Brief History of Gust Models for Aircraft Design

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Nomenclature

a = slope of the wing-lift curve, per rad
S = wing area
U = gust velocity
V = airplane velocity
W = weight of the airplane
Δn = increment in load factor
ρ = air density

Introduction

THE effect of atmospheric turbulence on the dynamic responses of flight vehicles has been an ongoing subject of vital interest since the earliest days of airplane design, as indicated by Ref. 1, the first report of the National Advisory Committee for Aeronautics (NACA). [NACA was reorganized into the National Air and Space Administration (NASA) in 1958.] Over the years, substantial literature has accumulated, including several summary reports at different stages of the growing understanding of the subject. Two relatively recent documents are reported in Ref. 2, which provides a comprehensive treatment from the viewpoint of structural-load determination, and Ref. 3, which covers the effects of turbulence on airplane flying qualities.

Further interest in this subject from the standpoint of establishing design standards was shown by the International Standards Organization (ISO) in early 1993 when it promulgated Ref. 4, which proposes standard mathematical models for the motions of the atmosphere. Aerospace engineers in the U.S. have typically not been involved with ISO standards, but there are increasing pressures in that direction. It should be noted that an AIAA standard issued in 1992[5] used ISO 1151-1[6] as a base, with modifications to be compatible with U.S. practice. (Reference 5 was developed by the AIAA Atmospheric Flight Mechanics Working Group, of which the author was a member. The various parts of ISO 1151 deal with motions of the aircraft relative to the air and the Earth, terms and symbols for flight dynamics, quantities used in measurements, aircraft geometry, flight points and flight envelopes, and dynamic characteristics of the aircraft.) Because of the possible future impact on U.S. standards, the proposed addition to ISO 1151 to establish standard gust and turbulence models must be of concern to us. These events motivated this Note to review some of the history of gust models and, in particular, to place in the historical record the circumstances by which the "1-minus-cosine" or "versine" discrete gust shape was established.

Discussion

The foundation for modern unsteady aerodynamics was established by Wagner,[7] which was extended by Jones[8] to wings of finite aspect ratio. Wagner's lift-lag function was applied to the entry of an aircraft into gusts by Küssner.[9] He derived the solution of the response of an airplane in the vertical plane, assuming no pitching, for the sharp-edged gust and for a gust with a linear gradient to the point of maximum gust velocity. Rhode and Lundquist published Ref. 10 a year before the Küssner paper; that report presents the "sharp-edged" gust equation as the basis for computing the applied load factor experienced by an aircraft flying from calm air into a gust blowing normal to the flight path. This is the familiar expression:

$$\Delta n = \frac{\rho U V a}{2W/S}$$

Gust velocities calculated from this formula and measured accelerations are "effective gust velocities" related to the aircraft in which the measurements were made. Based on early acceleration data, supplemented by information from meteorological sources, a value of 30 ft/s was accepted for design purposes. Küssner[9] had already given 15 m/s (49.2 fps) as a "true" gust velocity. Reference 10 also includes estimated true gust velocities up to 4000 ft alt of up to 22 fps due to convection currents, 27 fps or more due to obstructional disturbances, 43 fps in line squalls, and 108 fps calculated from large observed hail sizes. Since aircraft have always avoided flying through intense thunderstorms, except for special studies, the largest values were not considered necessary for structural design.

