GENERAL ASPECTS OF WIND-TUNNEL INVESTIGATION

by

A. M. Kuethe
University of Michigan
Ann Arbor, Michigan

The aeronautical engineer, like the hydraulic engineer, is confronted with a bewildering array of similarity parameters. The wind tunnel in its various forms provides a means of determining the separate effects of each parameter and the effects of interdependence between the parameters on the flow about a body. The most important of these are the Reynolds number VL/ν,[1] the Mach number V/a, the turbulence number $\sqrt{\overline{u^2}}/V$, a roughness parameter $\varepsilon\sqrt{\tau/\rho}/\nu$, a frequency parameter V/nL, and others, which, under various circumstances, have an appreciable effect on the flow over a body.

The object of this paper is to describe means by which the aeronautical engineer determines in the laboratory the flight characteristics of the full-scale aircraft, how he meets the requirements imposed by the most important similarity parameters, some of the difficulties he encounters, and the means he uses to study the details of the flow about bodies.

WIND TUNNELS

The wind tunnel was conceived by E. H. Wenham in 1871. Since that time its development has been no less remarkable than that of aircraft. Early types produced a blast of air of questionable uniformity and the models and measuring techniques were extremely crude.

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[1] $V =$ velocity of the airstream

$L =$ characteristic length of the model

$\nu =$ kinematic viscosity

$a =$ velocity of sound

$u =$ fluctuation velocity

$\varepsilon =$ length characteristic of roughness

$\tau =$ shearing stress at the wall

$\rho =$ density of air

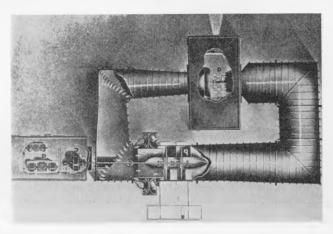$n =$ frequency of oscillation or rotation

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FIG. 1.—SKETCH OF WRIGHT FIELD WIND TUNNEL.

Perhaps the most spectacular development in use today is the large wind tunnel at Wright Field, a diagram of which is shown in Fig. 1. The working section is 20 feet in diameter, and the maximum section of the return passage is 45 feet. A 40,000-horse power electric motor, driving two 16-blade propellers 40 feet in diameter, furnishes the power. Wind speeds around 400 miles per hour are expected. Though this is not the largest wind tunnel in existence, the power used is far in excess of that used in any other. The Mach numbers attained are very near those reached in flight and the Reynolds numbers are within a factor of 3 or 4 of full scale.

A noteworthy feature of the tunnel is the air-exchange system, by which the air which has become heated by the friction at the surfaces is discharged into the atmosphere and fresh air is drawn in to replace it. This is a necessary feature of closed-section high-velocity wind tunnels if the temperatures and the rate of change of temperature with the time are to remain reasonably low. This system is shown in Fig. 1 directly upstream from the propellers.

The variable-density wind tunnel, the N.A.C.A version of which is shown in Fig. 2, was conceived by Dr. Max Munk in the early twenties. The outer shell is circular in cross section and is constructed to withstand internal pressures up to 20 atmospheres. The direction of airflow and the working section are designated in
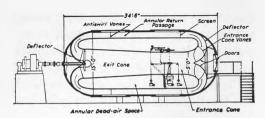
FIG. 2.—N.A.C.A. VARIABLE DENSITY WIND TUNNEL. (From N.A.C.A. Technical Report No. 416.)

the figure. The advantages of this type of tunnel are three-fold: (1) Since under constant-temperature conditions the velocity of sound and hence the Mach number are independent of the density, high Reynolds numbers can be obtained while keeping the Mach number at a low value. (2) Either the Mach number or the Reynolds number can be varied independently on the same model. (3) Since the power used is proportional to ρV^3 and the Reynolds number is proportional to ρV, it follows that the power used to reach a given Reynolds number will be inversely proportional to the square of the density of the air.

A disadvantage inherent in the type of variable-density wind tunnel shown is that, in general, it is difficult to proportion a tunnel inside a tank so that turbulence will be a minimum. Small and obstructed return passages are practically unavoidable. For that reason the more modern variable-density tunnels are roughly similar to the Wright Field tunnel shown in Fig. 1. Because of structural difficulties, it is not feasible to build this type to withstand very high internal pressures, but the turbulence can be kept to a very low value.

