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Evolution of Airplane Gust Loads Design Requirements

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Nomenclature

a = lift curve slope, per rad
a_n, b_n = Fourier series coefficients for c.g. acceleration
c = wing mean geometric chord, ft
F_g = flight profile alleviation factor
F_{gm} = flight profile factor due to airplane weight
F_{gz} = flight profile factor due to altitude
g = acceleration due to gravity, 32.2 ft/s
g_n, h_n = Fourier series coefficients for true gust velocity
H = gust gradient distance, ft
K, K_g = gust load alleviation factors
L = scale of turbulence, ft
M = Mach number
q = dynamic pressure, psf
R_1 = maximum landing weight/maximum takeoff weight
R_2 = maximum zero fuel weight/maximum takeoff weight
S = wing area, ft^2
s = distance along flight path, ft
T = local atmospheric temperature, °R
T_n, I_n = real and imaginary parts of the c.g. acceleration transfer function
T_0 = ambient atmospheric temperature, °R
U = gust velocity, fps, true airspeed
U_{de} = derived equivalent gust velocity, fps, equivalent airspeed
U_{ds} = design gust velocity, fps, equivalent airspeed
U_{dt} = derived true gust velocity, fps, true airspeed
U_{ref} = design reference gust velocity, fps, equivalent airspeed
U_σ = power spectral scale factor
V = aircraft velocity, fps, true airspeed
V_B = rough air penetration speed, Kt, equivalent airspeed
V_C = design cruise speed, Kt, equivalent airspeed
V_D = design dive speed, Kt, equivalent airspeed
W = aircraft weight, lb
Z_{mo} = maximum operating altitude, ft
γ = ratio of specific heats
Δn = incremental load factor, g
μ_g = airplane mass parameter
ρ = air density, slugs/ft^3

Introduction

SUBSONIC aircraft respond to atmospheric turbulent air motions or eddies of, approximately, 30–2000 ft in extent. Smaller eddies will generally be averaged out over the surface of the aircraft, larger eddies typically will not cause sharp or excessive aircraft accelerations or structural loads on the airplane. Aircraft in supersonic flight respond to ever longer wavelengths as the flight speed is increased.

From the aircraft design standpoint, atmospheric turbulence may be separated into two categories: 1) turbulence, which contributes to aircraft structural fatigue and passenger inconvenience and discomfort, is generally associated with the less intense, smaller scales (small eddy size or higher spatial frequencies as characterized by the turbulence power spectrum); and 2) turbulence that can cause aircraft upset, passenger injury, and possibly structural damage or failure is associated with the more intense larger scales of the turbulence spectrum. Whereas the first category may be in the inertial subrange of the turbulence power spectrum where local homogeneity and stationarity may be assumed, the second category is definitely associated with the larger energy-containing scales of turbulence that are definitely nonstationary and inhomogeneous. In fact, the second type of atmospheric turbulence may not be turbulence at all, but may be a part of, or derive directly from, the ordered convective or geostrophic motions of the atmosphere.[1]

Frictionally induced turbulence in the planetary boundary layer is dependent on wind speed near the ground and the surface roughness. Convective turbulence in the planetary boundary layer is dependent on the lapse rate (the rate of temperature change with altitude) and the depth of the mixing layer. Thus, the wind speed and surface roughness and the lapse rate and mixing layer thickness largely determine the intensity and scale of the boundary-layer turbulence. This low altitude boundary-layer turbulence will affect landing and takeoff operations for the larger commercial aircraft that normally cruise at high altitude, and it will be the primary cause of disturbance for small aircraft that operate at low altitudes. Usually, it can be characterized as random, locally stationary, and Gaussian, and the turbulence scale at the surface is of the order of 1000 ft and increases with altitude.

It is only natural that pilots avoid flying into areas of obviously rough air such as thunderstorms or even cumulus clouds;

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however, they often encounter extreme turbulent conditions in clear air without warning. Clear air turbulence (CAT) caused a great deal of consternation in the 1960s when high altitude commercial jet flight became more prevalent. There were several CAT encounters of a catastrophic nature. One of the first was an encounter off Gander, Newfoundland, by a Boeing 707 aircraft. The crew lost control as a result of the encounter, went into a dive, but recovered at low altitude even though severe structural damage was sustained.

As a result of these early encounters various study groups of aeronautical and meteorological specialists were formed to address the problem. The National Committee for Clear Air Turbulence in a 1966 resolution (U.S. Department of Commerce, 1966) adopted the following definition of clear air turbulence (CAT): "CAT comprises all turbulence in the free atmosphere of interest in aerospace operations that is not in or adjacent to visible convective activity. This includes turbulence found in cirrus clouds not in or adjacent to visible convective activity." The problem was largely resolved when it was realized that loss of control could be prevented, or at least alleviated, by defining piloting procedures to prevent upset. Also, airborne look-ahead radar has allowed more avoidance of convective turbulence.

Most CAT experienced by aircraft is of a patchy or pancake nature. Most of these patches seem to have horizontal dimensions of less than 50 n.mi. and are often restricted to rather thin altitude bands. A subsonic jet airplane traveling at 500 KTAS (knots, true airspeed) would traverse such a patch in less than 6.0 min, and the turbulence intensity would be expected to vary considerably over that short time period. In general, the average duration of the turbulence encounters decreases as the turbulence intensity increases. Also, the average value of the aircraft's airspeed fluctuations increases as the turbulence intensity increases. These observations would seem to support the idea that the area becomes turbulent as a result of the breakdown of some primary flow, and strong turbulent eddies form, breakup, and continue to spread out and decay. If the driving energy source subsides, the turbulent area disappears as the eddies become smaller and weaker.