The treatment of gust loads on a statistical basis was undertaken in the 1930s by collecting statistical data on gust loads experienced by commercial aircraft. The data were collected using V-g recorders, which used a stylus scratching on a smoked glass, driven by an airspeed sensor in the horizontal direction and an accelerometer in the vertical direction. After many hours of flight, the center portion of the glass was wiped clean, leaving only the extreme values clearly visible. This enabled a statistical description of the largest gust loads and airspeeds encountered as a function of a large number of flight hours. This is described by Rhode,[11] which shows the inadequacy of the simple sharp-edged gust formula in that it was unconservative for heavy aircraft and overly conservative for light aircraft. Rhode used the response solutions of Küssner to resolve this discrepancy. He also included a brief analysis of the energy content of air as a function of its volume to show that increasing gust velocity must be associated with increasing distances to peak velocity, and that even the gradients may decrease. This conclusion is shown to follow reasonably well the limited amount of data then available. During the period from 1933 to 1937, a considerable amount of data was collected on V-g recorders from operations of the Boeing B-247 transport airplane.[12] This airplane had a gross weight of 13,400 lb, and a wing loading of 16 lb/ft². It had higher gust loads than other aircraft due to a higher operating speed relative to design maximum level flight speed. The gust data are presented in the form of Pierson Type III probability curves and the flight miles to exceed a given gust velocity. Limit gust load was exceeded in about 2.5×10^6 flight miles. The V-g data was supplemented later with oscillographic records that provided data on the higher frequency of occurrence of small gusts.

In 1949 Donely published Ref. 13, which was a landmark report in summarizing all of the work that had been performed and reported in the previous two decades. He explained that because of the complexity of the problem in determining the response of an aircraft to gusts, it was decided to use the B-247 airplane as a reference, assuming that all aircraft of that time period had the general response characteristics of the B-247. Gust velocities were defined as "effective" gust velocities as determined from the response of the B-247, using the simple sharp-edged gust formula with no alleviation factor. An alleviation factor is then defined as the response of another aircraft relative to that of the B-247. The Küssner response solutions given in Refs. 9 and 11 were used. Since these give responses as a function of chord lengths traveled, the gradient distance of the gust was defined in chord lengths. The gust velocity distribution was defined as a linear ramp function rising to a maximum in 10 chord lengths traveled. Also, the alleviation factor was made a function of wing loading only for simplicity, rather than the mass ratio $2W/S/\rho gac + \frac{1}{4}$, as it appears in Küssner's equation, where c is the mean aero-

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dynamic chord and all other variables are as defined previously. The chord for the B-247 was 11 ft, and the range of chords for aircraft of the early 1940s was 4 ft for the Aeronca C-2 and 19 ft for the XB-15 bomber. Reference 11 shows that chord length is not a significant parameter for gradient gusts, so wing loading was considered to be an acceptable approximation for mass ratio. The "alleviation factor" thus defined is zero at zero wing loading, goes through unity at $W/S = 16$ lb/ft^2, and rises to values greater than unity at higher wing loadings. This had been incorporated in the Civil Air Regulations some time before, with a value of effective gust velocity of 30 ft/s for determining design limit gust load. This is shown in Ref. 14, which is a manual showing the user how to apply the regulations. Table III of Ref. 12 shows the numbers of gusts measured at different intensities and at different altitudes. Very few gusts are shown above 30 ft/s (effective), the largest gusts occurring between 15,000–25,000 ft. The largest gust reported was 55 ft/s (effective), corresponding to a true gust velocity of about 100 ft/s.

It is not clear from the references why a single value of gust velocity over a range of spatial gradients was chosen for design, notwithstanding earlier indications that the higher gust velocities are associated with longer gradients. Probably, there was not enough data available to enable a rational definition of this relationship. Even including the alleviation factor, the use of a single gust velocity tends to be somewhat conservative only for small, low-speed aircraft, but these are more likely to be designed for maneuvering loads than for gust loads. The choice of a gust shape of a ramp function of 10 chord lengths to peak value was based on oscillographic recordings of gust loads, from which it was noted by the NACA that the maximum gust loads in the records tended to rise to a peak in 10 chord lengths traveled. Donely[13] mentions the possibility of defining discrete gusts as sinusoidal, flat-top following a ramp, and triangular.

