THE ROLE OF WIND TUNNELS IN FUTURE AIRCRAFT DEVELOPMENT

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Abstract

The wind tunnel has been the chief source of experimental aerodynamic data for the aircraft designer since the Wright brothers. This paper discusses some of the factors which are expected to change this traditional role, at least for the major "development" wind tunnels. The growing shortage and cost of petroleum will increase the designer's emphasis on drag reduction and reduce his dependence on the wind tunnel for control information. Drag measurement has always been difficult in wind tunnels because of problems with transition and low Reynolds' number. Better simulation of these factors will become imperative, at a time when the wind tunnel will also be constrained to economize in power. Techniques to meet these requirements are discussed.

Aerodynamic design by computational methods is a growing skill which is now adequate to take over many of the wind tunnel's traditional development functions. The three phases of the interaction of the computer and the wind tunnel are discussed, and the factors which currently are delaying the complete replacement of the wind tunnel by the computer.

1. Introduction

Presentation of the Daniel and Florence Guggenheim International Memorial Lecture is both a high honor and a challenge. The challenge is implicit in the final two words--to present to you both a lecture and a fitting memorial to the remarkable Guggenheim family. I believe that the subject which I have chosen is particularly appropriate for this task. As many of you know, Daniel Guggenheim, in the years from 1925 to his death in 1930, sponsored and endowed the now famous Guggenheim Aeronautical Laboratories in major universities across the USA. It is clear from his writings that these were not simply gifts to the universities--conventional endowments--but that they reflected Daniel Guggenheim's vision of a future in which the aircraft would link cities and countries in a safe, efficient civil transport system surpassing all other modes of travel.

After Daniel's death on September 28, 1930, his family nurtured his vision, and the Daniel and Florence Guggenheim Foundation was established to continue and expand his support of aeronautical research and development. Today, after half a century, his dream has largely come to pass. The wind tunnels and other astronautical facilities established by his drive and enthusiasm have produced men and ideas which have been major factors in the growth of aeronautics. Many of these laboratories are still active in aerodynamic development and teaching. It is therefore very fitting that we should, in this lecture, look ahead to the aerodynamic facilities which will support future aircraft developments, and which are the direct descendants of those sponsored by the Guggenheim family.

In all of the Guggenheim laboratories, and, indeed, in every aeronautical center, it is noteworthy that, once the resource was available, there grew up around the facilities a team of people who knew how to use them, and use them wisely. This is perhaps the greatest contribution of any new facility, offering new or expanded capabilities. It provides the opportunity to build around it a new team, with new visions and spawning new concepts. Past history of aeronautical laboratories has clearly shown that the building of the superb team is of greater importance than the building of the superb facility; and we can be sure that this rule will hold true for the next generation.

2. Aircraft Developments in the Near Future

There are many "research" wind tunnels in the world, at universities and national laboratories, and projection of their future would be equivalent to forecasting the path of aerodynamic research, a very difficult task. The "development" wind tunnels, which serve more directly the needs of the airplane designer, are more closely linked to the new aircraft. They have usually been constructed to test complete aircraft models, and are capable of generating vast quantities of data from such models with "production-type" instrumentation and data reduction equipment. Since these are the mainstay of industrial and national aeronautical laboratories, much of this paper will focus upon their future role.

Evidently, the future of this group of wind tunnels will depend upon advances in wind tunnel techniques, but it will also be impacted by changes in the next generation of aircraft. At the head of the list of changes we must recognize the consequences of the growing scarcity and cost of energy, both in its influence on the wind tunnel itself and on the new aircraft which will be developed in it.

A few years ago, it was quite difficult

to foresee the range of test requirements, even for civil aircraft. We could conceive of aircraft ranging from the present subsonic jet transports (M=0.85) to the low supersonic zero-boom speeds (M=1.15), the supersonic cruisers (M=2 to 3) and the hypersonic or even boost-glide vehicles for really fast transport--all technically feasible and not too uneconomic; the high speeds and altitudes partially offset the higher fuel consumption. The large increase in aviation fuel cost, and the threat of even higher future cost, have severely bounded this range.

The most important NASA aeronautical program is now the Energy-Efficient Transport project, in which our current technical developments are aimed at holding down fuel consumption on future jet transports operating around 0.8 Mach number. Much of the burden of this project falls upon the propulsion system, but the aerodynamic concepts are also significant. For example, the supercritical airfoil sections are not used to push to higher transonic speeds, but rather to permit thicker wing sections to be used at current transport Mach numbers around 0.8, giving lighter structures and higher aspect ratios up to 11 or 12. There is also a revival of interest in the possibility of stabilizing the laminar boundary layer further aft on the airplane surfaces, by choice of profile combined with boundary layer manipulation (sucking or blowing).

