JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 48, No. 4, July–August 2011

Large-Scale Computations for Stability Analysis of Launch Vehicles Using Cluster Computers

Guru Guruswamy*
NASA Ames Research Center, Moffett Field, California 94035

DOI: 10.2514/1.51264

A procedure is developed to generate a large aerodynamic database suitable for the static stability analysis of launch vehicles in the transonic regime by using the Navier–Stokes equations. Effects of structural deformations are also included using modal representation. It is shown that a large number of cases suitable for design can be computed within practical time limitations by using efficient protocols suitable for massively parallel computations on superclusters. Results are validated with wind-tunnel measurements that show good comparisons within the limits of the model size. Massive computations on superclusters reveal important observations, such as higher modes having pronounced effects near transonic regime.

Nomenclature

C_A = axial force coefficient
$C_{m\alpha}$ = pitching moment coefficient slope with respect to angle of attack
$C_{n\alpha}$ = normal force coefficient slope with respect to angle of attack
C_p = pressure coefficient
D = maximum diameter of vehicle, in.
$\{d\}$ = displacement vector, in.
$\{F\}$ = aerodynamic force vector
$\{h\}$ = modal displacement vector
L = total lift coefficient of fin
M_∞ = freestream Mach number
X = vehicle axis location, in.
α = angle of attack, deg
δF_j = change in aerodynamic force due to perturbation of j mode shape
$[\Phi]$ = matrix of modal shape vectors

Introduction

LAUNCH vehicles cruise through various flow regimes during flight. Accurate coupled load analysis (CLA) techniques that account for structural motions are needed for safe design of these vehicles. Large general-purpose codes such as NASTRAN [1] can compute coupled loads of complex geometries using finite element structures and linear aerodynamic equations [2]. Transonic flight regimes, including low supersonic Mach numbers, are crucial, since such flows are dominated by nonlinearities associated with moving shock waves and flow separations. CLA needs to include computations near transonic Mach regimes, which is beyond the capabilities of linear aerodynamic theory. Transonic flows can result in larger loads, leading to significant structural deformations. It is observed in [3] that including structural deformation is important in the design of the Taurus launch vehicle. For cases beyond the limits of the linear aerodynamic theory, the current practices mostly use loads that are either measured in the wind tunnel or computed using computational fluid dynamics (CFD) on rigid configurations.

In this work, transonic aerodynamic loads including the effects of structural deformations are computed using the Navier–Stokes (NS) equations with turbulence models. It is a common practice in stability analysis to represent the structural properties in terms of natural mode shapes [4]. Here, the effect of structural deformations on aerodynamic forces is computed in the form of aerodynamic influence coefficients (AICs) [5] by using mode shapes [6].

Use of NS equations involves complexities that result from numerics, such as higher-order methods, and therefore are computationally orders of magnitude more expensive than the use of linear potential theory. Thousands of steady-state computations are needed for stability analysis and design, creating a need for massive computational resources. Here, this resource issue is addressed through efficient use of state-of-the-art large-scale single-system image cluster computers.

Development of new, larger superclusters, such as NASA's 81,920-core Pleiades system,[†] poses challenges to aerospace engineers in advancing engineering analysis tools by efficiently taking advantage of order-of-magnitude increases in computing resources. In this paper, a procedure for accurately and efficiently computing a large AIC database using the NS equations is presented. Pleiades computational environment comprises a Linux operating system, a portable batch system (PBS) for job scheduling [7], OpenMP [8] for parallel computing, and the MPIexec utility, an improved version of the script MPIrun[‡] successfully used in developing the high-fidelity multidisciplinary process [9].

This paper presents a procedure to efficiently compute a large aerodynamic database based on the NS equations, including the effects of structural deformations.

