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TRENDS IN COMPUTATIONAL CAPABILITIES FOR FLUID DYNAMICS

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SUMMARY

Milestones in the development of computational aerodynamics are reviewed together with past, present, and future computer performance (speed and memory) trends. Factors influencing computer performance requirements for both steady and unsteady flow simulations are identified. Estimates of computer speed and memory that are required to calculate both inviscid and viscous, steady and unsteady flows about airfoils, wings, and simple wing-body configurations are presented and compared to computer performance which is either currently available, or is expected to be available before the end of this decade Finally, estimates of the amounts of computer time that are required to determine flutter boundaries of airfoils and wings at transonic Mach numbers are presented and discussed

INTRODUCTION

Computers are playing an increasingly important role in aerodynamics research and development. Reasons for this trend are manifold, although they generally relate to the increasing availability of very powerful supercomputers, the improving methodology makes it easier to solve governing equations numerically, and a growing number of examples exist where computers have enabled substantial design improvements to be made rapidly and cost effectively The development and use of computational aerodynamics for rigid bodies and steady flows has, however, outstripped that for elastic bodies and unsteady flows One obvious reason for this trend is that the treatment of unsteady flows and aeroelastic applications requires greater amounts of computer time Another reason is that unsteady flows have received considerably less attention by the developers of user-oriented applications codes Nevertheless, many examples of the use of computational aerodynamics for the treatment of unsteady phenomena such as buffet, flutter, aileron buzz, dynamic store separation, and rotating components are appearing in the literature. The pace of this activity is expected to accelerate rapidly over the next decade

Milestones in the development of computational aerodynamics, and the motivations for investing substantial resources in the development of this relatively new discipline, will be briefly reviewed in this paper. Next, computer performance and cost trends for the past 25 years will be discussed, and forecasts for the remainder of this decade will be presented The forecasts are based on some knowledge of developments now under way both in the supercomputer industry and in NASA's Numerical Aerodynamic Simulation (NAS) program Factors influencing future computer requirements for both steady and unsteady flow simulations will be identified and will be related to the complexity of geometry and flow physics, the evolution of numerical methods, and the amount of time required for problem solution. Finally, estimates of computer power necessary to solve both steady and unsteady flow problems will be presented and compared to that which is either currently available or is expected to be available before 1990

MOTIVATIONS, GOVERNING EQUATIONS, AND MILESTONES

Ever since the days of the Wright Brothers, both theory and experiment have been used in a complementary fashion to design aircraft (Ref 1) Prior to the development of digital computers, however, the role played by theory was somewhat limited because of the complexity of the governing equations for all but the simplest flows and geometries In fact, not until about 1970 did computers and numerical methods mature to the point that solutions could be obtained for sets of equations governing anything more complex than linearized inviscid flows Beginning at that time, the relative roles of theory and experiment started changing, and they continue to change in favor of the theory at an ever-increasing rate. Numerical simulation now provides the opportunity to investigate far more configurations and flight conditions than normally would be possible in wind-tunnel tests because of the practical considerations of time and cost In addition, detailed flow diagnostic information that is extremely costly to obtain through experiment, if it is even accessible, now can be obtained through the use of computers. On the other hand, experiments still can provide information that is currently difficult to obtain by computer such as the total drag of complex configurations. The combined use of numerical and experimental methods has proven to be the cost-effective way to design aircraft that have greater maneuver performance and improved fuel economy

It is convenient to discuss the stages of development of computational aerodynamics in terms of levels of approximation to the Navier-Stokes equations which govern the behavior of fluids for most situations in aerospace applications (Ref 2) These levels are defined in Table 1 and are related to the periods when both research efforts and practical applications were initiated Both research efforts and applications involving the linearized inviscid form of the equations (level I) are relatively mature, even for unsteady flows and studies of aeroelastic bodies. For the nonlinear inviscid equations (level II), the technology for treating unsteady and steady flows is very advanced, much remains to be done for the treatment of those involving aeroelastic applications Although research on the Reynolds-averaged Navier-Stokes equations (level III) has been vigorous over a decade, because of the extensive investments of computer time required for all but the simplest of geometries, applications for steady flows have been limited and aeroelastic applications are almost nonexistent Large-eddy simulations (level IV) and studies that involve the full Navier-Stokes equations are still in the early stages of research Attention in this paper will be focused on the nonlinear inviscid and Reynolds-averaged forms of the Navier-Stokes equations when computational methods are used to treat unsteady flows and aeroelastic bodies

Milestones in the development of the technology for treating the nonlinear inviscid equations are shown in Fig 1 The first major advance was made (approximately 1970) (Ref 3) when results for the steady flow about an airfoil were published Within approximately 3 years, solutions for wing-body combinations treated with the steady-flow small-disturbance form of the equations were being published. Results of the first treatment of unsteady flows about airfoils appeared in the literature in 1975 (Ref 4) and aeroelastic applications were initiated around 1977. The first flutter analysis for a swept wing was published less than 4 years ago (Ref. 5) Aeroelastic analyses using this level of approximation are still limited by the performance of currently available computers.

