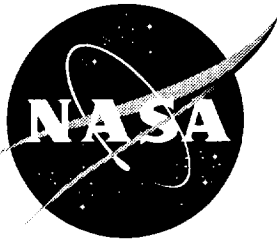


NASA Technical Memorandum 112861



CFL3D: Its History and Some Recent Applications

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May 1997

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Presented at the "Godunov's Method for Gas Dynamics: Current Applications and Future Developments" Symposium, University of Michigan, May 1-2, 1997

History

The CFL3D (Computational Fluids Laboratory - 3D) computer code is a result of the close working relationship between computational fluid dynamicists at the NASA Langley Research Center and visiting scientists to the Institute for Computer Applications in Science and Engineering (ICASE) at the same location. In the early 1980's, computational fluid dynamics (CFD) was still an emerging field. By bringing together many of the leading scientists in numerical methods to work with each other, NASA and ICASE enabled the crystallization of many new ideas and methods for CFD.

The initial spark for the CFL3D code was the application of the flux-vector splitting (FVS) monotone upstream-centered scheme for conservation laws (MUSCL) idea of van Leer^{1,2} to an implicit finite-volume code for the solution of the three-dimensional (3d) compressible Euler equations. Many of van Leer's ideas were inspired by the pioneering work of Godunov,³ who considered the fluid to be divided into slabs and determined the interaction of these slabs at their interface. The team of Thomas, Anderson, Walters, and van Leer^{4,5} explored several implicit solution strategies using FVS, particularly with regard to application on recently-developed vector-processor computers. Also, FVS was compared with other flux-splitting techniques, and various types of flux limiters were explored for transonic airfoil applications. The code was quickly extended to solve the 3d thin-layer Navier-Stokes equations.^{6,7,8} Initial applications were made on leading-edge vortex flows, for which the viscous terms are necessary to capture the secondary flow features. At about this same time, research was initiated into applying multigrid methods to the implicit algorithm.⁹ The three-factor approximate factorization (AF) strategy was settled upon as the best choice for a wide range of applications, due to its better smoothing rate and more complete vectorization than other strategies. It was determined that the conditional stability of three-factor AF is not a penalty since large time steps are generally not necessary for a multigrid smoothing algorithm. The multigrid algorithm with FVS and a fixed W-cycle cycling strategy was employed to solve the thin-layer Navier-Stokes equations over a delta wing in Thomas et al.¹⁰

In the mid-1980's, the flux-difference splitting (FDS) approximate Riemann solver of Roe,¹¹ also a derivative of Godunov's³ work, was recognized as an important advance for upwind CFD methods. In van Leer et al,¹² the importance of including (in the numerical flux formula for the convective terms) information about all different waves by which neighboring cells interact was

discussed in relation to the Navier-Stokes equations. Flux functions based on the full Riemann solution, such as FDS, accurately represent both grid-aligned shocks and boundary layers. Other methods, including FVS (which ignores entropy and shear waves), are inferior in either shock and/or boundary layer rendition on all but the finest grids. Therefore, FDS was incorporated into the CFL3D code, and most subsequent Navier-Stokes applications employed it. For the left-hand side implicit operator, the spatial factors for FDS were approximated with a diagonal inversion plus a spectral radius scaling for the viscous terms, significantly increasing the speed of the code.¹³ Vatsa et al¹³ also drew a link between the natural dissipation inherent in FDS and the artificial dissipation employed in central-difference methods.

