provide any graphical plotting capability, rather it retrieves the relevant data from the remote database and calls a third-party graphical application to display and analyze the results. In batch processing mode, a number of database entries can be selected to have certain tasks performed (with the results to be stored in the remote database), and the DBview tool again simply manages the data movement and choosing the proper application to run. With this approach, the GUI tool is both open-ended, since new third-party applications can simply be added as necessary, and lightweight, as the GUI simply must manage user input and data movement without needing to perform complicated or specialized analysis tasks.

The DBview "front-end" is shown in Fig. 10. Access tabs for choosing the desired database are in the upper left of the interface. In this example, the two possible databases are "Baseline" and "SNC01". The parameters shown in the selection area below the tabs change to those appropriate for the chosen database. Once the parameters are selected, the user can choose one or more of the check-buttons on the top right side of Fig. 10 to interrogate the grid and solution, or to view the load histories. Selecting the "grid" or "solution" check-button and pressing the "Get and

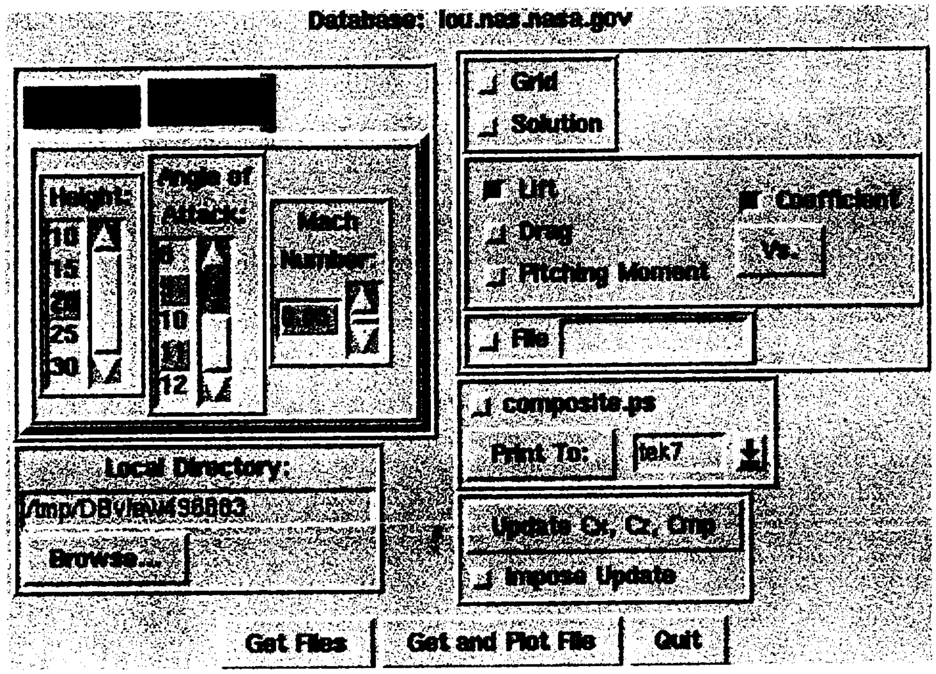



Figure 10: Database post-processing graphical user interface.

Plot File" button results in the retrieval of the appropriate files from the database followed by an interactive flow visualization session. To aid the analysis, pre-loaded flowfield visualizations are available, and can either be printed to hardcopy or stored in the remote database. An example of this "thumbnail" analysis is shown in Fig. 11.

The GUI tool can take arbitrary slices through the data, including constant planes, vectors, or arbitrary isolated points in the database. The main interactive features of the tool are graphical plotting of the load histories*, and 3-D visualization tools. An example of the load history post-processing is shown in Fig. 12. Arbitrary entries in the database can be selected and are automatically retrieved from the remote database and plotted in a third-party application. The labels and legends are also automatically generated.

# 6 Summary

A method of automating the generation of a time-dependent, Navier-Stokes static S&C database for the Harrier aircraft in ground effect has been outlined. Lightweight reusable components were created which allowed different facets of the CFD simulation process to utilize a consistent interface to a remote database. These components

*All of the computed solutions are time-dependent, hence the time-history of the load variation must be plotted, not just a steady-state value.