Studies have pointed out the importance of both upper level troughs and jet streams with strong vertical wind shear in the development of CAT. They have confirmed that curved segments of jet streams are more conducive to CAT than straight segments, and have pointed out that regions in which the values of wind speed, vertical and horizontal wind shear, and contour gradients increasing with time are conducive to CAT. Study has shown the importance of sharply curved flow patterns, both cyclonic and anticyclonic, in producing severe turbulence along the jet stream.

Severe turbulence is also associated with the breaking of internal gravity waves in the atmosphere. The breaking of these waves may occur because of some local instability or because of the existence of outside disturbances, e.g., the disturbances set up in airflow over mountains. It is well known that waves are possible in the air flowing over mountains and hills because of the buoyancy forces that exist in the normally stable atmosphere. It has become apparent from theory and experiment that disturbances can be sufficiently large to lead to local gravitational instability and severe turbulence. This comes about in one of two ways.

1) If a mountain wave gets large enough, it can create within itself large vertical shears. If the shear becomes great enough, local disturbances can become unstable and develop into turbulence.

2) Probably the main cause of turbulence in large mountain waves is the overturning instability that develops as the wave amplitude increases to the extent that the local air density variation with height reverses, potentially yielding heavy air over lighter air resulting in a Kelvin-Helmholtz instability. Generally, breaking gravity waves occur at or near cruise altitudes for jet aircraft.

Rotors (horizontal standing vortices) may form when the amplitudes of mountain lee waves become large. Rotor clouds develop in standing eddies that form the lower layers under the crests of the mountain wave. The upper region of a rotor moves in the windward direction while the lower portion moves backward towards the mountain. A succession of rotor clouds may form at regular intervals downwind from the ridge. The bases of rotor clouds are generally near or below the ridges, yet the tops may be considerably higher and may merge with the lenticular clouds above. Rotors are hazards for lower altitude climbout and descent operations.

Lenticular clouds in mountain waves are frequently visible above the rotors. Unlike the lenticular clouds, rotor clouds show evidence of strong and occasionally violent turbulence. However, rotor clouds often provide the only visible evidence of the mountain wave, depending on the moisture profile of the atmosphere. There have been a number of incidences involving rotors in recent years. A brief review of some of the accidents or incidences involving rotors in the past 30 yr includes the following.[2]

About 75% of the vertical stabilizer and rudder of a Boeing B-52 bomber were lost while flying at 350 KIAS (knots, indicated airspeed) at a pressure altitude of 14,300 ft, 5.4 miles east of Spanish Peak in Colorado, on January 10, 1964. The ground elevation was about 8500 ft. The mountain top level was 13,500 ft. Boeing estimated that the maximum gust velocity exceeded 140 ft/s during this event.

Structural failure occurred on a BOAC 707 while flying between 320–370 KIAS at 16,000 ft, about 4 miles east of the summit of Mt. Fuji, Japan, on March 5, 1966. There was a strong mountain wave system leeward of Mt. Fuji. The aircraft suddenly encountered abnormally severe gust loads exceeding the design limits and disintegrated in the air.

A BAC-111 experienced structural failure between 2000–3000 ft near Falls City, Nebraska, on August 6, 1966. Ground witnesses observed the aircraft fly into or over a rotor cloud preceding a thunderstorm and shortly thereafter saw an explosion in the sky followed by a fireball falling out of the cloud. In this case, the rotor was associated with the outflow of cold air from an approaching squall line. The forces and accelerations produced by this encounter caused failure of the fin and right tail-plane.

In-flight structural failure was experienced on a Fairchild F-27B, flying at approximately 11,500 ft and 220 KIAS, resulting from an encounter with severe to extreme turbulence on December 2, 1968, at Pedro Bay, Alaska. A rotor region was estimated to have existed over the northern tip of Pedro Bay. The investigation showed that the right outer wing, the empennage, portions of the left wing, and other components of the aircraft structure had separated from the aircraft in flight.

On March 3, 1991, a United Airlines Boeing 737, on a scheduled passenger flight from Denver, Colorado, to Colorado Springs, Colorado, was lost shortly after completing its turn onto the final approach to Colorado Springs Municipal Airport. The airplane rolled steadily to the right and pitched nose down until it reached a nearly vertical attitude before hitting the ground. The National Transportation Safety Board, after an exhaustive investigation effort, could not identify conclusive evidence to explain the loss of the 737. The most likely atmospheric disturbance to produce an uncontrollable rolling moment was a rotor produced by a combination of high winds aloft and mountainous terrain. Conditions were conducive to the formation of rotors, and witness observations support the existence of a rotor at or near the time and place of the accident.

On March 31, 1993, the no. 2 engine and engine pylon separated from Japan Airlines, Flight 46E, a Boeing 747-121, shortly after departure from Anchorage, Alaska. The airplane was substantially damaged during the separation of the engine. Nobody onboard the airplane or on the ground was injured. After takeoff, at an elevation of about 2000 ft, the airplane experienced an uncommanded left bank of approximately 50 deg. While the desired airspeed was 183 KIAS, the airspeed fluctuated about 60 KIAS from a high of 245 KIAS to a low of 170 KIAS. Shortly thereafter, the flight crew reported a huge yaw, the no. 2 throttle slammed to the aft stop, the no. 2 reverser indication showed thrust reverser deployment, and the no. 2 engine electrical bus failed.[3]

Several witnesses on the ground reported that the airplane experienced several severe pitch and roll oscillations before the engine separated. Shortly after the engine separated from the airplane, the flight crew declared an emergency, and the captain initiated a large radius turn to the left to return and land. The National Transportation Safety Board determined that the probable cause of this accident was the separation of the no. 2 engine pylon due to an encounter with severe or possible extreme turbulence. Flight 46E took off toward the mountains and encountered severe and possible extreme mountain wave and mechanical turbulence on departing Anchorage.