Milestones that involve the use of Reynolds-averaged Navier-Stokes equations are shown in Fig. 2. Dates for the first significant accomplishments in steady-flow, unsteady-flow, and aeroelastic applications are remarkably similar to those that involve the nonlinear equations. However, the use of the Reynolds-averaged Navier-Stokes equations (level III approximation) has been restricted almost exclusively to two-dimensional flows because of computer limitations.

COMPUTATIONAL PERFORMANCE AND COST TRENDS

The development of computational aerodynamics is intimately connected to the development of both computers and numerical methods. Therefore, it is appropriate to review past advances and to quantify future prospects. The information that demonstrates the growth of computer speed and cost (Ref. 6) is shown for existing and planned machines in Fig. 3. It is noteworthy that computer speed has increased approximately 4 orders of magnitude over a period of 30 years whereas monthly rental cost has only risen by approximately a factor of 10. The growth of computer memory (Ref. 6), which is shown in Fig. 4, has been only about half as large as that for computer speed, the rate of growth is projected to increase during the last half of this decade. It is almost certain that memory sizes as large as 256 million 64-bit words will be available before 1990.

A major effort called the NAS program has been undertaken by NASA to provide the U.S. aerospace community with the most advanced computational capability possible (Ref 7) The thrust of this effort is to assemble a computational system composed of the most advanced components and to continue the upgrading of this system indefinitely. Initial goals are to provide a sustained computing speed of 250 million floating point operations per second (MFLOPS) and a memory of 64-million 64-bit words by 1986 and to expand the computing rate and memory to 1000 MFLOPS and 256 million words, respectively, by 1988. The system is being planned to support at least 100 local and remote users simultaneously on a time-sharing interactive basis The presence of this system and the promises of timely upgrades should serve as a stimulus to both the manufacturers of supercomputers and to the developers of computational technologies in the fields of science and engineering.

Improvements in computer performance have been closely paralleled by improvements in numerical methods over the past 20 years. This is illustrated by the data presented in Fig 5 which show how the cost of performing a computation has been driven down by the advances that are being made in computers and in numerical methods Results of these improvements compound to a result in a 10^5 reduction, over a 15-year period, in the cost of performing a computation. These numerical simulation cost trends are expected to continue well into the future.

Over the same period of time that computations have become less expensive, the cost of performing experiments has been increasing because of the rising costs of models, labor, and energy. In addition, aircraft are becoming more refined so that the number of models and test hours required to develop a new system continue to increase. The move to accelerate the development of computational aerodynamics has been influenced by cost trends which favorably compare with those for experiments and by the fact that computational results are becoming more realistic.

FACTORS INFLUENCING COMPUTER PERFORMANCE REQUIREMENTS

Computer requirements for computational aerodynamics are driven largely by the factors identified in Table 2 One factor is the number of grid points that are required to resolve the flow about a configuration This factor is influenced by the complexity of the geometry that is being considered and by the complexity of the physics being simulated Obviously, more grid points are required to resolve the flow about a complete airplane than are about a simple airfoil Likewise, the use of higher levels of approximation to the full governing equations will require more grid points than those for the simpler forms of the equations that do not represent the physics to the same level of detail For example, between 4 and 5 decades of scale are of practical importance in turbulent flows Computations intended to resolve all of these scales require the use of correspondingly larger numbers of grid points than would be necessary if turbulence were computed with the use of techniques in which the effects of all of those scales are modeled with simple averaging

Estimates of the number of grid points required for treating airfoils, wings, and simple wing-body configurations for both inviscid and viscous flows are shown in Table 3 The inviscid-flow estimates assume the use of the full potential equations and the viscous-flow estimates are based on the use of the Reynolds-averaged Navier-Stokes equations These estimates are consistent with those made in Ref. 2 and with current experience. The number of grid points varies by approximately three orders of magnitude over the range of problem complexity considered These grid-point requirements are not likely to be reduced significantly over the coming years

Another factor that drives computer performance requirements is the efficiency of the available numerical method. A measure of this efficiency is the number of numerical operations required per grid point in order to obtain a converged solution. This factor is influenced by the complexity of the physics and geometry being treated as well as the form of the numerical solution algorithm Algorithms for simple two-dimensional steady flows without severe gradients due to shock waves and/or viscosity are more efficient than those for three-dimensional steady flows without severe gradients The development of algorithms is more of an art than a science so that optimization of numerical methods cannot be done in a rigorous manner.