Further in the future, many of us believe that the petroleum shortage will force a change to an alternative aircraft fuel, and hydrogen appears to be the most attractive. Such a change would add impetus to the work on laminar flow stabilization; as Reshotko points out in a paper presented at this Congress,(1) hydrogen may permit us to cool the surfaces sufficiently for complete stabilization of the laminar boundary layer.

When we look ahead to a possible hydrogen-fueled aircraft, the most attractive application to the aircraft designer is the supersonic civil transport. The Concorde, a magnificent technical achievement, is showing that the traveling public is interested in higher-speed transporation, even though the time saved on the short Atlantic hop is swamped by the wastage at each terminal. Hydrogen fuel permits a supersonic transport to be built which will meet current noise limitations at the terminals and will fly for over 6,000 miles --far enough to show the very clear advantage of higher speed. This could be a very positive contribution to aeronautics as a direct result of the petroleum fuel shortage.

The trend towards "control-configured aircraft," in which electronic devices take over the function of stabilization of the vehicle, is also expected to be accelerated by the fuel problem. This offers reduced drag from smaller control surfaces, adequate for all control moment requirements but not large enough to meet traditional unaugmented stability requirements in all modes of flight. From the viewpoint of wind tunnel development, this change should reduce the test requirements; the fine tuning of aircraft controls in the wind tunnel has in the past absorbed a great deal of wind tunnel time.

In this brief review of the new developments which will demand wind tunnel time in the near future, it may appear that the military aircraft has been neglected. In fact, its future is very difficult to assess. It appears to be dominated by the tremendous increases in our electronic capability, which have almost ended the traditional quest for speed and altitude as the means of survival. If this trend continues, the military aircraft as a transporter of sophisticated electronic equipment, fixed or in auxiliary missiles, must ultimately be defined by the same economic constraints that establish civil transport performance. Perhaps the only additional requirement will be for high maneuverability at transonic speeds, and this does not dictate any novel features in the transonic wind tunnels in which most of our development will be done.

In summary, the bulk of development work in wind tunnels for the next decade will require transonic Mach numbers--this represents no change from the requirements of the last decade. The high fuel cost will force greater emphasis to be placed on cruise drag reduction, and we can expect much more detailed wind tunnel work to minimize interference drag components. This type of development work has always presented problems in the present generation of transonic wind tunnels, because of their low Reynolds' number. They typically provide a Reynolds' number of about 3 millions based on the wing chord of a complete model, whereas flight values of 30 millions or more during cruise are common.

The adoption of supercritical wing sections will exaggerate these problems in the future. These wing sections are designed to provide an extended supersonic flow region over the forward part of the airfoil, and to take the necessary final compression over a region of high pressure gradient further aft. The acceptable amount of this pressure gradient is greatly dependent upon Reynolds' number. If the airfoil is designed to optimize this gradient at flight Reynolds' numbers, the flow will separate when the boundary layer encounters the same pressure gradient at lower R.

A few years ago our Lockheed Georgia Company built a special "Compressible Flow Facility" to investigate these effects, providing a range of Reynolds' numbers from 3 to 30 millions on typical airfoils in two-dimensional flow spanning the test section. This wind tunnel will be discussed later; its results with typical 10%

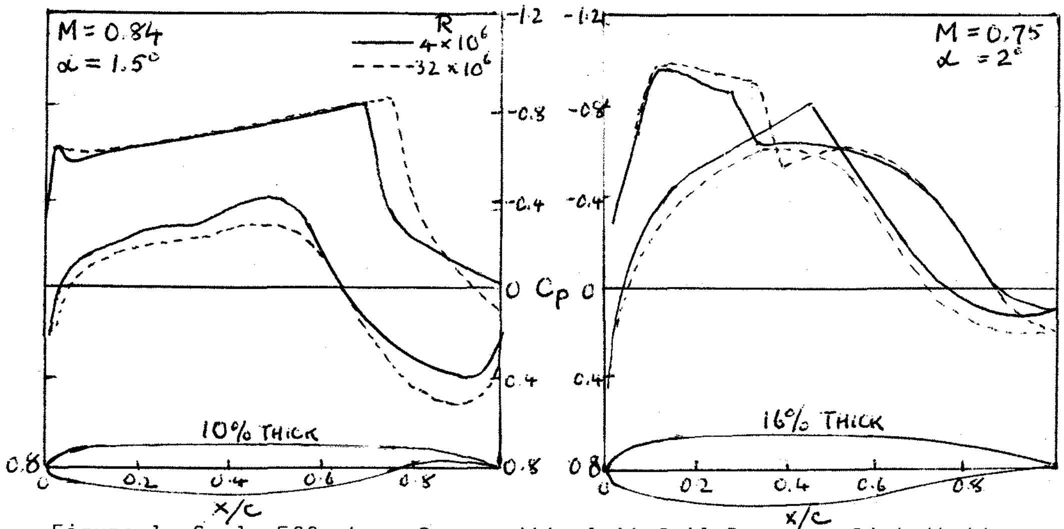


Figure 1. Scale Effect on Supercritical Airfoil Pressure Distributions

and 16% thick supercritical airfoils were(2) described in a recent paper by Blackwell. I have taken Figures 1-3 from this paper to illustrate the general nature of scale effect upon supercritical airfoils.

