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Summary of Research Report
For
NASA Grant NAG-1-2093

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Summary

This report describes a project to predict ducted fan noise using massively parallel computers. The investigators are part of a larger team of researchers, most of whom are working at NASA Langley Research Center. The portion of the project described below not only stands alone as an individual research project, it also compliments the NASA Langley work. The write-up included in this report is relatively brief, since the details are described in technical papers.

Problem

The accurate prediction of far field noise radiation from advanced high by-pass ratio ducted fans is an extremely difficult problem. Nonlinear aeroacoustic effects associated with transonic flow, liners (acoustically treated walls), and sound propagation through (possibly turbulent) boundary layers and temperature gradients form a highly complicated and time-dependent physical phenomenon. In addition, the engine ducts are not usually axisymmetric and can be at an angle of attack, requiring a three-dimensional method. Solving this problem therefore requires highly accurate algorithms in both space and time, and the enormous computational requirements are obvious.

Objective

The objective was to develop an efficient CFD time-marching code to solve this highly nonlinear and unsteady problem using massively parallel computers. During this grant we have begun the development of two computer programs. One of the codes is called the Nonlinear Disturbance Equation (NLDE) code. The other computer program is called the PENN (PErturbed Nonconservative, Nonlinear) code. While previous versions of our codes have used structured curvilinear grids, these new parallel codes use Cartesian grids.

Approach

The codes solve the 3-D Euler equations to obtain the entire unsteady flow field that is excited by the acoustic (unsteady) source at the fan. The source field (input at the fan stage) is a time-dependent boundary condition or a time-dependent source, and is obtained from existing codes/theories or from a simple model.

It is not possible to use a computational domain that extends out to the point where the noise level is of interest. This is due to both computational limitations and accuracy problems (the difficulty in propagating waves numerically over large distances). Instead, the computational domain is kept sufficiently small and the far-field noise radiation is obtained using the FW-H method. A FW-H surface is constructed using portions of the computational grid. The time history of the acoustic pressure is obtained on this surface using the massively parallel CFD code. Then, the FW-H formula for permeable surfaces is used to compute the far-field acoustic time history. The acoustic time history can then be transformed into the frequency domain using FFT techniques, and thus the OASPL (overall sound pressure level) can be computed. This is much less restrictive than trying to compute all the way to the far-field.

We have developed massively parallel finite volume/Runge-Kutta time stepping codes for the Navier-Stokes equations on structured and unstructured grids. For the present work, we have modified the structured-grid code to achieve higher-order accuracy in space and time. This code was originally second order accurate. With a second order accurate scheme, the minimum number of grid points, from numerical experiments, is approximately 40 per wave length, and for a frequency of 10 KHz, the maximum cell size must then be approximately 0.8 mm, which is extremely small. An alternative is to use fourth order compact differencing (Huh et al., 1992). This differencing uses only three grid points, and the required minimum number of grid points per wave length is about 10. This means that in three dimensions the fourth order accurate scheme will require 64 times fewer grid points (and 64 times fewer computations). Compact differencing creates tridiagonal systems of equations, however, which require an inversion at every time step, which are not efficient on massively parallel computers. More traditional fourth-order accurate schemes were used for this project. On parallel computers, these higher-order accurate schemes require an increase in inter-processor communication, however. They will only be more effective than second-order accurate schemes if the increase in communication costs are off-set by the reduction in the number of grid points required.

The numerical flow simulations are performed within a finite domain, and therefore appropriate boundary conditions are required at the boundaries of this domain. For time-dependent problems these conditions are extremely important, and accurate computations depend on the correct definitions of these conditions. These conditions must be such that they allow information to be propagated out of the domain, but should annihilate the information coming from outside of the domain, since this information is not part of the solution. Such boundary conditions were given by Bayliss and Turkel, Tamm and Webb, Thompson, and Giles for compressible flows. The efficient implementation of these conditions is a difficult task using a massively parallel finite volume technique. We have to be careful not to have too many processors sitting idle for extended periods of time.

Progress

Euler / Navier-Stokes Algorithm

The Euler / Navier-Stokes algorithm is a high-accuracy finite-volume scheme with Runge Kutta time marching. We use structured grids, but can accept a number of different topologies. It is described in detail in the technical papers. The nonreflecting boundary conditions (B1) of Bayliss and Turkel (1982) have been extended to 3-D, and the conditions have been formulated for a finite volume method.