Significant improvements in the efficiency of numerical methods have been achieved over the past 20 years as shown by the data presented in Fig. 6. These results are an extension of those presented in

Ref. 8 for developments prior to 1980. Steady inviscid flows now require about 10,000 operations per grid point to obtain a solution whereas the count for steady viscous flows is about 500,000. Solutions for both inviscid and viscous flows about aeroelastic surfaces require approximately 50 times more work than for steady flows about rigid surfaces. This increase in the amount of work required results from (1) having to calculate unsteady flows over several cycles of motion as opposed to having to calculate the equivalent of one cycle for steady flows, and from (2) the fact that unsteady flow calculations cannot employ non-time-accurate convergence acceleration techniques commonly used in steady-flow simulations Numerical methods for aeroelastic applications have not received as much attention as those for treating steady flows With appropriate levels of research attention, it should be possible to reduce the factor of 50 by at least an order of magnitude. This achievement would greatly stimulate the use of computational methods for the treatment of problems in aeroelasticity.

The final factor that determines computer performance requirements is the acceptable amount of computer time that can be invested to obtain a problem solution. This is influenced by the availability of computer time and the availability of necessary resources to acquire the time for use on the problem at hand. The amount of time that can be invested usually depends on the application and on the importance of the work It is not uncommon to invest many hours of computation to obtain a single solution in a research environment where that single solution can produce new fundamental understandings of fluid physics. However, in a design environment where it is necessary to conduct parametric studies, experience shows that solutions must be obtained in a matter of minutes or even seconds for the use of computers to be practical Of course, even in a design environment, it is sometimes possible to invest greater amounts of time if the necessary information is not obtainable in a more cost-effective manner.

COMPUTER REQUIREMENTS FOR APPLICATIONS INVOLVING STEADY FLOWS AND AEROELASTICITY

Estimates of the computer performance requirements for treating unsteady flows about aeroelastic bodies will be presented in this section and will be compared to the more well-known requirements for solving steady flows about rigid bodies These estimates are based on the grid point requirements displayed in Table 3 and on the algorithm efficiency information presented in Fig 6 Also, it has been assumed that when the number of dimensions involved are reduced from 3 to 2, the number of operations required per grid point are reduced by a factor of 2 for inviscid calculations, and by a factor of 3 for viscous calculations These assumptions are consistent with current experience with the full-potential and Reynolds-averaged Navier-Stokes equations

The times required to calculate flows about airfoils, wings, and simple wing-body configurations are presented as a function of computer speed in Figs 7, 8, and 9, respectively For computers that have a similar range of speed as the CRAY 1S does, solution times range from approximately 1 sec for steady inviscid flows about airfoils to approximately a month for unsteady viscous flows about simple aeroelastic wing-body configurations. Of course, each order of magnitude increase in computer speed reduces the required computing time by a factor of 10 Therefore, in just 4 years (1988) when sustained computing speeds of 1000 MFLOPS are expected to be reached with the NAS system, it should be possible to calculate the unsteady inviscid flow about an aeroelastic wing-body combination in approximately 1 min.

Combined speed and memory requirements for computing flows about airfoils and wings are displayed in Fig 10 and are compared with performance factors for various computers. These results are based on obtaining solutions in 15 min using the 1984 algorithms. Memory estimates are based on the use of 20 words of memory per grid point for calculations involving the full-potential equations, and 18 and 30 words of memory, respectively, for two-dimensional and three-dimensional calculations using the Reynolds-averaged Navier-Stokes equations

Routine applications of the inviscid flow and steady two-dimensional viscous flow technologies are shown to be possible with today's class VI computers such as the CRAY 1S Performance levels expected to be available with the NAS system in 1988 will extend the realm of routine calculations to include steady three-dimensional viscous flows and two-dimensional viscous flows about aeroelastic bodies About 50 times more computer speed will still be required, however, to obtain solutions for viscous flows about aeroelastic wings in 15 min using the 1984 algorithms It is entirely possible that algorithm performance for unsteady flows about aeroelastic bodies will be improved by a factor of 10 before 1990 and this would cause the required amount of computer speed to be reduced by a corresponding factor.