The pressure distributions in Figure 1 show clearly the limitation of the magnitude of the "recovery" pressure gradient at lower Reynolds' numbers, and the forward movement of the shock on the upper surface. The consequence, as shown in Figure 2, is a reduction in the normal force (c_n) and the nose-down moment ($-c_m$)--effectively a great reduction in the apparent angle of attack, requiring the airplane to fly at a higher geometric angle of attack to counter. In consequence, the drag rise at constant load (c_n) occurs much earlier in Mach number at low R, as shown in Figure 3.

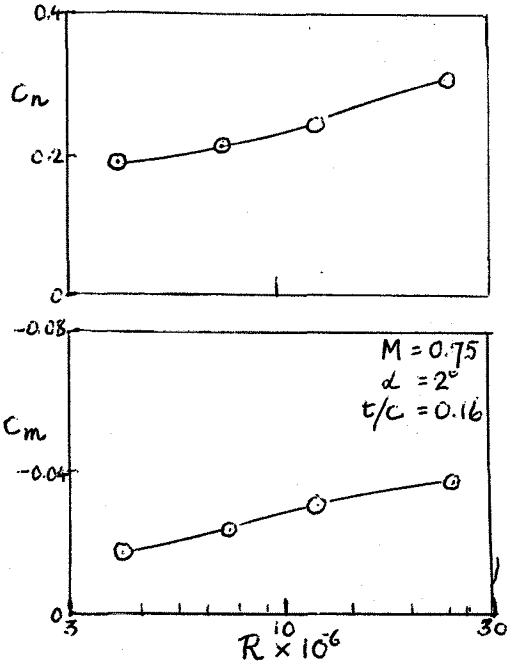


Figure 2. Scale Effect on Supercritical Airfoil Normal Force and Moment

Evidently these effects on an airfoil in two-dimensional flow will be greatly complicated on a complete aircraft by the interaction of fuselage and nacelle flows. If methods of extending the laminar flow region are also developed, the aircraft designer has a major problem--no wind tunnel presently exists which can simulate the Reynolds' number and low stream turbulence of flight conditions on a complete model of the design. This has at last become generally recognized, and new wind tunnels to fill the need are being constructed or planned, both in Europe and the United States.

3. Wind Tunnel Design for Power Economy

We can expect these future wind tunnels to have a further requirement imposed upon

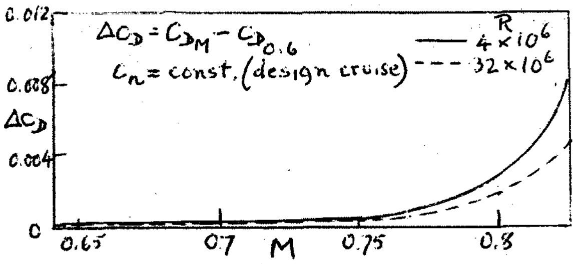


Figure 3. Scale Effect on Drag Rise, 10% Thick Supercritical Airfoil

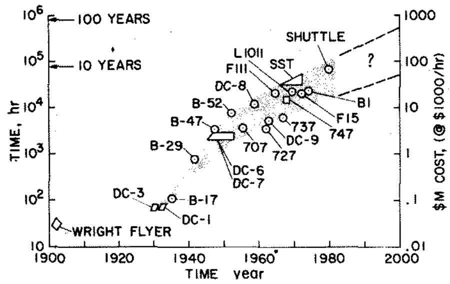


Figure 4. Wind Tunnel Test Hours for Aircraft Development

them which has not been a serious factor previously, namely the need for economy in operation. The cost of wind tunnel tests for a new aircraft development in the past has been only a very small fraction--1% or 2%--of the total cost of development, and the aircraft industry has been very willing to accept this as insurance against possible design errors which could cost much more to correct in the later flight phases of the program. But the amount of wind tunnel test time, and therefore the cost, has been increasing steadily with each new project over the past few decades. Figure 4, which illustrates this increase, is probably already familiar to you, since it appeared in April 1975 in a very significant paper by Chapman, Mark, and Pirtle(3) of Ames Research Center.

The Tristar (L-1011) development by my own company, Lockheed, is probably representative of the conditions for most of the wide-bodied transports now in service; it used over 25,000 hours of wind tunnel time during its development, at a cost of over $20 M dollars. The trend in Figure 4 would imply even greater time and cost for future aircraft, and indeed the requirement for greater attention to drag reduction and aircraft performance, discussed above, would generate this growth. On the other hand, as mentioned in the last section, there may be a decreasing requirement for wind tunnel work on control surface balance and stability if "control-configured" aircraft concepts are adopted.