It might be concluded that if the effect of mountain wave activity is dominant in causing severe CAT, the frequencies would be higher over land than over water. On the other hand, if the turbulence is mostly due to upper level troughs, ridges, and jet streams, the difference would not be so great. In any case, the difference in the frequency of severe turbulence over land as compared to that over water has not been found to be as great as expected.

If ordered atmospheric flow phenomena are considered as the energy suppliers to the resulting turbulent flow, then, attention to the ordered phenomena may enhance our understanding the limits of velocities possible in vortex and wave motions in the atmosphere and the characteristic sizes or wavelengths. It is known in fluid dynamics that vortex or wave motion, when generated from instability and breakdown of rectilinear shearing motion, has the characteristic velocity and scale of that motion. Thus, in the atmosphere, rectilinear motion, such as the jet stream or such as vertical flow up the tube of a convective cell, such as a tornado, a thunderstorm, or a hurricane, may generate vortical motion with maximum circular velocity of the order of the maximum velocity in the rectilinear motion and with lateral extent of the order of the width of that rectilinear motion.

To initiate and to challenge research effort on ordered wave and vortex motion of mesoscale size (less than 20 km) in the atmosphere, Pao and Goldberg put forward an overview of pertinent data (Table 1) showing the maximum wavelengths and associated velocities observed for various classes of atmospheric events. The same information is also summarized in Figs. 1–3.[1]

Table 1 Characteristic half wavelengths and velocities for atmospheric disturbances

Disturbance	Half wavelength, ft	Maximum velocity, fps
Hurricane, horizontal	100,000	150
Hurricane, horizontal	250,000	200
Hurricane, vertical	100,000	20
Jet stream, crest	1,000	485
Jet stream, meander	32,000	485
Mountain wave, lee wave	46,000	70
Mountain wave, rotor	8,000	70
Thermals	3,300	50
Thunderstorm, cumulus	16,000	30
Thunderstorm, dissipative	22,000	70
Thunderstorm, mature	31,000	100
Tornado, horizontal	150	250
Tornado, horizontal	600	150
Tornado, tube up	50	220
Tornado, tube up	100	130
Tornado, tube up	1,300	40

The striking characteristic of this data is the fact that the maximum velocities are in the range of 300–500 fps, independent of scale size. The simplest physical explanation is that the maximum potential difference in temperatures observed in the atmosphere between adjoining air masses, independent of size, is 20°F. If this temperature difference (°R) is inserted into the one-dimensional isentropic fluid flow equation, one arrives at approximately 500 fps for the resulting air velocity:

$$M^2 = [(T_0/T) - 1](2/\gamma - 1)$$

Thus, the simplest theory of air motion applied to the most elementary atmospheric data yields self-consistent results for

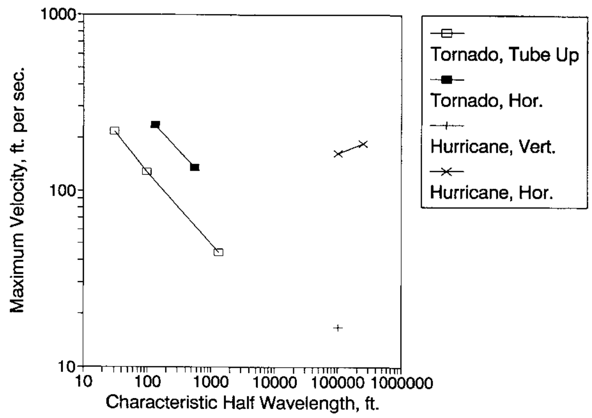

Fig. 1 Observed wavelengths and velocities in the atmosphere, tornados and hurricanes.

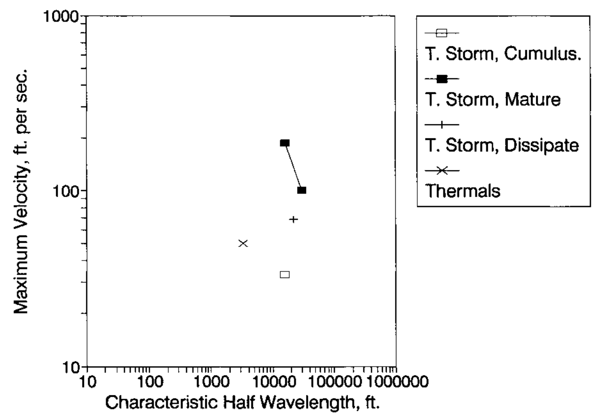

Fig. 2 Observed wavelengths and velocities in the atmosphere, thunderstorms and thermals.

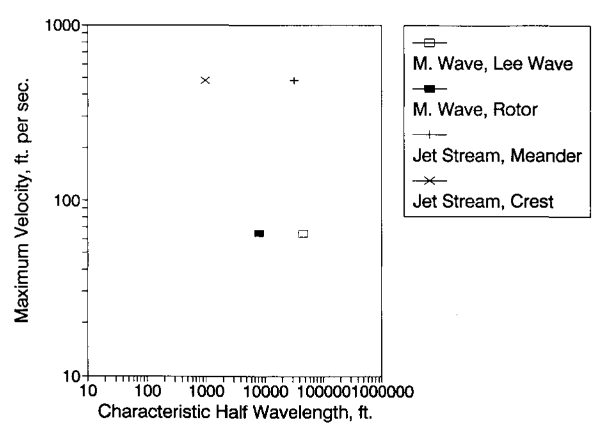

Fig. 3 Observed wavelengths and velocities in the atmosphere, mountain waves and jet stream.

ordered atmospheric motion of mesoscale size. The ordered motion of mesoscale size contains the critical scale lengths for the dynamic response of modern civil jet aircraft. Thus, it is essential that the meteorological sciences press forward to analyze the details and occurrence statistics of ordered atmospheric motions affecting aircraft responses according to the most advanced understanding of the laws of fluid dynamics and nonequilibrium thermodynamics. In the interim, the aeronautical engineer must set design loads criteria to provide adequate airplane strength for rough air operations. This effort began almost 80 yr ago in a study of the effects of gusts on airplanes.