Finally, estimates of the times required to compute flutter boundaries of airfoils and wings are summarized in Table 4 These estimates are based on performing the aeroelastic analyses in an uncoupled fashion That is, the aerodynamic calculations are performed for a number of modal shapes and frequencies of a wing, say, without including structure response effects The mode shapes are, of course, obtained from a structural analysis of the wing Calculations for five Mach numbers and four frequencies for each mode are usually sufficient for defining the flutter boundary through the transonic Mach number range Thus, the number of cases that must be computed range from 40 for airfoils with two modes, to 160 for wings with as many as eight modes Once the flutter boundary is identified using the uncoupled procedure, then a much more limited number of cases can be analyzed with coupled aerodynamics and structures equations to investigate stability considerations Eventually, as methods for solving aeroelastic problems with coupled aerodynamics and structures equations are improved, the use of the uncoupled approach will be less attractive A more comprehensive discussion of the computational treatment of unsteady transonic flows is presented in Ref 9.

Wing flutter boundaries that now require between 37 and 74 hr of computation using inviscid-flow equations should be obtainable with 1 to 2 hr of computation on the NAS system in 1988 Even with 1988 NAS capability, however, the routine calculation of wing flutter boundaries with the Reynolds-averaged Navier-Stokes equations will not yet be practical unless algorithm efficiency is improved considerably

CONCLUDING REMARKS

Computational aerodynamics is a rapidly developing and increasingly important discipline. Both computer and algorithm performance continue to increase while computation cost continues to decrease. These trends, together with the fact that simulations are becoming more realistic, are making the computational approach an attractive complement to experimental investigations.

Advances in unsteady flow and aeroelastic applications are not as great as the advances being made in steady flow applications, however, because of differences in computer requirements and in the level of effort that is being expended. Unsteady flow simulations require approximately 50 times more computation than steady flows do, and this has influenced the amount of attention that is being placed on the numerical treatment of aeroelasticity.

Computers with sufficient speed and memory soon will be available to permit the routine calculation of wing flutter boundaries at transonic Mach numbers that use the nonlinear inviscid form of the governing equations with or without boundary layer corrections. When this time comes, attention to the numerical simulation of unsteady flows is expected to greatly increase, and the rate of advance in the use of computers for studies of aeroelasticity will accelerate accordingly.

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Table 1 Levels of approximation as they are related to the Navier-Stokes equations, and the time period required for initiation of major efforts for computational treatment of these equations.

APPROXIMATION LEVEL	CAPABILITY	INITIATION TIME PERIOD	
		RESEARCH	APPLICATIONS
I LINEARIZED INVISCID	SUBSONIC/SUPERSONIC • PRESSURE DISTRIBUTIONS • VORTEX AND WAVE DRAG	1950s	1960s
II NONLINEAR INVISCID	ABOVE PLUS • TRANSONIC • HYPERSONIC	1960s	1970s
III RE AVERAGED NAVIER STOKES MODEL TURBULENCE	ABOVE PLUS • TOTAL DRAG • SEPARATED FLOW • STALL/BUFFET	1970s	1980s
IV LARGE EDDY SIMULATION MODEL SUBGRID SCALE TURBULENCE	ABOVE PLUS • TURBULENCE STRUCTURE • AERODYNAMIC NOISE	1970s	1990s
EXACT FULL NAVIER STOKES EQUATIONS	ABOVE PLUS • LAMINAR/TURBULENT TRANSITION • DISSIPATION	INCREASING INTENSITY OF RESEARCH 1970s ⟶	

Table 2 Determining factors for computer performance requirements

FACTOR	INFLUENCED BY
NUMBER OF GRID POINTS	COMPLEXITY OF PHYSICS AND GEOMETRY
NUMERICAL OPERATIONS PER GRID POINT	NUMERICAL ALGORITHM, AND COMPLEXITY OF PHYSICS AND GEOMETRY
ACCEPTABLE SOLUTION TIME	AVAILABLE TIME AND BUDGET FOR SOLVING PROBLEM

Table 3 Estimates of the number of grid points required for the simulation of inviscid flows with the full-potential equations, and viscous flows with the Reynolds-averaged Navier-Stokes equations

COMPONENT	INVISCID FLOW	VISCOUS FLOW CHORD REYNOLDS NO		
		10^6	10^7	10^8
AIRFOIL	5 × 10^3	1 × 10^4	1 6 × 10^4	2 5 × 10^4
WING	1 × 10^5	8 × 10^5	2 × 10^6	4 × 10^6
WING BODY	1 2 × 10^5	9 5 × 10^5	2 2 × 10^6	4 4 × 10^6

Table 4 Estimates of computer time required for calculating flutter boundaries.