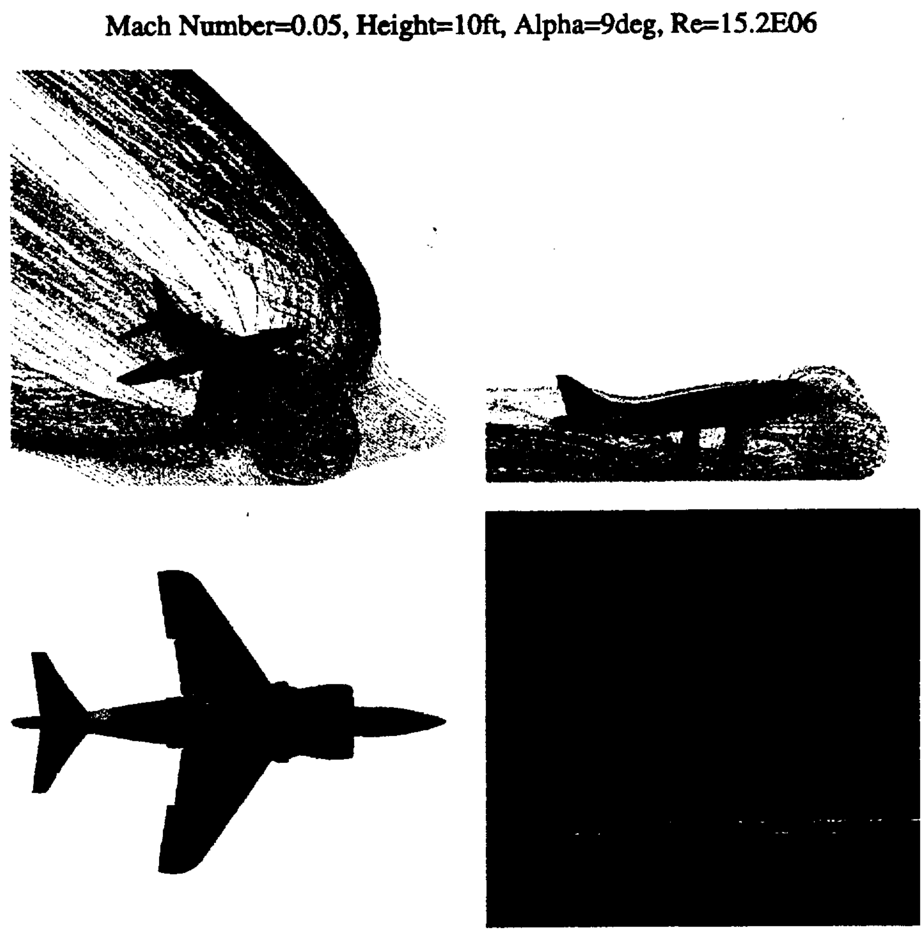



Figure 11: Pre-loaded "thumbnail" composite flow visualizations.

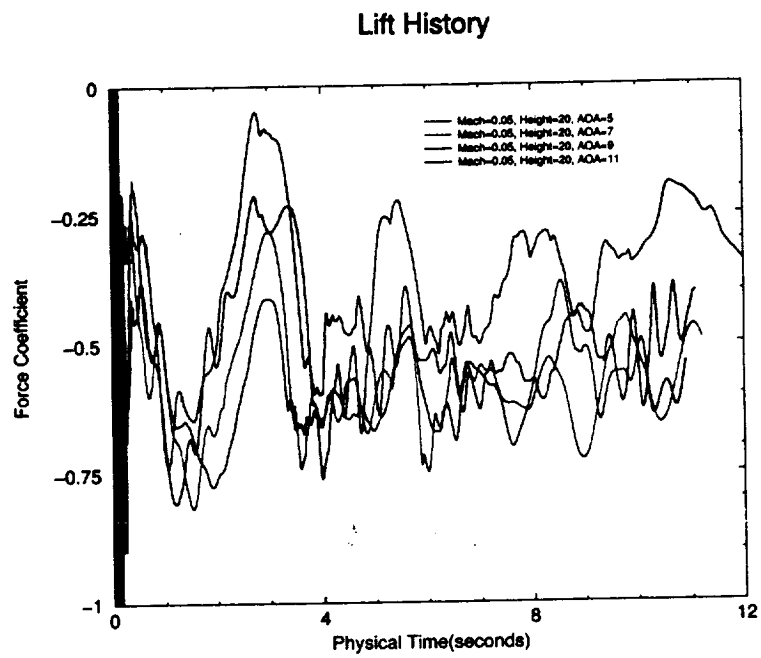



Figure 12: Example of post-processing time-dependent load histories.