Gust Load Formulas

It was recognized early in the evolution of the airplane that atmospheric turbulence produced structural loads that could be of concern; it is of interest that NACA (U.S. National Advisory Committee for Aeronautics, now NASA) report no. 1, published in 1915, was entitled, "Theory of an Aeroplane Entering Gusts."[4] This report showed analytically the effects of gusts and that the gust component normal to the flight path was most effective in imposing loads on the aircraft. The basic gust loads equation was formulated almost at the beginning of gust loads studies, and this general equation has prevailed to the present time as the basis for determining design gust loads. Consider that an airplane encounters a sharp edge or step function gust of intensity U; if we use quasisteady aerodynamics and assume no vertical motion of the airplane, the incremental lift due to the gust is given by

$$\Delta L = aqS(U/V) = a(\rho V^2/2)S(U/V)$$

where U/V is the angle of attack in radians due to the gust encounter. According to Newton's second law, the vertical acceleration increment, in g units, implied by the lift force is

$$\Delta n = a\rho VU/(2W/S)$$

The sharp-edge gust concept was reported in 1931 and led to the first gust loads regulation in 1934. Prior to 1934, maneuver load factors for all aircraft, including those used for passenger transport were high, in the range of 3.5–8.0 g. In 1934, maneuver load factors for transports were reduced to the range of 2.5 to 4.0 g. The cruising speed of the then newly designed Boeing 247 airplane was about double that of the previous Ford Tri-motor (the first effective U.S. transport airplane introduced in 1926), but the wing loading W/S of 16 psf was about the same. Thus, the possibility of gust loads becoming critical became significant, because the sharp-edge gust formula would indicate that Δn would vary directly with the airplane speed V if the wing loading W/S remained the same.

The characteristics of the Boeing 247 were considered so significant that they were used as the standard for comparing the gust loads on other transport airplanes. The Douglas DC-3, in 1935, had all the features of the Boeing 247, plus a capacity of 21 passengers and split-type landing flaps. The maximum airspeed of the DC-3 was 255 mph and the wing loading was 25.3 psf. The increase in wing loading tended to reduce the gust load factor. This period saw the beginning of rapidly increased wing loadings to the present value of over 150 psf. The higher wing loadings reflect the rapid increase in operating airspeeds.

The development of the bomber in World War II with altitude capabilities in the range of 15,000–30,000 ft required NACA to acquire gust measurements at higher altitudes. The XC-35 airplane, which had a pressurized cabin, was used for this purpose. In 1943, the Lockheed Constellation transport airplane was introduced, featuring many of the improvements first applied to the bombers, including a pressurized cabin.

NACA studies of flight and gust-tunnel data placed emphasis on the gust gradient distance. It was recognized that nonsteady aerodynamic effects due to gust penetration and airplane vertical response motion were present and that the airplane would move vertically to alter the load. Analysis indicated that these effects could be accounted for by introducing a factor K into the sharp-edge gust equation. In order to allow for these effects, K was calculated on the basis that the gust shape was a ramp (gust velocity increasing linearly with distance up to a limit of 10 chords), and by considering the effects of gust penetration and of the resulting vertical motion of the airplane. A small adjustment was made to the parameter K on the basis of gust-tunnel model tests and analyses to allow for the overall effects of pitching motion on the normal acceleration.

In 1941 the U.S. Civil Aeronautics Manual, Part-04 introduced the 30 fps, equivalent airspeed (EAS), 10-chord ramp gust with an alleviation factor based on wing loading. The Boeing 247 with a wing loading of 16 psf was taken as the reference airplane with an alleviation factor K equal to 1.0. The factor K was less than 1.0 for airplanes with wing loadings less than 16 psf and greater for airplanes with wing loadings greater than 16 psf. The K factor correction made to the sharp-edge gust equation implied that the acceleration would be affected to about the same degree by the pitching motion on all aircraft; this assumption was reasonable only for conventional aircraft having satisfactory flying qualities:

$$\Delta n = (a\rho VKU/2W/S)$$

In 1946, U.S. Civil Air Regulations, Part 04-D, introduced gust design in connection with the V-n (forward velocity vs airplane load factor) diagram; thus, gust design values were made dependent on airplane speed. By 1951, NACA had conducted studies of wing flexibility effects, and the CAA (U.S. Civil Aviation Administration, now FAA) added a requirement to consider transient effects on flexible airplanes. Later a more rational analysis indicated that the revised alleviation factor K_g should be a function of the mass parameter μ_g where

$$\mu_g = (2W/S/a\rho cg)$$

Note that μ_g is dimensionless and encompasses not only wing loading but also air density, chord, and lift curve slope; it derives directly from the single degree-of-freedom equation of motion for the airplane allowing only plunge freedom (vertical translation). The mass of the airplane W/g, was divided by the coefficient aqS/V, for the aerodynamic damping force and the gust excitation force. Multiplying and dividing by the chord c, yields $\mu_g c/V$ as the coefficient of the acceleration term in the one degree-of-freedom equation of motion. The units of the factor c/V are wing chords (traversed) per unit time.