COMPONENT	FLOW	MODES	COMPUTER TIME HOURS	
			CRAY 1 S 30 MFLOPS	1988 NAS 10^3 MFLOPS
AIRFOIL	INVISCID	2	0 46	0 014
	VISCOUS	2	49 33	1 48
WING	INVISCID	4	37 03	1 11
		8	74 06	2 22
	VISCOUS	4	$3 7 \times 10^4$	$1 11 \times 10^3$
		8	$7 4 \times 10^4$	$2 22 \times 10^3$

INVISCID – FULL POTENTIAL

VISCOUS – RE AVERAGED NAVIER STOKES

$Re_c = 10^7$

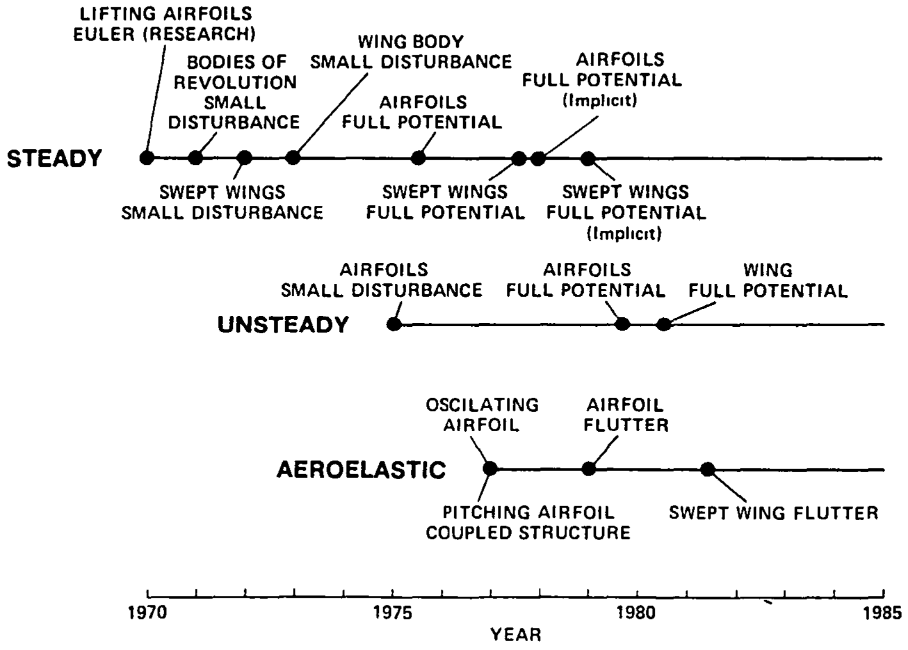


Figure 1 Milestones in the development of computational aerodynamics, inviscid transonic flows.