The right-hand ordinate of Figure 4 assumes a constant cost of $1,000 per hour for wind tunnel time, a good average figure for the 1960-1970 period. It is inevitable that this figure will increase markedly as a result of the growing cost of energy, since the wind tunnel (particularly the larger development facility) is a major consumer of electrical energy. At present, roughly half of the operating cost of such a wind tunnel is electricity cost, the remainder being mainly salaries of staff, and overhead. If we assume the dire predictions of future electricity cost increase now being threatened (almost an order of magnitude increase in the next decade), we must expect a corresponding increase of five or six times in the cost of wind tunnel usage.

I believe that this estimate is much too crude, but any attempt to improve it becomes involved in such weighty matters as the magnitude of inflationary effects, the extent to which increasing electricity costs will reflect an overall inflationary ratcheting which will apply also to wages and to the costs of everything, including aircraft. Further, it is evident that the energy cost will depend greatly upon the type and location of the wind tunnel. We could not expect the water-driven wind tunnels at Modane, for example, to show the same energy cost increases as the wind tunnels in California, powered from utilities depending upon petroleum products. Nevertheless, energy is becoming a scarcer and more valuable commodity, and future wind tunnels must reflect this in their design and operation.

Back in 1945, while at the Royal Aircraft Establishment, I wrote a paper(4) on design concepts which could be employed to reduce significantly the power requirements of transonic wind tunnels. This paper has recently received some attention because it recommended the cryogenic wind tunnel concept, now being used in the new NASA high-R wind tunnel at Langley Research Center, along with some other methods of power reduction. These are easily recognized if the power requirement of the wind tunnel is expressed in the following manner:

Power $P = \frac{1}{2}\rho V^3 A/\eta$ with wind tunnel efficiency factor η

Reynolds' number $R = \rho Vc/\mu$

Mach number $M = V/a$

where the sound speed $a = \sqrt{\gamma p/\rho}$ for a perfect gas with constant γ.

These can be written $p = (AR^2M/2\gamma c^2)\mu^2 a^3/p\eta$ --(1)

$c = (R/\gamma M)\,\mu a/p$ --(2)

where A is the working section cross-sectional area

c is the model typical dimension (e.g., wind chord)

V, p, ρ, T and μ are velocity, pressure, density, temperature, and viscosity of the fluid in the working section.

The bracketed terms in front of expressions (1) and (2) are constants for given R and M. The quantity A/c^2 expresses the size of the tunnel in relation to the model, and must be kept constant to maintain the same wall corrections. Thus, we can reduce the power requirement by reducing the value of $\mu^2a^3/p\eta$; at the same time the size of tunnel and model will scale as $\mu a/p$. These expressions indicate four possible ways of economizing in wind tunnel power:--

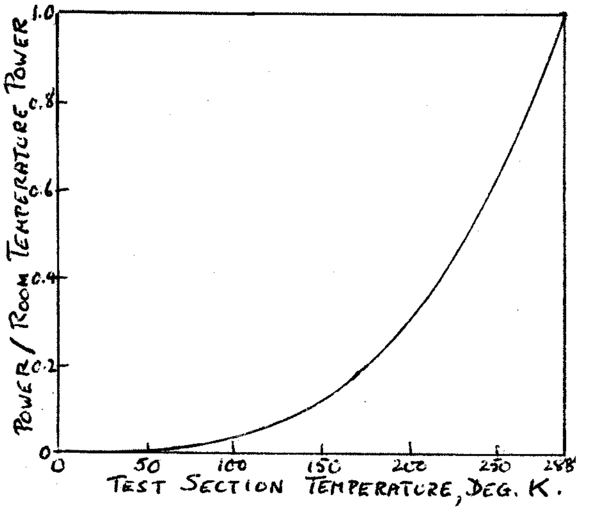


Figure 5. Power Reduction in Cryogenic Wind Tunnel

(1) Improvement of wind tunnel efficiency factor η.

In my 1945 paper, I treated η as a constant, but there are evidently two reasons for now urging the wind tunnel designer to re-examine it. First, the efficiency can be improved by smaller expansion angles in the return circuit, lower velocities through corner cascades, and similar measures which generally represent a best compromise between construction cost and operating power cost. As power costs increase, there must necessarily be a trend towards higher efficiency factor η to retain this best compromise.

A further consideration is the possible future need for lower turbulence level in the test section, discussed in earlier paragraphs. This also calls for flow expansion to lower velocities in the return circuit and general improvement of flow quality around the wind tunnel. Although we still have much to learn about wind tunnel disturbance vectors and their role in transition, it is good policy to construct the facility with the lowest practicable noise and turbulence.