Although the laminar Navier-Stokes equations were solved for many vortex-dominated and low Reynolds number flows,^{7,8,10,14} including hypersonic flows,¹⁵ it was realized that the Reynolds-averaged Navier-Stokes equations (with the inclusion of a turbulence model) are necessary to adequately model the physics of most high Reynolds number aerodynamic flows of interest. The Baldwin-Lomax algebraic eddy viscosity turbulence model was the first incorporated into CFL3D,^{13,16,17} with other more advanced one- and two-equation linear and nonlinear field-equation models to follow later.^{18,19}

In the mid 1980's, research with CFL3D was also initiated toward solving the Euler and Navier-Stokes equations time-accurately, both for stationary bodies with inherently unsteady flow^{20,21,22} as well as for unsteady flow over bodies in motion.^{23,24,25} The time-advancement algorithm in the code has continued to evolve since that time, incorporating subiterations to reduce linearization and factorization errors, as well as employing a pseudo-time-stepping algorithm with multigrid to allow the use of more physically-relevant time steps for time-accurate turbulent flow computations.²⁶

Beginning in the late 1980's, the CFL3D code's capabilities to solve flows over complex configurations were developed through the use of various grid-zone-connection strategies. Beside simple one-to-one connectivity, Thomas et al¹⁶ introduced the patched-grid connection capability into the code with further enhancements and generalization made later,²⁷ including application to sliding patched-zone interfaces.²⁸ Overset grid capability was also included,²⁹ as was an embedded grid capability in order to employ finer mesh density in desired regions of interest such as a delta wing vortex core.³⁰

CFL3D is currently used by well over one hundred researchers in twenty-two different companies in industry, thirteen universities, as well as at NASA and in the military. It owes much of its success to its strong foundation in the upwind methods that arose from Godunov's original ideas.

Recent Applications

CFL3D has been applied to flow regimes ranging from low-subsonic to hypersonic. Configurations have ranged from flat plates to complete aircraft with control surfaces. Below we present a few of the recent applications carried out by NASA-Langley researchers.

Partial-Span Flap

Figure 1 shows the results of an analysis of a rectangular wing with a 58% span flap.³¹ Shown

in the figure is a representative view of the grid, which makes use of the generalized grid-patching capability of the code. Also shown are computed total pressure contours on the surface and streamline traces following the roll-up of the flap-edge and wing-tip vortices. Comparison to wind-tunnel pressure data indicate that flow over both the flap and the wing are accurately computed.

F/A-18 Forebody Control Strake

At high angles of attack, traditional yaw-control devices such as the rudder lose effectiveness due to immersion in the low-speed wake of the wing. The forebody-strake concept was developed in order to provide control effectiveness at very large angles of attack. Figure 2 shows two results from CFL3D computations that were performed to help validate the forebody-strake concept. In the top part of the figure, the complete configuration is modeled in order to simulate flight conditions. For these computations, CFL3D is coupled to an unstructured flow solver, with CFL3D being used over the forward part of the aircraft, and the unstructured solver being used over the aft part of the aircraft.³² The use of this hybrid approach renders the grid generation problem much simpler. The bottom part of the figure shows the results of a computation performed only on the forward portion, without coupling to the unstructured solver, simulating a wind-tunnel test. The object of this study was to investigate the control reversal (change of sign of yawing moment) that occurs for small strake deflections. Computations were performed for 0, 10, and 90 degrees of strake deflection. The predicted yawing moments are in good agreement with the wind-tunnel data.

Advanced Ducted Propeller

Figures 3 and 4 show an application of the code to a turbomachinery flow. The configuration is a wind-tunnel model of an advanced ducted propeller,³³ with 16 fan blades and 20 exit guide vanes. The rotor speed is 16,900 RPM and the Mach number is 0.2. The computations are performed time-accurately, using dynamic grids that move relative to one another across a planar interface midway between the fan blades and the exit guide vanes. Passage-averaged aerodynamic results agree well with data and results from another code.³⁴ The grid and time step used in this simulation are chosen to capture a particular forward-propagating duct acoustic mode that results from the highly nonlinear rotor wake-stator blade interaction. The CFL3D computation successfully generates this mode and propagates it forward of the fan face in the duct without attenuation. The inlet pressures from the computation are used as input to a linearized far-field noise-prediction code.