Approach

In CLA, structural properties are represented by a set of mode shapes, which can be obtained from either computations or from ground vibration tests. The displacements $\{d\}$ can be expressed as a summation of scaled natural modes,

$$\{d\} = [\Phi]\{h\} \tag{1}$$

where d is the displacement vector, $[\Phi]$ is the modal matrix composed of the vibration mode shapes, and $\{h\}$ is a scale factor known as generalized displacements computed from modal analysis. Aerodynamic forces $\{F\}$ for any given deformation can be represented by

Presented as Paper 2010-2954 at the 51st AIAA/AHS/ASME/ASC Structures, Structural Dynamics, and Materials Conference, Orlando, FL, 12–15 April 2010; received 18 June 2010; revision received 28 February 2011; accepted for publication 28 February 2011. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States. Copies of this paper may be made for personal or internal use, on condition that the copier pay the $10.00 per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923; include the code 0022-4650/11 and $10.00 in correspondence with the CCC.

*Senior Scientist, NASA Advanced Supercomputing Division, Applied Modeling and Simulation Branch; guru.p.guruswamy@nasa.gov. Associate Fellow AIAA.

[†]Data available at http://www.nas.nasa.gov/hecc/resources/pleiades.html [retrieved 7 June 2011].

[‡]Data available at http://www.nas.nasa.gov/hecc/support/kb/Running-Multiple-Serial-Jobs-to-Reduce-Walltime_184.html [retrieved 7 June 2011].

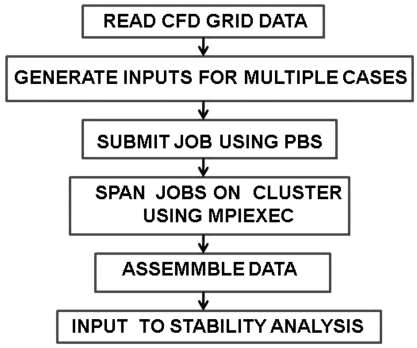


Fig. 1 RUNMAS parallel AIC computing approach.

summing aerodynamic forces computed on each mode separately by using

$$\{F\} = [\Phi]^T \{\delta F\} \tag{2}$$

where δF_j is the change in force (side force on a launch vehicle or total lift of a wing) induced by a modal deformation of mode Φ_j.

Using this approach, a given configuration is represented by several modes. The effects of modal perturbations are independently computed. By using a linear combination of modal loads, aerodynamic forces for any arbitrary displacements can then be computed using Eq. (2). The following approach is taken to compute AIC using CFD codes:

1) For a given configuration, a suitable CFD grid is generated.

2) Using an algebraic approach, deformations due to mode shapes are superimposed on the base grid of the rigid configuration.

3) Inputs for different cases with varying angles of attack (AOAs) α and Mach numbers are generated using a C program.

4) Loads are computed on the deformed geometry using the OVERFLOW2 code [10]; computations for each Mach number, AOA, and mode are assigned to a separate processor.

5) Multiple cases are run using the PBS job control language [7], which has the ability to spawn cases to different processors.

A flowchart of the preceding process, RUNMAS, based on PBS, is shown in Fig. 1.

Results

In this work, all computations are done on the Pleiades supercluster; see footnote †.

Validation for Fin Configuration

To test the process, a single panel fin of a typical spacecraft with five bending modes is selected. The wing is modeled using C-H grids of sizes 151 (streamwise), 44 (spanwise), and 35 (normal) points. The selected five bending mode shapes [11] are shown in Fig. 2.

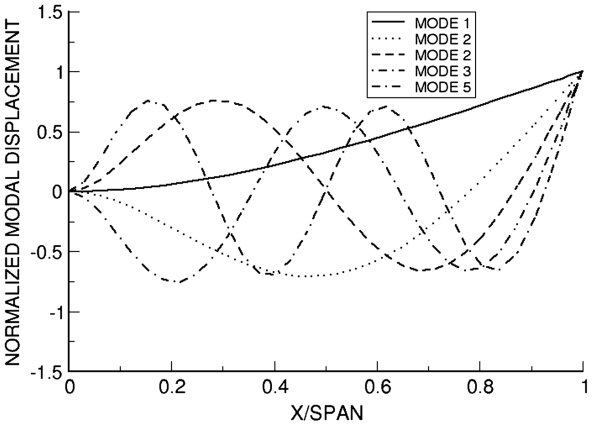


Fig. 2 Bending mode shapes of a fin.