Test Cases

Gaussian Pulse

In order to test the code and algorithm, we have run several aeroacoustic benchmark problems. The first one is a three-dimensional Gaussian pulse:

$$\rho'(x,y,z,0) = 0.01\ \rho_o\ \exp\left[-\ln(2)\ \frac{x^2+y^2+z^2}{9}\right]$$

$$p'(x,y,z,0) = c_o^2\ \rho'$$

This is in a uniform Mach=0.5 stream in the x-direction. This is a good test of the algorithm and the far-field boundary conditions. The exact solution is contained in the aeroacoustic benchmark report. The number of grid points used was 60x60x60. The grid size was uniform with each element being one unit. Figure 1 shows color views of the flow field after 1125 timesteps, virtually no reflections are present. Also, there is virtually no difference between the second order spatial accuracy and the 4th order spatial accuracy for this problem. This case took 1.38 hours on a 400 MHz Pentium II computer with 512 MB's of memory (one node of our Beowulf cluster). This equates to only 20 microseconds per grid point per timestep, using a *single* Linux-based PC.

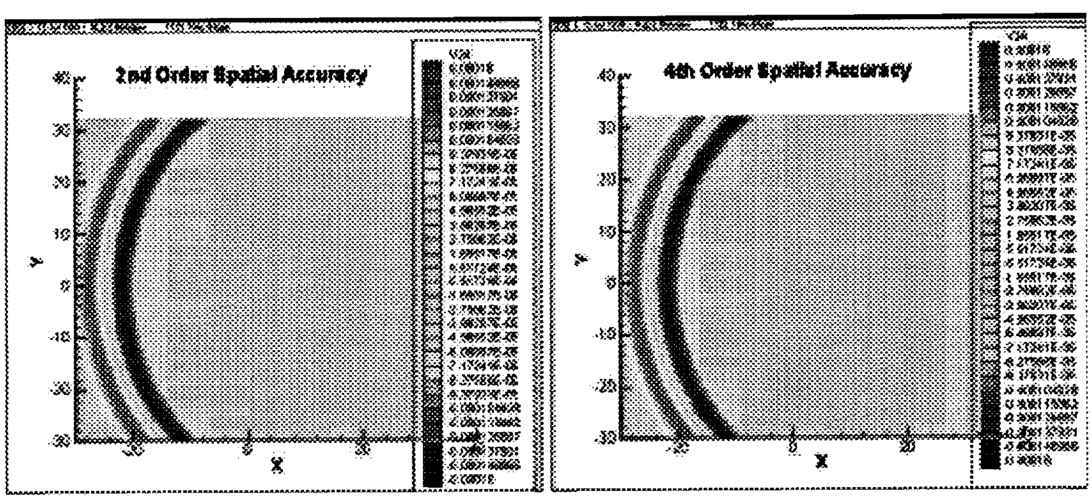


Figure 1. Perturbation pressure (Pascals) in a 3-D Gaussian Pulse in Mach=0.5 flow after 1125 time steps (CFL=0.2)

Figure 2 shows the pressure along the y=0 axis after 1125 time steps for the two different spatial accuracies. These agree very well with the exact solution, the previous NLDE solution, and with each other.

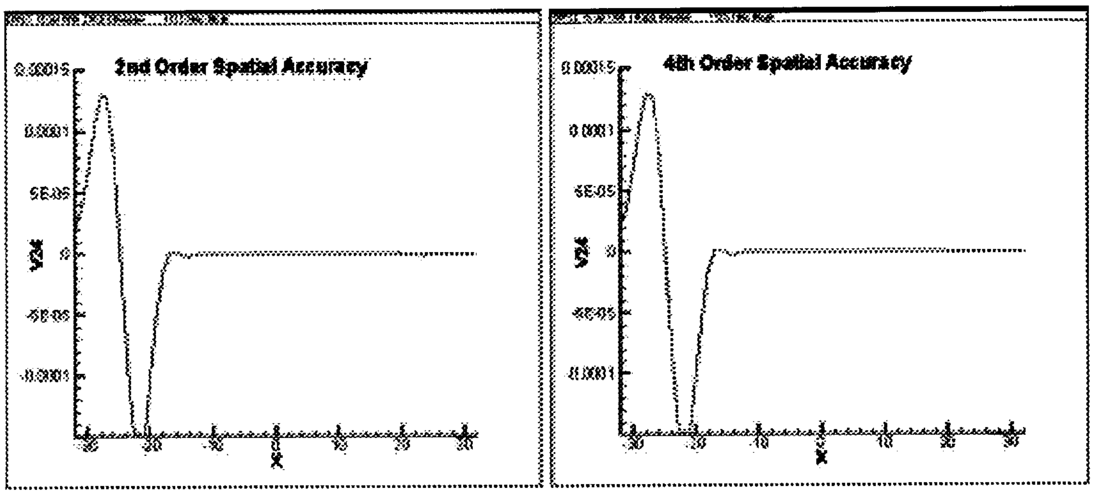


Figure 2. Perturbation pressure (Pascals) from 3-D Gaussian Pulse in Mach=0.5 flow after 1125 time steps (CFL=0.2)