μ_g was used as the sole variable in computing K_g, in the so-called revised gust load formula. A 1-cosine gust shape was used with a gradient (one-half wavelength) distance of 12.5 chords. The assumptions in the analysis were 1) the airplane is a point mass, 2) only vertical motion is allowed, 3) the gust velocity is constant in the spanwise direction, 4) the Kussner unsteady lift function is used for gust penetration effects, and 5) the Wagner function is used for airplane motion effects. K_g is related to μ_g by a simple function fitted to the dynamic analysis solutions[5]:

$$K_g = [0.88\mu_g/(5.3 + \mu_g)]$$

Elastic Dynamic Effects

As airplanes became larger, faster, and more flexible, the importance of wing flexibility in aggravating the airplane response became a concern. NACA studies showed, e.g., that structural dynamic elastic effects increased the wing bending loads on the Boeing B-29, a four-engine bomber, by 30% over that predicted by a quasistatic gust encounter.

In 1957, the revised gust formula was incorporated into the U.S. Civil Air Regulations, Part 4B-3, and the first step was taken in the development of the necessary techniques to include airplane dynamic response. At that time it became apparent that the earlier airplanes had satisfactory service and safety records even though no provision had been made in their design loads for dynamic effects that were known to be present. Thus, it became evident that the design gust velocities had been set high enough so that, for these airplanes, no increase in design loads for dynamic effects was required. On the other hand, it was obvious that, with the noted trends, the relative dynamic effects might well increase. Sooner or later, design to static loads alone could lead to aircraft structure of inadequate strength. Consequently, to prevent any deficiency in strength that might otherwise have resulted from this trend, the CAA agreed that if a manufacturer showed that the percentage increase in load due to transient dynamic effects for a new model was no greater than that of a previous model it would not be necessary to design for the increased load; however, if the increase was greater than for the previous model, this increase should be accounted for in the design loads.

This policy, reflecting what T. J. Barnes of the FAA calls the concept of "limited dynamic accountability," was applied, e.g., to the design of the Lockheed Model 1649 Constellation and the Lockheed Electra. As was the practice at that time, primary emphasis was placed on a comparison of dynamic magnification factors of wing bending moment.[6]

In this same time period, the Boeing 707, the first swept wing commercial turbojet airplane in the U.S., was being designed based on a similar military version, the KC-135 tanker-transport. Dynamic gust loads analyses were conducted for the 707 and compared with similar analyses for the Boeing Model 377 Stratocruiser. The Model 377 was a commercial derivative of the KC-97, a military tanker transport with four wing-mounted 28 cylinder radial engines and a wing design derived from the B-29 bomber. The Model 377 had enjoyed a satisfactory service life, and it was in service on long routes for several major air carriers.

In spite of much treatment of gusts on an isolated or discrete basis, the continuous nature of atmospheric turbulence was recognized. Around 1952 research efforts were initiated by NACA to apply the method of generalized harmonic (power spectral) analysis to aircraft gust loads, both in describing atmospheric turbulence by a characteristic power spectrum for true gust velocity and in quantifying the resulting airplane dynamic elastic responses by their power spectra. Power spectral methods had been used in the communications industry in their efforts to minimize noise in telephone circuits.[7]

The philosophy followed in obtaining a margin for wing gust dynamics for the 707-120 was to presume that the proper allowance for dynamics for the 377 airplane was provided by the specification criteria that were in force at the time the Model 377 wing was designed. It would appear that these criteria were at least adequate, because the 377 wing was considered to have been successfully proven in service. One way of assessing the capability of the two airplanes to sustain gust dynamic loading was to examine the so-called sigma-ratio for wing bending moments determined by power spectral analysis.[8]

The sigma-ratio was defined as the ratio of the rms wing bending moment at a given wing station determined for the fully elastic airplane divided by the rms bending moment at the same wing station for the pseudostatic airplane. The elastic equations of motion and load equations were simplified to obtain the pseudostatic or static-elastic equations of motion and load equations. These pseudostatic equations describe the behavior of the airplane, wherein the elastic deformations follow the applied gust loading. This is nearly comparable to using the static-aeroelastic lift curve slope with the revised gust formula.

Figure 4 shows the variation of sigma-ratio along the wing semispan for the 377 and the 707-120 airplanes. The incremental gust load factor, as computed by the revised gust load formula with the flexible lift curve slope, was arbitrarily increased by 40% to obtain the incremental limit design gust load factor for the 707-120. The information in Fig. 5 shows the wing strength margins available for gust dynamics on a number of Boeing airplanes. The data indicate that a margin greater than 40% was already available for gusts for the 707 series airplanes. This margin existed because of the controlling design maneuver conditions.

The FAA's major objection to a continuation of this type of approach was that detailed engineering data on the various satisfactory existing airplanes were available only to the manufacturers of those airplanes. Consequently, a manufacturer whose past airplanes may not have been gust-critical, or for other reasons may have had more than the required strength, had to design a new aircraft to more severe criteria than the manufacturer whose past aircraft happened to have less margin. Furthermore, with few exceptions, no criteria short of "full dynamic accountability" were available to a manufacturer who had no previous aircraft in operation with a long satisfactory service life.

The FAA decided to develop new gust criteria using the power spectral technique. The results of study contracts let to Lockheed and Boeing for the purpose of helping the FAA define procedures and criteria were completed in 1966.[9,10] The criteria that the FAA incorporated into the U.S. Federal Aviation Regulations (FAR) as Appendix G to FAR 25 in September 1980 were the result of extensive discussions between the FAA and U.S. industry in the intervening period, 1966–1980.

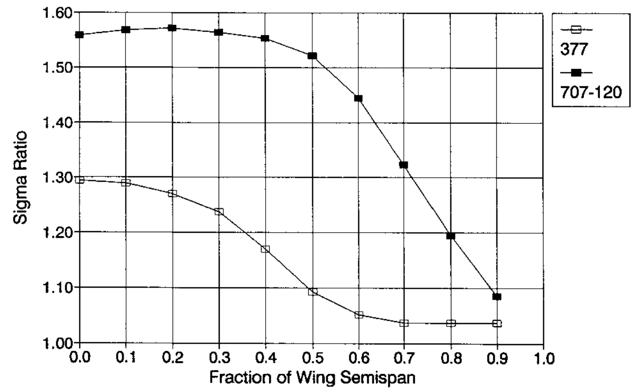

Fig. 4 Sigma-ratio, wing bending moment (models 377 and 707-120).