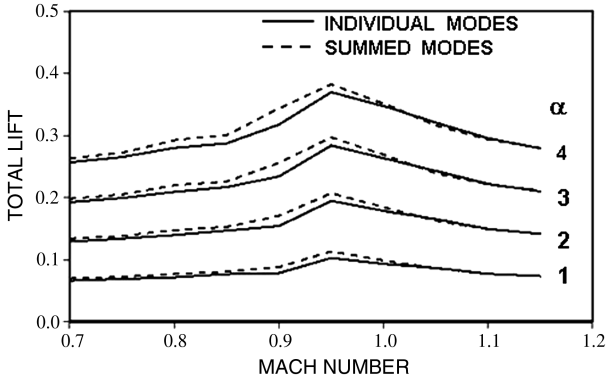


Fig. 3 Comparison lifts between individual modes and summed modes.

The purpose of this work is to show how aerodynamic data computed on each mode can be used to compute aerodynamic data for arbitrary deformation. To validate the procedure, a deformed shape of the wing is computed by summing the deformed shapes of individual bending modes.

Total lifting forces L are computed for this deformed shape at four AOAs and Mach numbers. Figure 3 shows good comparison between total lifting forces computed using a deformed shape and those obtained by summing lifting forces of individual modes from Fig. 2. Comparisons are better at lower AOAs than at higher AOAs. The lifting force from the summed-deformed shape is slightly higher than that obtained by summing the lifting forces associated with the individual modes. In addition, results compare better in the supersonic and subsonic regimes, compared with the transonic regime. This demonstrates that the modal approach can be successfully used to compute aerodynamic forces needed for AIC computations.

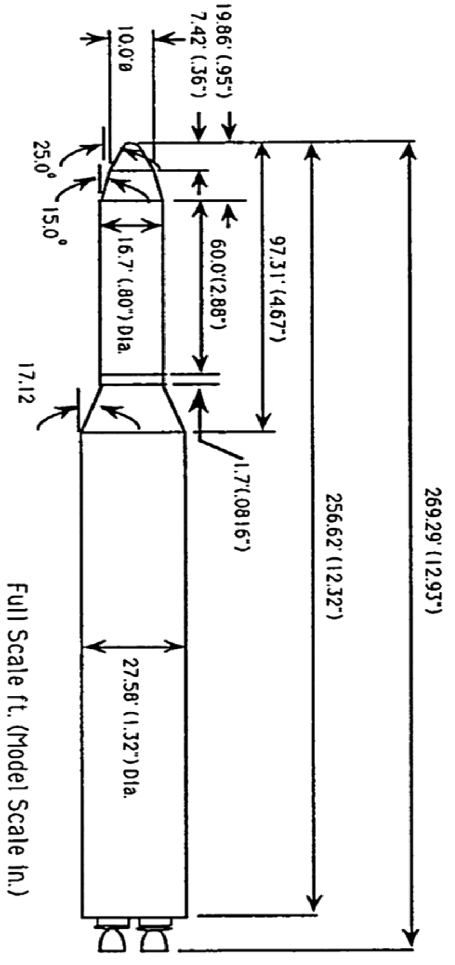


Fig. 4 NLS model [12].

Computations for Launch Vehicle

The remainder of the calculations are done for the National Launch System (NLS) model, designed and tested at NASA Marshall Space Flight Center [12] and shown in Fig. 4. Experimental results are available for a 2.5% model. In this paper, computations are made using 1 million grid points.

Figure 5 shows the comparison $C_{n\alpha}$, the rate of change in normal (side) force coefficient with respect to AOA, at $M_\infty = 0.90$. The rate of change is computed based on normal forces at 5 and 6 deg AOA. Computed results compare well with the experiment, given the small size of the 2.5% model. The experiment predicts slightly higher and lower peaks near $X/D = 3.8$ and $X/D = 4.0$, respectively.