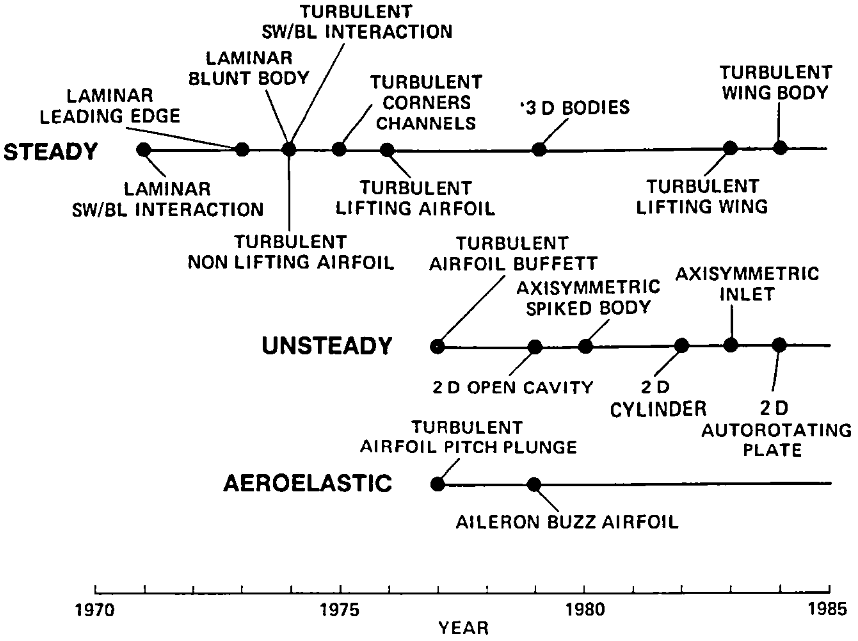


Figure 2 Milestones in the development of computational aerodynamics, compressible viscous flows.

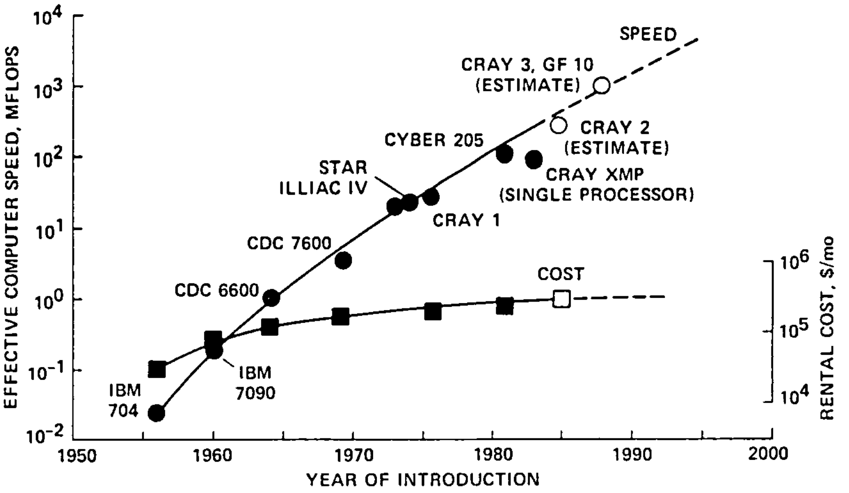


Figure 3 Growth with time of computer speed and cost.

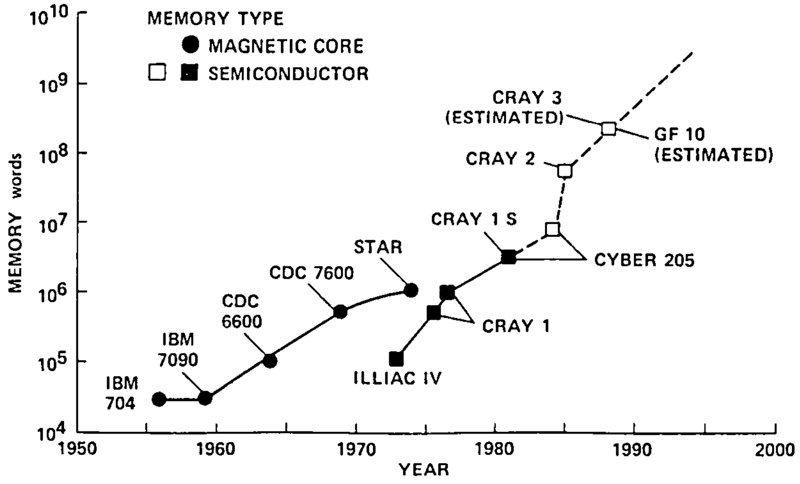
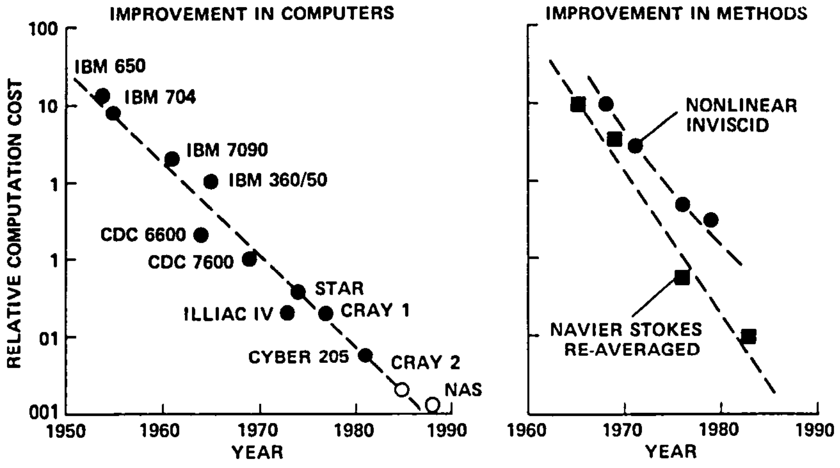