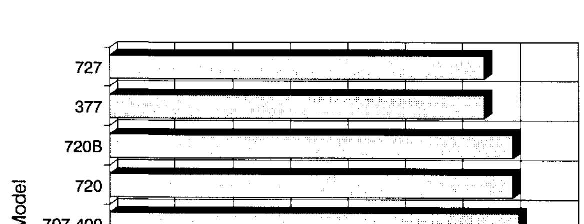

Fig. 5 Wing strength margins for gust dynamics (limit 1 *g*, moment/gust formula movement).

The primary difference between the criteria prescribed in the study contracts and the resulting FAA criteria was in the specified U_σ, and its variation with altitude in the so-called design envelope criteria. The scale factor U_σ in the design envelope criteria multiplies the rms loads due to an rms gust velocity of 1.0 fps, true airspeed (TAS), to obtain incremental design loads. The design envelope criteria are similar to past discrete gust criteria as well as to design maneuver loads criteria. Operational usage of the aircraft is ignored. Instead, the aircraft response is evaluated for a specified design envelope of speed, altitude, gross weight, fuel weight, and c.g. position.

These FAA criteria provided the basis for all current continuous turbulence criteria, regardless of the certifying agency. For example, the European civil regulations (joint airworthiness requirements) of January, 1987 (JAR 25) were identical to those given in Appendix G of FAR 25, with one major exception. JAR 25 made no reference to reducing U_σ for airplanes that had extensive satisfactory service experience.

As specified in Appendix G of FAR 25, power spectral gust loads criteria are presented in two basic forms: 1) the design envelope analysis, employing the scale factor U_σ, and 2) the mission (flight profile) analysis. Appendix G of FAR 25, item (b)(3)(f), also provides for reduced design values of U_σ. Specifically, "Where the Administrator finds that a design is comparable to a similar design with extensive satisfactory service experience, it will be acceptable to select U_σ less than 85 fps at V_C, but not less than 75 fps, with a linear decrease from that value at 20,000 ft to 30 fps at 80,000 ft." To apply the reduced U_σ values requires that 1) transfer functions for the new design are similar to the prior design and 2) typical missions of the new airplane are substantially equivalent to that of the similar design.

This modification to the design envelope criteria came about from a U.S. Aircraft Industries Association (AIA) proposal to the FAA after extensive studies of midrange to long-range transports, such as the Lockheed L-1011, Douglas DC-9, and DC-10, and the Boeing 727, 737, and 747, that showed U_σ of 75 fps at V_C should be permissible. The higher U_σ values, specified by the unmodified design envelope criteria, are more appropriate for the lower cruise altitudes, i.e., the more severe types of operation. The more severe types of operation are represented by short range or commuter operations where cruise altitudes of 20,000–30,000 ft are typical. The midrange or long-range airplanes normally have cruise altitude in the vicinity of 35,000 ft.

As originally developed, the mission analysis approach was a "stand alone" method. However, it was suggested that the most appropriate requirement would be a combination of the design envelope and the mission analysis approaches.[10] Combining these two approaches constitutes the mission analysis requirements that were specified in FAR 25, JAR 25, and various U.S. military specifications.

In addition to a mission profile analysis, the mission analysis criteria required that a design envelope analysis be performed similar to the design envelope requirements, but with reduced U_σ values specified as 60 fps at V_C from 0 to 30,000 ft with a linear reduction to 25 fps between 30,000–80,000 ft. The V_B value was still 1.32 times that at V_C, and the V_D value was 0.5 times that at V_C. These factors for V_B and V_D speeds are identical to those used with the gust formula criteria.

There was a transition period for FAA gust load certification requirements during which dynamic response to both discrete gust encounters and continuous turbulence was considered. This resulted in a different balance of reliance on the two methods, depending on the manufacturer. Dynamic analysis of the discrete gust encounters required the evaluation of the 12.5-chord gradient 1-cosine gust shape of FAR 25.341(b)(1), including rigid body and flexible airplane responses. The Boeing 747 was the last airplane certified during the transition period. Subsequent airplane certifications commencing with the Lockheed L-1011 and Douglas DC-10 used power spectral gust criteria similar to those discussed above.

In Europe, the discrete gust requirements of JAR 25 required full account to be taken of the aircraft dynamic response to discrete gusts prior to the adoption of the Notice of Proposed Amendment NPA 25C-101. A tuned discrete gust requirement was introduced into the BCAR (U.K. Civil Airworthiness Requirements), Section D, in the early 1960s. This requirement called for the investigation of airframe dynamic responses, and required variation of the gust gradient distance to find the most critical cases. Although the use of the so-called tuned discrete gust analysis was practiced by major U.S. manufacturers, a requirement was never incorporated into FAR 25. The tuned discrete gust requirement was used for the U.K. certification of both British and foreign aircraft from about 1960 until the adoption of BCAR Paper 25-55 into JAR 25, Change 8, resulted in the issue of the Tuned Gust National Variant.

The majority of members of the European JAR Structures Study Group, while expressing support for the concept of a tuned gust requirement, concluded that the requirement was too severe and was never properly justified. They proposed adoption of the FAA discrete gust requirement discussed above. According to V. Card of the U.K. Civil Aviation Authority, CAA, the CAA was not able to support the proposal for the following reasons:

1) The FAR discrete gust requirement only called for consideration of response to a single arbitrary 12.5-chord gradient distance. In this respect, it was felt to be deficient through failing to highlight significant aircraft responses to other gust gradient distances. The CAA presented results (Fig. 6) from a study it sponsored in a contract with British Aerospace (BAe), showing the effects of tuning and other analysis assumptions on the response of an airplane to 50 fps, EAS, 1-cosine discrete gusts.