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Figures

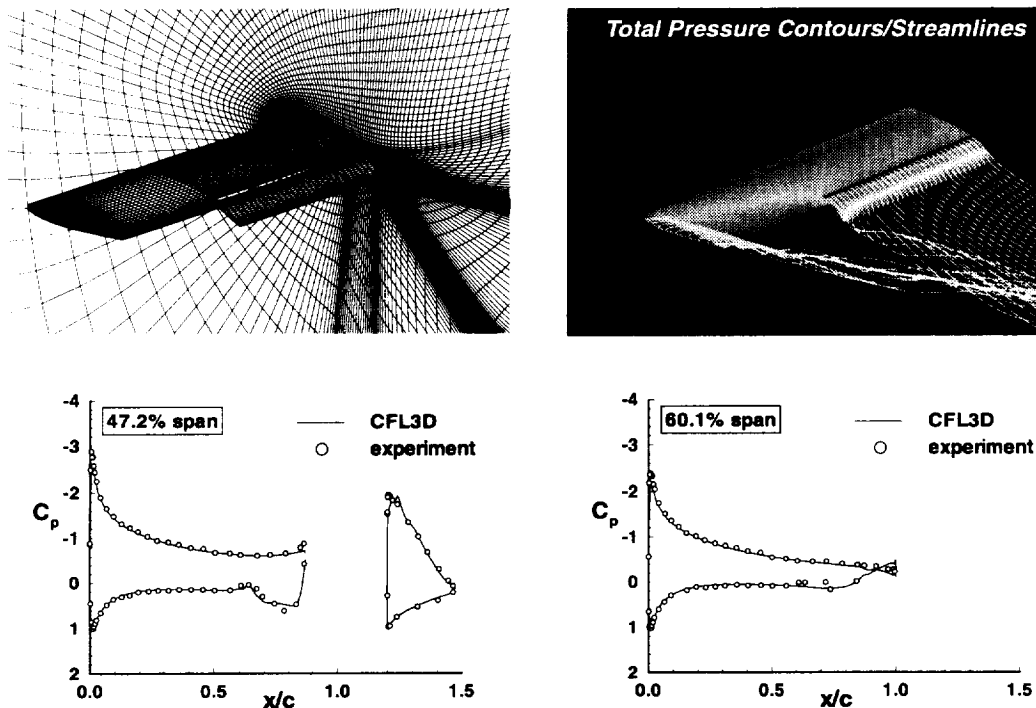


Figure 1: Flow past a wing with a partial-span flap. The Reynolds number is 3.3 million, the Mach number is 0.15, the angle of attack is 4 degrees, and the flap deflection is 30 degrees. Shown are the grid, computed total pressure contours and streamlines, as well as comparison of computed surface pressures with wind-tunnel data.