Figure 4 Growth with time of computer memory



IMPROVEMENTS COMPOUND TO RESULT IN 10^5 REDUCTION IN COST OF PERFORMING A COMPUTATION OVER A 15-YEAR PERIOD

Figure 5 Comparison of numerical simulation cost trend resulting from improvements in computers with that owing to improvements in numerical methods

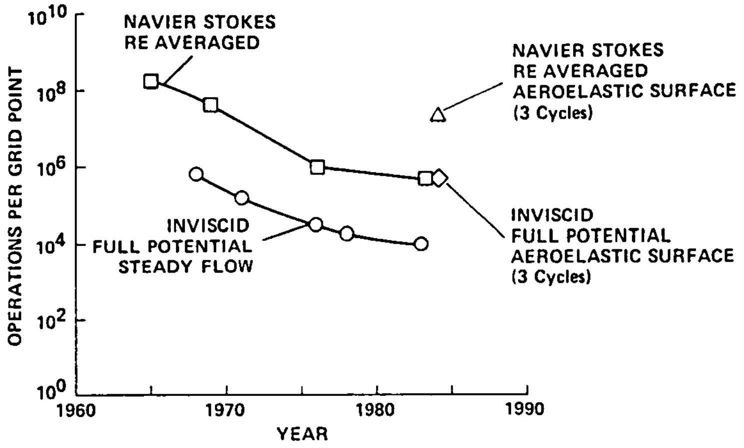


Figure 6 Number of operations per grid point required for problem solution

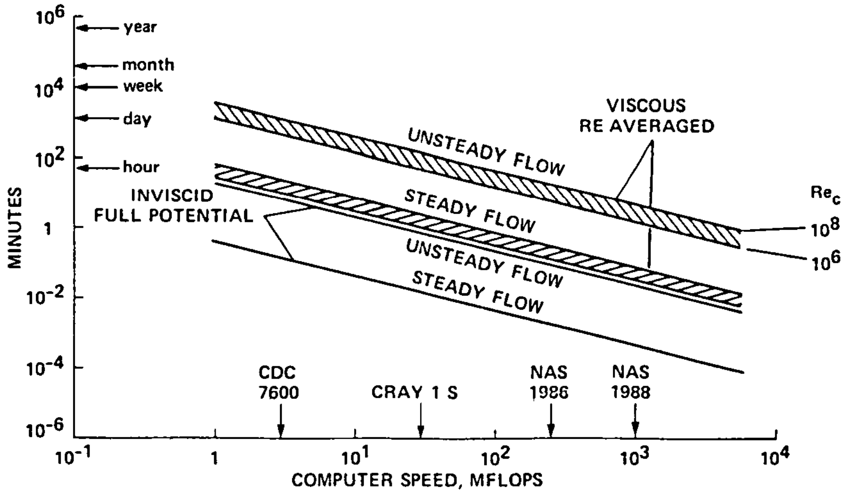


Figure 7 Estimates of times required to compute steady and unsteady flows about airfoils using the 1984 algorithms.

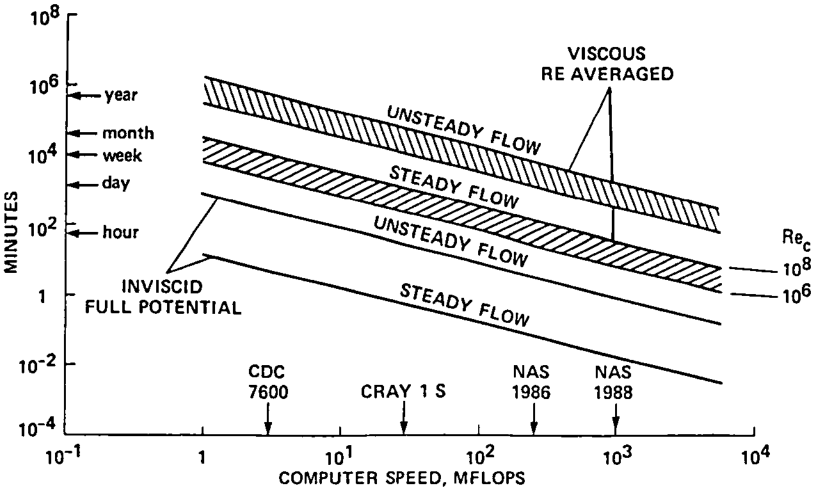


Figure 8 Estimates of times required to compute steady and unsteady flows about wings using the 1984 algorithms.