2) The 12.5-chord gradient gust, fixed for the FAR discrete gust requirements, had its origin in the observed response of aircraft with very different response characteristics to the majority of modern commercial transport airplanes.

3) The FAR 25 gust requirements were essentially based on the belief that the continuous turbulence (power spectral) method provided an adequate basis for the examination of structural loads resulting from dynamic response to gusts and turbulence.

With the adoption of Paper 25-55, the gust velocities in JAR 25 were reduced by 10% for tuned gust analysis (i.e., 45 fps, EAS, at V_C was introduced in place of the previously specified 50 fps, sea level to 20,000 ft). This reduction took account of the fact that the design gust velocities were considered to be conservative, because their derivation from airplane gust statistics had failed to take account of dynamic

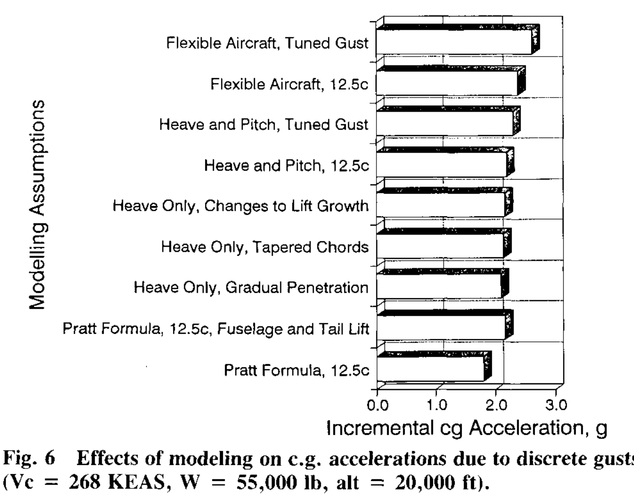

Fig. 6 Effects of modeling on c.g. accelerations due to discrete gusts (Vc = 268 KEAS, W = 55,000 lb, alt = 20,000 ft).

response effects in the data gathering aircraft. Provision was also made to refine the discrete gust method through the introduction of agreed relationships between gust velocity and gust gradient distance for shorter gusts. The tuned discrete gust requirements were used in this form for certifications of the A310, 757, 767, 737-300, SF340, DHC-8, Brasilia, etc.

While the U.K. Civil Aviation Authority, CAA, was convinced that consideration of the response to continuous turbulence should form a part of the overall gust load requirements, it was not satisfied that the continuous turbulence method adequately accounted for all types of atmospheric turbulence. In particular, V. Card of the CAA noted that the majority of gust load accidents appear to have been related more to "sudden events" than to continuous turbulence (e.g., Mt. Fuji 707, Braniff BAe 111, F-28). It was also noted that a significant proportion of high-load turbulence events detected during the monitoring of civil transport operations in the CAADRP (U.K. Civil Aviation Authority Data Reduction Program) program, and a significant proportion of occurrences involving passenger injury, occur in events that are more discrete than continuous in nature. In the light of this evidence, the CAA considered that the response to discrete gusts should continue to play a major role in the gust loads requirements.[11]

The U.K. National Variant, the modified form of the tuned gust requirement that had been used for U.K. certification since the late 1950s, and was a part of JAR 25 prior to the adoption of NPA 25C-101, treated the tuned gust design condition as a design envelope condition, with a need to establish the critical loads by considering the most conservative combination of weight, payload, fuel, c.g. position, speed, and altitude. Where a typical operation was remote from the critical boundaries of the flight envelope, this approach was seen to be overly severe, but it did allow totally unrestricted operation at all times without fear of infringing the required minimum safety margins.

The European authorities recognized that there are some features of modern transport aircraft operations that continue to provide safety margins beyond those normally demanded of a most critical flight condition approach. With respect to gust loads, it has long been accepted that gust occurrence frequencies are a function of altitude, with a higher probability of meeting a severe gust at low altitude; however, the design gust velocities specified in both FAR 25 and JAR 25 were constant from sea level to 20,000 ft. For economic reasons, a pressurized aircraft will normally cruise at the highest possible altitude consistent with the route length and air traffic pattern. This is beneficial to the airframe, since it greatly reduces the exposure to the more severe atmospheric conditions that are more frequent closer to the ground. Hence, there is a significantly reduced risk of encountering a gust approaching design magnitude. The tuned discrete gust requirement gave no credit for this feature of modern aircraft usage, which could lead to higher strength margins relative to other design criteria. This point had often been made by European manufacturers and members of the JAR Structures Study Group, and had been raised previously as an important obstacle to the wider acceptance of the tuned discrete gust as a foundation for a basic JAR 25 requirement.

The need to update aircraft gust load design requirements became apparent to the JAA and FAA in the late 1980s as new aircraft designs evolved whose active control systems depended on descriptions of design level atmospheric isolated gusts and continuous turbulence. Current gust requirements demand the investigation of design loads due to two separate types of atmospheric phenomena; namely, discrete gust and continuous turbulence. The more recent continuous turbulence model was introduced in an attempt to provide a more realistic description of the random nature of gust loading on aircraft; however, in spite of the intended improvements, the continuous turbulence analysis has not been allowed to supersede the more artificial, but well proven, discrete gust requirements in either FAR 25 or JAR 25.

It has been noted from flight recorder data collected during the CAADRP program that the larger gusts often stand out as discrete events above a background of more moderate atmospheric turbulence. Also, it was noted that the majority of gust load accidents appeared to have been more related to "sudden events" than to continuous turbulence. A number of high load turbulence events and a significant number of incidents involving passenger injury were noted to have been more discrete than continuous in nature. In summary:

1) It was believed that response to discrete gusts should continue to play a major role in design requirements for future aircraft.