(2) Increase of test section pressure

Equations (1) and (2) indicate that both power requirement and size are inversely proportional to test section pressure p. Since many aeronautical laboratories are already equipped with high pressure air storage tanks to feed supersonic or hypersonic blow-down wind tunnels, it is relatively straightforward and economical to add a blow-down high-R test section to the same source. The Lockheed-Georgia "Compressible Flow Facility," which produced the supercritical airfoil data of Figures 1 to 3, is of this type. The test section is 71 cm high and 53 cm wide, and it achieves Reynolds' numbers up to 55 millions per foot by utilizing test section pressures approaching 10 atmospheres.

The fundamental problem with this type of facility is that model loads are excessive. The pressures and forces per unit model area are proportional to $\frac{1}{2}\rho V^2$ or $\frac{1}{2}$ p M^2, so that the problem of supporting the model with acceptably small support interference becomes steadily more difficult with increasing pressure, and the construction of the model to avoid distortion under load requires high-strength steels or similar special materials. Nevertheless, as our facility has shown, this approach to high-R testing can be quite productive if configurations are limited to simple airfoils, components or half-models.

(3) Reduction of temperature of the working fluid

Quoting directly from Reference 3, "If $\gamma = 1.4$ is essential, then power economy is best achieved by refrigeration." Both sound speed and viscosity decrease with decreasing temperature:

a varies as $T^{\frac{1}{2}}$

μ varies as $T^{3/2}$ (T+C)

where C is Sutherland's constant, and has a value of 124°K for air. Thus the power falls very rapidly with decreasing temperature in accordance with the relation;

P varies as $T^{9/2} / (T+C)^2$ from equation (1), and the tunnel and model dimensions also are reduced, somewhat less rapidly:--

C varies as $T^2 / (T+C)$ from equation (2).

The spectacular reduction in power with temperature is shown in Figure 5. This curve raises the obvious question: how far down, how close to liquefaction, is it permissible to go? In my earlier paper, the conservative assumption was made that the temperature must not fall below the steady-state liquefaction point anywhere in the flow, even at the highest local supersonic speed. This led to the following limiting free-stream temperatures and power requirements:

Working Fluid	γ	Min. Temp. (Deg. K)	Power ÷ Room Temp. Pwr.
air	1.4	126	0.07
nitrogen	1.4	108	0.038
hydrogen	1.4	28	0.0048
helium	1.67	7	1.9×10^{-4}

In 1945, when this table was produced, all of these conditions appeared equally impracticable; but, as you are aware, a dedicated team at Langley Research Center has now operated a pilot cold-nitrogen wind tunnel successfully for several years. In my view, this team deserves all the credit for the cryogenic wind tunnel; by solving the many practical problems, they have converted an intellectual exercise into a very useful power-saving device.

They have in fact operated at temperatures well below my conservative limit. Experience with hypersonic wind tunnels during the 1950s would confirm that this is possible. These hypersonic tunnels also operate close to the liquefaction limit in the test section, and there is much experimental and theoretical work showing that a considerable degree of local supersaturation in the flow around a model can be accepted without actual condensation or spurious results. There is a need for some caution here, since the transonic tunnel operating at the same temperature has a much higher density than the typical hypersonic tunnel, and therefore much more pronounced deviations from perfect gas characteristics near the condensation point. I believe, however, that the acceptable limits for different model conditions will rapidly be defined as the cryogenic tunnels move into development testing.

(4) Working fluids with higher molecular weight

My original paper(4) examined the use of high-molecular-weight gases as an alternative to refrigeration. The speed of sound is inversely proportional to the square root of the molecular weight, and the viscosity also decreases significantly for the heavier molecules. The condensation point also increases, of course, but there are a number of heavy gases, mainly fluorine compounds, which remain gaseous at reasonable pressures well below room temperature. With the freons and hexafluorides (all very stable compounds), for example, it is possible to reduce the wind tunnel power to 2% to 5% of the requirement with room-temperature air, and the dimensions to about one-quarter. A few special wind tunnels in the USA have made use of freon in this way, but not at very high subsonic speeds.

The reason for this lack of interest undoubtedly lies in their low specific heat ratio ($\gamma = 1.15$ to 1.2 compared with 1.4 for air). This evidently would cause some differences in flow conditions with large velocity excursions or heavy shock waves, but I have been unable to find any experimental data on the effect of γ change upon an efficient transport aircraft model at cruise conditions. Analysis suggests quite negligible changes in pressures and forces; in the expansion of the exact compressible flow equations around the ambient flow conditions, γ does not appear explicitly in the lower terms. In fact, the well known Von Karman-Tsien approximation for transonic flows assumes just such an expansion of the hodograph equation, with a gas law of the form

$$p = A - B/\rho \text{ instead of } p = A\rho^{\gamma}$$

Perhaps power shortages in the future will stimulate re-examination of the use of heavy gases, possibly mixed with helium to re-adjust the specific heat ratio if necessary.