By the early 1950s, the designs of aircraft differed more widely and the need to take structural-dynamic response into account became evident. Therefore, the ANC-1 Flight Loads Subcommittee of the NACA convened to update and standardize gust-load requirements among the three services. (Note: ANC stood for Air Force-Navy-Civil.) The objective was to discontinue the concept of an effective gust velocity having a 10-chord linear ramp, and instead, to define a more rational discrete gust for rigid-body and structural-dynamic analyses. Also, this design gust was intended to more closely represent actual gust velocities in the atmosphere. Any representation of a discrete, single gust is idealized, of course, because gusts usually do not occur in isolation.

The ANC-1 Flight Loads Subcommittee considered both the first half cycle of a sine wave, proposed by this author, and a single full cycle of a 1-minus-cosine function, proposed by Walter Boccius, the Air Force representative, as possible definitions for the shape of the idealized discrete gust. The latter was selected because it did not have a discontinuity at time zero. Donely[13] of the NACA was then asked to reevaluate its oscillograph records in terms of the calculated airplane response to the 1-minus-cosine gust shape. His conclusion was that the way the records had been read, the definition of 10 chord lengths from zero to peak would correspond to the beginning of a tangent to the 1-minus-cosine

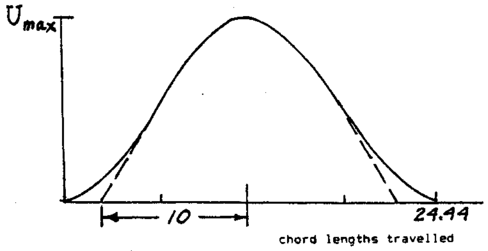

Fig. 1 NACA evaluation of 1-minus-cosine gust shape.

curve at one-fourth of the cycle, as shown in Fig. 1. It can be calculated that this will give a total cycle length of 24.44 chord lengths, which was rounded up to an even 25 chord lengths. This was adopted for Air Force, Navy, and Civil (Federal Air Regulation) requirements. The response of aircraft in the vertical plane to this new gust, assuming no pitching, was determined and a new curve of gust alleviation factor Kg was developed as a function of "mass ratio," $\mu_g = 2W/S/\rho gca$. Kg is approximated by the expression

$$\frac{0.88\mu_g}{5.3 + \mu_g}$$

for subsonic aircraft. With this new response factor, the NACA re-evaluated its statistical data[15] to compute probabilities of occurrence of "derived" gust velocities, which they pointedly did not want to call true velocities, but were nevertheless considered to be more representative of actual atmospheric gusts. With the new gust-alleviation factor, a gust velocity of 50 ft/s was selected for design purposes by all three services. The Federal Air Regulations for civil aircraft specifies this velocity in combination with design cruising speed, whereas the military specifies maximum level flight speed. A 25-ft/s gust at maximum dive speed, and a 66-ft/s gust at a lower speed for flight in heavy turbulence were also specified in both civil and military requirements. These standards were adopted in the early 1950s and continue almost unchanged in today's requirements.

In the 1940s, papers began to appear in the fields of both aeronautical and electrical engineering on the response of dynamic systems to random inputs. By the mid-1950s, there was a growing interest in the determination of airplane rigid-body and structural-dynamic response to atmospheric turbulence treated as a stationary random field of gust velocities. This was especially so because of the importance of structural modes of vibration higher than the fundamental, with respect to repeated loads and structural fatigue. The NACA and, subsequently, NASA, published a number of reports on the description of the atmosphere in terms of the power spectra of gust velocities and flight-vehicle responses to them. A comprehensive presentation of these developments is given by Houbolt et al.,[16] which shows the analogy between discrete-gust and power-spectral methods of analysis. They concluded at that time that power-spectral techniques would eventually be used to predict gust loads on an absolute basis. This prediction has come true in present-day civil and military specifications, which include both discrete-gust and power-spectral methods for analysis. The structure must be designed for the greater of the loads resulting from these two approaches. Finally, a more recent paper that also compares discrete and continuous gust methods is Ref. 17. It is made clear in this paper that the essential difference in the methods is in the use of a single gust velocity for gusts of different lengths in the discrete method, whereas the power-spectral approach embodies a variation of gust velocity as a function of wave length. In view of the fact that it was recognized 60 yr ago that gust velocity must vary with length, current discrete-gust requirements will eventually decline in significance, and, certainly, the 10-chord ramp function should not be perpetuated. Although turbulence models have been put into specifications for aircraft structural strength and flying qualities, the inclusion of a number of mathematical turbulence models in the proposed standard of Ref. 4 indicates that there is still no consensus as to what should be used as design standards in general, including, e.g., for structural strength of other flight vehicles, or for error analyses of the trajectories of missiles and projectiles.