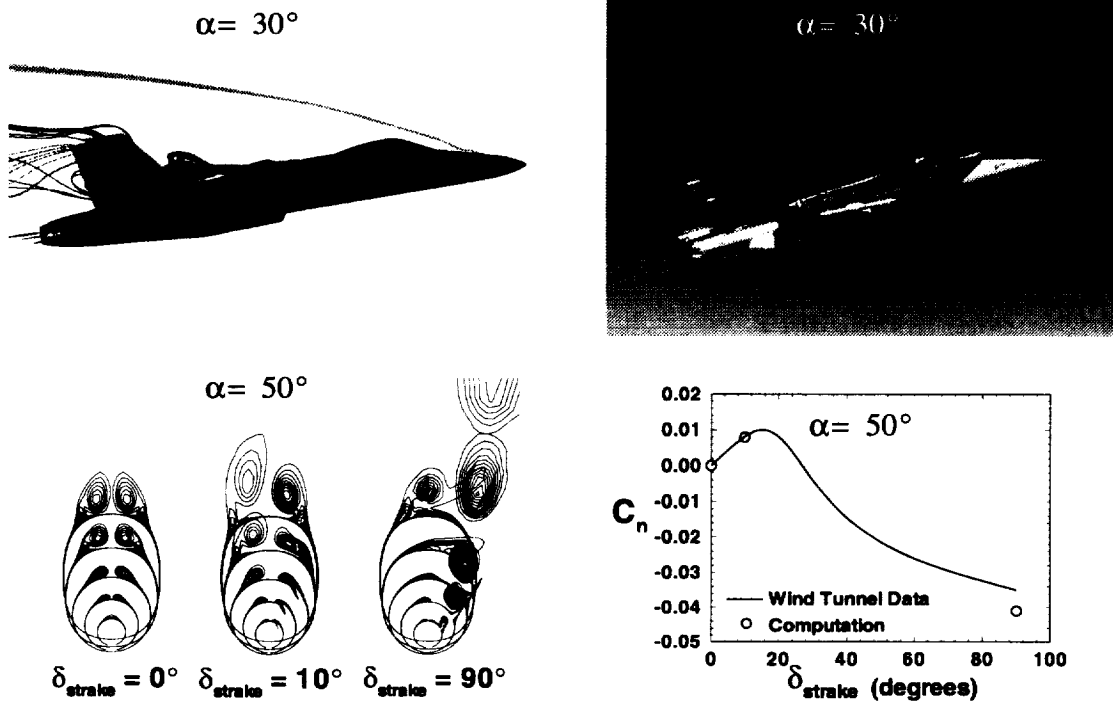


Figure 2: High-angle-of-attack control strake for the F/A-18. The top pair of images shows the comparison of the computed strake vortex and in-flight flow visualization. The bottom pair of images shows a computation illustrating control reversal at low strake deflections, with comparison to yawing-moment data from wind-tunnel tests.

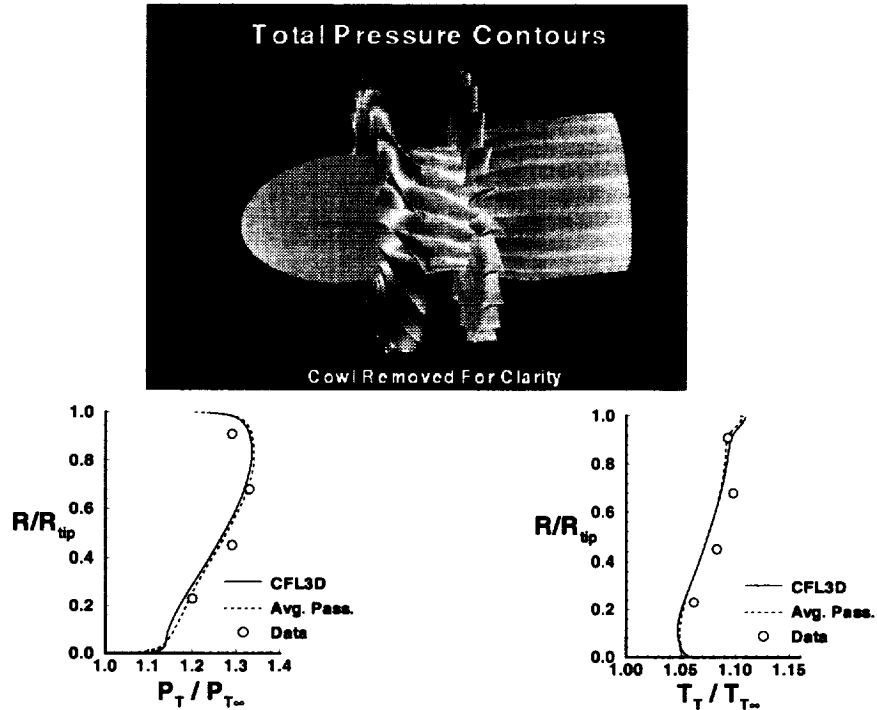


Figure 3: Flow through an ADP model with 16 rotor blades and 20 exit guide vanes. The rotor speed is 16,900 rpm, and the Mach number is 0.2. Shown are total pressure contours, as well as comparison of the passage-averaged CFL3D computation with experimental data and a computation using the average passage equations.