4. Laminar Flow and the Transition Problem

Although the incentive for attaining large areas of laminar flow on transport aircraft is now very strong, as stated earlier, the development wind tunnels of the world will probably make no contribution to the problem in the near future, but will continue to test with full turbulent flow and artificially fixed transition. This does not imply that there has been no progress in the understanding of transition; on the contrary, the recent work of L. M. Mack,(5) E. Reshotko,(6) J. M. Kendall(7) and many others has detailed the oscillatory modes of the disturbed laminar layer and the manner in which disturbances of differing frequencies propagate through the layer. But these advances have served to show how little is known about the manner in which disturbances in the stream or on the surface, either in flight or in the wind tunnel, couple with the normal modes and excite the growth into non-linearity and turbulence. It is evident that the frequencies and orientation spectra of the several disturbance sources determine this coupling and the ultimate transition. We now recognize that phenomena such as the "unit Reynolds' number effect"(8) in wind tunnels are related to this problem, but we are far from any capability to match the disturbances--stream turbulence, noise, surface roughness--in tunnel and flight.

We in Lockheed are therefore approaching the laminar flow problem at present via a combination of small research facilities and flight test focussing upon the manner in which the external disturbances trigger the transition process. The ground facilities are straightforward--a small (test section 60 X 90 cm) wind tunnel designed for a turbulence level in the 0.05% range and a simple water channel. We believe that the recent advances in instrumentation can give information not previously attainable in conventional tunnels of this type. In particular, we are employing the laser anemometer with great success in both our wind tunnel and flight experiments on transition. Never before have we had non-intrusive instrumentation which could yield not only velocity vector fields, but at the same time measurements of turbulence intensities, shear stress, and turbulence correlation coefficients. Access to such data will greatly enhance our ability to construct valid physical and mathematical flow field models.

As an example of novel water-tunnel instrumentation, we have developed a system for obtaining quantitative data on mean and fluctuating velocities from the hydrogen bubble lines generated when current is pulsed through a fine wire stretched across a water channel. Photographic records of the bubble line as a function of time are first digitized by a video digitizer. Then through a mini-computer interface the bubble lines are scanned, optical centers of bubble positions are defined, and local Eulerian velocities are computed. Results from feasibility studies show good agreement with more conventional techniques and are most encouraging.

Although the stream turbulence is minimal in flight, the noise, vibration and surface roughness and waviness still remain, with much different wave numbers than in ground facilities. To minimize these disturbance components also, we are experimenting on a Caproni sailplane with a carefully finished cuff section on the wing. Here again, new instruments such as the laser anemometer should give detailed information which was not possible in earlier flight transition experiments of this type.

5. The Wind Tunnel and the Computer

It is now very evident to the airplane designer that the greatest change in the role of the wind tunnel in the near future will come from advances in aerodynamic computational capability, permitting the computer to assume a major part of the development function. The development wind tunnel and the computer have been closely linked since the early 1950s --prior to that time, I remember that the computer was much more attractive, and, furthermore, she could provide the Englishman's afternoon cup of tea!

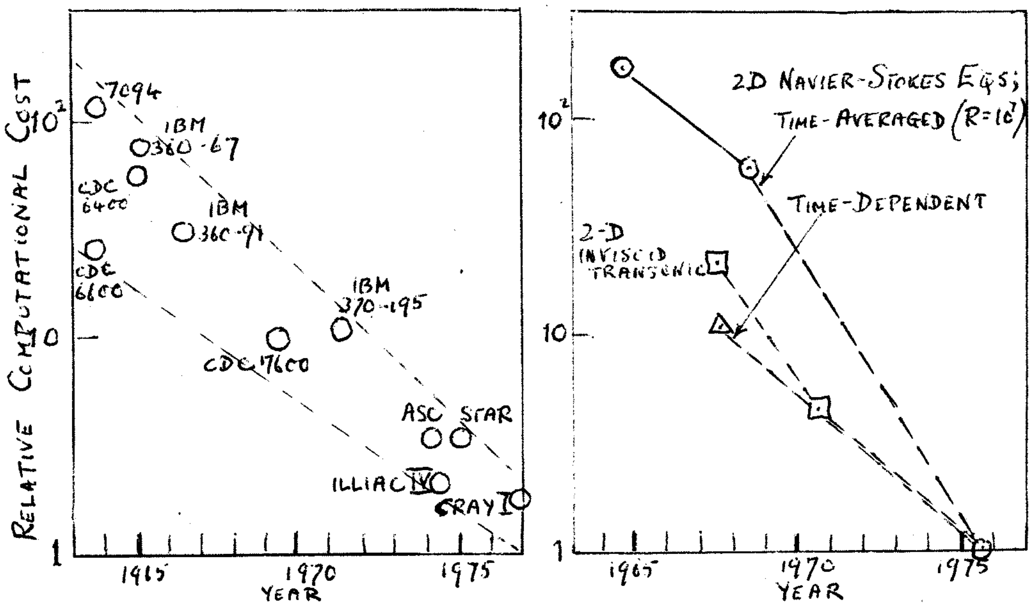
The early computers such as we installed in the wind tunnels at AEDC Tullahoma were fearsome arrays of vacuum tubes converting kilowatts of electric power to heat, but they made a major contribution to the utility and economy of the wind tunnel by rapid reduction of the data to coefficient form including wall corrections. These could then be digested easily by the engineer to permit decisions on the next test to be made without delay. Thanks to the revolution in solid-state electronics, the same data-reduction function is now performed even faster and with far greater reliability by minicomputers almost one hundredth of the size, and less costly by a factor of about a thousand. I have already mentioned a typical application to the analysis of the bubble line data in our water channel. This straightforward function of rapid data handling is still the most valued, and most universal, application of the computer to the wind tunnel; it is the first phase of a three-stage process in the interaction of the two devices.