As part of the validation with experimental results, the effect of Mach number on forces is studied in the transonic regime. Figure 6 shows the comparison of the axial force coefficient C_A at zero AOA. Both computed and measured C_A levels off near $M_\infty = 1.0$. The comparisons are favorable at all Mach numbers considered. Figure 7 shows the comparison between computed and experimental $C_{n\alpha}$ at a 5 deg AOA. The normal force coefficient rises until $M_\infty = 1.0$, then it drops sharply. Results compare better with the experiment for Mach numbers away from $M_\infty = 1.0$. The comparisons of moment coefficient slopes $C_{m\alpha}$ computed at a 5 deg AOA are shown in Fig. 8. Both results agree in trend. Similar to a normal coefficient, $C_{m\alpha}$ has a peak near $M_\infty = 1.0$. A comparison for the moment coefficient is less favorable compared with axial and normal forces, shown in Figs. 6 and 7, respectively.

The results in Figs. 5–8 show that the grid topology and size are adequate for flow computations. The differences between experiments and computations, particularly for moment coefficients in Fig. 8, can be attributed to the scale effects, since the model was only 2.5% of the full size. In this work, computations are made by accounting for modal deformations. The first four modes shapes are taken as defined in [11] and shown in Fig. 9.

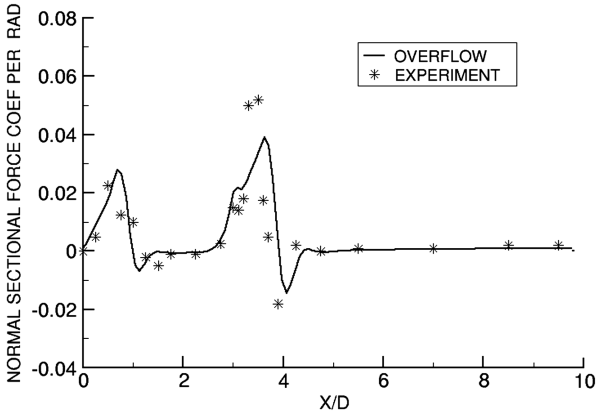


Fig. 5 Comparison of rate of normal sectional force coefficient with respect to AOA.

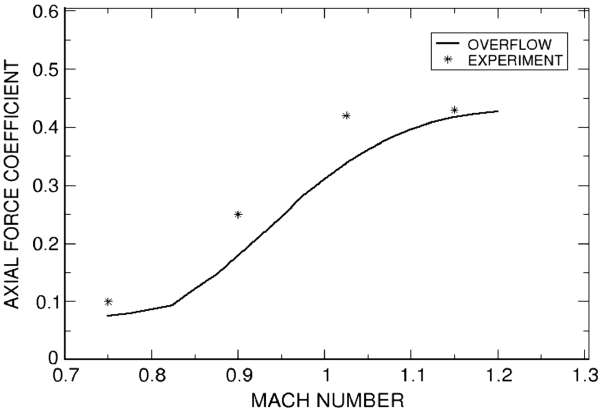


Fig. 6 Effect of Mach number on axial force coefficient.

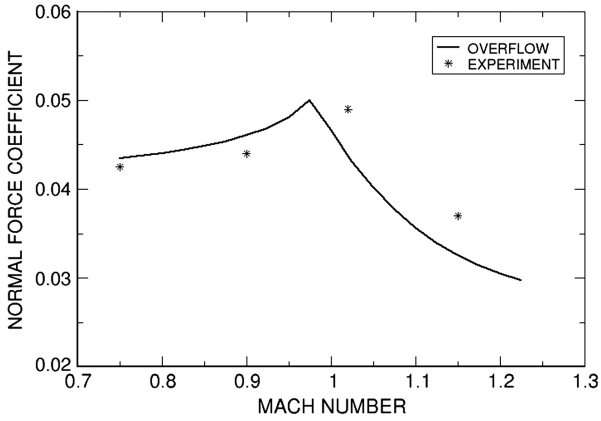


Fig. 7 Effect of Mach number on slope of normal force coefficient.

First, computations are made when the vehicle is deformed under the first bending mode with a tip amplitude of 2.5% of the total length. Figure 10 shows the pressure distribution on the deformed configuration at $M_\infty = 0.90$.