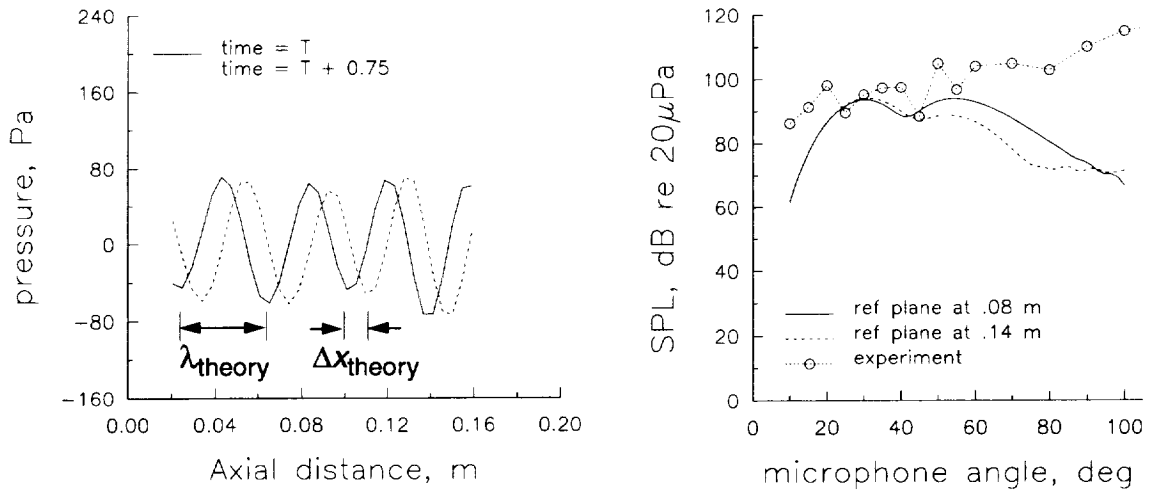


Figure 4: Flow through an ADP model with 16 rotor blades and 20 exit guide vanes. The left figure shows the real part of the magnitude of the (-4,1) duct acoustic mode at two instants in time, in comparison with infinite duct theory. The right figure shows the far field sound pressure levels due to all the radial orders of the (-4,n) modes as a function of microphone angle, using two different reference planes inside the duct. The left-hand lobe, which is insensitive to reference plane position, is due primarily to the (-4,1) mode. High experimental noise levels at the largest microphone angles are due to contamination from aft-end noise.

REPORT DOCUMENTATION PAGE

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Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 1997	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE CFL3D: Its History and Some Recent Applications			5. FUNDING NUMBERS 522-31-21-01	
6. AUTHOR(S) Rumsey, C. L., Biedron, R. T., and Thomas, J. L.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Langley Research Center Hampton, VA 23681-0001			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING / MONITORING AGENCY REPORT NUMBER NASA TM-112861	
11. SUPPLEMENTARY NOTES Prepared for the "Godunov's Method for Gas Dynamics: Current Applications and Future Developments" Symposium, University of Michigan, Ann Arbor, MI, May 1-2, 1997. Responsible person Christopher L. Rumsey (757) 864-2165				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 02			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The history of the Computational Fluids Laboratory -3D (CFL3D) Navier -Stokes computer code is discussed and a comprehensive reference list is given. Three recent advanced applications are presented (1) Wing with partial-span flap, (2) F/A-18 with forebody control strake, and (3.) Noise predictions for an advanced ducted propeller turbomachinery flow.				
14. SUBJECT TERMS Navier-Stokes, aerodynamics, computational fluid dynamics			15. NUMBER OF PAGES 8	
			16. PRICE CODE A02	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	