Duct Radiation

One of the primary applications of the algorithm and code described herein, is to simulate aircraft engine noise, both fore and aft radiation. Shown in Figure 3 are results from a simulation for a circular duct of diameter 1.0 and length 1.0. The noise is due to a point force source inside the duct, simulating a dipole. The force is spread over a few grid cells using a Gaussian distribution. The radiated (perturbation) pressure, in Pascals, is shown in Figure 3. There is a mean flow of Mach = 0.3 also, which can be seen by in the figure as a Doppler effect. This simulation used a grid of 101x101x101 grid points and was run on a PC (using Linux and the Portland F-90 compiler) for 10,000 timesteps. It is amazing that we can now run one million grid points on a single PC. This could be run on a parallel machine or workstation cluster and would scale almost linearly.

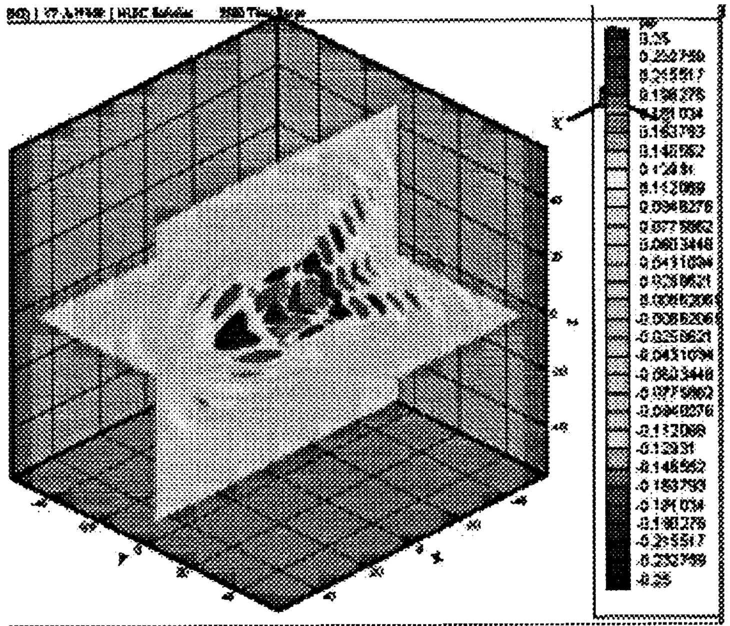


Figure 3. Perturbation pressure for a duct of L/D = 1 with a point source (force) on the axis.

Figure 4 shows the results of the PENN code compared to a similar, but not exactly the same, simulation from the TDBIEM3D code. The TDBIEM3D code is a frequency domain code, which was run for a single mode here, while the PENN code includes all the modes. Also, the PENN code's source is distributed over a few grid cells, while the TDBIEM3D code uses a point dipole source. While these are only qualitative comparisons for now, they are very encouraging since they seem to agree so well. While the TDBIEM3D code is incredibly useful for quickly evaluating different duct conditions, the PENN code has the capability of including effects such as non-uniform flow, nonlinear effects, 3-D effects (e.g. non-axisymmetric ducts), and eventually viscous effects.