The effect of the first mode on the normal sectional coefficients is shown in Fig. 11. Most of the effects are near the nose, corresponding to the maximum displacement. The effect reduces to zero toward the tail.

The main focus of this work is to demonstrate the use of large cluster computers for generation of massive amounts of data required for stability analysis. Here, computations are made for 1000 cases involving 20 Mach numbers ranging from 0.75 to 1.25, 10 AOAs ranging from 0.0 to 4.5 deg, and five modes (one rigid and four flexible modes).

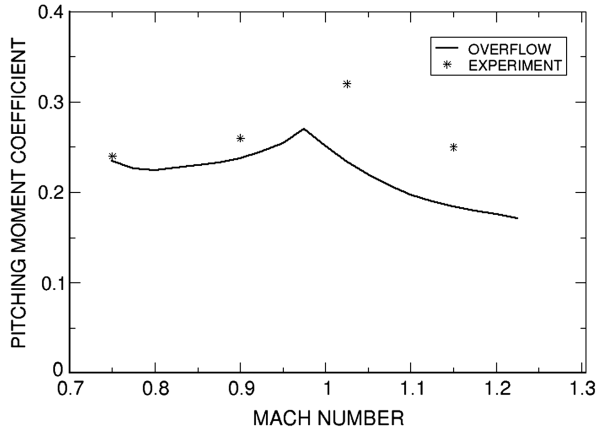


Fig. 8 Effect of Mach number of moment coefficient.

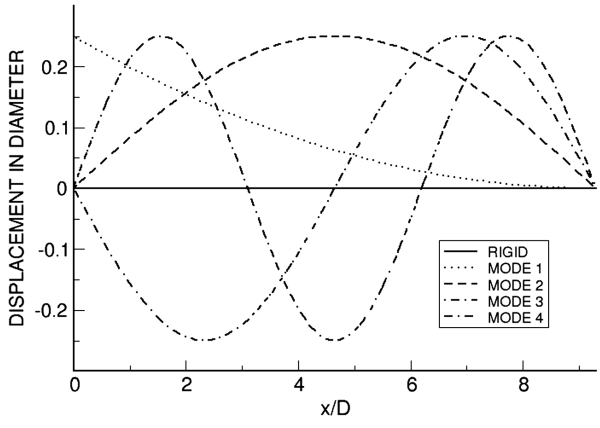


Fig. 9 First four modes of launch vehicle.

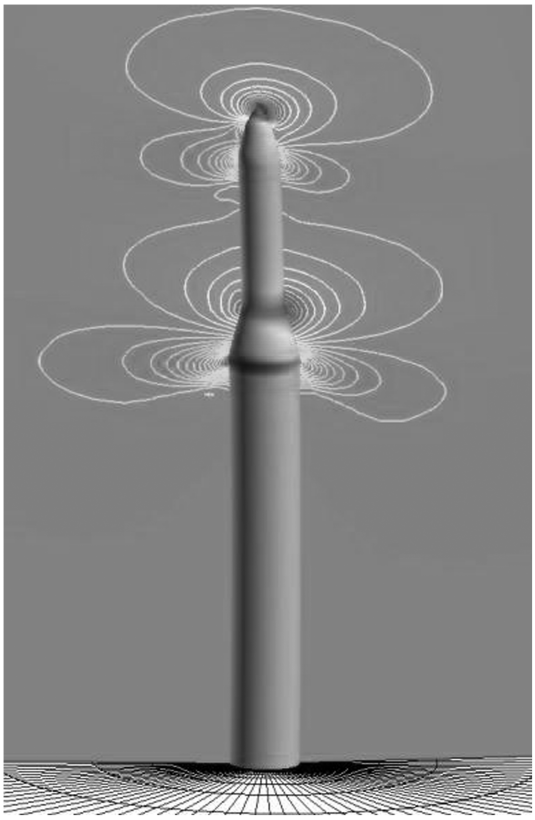


Fig. 10 Pressure distribution on deformed configuration.