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Effect of Ground and Ceiling Planes on Shape of Energized Wakes

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Nomenclature

b = span of actuator
ds = increment along wake edge
h = height
$\dot{m}$ = mass flow through wake
U_∞, V_∞ = freestream velocity components
u, v = velocity components in x, y directions
x = distance in horizontal direction
y = distance in vertical direction
γ = circulation

Subscripts

c = ceiling
g = ground or floor plane
t = tunnel

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Introduction

DURING the planning and design stages of the 80- by 120-ft Wind Tunnel at NASA Ames Research Center, a variety of circuit and test section configurations were considered for the new structure. It was desired that a test section arrangement could be found that would permit the testing of helicopters and augmentors from zero forward velocity, or hover, up to full forward speed. If this were possible, one experimental setup could be used to test the device over its full speed range, thereby saving time and expense to obtain the needed data. In order to accomplish such a goal, the necessary wind-tunnel wall corrections must be available, and the configuration of the test section must be such that excessive interference does not occur. With the technology currently available, interference from the walls of the wind tunnel when powered-lift models are being tested is a difficult but manageable procedure when the freestream velocity is not too small.[1–12] However, as the test section velocity approaches zero, the energized wakes of rotors and augmentors may begin to recirculate so that a portion of the energized wake re-enters the rotor or augmentor. A method of correcting for interference of this kind is not currently available. In order to test at hover and low wind-tunnel speeds, it is therefore necessary that the sidewalls of the wind tunnel have openings that allow the energized wakes to exit the facility without recirculating (Fig. 1). It is then only necessary to determine the factors, or procedure, needed to correct for the presence of the floor (ground) and ceiling planes of the wind tunnel (Fig. 2). In an effort to obtain an estimate of the magnitude and variation of such a correction on the performance of rotors, experiments[13,14] were conducted with a rotor of 12.75 in. diam between large plywood surfaces that represent the ground and ceiling planes of the wind tunnel. Although the configurations tested only covered one blade angle and one rotor diameter, the combination of ground- and ceiling-plane distances were extensive. In addition to the accumulation of data on the variation of thrust with proximity of ground and ceiling planes, it was found that the thrust of the

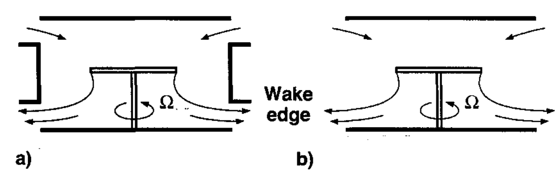

Fig. 1 Wind-tunnel cross sections that illustrate how energized wakes of a rotor can exit the test section without recirculating. Side walls a) partially and b) completely open.

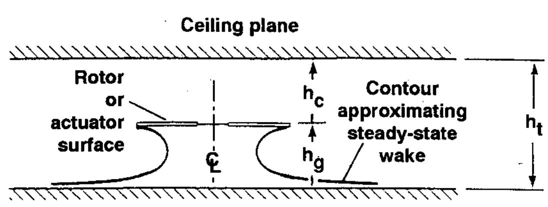

Fig. 2 Cross section of energized wake in the presence of ground and ceiling planes when side walls are not present.