Wind tunnels providing wind speeds in the vicinity of the sound velocity have been used to a limited extent for determining airfoil characteristics at high speeds. The N.A.C.A. high-speed tunnel is shown in longitudinal section
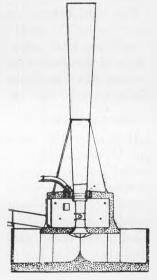

FIG. 3.—N. A. C. A. HIGH SPEED WIND TUNNEL. (From N. A. C. A. Technical Report No. 664.)

in Fig. 3. It is circular in cross section and is of the induction

type—i.e., air from the tank of the variable-density wind tunnel shown in Fig. 2 discharges in an upward direction through an annular slot a short distance above the working section, thus inducing a flow from the atmosphere through the working section. The working section is 24 inches in diameter, so that, while the Mach numbers may approach unity, the Reynolds numbers are quite low. Comparative tests indicate, however, that for Mach numbers above 0.5 the influence of the Reynolds number is small compared with compressibility effects. Hence, the extrapolation of the results to high Reynolds numbers can be carried out with small error.

Wind tunnels in which speeds greater than the velocity of sound are to be attained must be specially proportioned. The one shown in Fig. 3 is entirely unsuitable for this purpose since the velocity at the throat can never exceed the local velocity of sound. The supersonic wind tunnel has the special function of providing a means for investigating the aerodynamic characteristics of propeller sections for high-speed aircraft.

The wind tunnels described represent in general arrangement and function the great majority of those in use today. There are in addition many other types of tunnels designed for the investigation of particular aspects of flow or particular attitudes of flight, such as icing conditions, streamlines of a flow, spinning of airplanes, curved flight, control characteristics of airplanes, etc.

INTERFERENCE EFFECTS

If the free-flight values of various parameters mentioned above can be duplicated in wind-tunnel tests, there still remains the necessity of correcting the results for flow interference. One source of interference includes the various effects traceable to the finite extent of the wind-tunnel airstream. First, the placing of the model in the stream has a blocking effect which alters the mean speed in the throat and, if the cross-sectional area of the model is more than a few per cent of the cross-sectional area of the wind stream, the velocity distribution over the various parts is altered appreciably from its value in free flight. Second, the boundaries of the stream impose conditions on the flow which alter the forces experienced. For a closed-section wind tunnel the condition imposed is that the normal component of the flow must vanish at the walls; for an open-section wind tunnel the condition is that the

pressure at the boundary of the stream must be constant. The magnitude of the corrections due to the above effects amounts to a few percent in carefully planned tests.
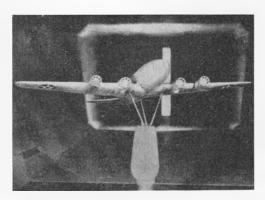
The model supports are another source of interference. The flow near these supports is necessarily altered considerably by their presence. The guiding features of support design must therefore be: (1) To make them as small as possible, compatible with their functions of holding the model at a definite attitude with a negligible deflection under the action of the air forces, of providing a convenient means for changing the attitude of the model, and of

FIG. 4.—PHOTOGRAPH OF MODEL MOUNTING IN UNIVERSITY OF WASHINGTON WIND TUNNEL [1].

transmitting the forces and moments to balances where they can be weighed; and (2) to attach them to the model at points where flow interference will have a minimum effect on the over-all aerodynamic characteristics of the model.

Until recently, wire supports were used, but these have given way to strut supports such as that shown in Figs. 4 and 5. The arrangement shown is that used in the University of Washington wind tunnel [1].[1] Wind-tunnel balance systems used at the N.A.C.A., the California
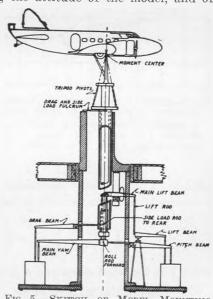

FIG. 5.—SKETCH OF MODEL MOUNTING AND BALANCE SYSTEM OF UNIVERSITY OF WASHINGTON WIND TUNNEL [1].

[1] References appear at the end of the article.

Institute of Technology [2], and the Massachusetts Institute of Technology are also of this general type.

MODEL TESTS ON AIRPLANES

In order to carry out representative tests on a model airplane one must answer the question: ''How closely must the details of the model conform in scale to those of the full-scale airplane?'' A complete and general answer is not possible. Those parts which are apt to exert a critical influence on the flow must be duplicated in great detail on the model. Every effort must be made, for instance, to form the wing contour as closely as possible. Comparable care must be exercised on the tail surfaces.
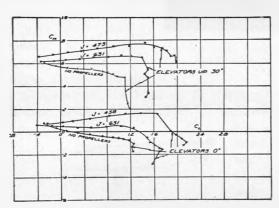

FIG. 6.—EFFECT OF ROTATING PROPELLERS ON MOMENT COEFFICIENTS VS. LIFT COEFFICIENT. A negative slope indicates static longitudinal stability [3]. $J = V/nd$, where V = velocity, n = propeller r.p.m., d = propeller diameter.