The computational turnaround wall-clock time required for massive computations can be reduced using either MPIexec or OpenMP, or both. In this work, both MPIexec and OpenMP are used to minimize wall-clock time. The optimum number of cores (processors) required to obtain best performance using OpenMP is first determined by running a single case. Figure 12 shows the effect of the number of cores on wall-clock time. For a single case, one core takes 45 min on the Pleiades supercomputer. For OpenMP runs, wall-clock time reduces exponentially until four cores and then stays almost constant. For the grid used in this work, it appears there is no advantage to using more than four cores for OpenMP computations.

Massively parallel computations are made by increasing the number of cores and corresponding cases using MPIexec. A plot of wall-clock time with respect to the number of eight-core nodes is shown in Fig. 13. Wall-clock time increases at a rate of about 0.22 min per node up to 100 nodes, and then it almost remains constant. Computations are made on up to 125 nodes, resulting in 1000 parallel cases.

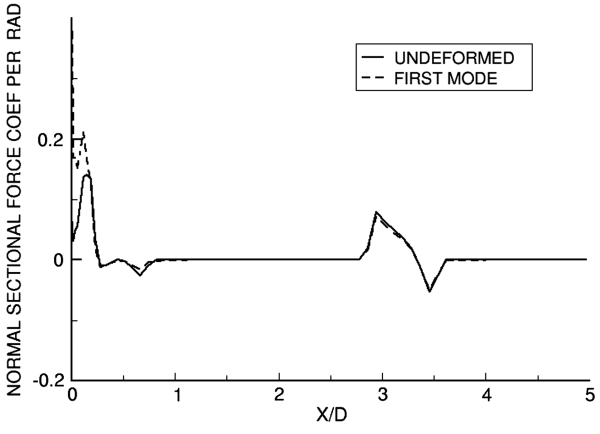


Fig. 11 Effect of first mode on normal sectional force coefficient.

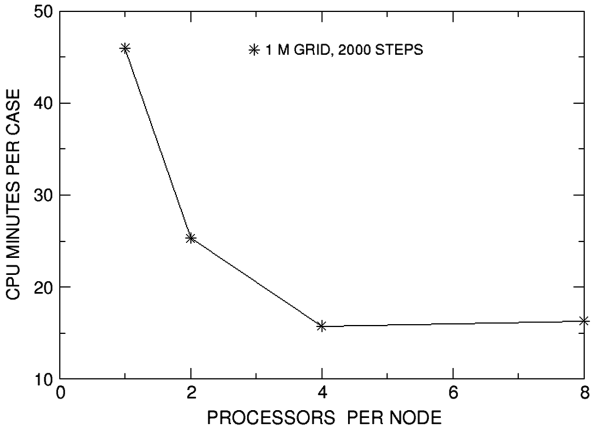


Fig. 12 Effect of OpenMP processors on computing time.

Then, 1000 cases are run using OpenMP cores. Results are shown in Fig. 14 for 1000 nodes using 2-OpenMP and 4-OpenMP cores. The 2-OpenMP results are better than the non-OpenMP results. The wall-clock time with 4-OpenMP is reduced by almost 70% compared with the non-OpenMP run. In summary, 1000 transonic cases were computed with 15 min of wall-clock time by using 1000 nodes, each with 4-OpenMP cores.

The results from 1000 cases are summarized in Fig. 15. Plots of normal (side) force as a function of Mach number and AOA are shown for the first four flexible modes. All modes have significant influence on the normal forces. The effect is more pronounced near $M_\infty = 1.0$. The rates of change of $C_{n\alpha}$ near transonic Mach numbers are more pronounced for higher modes.

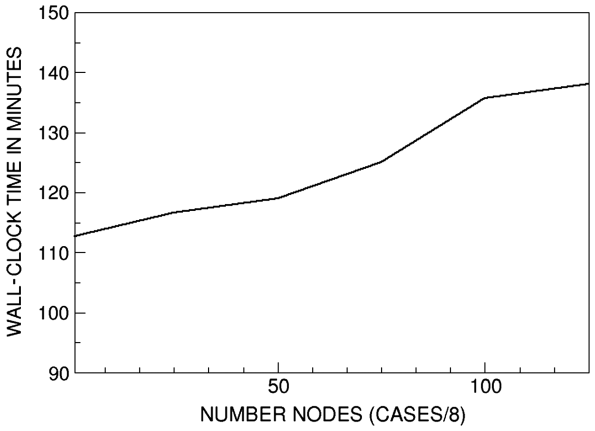


Fig. 13 Wall-clock time vs nodes.