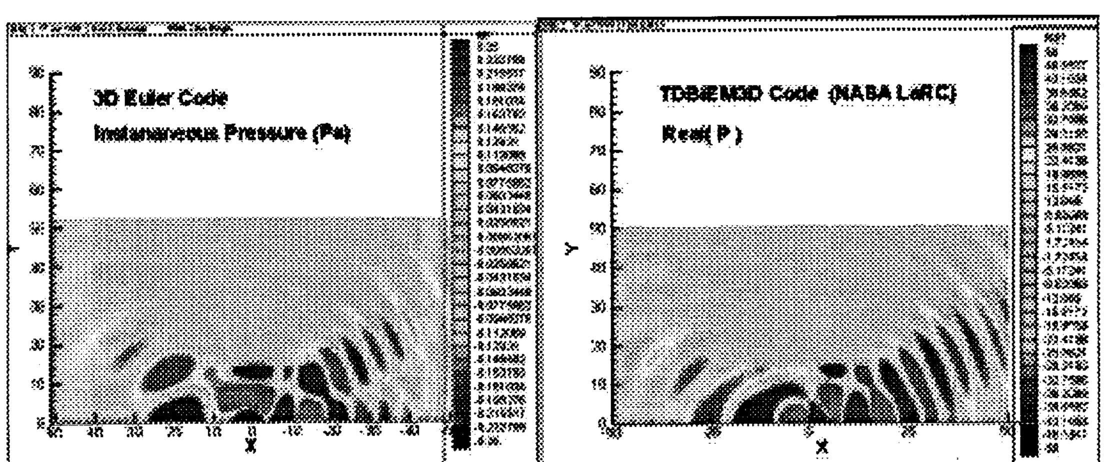
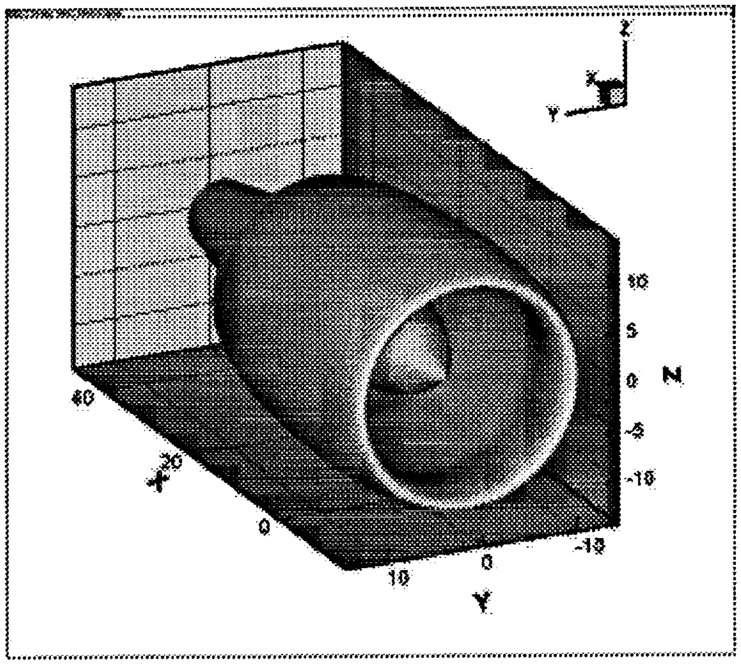


Figure 4. Qualitative comparison between PENN time domain code (perturbation pressure in Pascals) and TDBIEM3D frequency domain code (real part of pressure).

Fore and Aft Radiation from a Generic Duct

The final AIAA Aeroacoustics paper will include fore and aft radiation results for the inlet shown below:



For this case the goal is to use the mean flow solution from CFL3D (from C. Rumsey and R. Biedron), and use the PENN code to compute the radiated noise. The sources are represented by either spinning mass or momentum sources.

Code Performance

Figure 5 shows how the PENN Code scales with number of processors, for a fixed problem size. In this case we used 1 million grid points and 100 time steps. The code was run on our Beowulf cluster. The figure shows that the code scales quite well even on a cluster of PC's.

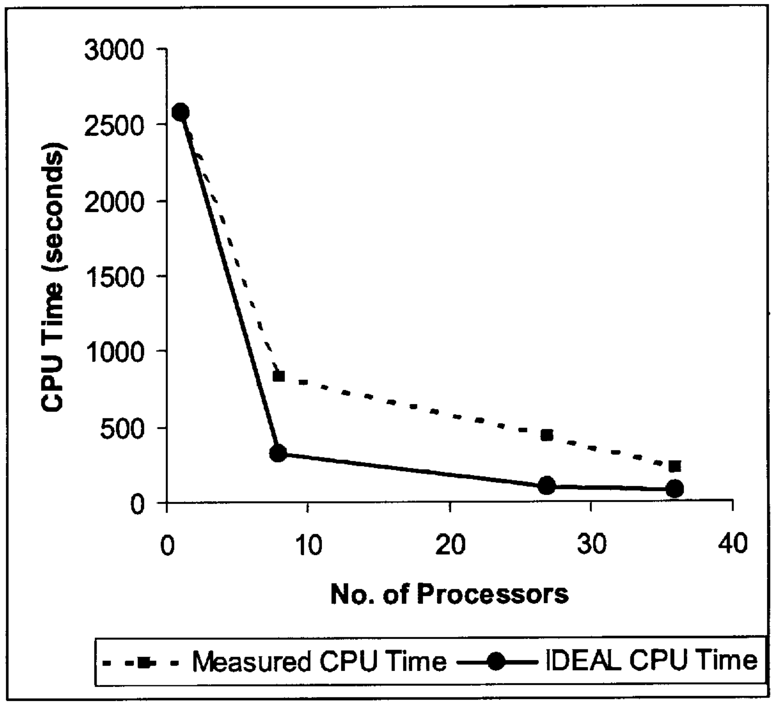


Figure 5. CPU time of PENN code with 1 million grid points on a cluster of PC's.