Only in recent years has the importance of power-on tests been realized [3]. Model propellers are fitted to the model and a small electric motor is placed inside the nacelle or fuselage to operate the model propeller. Since the greatest effect of the rotating propeller on airplane characteristics is attributable to the slipstream, the main problem is to duplicate slipstream effects on model scale. This is accomplished approximately by making

$$\left(\frac{Thrust}{\rho V^2 d^2}\right)_{model} = \left(\frac{Thrust}{\rho V^2 d^2}\right)_{prototype}$$

where V is the wind speed and d is the propeller diameter.

Fig. 6 shows the marked effect of running propellers on pitching-moment coefficients and on static longitudinal stability.

MEASUREMENT OF FLOW DETAILS

The general trend of wind-tunnel research is toward the more and more detailed investigation of the flow about bodies and the effects of the various similarity parameters on the flow, rather than on the over-all forces experienced by the body. It is obviously possible in a short space to give only a few of the more important techniques used in wind-tunnel measurements. The balance systems used for measuring forces on a model, for instance, cannot be described herein, for the reason that they are too complicated to be adequately treated in a short account. The momentum method of drag determination is another important aspect which must be omitted. The following phases of wind-tunnel studies, however, are of general importance in fluid mechanics.

Turbulence in Wind Tunnels

An important source of error or uncertainty in wind-tunnel measurements is connected with the degree of turbulence in the main stream. All attempts to measure the turbulence in the free atmosphere indicate that its magnitude, in so far as it affects the boundary layers on aircraft, is very small, if not essentially zero. Therefore, representative model tests should be made in an airstream of low turbulence. This guiding principle is recognized today and modern wind-tunnel designs are greatly affected by it.

A measure of the magnitude of turbulence is the ratio of the root-mean-square value of the fluctuations in wind speed to the mean speed. These fluctuations originate at the surfaces over which the air must pass—i.e., propeller, guide vanes, etc.

The effects of turbulence on the aerodynamic forces acting on a body are known in general and are directly or indirectly attributable to its influence on the location on the body of the transition from laminar to turbulent flow in the boundary layer. The effect on skin friction is that the transition from laminar to turbulent flow in the boundary layer moves forward on the plate as turbulence increases. The result is an increase in skin friction. Dryden [5] reported some results obtained at the Bureau of Standards in which the Reynolds number of the transition point from the laminar to the turbulent boundary layer changed from 1×10^5 to 1.1×10^6 as a result of a decrease in the turbulence number of the main stream from 0.03 to 0.005.

For a body which has extensive and severe adverse pressure gradients, earlier transition, as caused by increased turbulence, is likely to cause the separation point to move rearward, thus decreasing the size of the turbulent wake and decreasing the total drag. This phenomenon is demonstrated by curves of the drag of circular cylinders and spheres *versus* the Reynolds number. On an airplane wing at high angles of attack, delaying the separation results in an increase in the maximum lift coefficient.

Hot-Wire Anemometer

Measurements of the magnitude of turbulence are made by means of the hot-wire method. A fine wire is placed in the airstream normal to the flow and heated electrically. The fluctuations in wind speed cause fluctuations in the temperature and voltage drop across the wire; these fluctuations are transmitted to an amplifier. The output from the amplifier may be impressed across an oscillograph for a visual record, or the mean-square value of the fluctuations may be read by means of a thermogalvanometer.

The frequencies present in a turbulent airstream at reasonable speeds range from very low values to several thousand per second. The temperature fluctuations of the hot-wire will not follow high-frequency fluctuations accurately, and it is therefore necessary to compensate for the drop in the response with frequency. This is done electrically by a filter circuit in the amplifier which causes the high frequencies to be amplified more than the low frequencies in the same ratio as they are cut down by the lag of the hot wire. The working of this filter circuit is such that it introduces an attenuation factor which may be as low as 0.01. In practical circuits the voltage fluctuation may have an amplitude of 0.0001 volt; the amplifier plus compensation has a voltage gain of about 50,000. Without the compensation circuit with its attenuation factor of 0.01 the gain would be 5,000,000. The additional requirement that the amplifier must have a flat response (constant amplification) from about 10 to several thousand cycles per second imposes another difficult condition. As a result, the apparatus is not a standard laboratory instrument but rather a research tool requiring close attention and frequent checking.