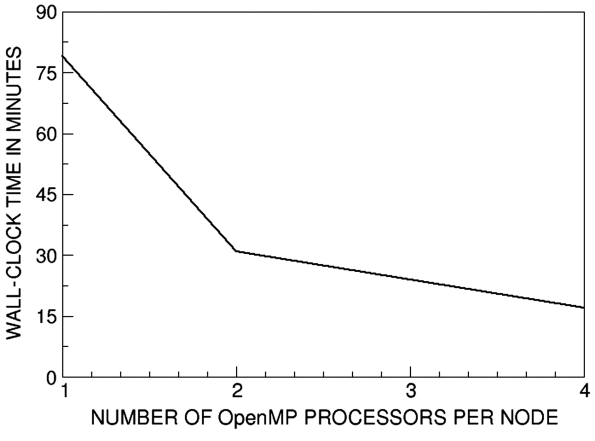
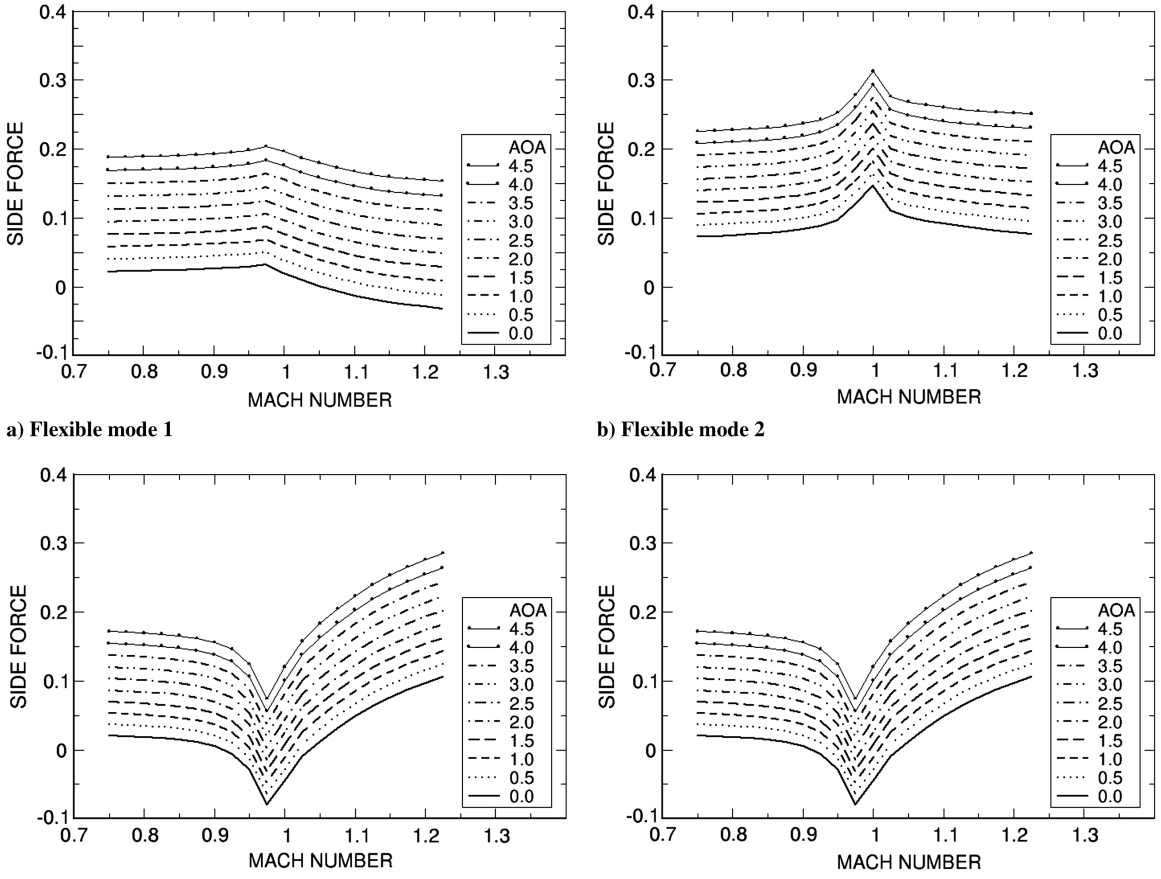