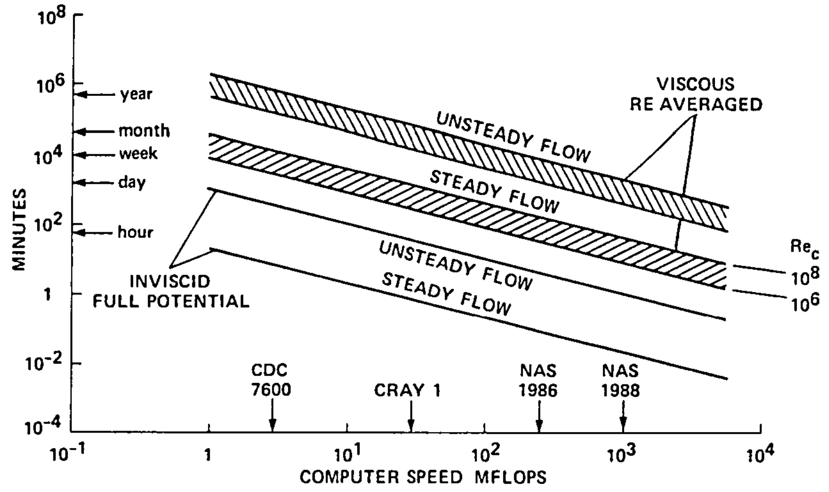


Figure 9 Estimates of times required to compute steady and unsteady flows about simple wing-body configurations using the 1984 algorithms

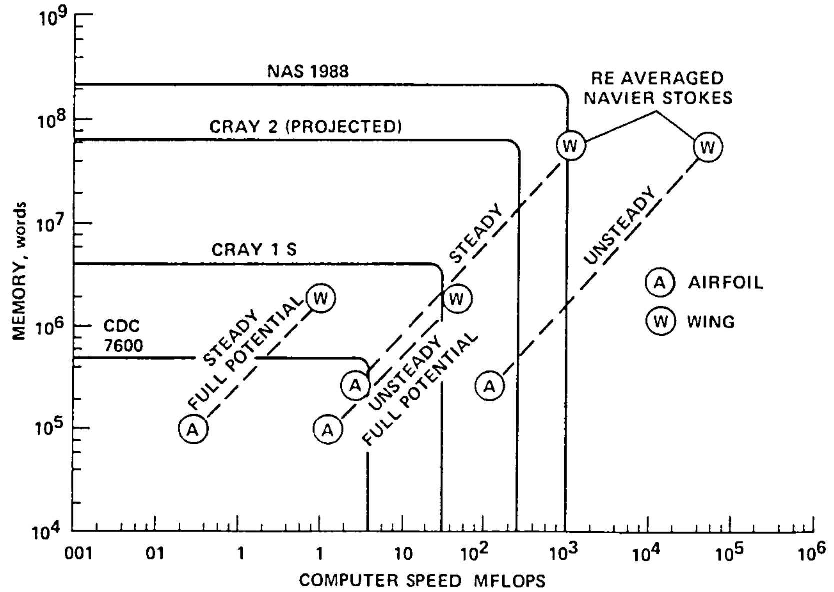


Figure 10 Computer speed and memory requirements for aerodynamic calculations compared with the capabilities of various machines, 15-min runs using the 1984 algorithms.

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15 Supplementary Notes

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16 Abstract

Milestones in the development of computational aerodynamics are reviewed together with past, present, and future computer performance (speed and memory) trends. Factors influencing computer performance requirements for both steady and unsteady flow simulations are identified. Estimates of computer speed and memory that are required to calculate both inviscid and viscous, steady and unsteady flows about airfoils, wings, and simple wing-body configurations are presented and compared to computer performance which is either currently available, or is expected to be available before the end of this decade. Finally, estimates of the amounts of computer time that are required to determine flutter boundaries of airfoils and wings at transonic Mach numbers are presented and discussed.

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