We also ran the code and scaled the number of processors with the number of grid points. The results of this study are shown in Figure 6. On one processor a grid of 60x60x60 was used, and on the 36 processors a grid of 180x120x360 was solved. There is a jump in CPU time as one increases the processors beyond 1 processor, but after that all the cases are very similar in speed, as you would expect.

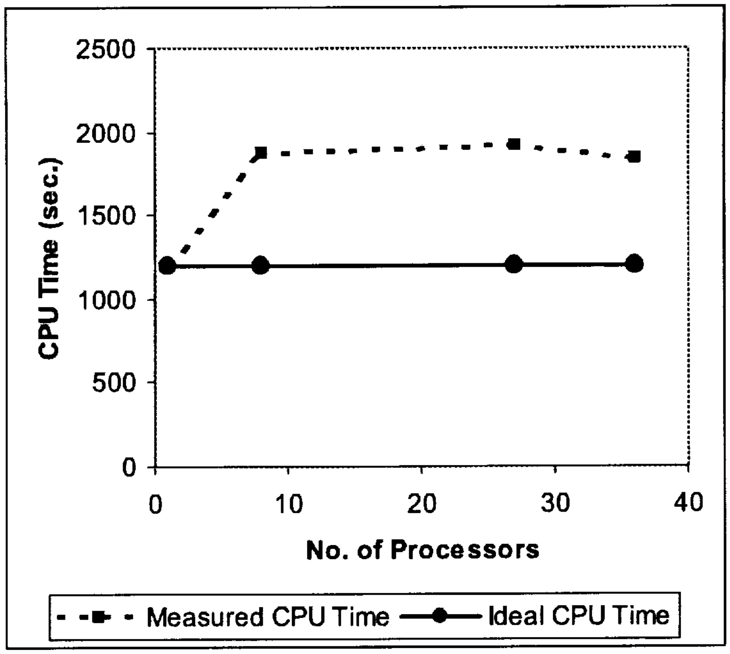


Figure 6. CPU time of PENN Code with number of processors scaled from 1 to 36 (and grid points scaled from 0.2 to 7.8 million) on a cluster of PC's

Conclusions

This grant has taken a wide variety of numerical algorithms and implemented them on parallel computers to solve noise radiation problems for ducted fans and other test cases. The impact of the grant has been quite extensive, with approaches such as ours being widely accepted now. The following section lists the numerous publications that resulted from this grant.

Publications

Journal Papers

Y. Ozyoruk, L.N. Long, and M.G. Jones, "Time-Domain Numerical Simulation of a Flow-Impedance Tube," **Journal of Computational Physics**, Vol. 146, 1998, pp. 29-57.

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Y. Ozyoruk and L. N. Long, "A New Efficient Algorithm for Computational Aeroacoustics on Massively Parallel Computers, **Journal of Computational Physics**, Vol. 125, No. 1, pp. 135-149, April, 1996.

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J. Nucciaroni, Y. Ozyoruk, and L. N. Long, "Recent Experiences with High Performance Fortran," Supercomputing '97, Nov., 1997.

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P. J. Morris, L. N. Long, A. Bangalore, T. S. Chyczewski, D. P. Lockard, and Y. Ozyoruk, "Experiences in the Practical Application of Computational Aeroacoustics," in Proceedings of the ASME Fluids Engineering Division Summer Meeting, FED-Vol. 238, San Diego, CA, July 1996, pp. 465--470.

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Y. Ozyoruk and L. N. Long, "Time-Domain Impedance Boundary Conditions for Computational Aeroacoustics," AIAA- 96-1663, 17th AIAA Aeroacoustics Conference, State College, PA, May, 1996.

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L. N. Long, "Recent Developments in Computational Aeroacoustics," Invited Lecture. 130th Annual Meeting, St. Louis, The Journal of the Acoustical Society of America, Vol. 98, No. 5, Pt. 2, Nov., 1995.

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Morris, P. J., L. N. Long, C. Chung, and T. Chyczewski, "Computational Aeroacoustic Algorithms: Nonuniform Grids" AIAA 25th Fluid Dynamics Conf., Colorado Springs, CO, June, 1994.

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Y. Ozyoruk and L.N. Long, "A Hybrid Scheme for Noise Radiation from Ducted Fans," in Proceedings of Noise-Con '93, Williamsburg, VA, May, 1993.

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