Fig. 14 Effect of OpenMP on wall-clock time.



a) Flexible mode 1 b) Flexible mode 2

c) Flexible mode 3 d) Flexible mode 4

Fig. 15 Effect of Mach number and AOA on normal (side) force for four flexible modes.

Conclusions

A procedure is presented by using the NS equations to compute a large aerodynamic database for aerospace vehicles in the transonic flight regime, including the effects of structural deformations. Aerodynamic data are generated in the form of responses to modal deformations, which can be used as a database for CLA. Computations are made on a single image cluster computer system with efficient parallel protocols PBS blended with MPIexec and OpenMP. One thousand computations required about a $\frac{1}{4}$ h wall-clock time using 4000 processors, making the use of the NS equations practical for design. This tool can be extended to compute unsteady loads associated with structural vibrations.

Acknowledgments

The author thanks Johnny Chang and Dennis Jespersen of the NASA Advanced Supercomputing Division, NASA Ames Research Center, for helpful suggestions in efficiently using the Pleiades supercomputer.

References

[1] "NASTRAN User's Manual," NASA SP-222, June 1986.

[2] Foist, B. L., Grau, E. L., and Nejad, B. I., "Launch Loads Development Using Sine Vibration Methodology," AIAA Paper 2004-1800, April 2004.

[3] Reinbold, D., and Canu, V., "The Aerodynamic Predictions of an Elastic Launch Vehicle," Orbital Science Corp., Paper 2001-131, Dulles, VA, 2001.

[4] Alley, V. L., and Gerringer, A. H., "An Analysis of Aeroelastic Divergence of Unguided Vehicles," NASA TND-3281, March 1966.

[5] Rodden, W. P., Farkas, E. F., Malcolm, H. A., and Kliszewski, A. M., "Aerodynamic Influence Coefficients from Piston Theory. Analytical Development and Computational Procedure," Aerospace Corp., Rept. TDR-169 (3230-11) TN-2, Los Angeles, CA, Aug. 1962.

[6] Dugundji, J., "On the Calculation of Natural Modes of Free–Free Structures," *Journal of the Aerospace Sciences*, Vol. 28, No. 2, Feb 1961, pp. 164–166.

[7] Stanzione, D., "LSF/PBS Scripting Nuts and Bolts," *Cluster Monkey* [online journal], June 2006, http://www.clustermonkey.net//content/view/132/32/ [retrieved 6 June 2011].

[8] "Message Passing Interface, MPI," *A Message-Passing Interface Standard*, Univ. of Tennessee, Memphis, TN, May 1994.

[9] Guruswamy, G. P., "HiMAP: A Portable Super Modular Multilevel Parallel Multidisciplinary Process for Large Scale Analysis," *Advances in Engineering Software*, Vol. 31, Nos. 8–9, 2000, pp. 617–620. doi:10.1016/S0965-9978(00)00030-2

[10] Jespersen, D. C., Pulliam, T. H., and Buning, P. G., "Recent Enhancements to OVERFLOW," AIAA Paper 1997-0644, Jan. 1997.

[11] Hurty, W. C, and Rubinstein, M. F., "Bending Vibrations of a Uniform Slender Cantilever Beam," *Dynamics of Structures*, Prentice–Hall of India Ltd., New Delhi, 1964.

[12] Springer, A. M., and Pokora, D. C., "Aerodynamic Characteristics of the National Launch System (NLS) 11/2 Stage Launch Vehicle," NASA TP 3488, May 1994.

R. Cummings
Associate Editor