The second phase developed when the growing capability of computers led engineers to realize that they could now assist in two other routine functions in the wind tunnel--the programmed operation of wind tunnel controls, and the comparison of experimental results with available aerodynamic theories such as were used in the preliminary design process. This check of results against theory has always been a part of wind tunnel art; but the ability to do so in real time, comparing with several current alternative theoretical approaches of steadily increasing complexity, gave the engineer new confidence. It enabled him to correlate a mass of experimental data, and gave a clearer insight into the physical processes at work in his design.

The applications of the computer to wind tunnel control in this second phase are many and varied, but they have the common element that some measured quantities are used via the computer in a feedback loop to instruct the model or wind tunnel controls in simulation of some particular flight condition. For example, the measured forces on a model re-entry vehicle can be entered into the equations of motion, in the computer, to derive changes in attitude, velocity, and altitude which can be used to direct the model and wind tunnel controls to the next point on the trajectory. The time savings offered by this technique have been particularly valuable in some of our special supersonic and hypersonic facilities operating with limited air supply at extremes of temperature and pressure; but similar techniques may find wider application in the future as power cost increases place a higher value on wind tunnel time. Thus the climb of a supersonic aircraft through the transonic speed range, where climb-rate, drag and acceleration are at their most critical condition, can be optimized most economically in this manner. We will find that limitations to such applications in the future will not be in the computer, nor in the capability of the engineers to devise the complex control systems--control theory has become almost an essential tool for the modern aeronautical engineer. The limitation will probably be set by the speed and range of wind tunnel control available; and I therefore make a plea to the designers of new wind tunnels to remember these possible adaptive control applications in their design of controls.

In this second phase of computer applications we must include those developments where the computer assists in better simulation of flight conditions by using both features, real time solution of complex aerodynamic theory combined with adaptive control of the wind tunnel. Adaptive control of the porous or slotted wall of the transonic wind tunnel is a good example. The required wall condition (air bleed or open/closed area ratio) is a complex function of model blockage and Mach number, and the past practice of operating at a fixed wall condition is inadequate. The adaptive approach chooses a strategic flow parameter (e.g., a set of wall pressures) which can be measured conveniently and also be calculated rapidly with sufficient accuracy from current transonic theory; the porosity control is then moved to bring these into line at each test condition.

This adaptive approach may find more applications in future wind tunnel simulation of flight conditions. For example, Blackwell(9) has proposed that instead of



Improvement in Computers　　Improvement in Mathematical Methods

Figure 6. Reductions in Cost for Simulation of a Given Flow

the current practice of fixing transition on a model very far forward (5% chord) for transonic tests at low R, a better simulation of high-R conditions is possible with the transition point farther aft. We may be able to prolong the useful life of current low-R wind tunnels, as theories of transonic shock-boundary layer are improved, by utilizing the measured shock position or trailing-edge boundary layer thickness in an adaptive loop to control the boundary-layer trip position.

At this point the purist may argue that when our theoretical capability is improved to to this extent, there appears to be no further need for experimental results and wind tunnels. This brings us to Phase 3 of the relation between the computer and the wind tunnel, when experimental aerodynamic developments may be replaced, in whole or in part, by computational methods.

6. Computational Aerodynamics and the Wind Tunnel in the Future

It is not necessary to point out to ICAS members the tremendous current interest in computational aerodynamics; this is evident in the programs of this and preceding meetings, and in the activities of many aeronautical laboratories, national and industrial. It is also probably unnecessary to call attention to my Reference 3, the 1975 paper by Chapman, Mark and Pirtle which puts together the effects of these computational advances, the continuing improvements in computer capability and cost, and the increasing cost of the conventional wind tunnel approach to aircraft design. These factors lead inexorably to the conclusion that within a decade the computer will begin to supplant the wind tunnel for aerodynamic design.