The lag of the response of the hot wire can be made small by

using hot wires of small diameter. Those in use today are around 0.0002 inch in diameter and about 0.10 inch long.

The single hot wire measures fluctuations in wind speed; wind direction can be measured by placing two hot wires at an angle to each other and to the mean wind direction and amplifying the difference between the response of the two.

The hot-wire instrument is applicable to the measurement of practically all of the significant velocity fluctuations and correlation coefficients involved in present turbulence theories. The correlation coefficient, defined as the relative mean value of the product of two or more instantaneous values of the velocity fluctuations at different points, is used extensively in the turbulence theories evolved by Taylor and von Kármán. Two or more hot wires placed at variable distances apart can be adapted to these measurements.

Various investigators have tried to use the hot wire in water. These attempts have not been successful for the reason that so much electrical energy is required to heat the wire that hot spots develop when dust particles or air bubbles strike the wire. As a result the wires frequently burn out.

Transition from Laminar to Turbulent Flow in the Boundary Layer

Transition from laminar to turbulent flow in the boundary layer
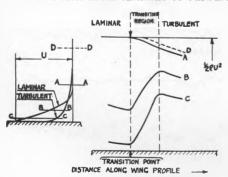

FIG. 7.—LAMINAR AND TURBULENT BOUND-ARY LAYER VELOCITY PROFILES [4]. Traverses of $\rho v^2/2$ along lines A, B, C, D, through the transition region are shown.

may be effectively detected in two ways. Both methods depend upon the fact that as we move backward along a surface the velocity at a small distance from the surface rises when we pass through the transition region. This results from the fact that the velocity gradient at the surface in turbulent flow is many times greater than it is in laminar flow. Fig. 7 shows the laminar and turbulent layer

and the change in $\rho V^2/2$ at various stations in the transition region. The instrument for utilizing this phenomenon to detect the transition point is shown in Fig. 8. It consists of several total-head tubes at various distances from the surface. The tubes are flattened and in the direction of the flow one of them presses against the surface. The regis-
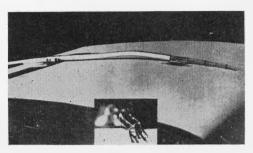

FIG. 8.—PHOTOGRAPHS OF A FIVE-TUBE HEAD USED FOR EXPLORING THE BOUNDARY LAYER IN FLIGHT [4].
The four tubes with slit openings measure the total head at various stations through the boundary layer. The tube with rounded end measures static pressure.

tration of the instrument when connected to a manometer and moved along the surface is shown in Fig. 7.

The hot wire has also been employed to utilize this effect. The transition region is characterized by an increase in the mean velocity near the plate. However, the transition region is in many
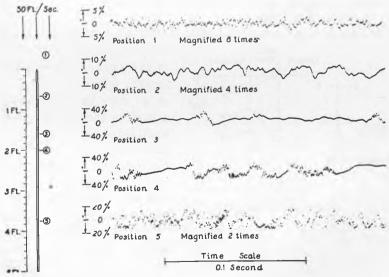

FIG. 9.—WIND-SPEED FLUCTUATIONS AT SEVERAL POINTS NEAR A PLATE [5].

cases more easily detected by observing the fluctuations in velocity. Fig. 9 shows fluctuations in the transition region, as well as in the laminar and turbulent boundary layers and in the free stream. The increase in the frequency of the fluctuations from the laminar to the turbulent regimes is particularly noticeable. The transition region (see positions 3 and 4) is characterized by relatively sudden "bursts" of high frequency fluctuations. These results indicate that the transition to the turbulent regime is sharp but its position moves back and forth along the plate.

The magnitude of the fluctuations is also a reliable indication of the location of the transition region. The fluctuations are high in the transition region and drop off appreciably ahead of as well as behind the transition.

Unsteady-Flow Problems

Problems in unsteady flow are particularly adapted to the hot-wire method. One of the most important of these is the stalling of airfoils. Some of the factors governing the stall are susceptible to analysis—for instance, the separation point of the laminar boundary layer—but the prediction of the stalling point of an arbitrary airfoil is not possible on the basis of present theories. A detailed study of the unsteady flow conditions at angles of attack near the staff would provide valuable data for the formulation of such a theory.

The problem of the stalling of a finite wing is being attacked at the University of Michigan. Spanwise flow develops at high angles of attack of a swept-back or swept-forward wing and results in a convergence of the flow in the boundary layer over some parts. The details of this flow are being studied with a view to determining conditions near and at the stall. The instrumentation and techniques thus developed should be applicable to a study of the stalling of the two-dimensional wing section.

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