also allowed changes and customizations to easily be facilitated into the solution process to enhance performance without relying upon third-party support. An analysis of the multi-level parallel solver OVERFLOW-MLP was presented, and the results indicate that it is feasible to utilize large numbers of processors ($\approx 100$) even with a grid system with relatively small number of cells ($\approx 10^6$). The full paper will include a more detailed discussion of the simulation process, as well as refined data for the scaling of the OVERFLOW-MLP flow solver.

# References


[1] Siuru, W. D., *British Aerospace and McDonnell Douglas Harrier AV-8A/B*. Aero Publishers, Inc., 1985.

[2] Van Dalsem, W. R., Chawla, K., Smith, M. H., and Abeloff, P. A., "Numerical Simulation of Powered-Lift Flows," in *International Powered Lift Conference Proceedings*, pp. III.16.1–14, The Royal Aeronautical Society, 1990.

[3] Chawla, K., and Van Dalsem, W. R., "Numerical Simulation of a Powered-Lift Landing," AGARD-CP 534, 1993.

[4] Roth, K. R., "Comparison of Computation with Experiment for a Geometrically Simplified Powered-Lift Model," *AIAA Journal of Aircraft*, vol. 34, no. 2, pp. 160–167, 1997.

[5] Gea, L. M., Chyu, W. J., Stortz, M. W., Roberts, A. C., and Chow, C. Y., "Flight Test and Numerical Simulation of Transonic Flow Around YAV-8B Harrier II Wing," AIAA Paper 91-1628, 1991.

[6] Mysko, S. J., Chyu, W. J., Stortz, M. W., and Chow, C. Y., "Navier-Stokes Simulation of External/Internal Transonic Flow on the Forebody/Inlet of the AV-8B Harrier II," AIAA Paper 93-3057, 1993.

[7] Smith, M.H., Chawla, K., and Van Dalsem, W. R., "Numerical Simulation of a Complete STOVL Aircraft in Ground Effect," AIAA Paper 91-3293-CP, July 1991.

[8] Chaderjian, N.M., Pandya, S., Murman, S.M., and Ahmad, J., "Parametric Time-Dependent Navier-Stokes Computations for a YAV-8B Harrier in Ground Effect," submitted for publication at AIAA 40th Aerospace Sciences Meeting.

[9] Benek, J.A., Buning, P.G., and Steger, J.L., "A 3-D Chimera Grid Embedding Technique," AIAA Paper 85-1523, July 1985.

[10] Buning, P.G., Chiu, I.T., Obayashi, S., Rizk, Y.M. and Steger, J.L., "Numerical Simulation of the Integrated Space Shuttle Vehicle in Ascent," AIAA Paper 88-4359-CP, Aug. 1988.

[11] Chan, W.M., Meakin, R.L., and Potsdam, M.P., "CHSSI Software for Geometrically Complex Unsteady Aerodynamic Applications," AIAA Paper 2001-0593, Jan. 2001.

[12] Rogers, S. E., Roth, K., Nash, S. M., Baker, M. D., Slotnick, J. P., Whitlock, M., and Cao, H. V., "Advances in Overset CFD Processes Applied to Subsonic High-Lift Aircraft," AIAA Paper 2000-4216, Aug. 2000.

[13] Suhs, N.E. and Tramel, R.W., "Pegsus 4.0 User's Manual," AEDC Tech. Report TR-91-8, 1991.

[14] Buning, P.G., Jesperson, D.C., Pulliam, T.H., Chan, W.M., Slotnick, J.P., Krist, S. E., and Renze, K.J., *OVERFLOW User's Manual.* NASA.

[15] Taft, J.R., "Multi-Level Parallelism, A Simple Highly Scalable Approach to Parallelism for CFD," in *HPCCP/CAS Workshop 98 Proceedings* (C. Schulbach, ed.), 1998.