We cannot take issue with this conclusion; the replacement of aerodynamic experiment by calculation has been going on since the Wright brothers. They made measurements of the lift of over 200 airfoils to optimize their first flying machine, but we have now had the analytical tools to perform the task of subsonic airfoil optimization for at least the last three decades. Our largest computers, using the two-dimensional Reynolds averaged Navier-Stoker equations, can now compute with good accuracy the transonic flow around an airfoil with a separating turbulent boundary layer, including the unsteady shock motions and buffet pressures (Peterson, Reference 11). *

On the other side of the picture, the computational simulation of a complete three-dimensional flow field around the total airplane of course requires considerable detail in the computer, but there are many examples in the literature to demonstrate its feasibility with today's computers if

* *The literature on computational aerodynamics is now so vast that, instead of selecting a few of the many excellent contributions, I have preferred to give the reader references to two comprehensive collections which define the state of the art; the summary by Spreiter and Stahata given at the last ICAS meeting in Ottawa (Reference 10), and a very recent Workshop report from Ames Research Center (Reference 11) at which a large cross-section of the aeronautical and computer communities outlined the present state of the art and future prospects.*

this flow is inviscid and transonic (Reference 10, 11). The inclusion of viscosity in three-dimensional flows in general is beyond the capability of the largest computers now operating, but larger-capacity computers are feasible, and a Numerical Aerodynamic Simulation Facility is now under study in NASA. In addition, advances in the computational methods--the algorithms--largely contributed by NASA engineers, have produced order of magnitude decreases in the computer time and cost requirements, superimposed on the steady improvement in computer cost, as can be seen in Figure 6. We are approaching the point where the traditional development tasks which have employed complete models in transonic wind tunnels can be done faster and at less cost by computational methods in our largest computers.

The major obstacle to a complete changeover from wind tunnel to computer appears to lie in the area of turbulence, the long-standing problem of the aerodynamicist. Put very simply, the computer has a problem with high Reynolds' number and transition, just like the wind tunnel--perhaps inherited from the wind tunnel, and our past incomplete resolution of the problems of turbulence. In principle, a complete solution of the time-dependent Navier-Stokes equation will numerically simulate turbulence and transition. However, as the Reynolds' number increases the scale of the turbulent eddies which must be treated for correct simulation becomes smaller and smaller and the required computer size increases. This problem was examined by Case et al (Reference 12), who concluded that the resolution of all the relevant scales of motion would require $R^{9/4}$ independent variables in time, for which the arithmetic operations would be of the order of $R^3 \ln R$. Since we are interested in flight R values of at least 3×10^7, these requirements are far beyond the capacity of any computer which can presently be envisaged.

The simplest practical solution has been to replace the detailed eddy structure by the scalar eddy viscosity, familiar from our old semi-empirical approach to turbulent boundary layers. This fails at just the points of most concern in our engineering design--in the vicinity of shocks and interacting layers, and in separating flows at high R. More sophisticated approaches have been examined, such as modeling the vector Reynolds' stresses or curtailing the eddies below some practical level and approximating the small-scale structure. This problem of the high-Reynolds' number boundary layer and the transition to turbulence presents the greatest current challenge to computational aerodynamics, and a great deal of work is going on. It is probable that solutions which are satisfactory approximations for engineering design will emerge in the near future. There is an evident problem in verifying that any technique is satisfactory, since the only valid check of the utility of a particular approach appears to be by recourse to experiment, in an area where the wind tunnel itself has difficulties.

In spite of these limitations, the aircraft developer must take advantage of the improved cost and convenience offered by computational aerodynamics, as well as its potential for design optimization in detail. We can conclude that in the next decade the computer will in fact supplant the wind tunnel as asserted by Chapman et al(3), at least in the more quiescent regions of the flow. There will evidently be a period during which we are developing the capability of the computer in the more difficult aerodynamic areas--the near-stall conditions at high subsonic Mach numbers, the complex flow at a wing-nacelle-support pylon junction, the mixed supersonic-subsonic flows at the nozzle exit of a ducted fan. The wind tunnel in the next decade must assume the new role of verifying the adequacy of these computational techniques; this highlights the need for better simulation of viscous and turbulent phenomena, particularly at high Reynolds' number, which I have stressed earlier in this paper.

In this role of providing data on which the engineering applications of computers can be built, it may appear that the wind tunnel is condemned to erect its own gravestone. But as its part in the design process is supplanted, I believe that it will revert to its function in aerodynamic research. Perhaps, with its capability strengthened by the aid of the computer, we can hope to solve some of the fundamental problems of fluid flow which we have by-passed in our past headlong drive for aeronautical development.

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