2) Investigations of operational events showed that it was illogical to restrict consideration to a single gust gradient—a gradient that was based on wing chord dimensions and which varied from aircraft to aircraft.

Investigations of c.g. acceleration statistics for routine airline operations over a 10-yr period, 1980–1990, enabled a revised discrete gust probability model to be derived. This model confirmed again that the probability of encountering large gusts decreases as the altitude increases; therefore, altitude weighting of limit load gust design levels would achieve an acceptable and more uniform airworthiness requirement.

The continued evolution of gust design requirements among the various world aviation authorities has resulted in many separate gust load design criteria with which the transport airplane manufacturer must comply in order to export its product. Recent efforts between the FAA and the JAA in cooperation with the commercial transport aircraft manufacturers resulted in a proposal to refine the criteria and consolidate them into a common set of gust requirements.[12] A review was made of analytical methods to find a single method that would simulate both discrete gusts and continuous turbulence and produce design loads that could be used directly for structural analysis. However, no single method was found, therefore, the airworthiness authorities decided that separate criteria should be retained in the requirements until more suitable or representative atmospheric gust models are defined. Initial efforts to define revised criteria have dealt only with 1-cosine-shaped discrete gusts. Revisions to continuous turbulence, power spectral requirements are now being considered.

The original version of a Notice of Proposed Amendment to JAR 25, NPA 25C-205, entitled, A Unified Discrete Gust Requirement and Associated Means of Compliance (and deletion of U.K. National Variants), was issued for comment on May 13, 1988.[13] The major feature of the NPA was the introduction of a "Flight Profile Altitude Weighted Analysis" procedure for calculation of discrete gust loads. This philosophy was developed as a result of study of some of the most recent operational gust statistics that showed conclusively that the variation of derived gust velocity with altitude significantly departed from a constant probability line below 20,000 ft. This was inconsistent with the variation of design gust velocities specified by the JAR 25 and FAR 25, which prescribe constant design gust velocities (fps, EAS) from sea level to 20,000 ft. Working on the basis that the design gust velocities are used to define limit loads, and using the concept that limit loads are intended to be the maximum loads occurring in a fixed period of time (nominal airplane lifetime), it appeared that the design gust velocities were too severe between 14,000–40,000 ft, and not severe enough below 14,000 ft.

While the major objective of the NPA was to provide new requirements for JAR 25, the views of the FAA were solicited in an attempt to achieve commonality or harmonization with FAR 25. In general, the FAA supported the view that the existing discrete gust requirements did not adequately account for the proportion of time that an aircraft operates at any given altitude, and that any new discrete gust criteria should account for the variation of gust occurrences with altitude. However, the FAA was concerned that an altitude-weighted flight profile approach would introduce complexities and inconsistencies associated with definition of aircraft missions or prospective usage. The European Joint Aviation Authority (JAA) specialists accepted an action to find a simplified procedure that would achieve the same end as the full altitude-weighted flight profile analysis that was initially proposed.

The initial approach to a simplified flight profile factor to approximate the more involved and controversial altitude-weighted flight profile analysis was based on an FAA proposal to devise an approximation function using the ratio of maximum takeoff weight-to-maximum landing weight. The European Aircraft Industries Advisory Group (AECMA) counterproposal for a formula based on a combination of several easily defined parameters was accepted, because it was shown to give the best fit to the load levels from full profile analyses for a range of load quantities on different types of aircraft.

A limiting or design reference gust velocity U_{ref}, was defined which would be multiplied by the proposed F_g, to obtain U_{ds}. If an airplane was assumed to fly at its V_C at its normal cruise altitude for its entire lifetime, that gust velocity which would be exceeded once in the airplane lifetime was defined as the design reference gust velocity U_{ref} for that altitude. V_C and the normal cruise altitudes of a wide range of models of commercial aircraft were used to define the distribution of U_{ref} with altitude. At the same time, a reference gust gradient of 350 ft was selected. A 350-ft gradient distance is almost exactly 12.5 wing chords for the Boeing Model 747. The envelope of these individual reference gust velocities was selected to define the following variation of U_{ref} with altitude. The reference gust velocity for a 350-ft gradient 1-cosine gust is 56.0 fps, EAS, at sea level and may be reduced linearly from 56.0 fps, EAS, at sea level to 44.0 fps, EAS, at 15,000 ft. The reference gust velocity may be further reduced linearly from 44.0 fps, EAS, at 15,000 ft to 26.0 fps, EAS, at 50,000 ft.

At aircraft V_D, the reference gust velocity is 0.5 times the values obtained for V_C. Also, for gusts with gradient distances less than 350 ft, the gust velocities may be reduced below the prescribed reference gust velocities to a value proportional to the sixth root of the gust gradient distance.

At sea level, F_g is taken to be numerically equal to

$$F_g = 0.5(F_{gz} + F_{gm})$$

where

$$F_{gz} = 1 - Z_{mo}/250{,}000$$

$$F_{gm} = [R_2 \tan(\pi R_1/4)]^{0.5}$$

The flight profile alleviation factor should be increased linearly from the value at sea level to a value of 1.0 at the maximum operating altitude. Also, any significant system nonlinearities should be accounted for in deriving limit loads from limit gust conditions when a stability augmentation system is included in the analysis.

In summary, it can be stated that continual improvements have been made in airplane gust loads design criteria since the subject was first seriously discussed in 1915; however, troublesome questions remain, particularly, concerning the characterization of gust structure for deriving design gust loads.

Gust Loads Research Objectives

In 1950 Philip Donely of NACA stated that the major gust research efforts should be divided into the following three categories; these categories are still pertinent[14]: 1) definition and characterization of gust structure, 2) aircraft response analysis, and 3) encounter or operation statistics. Perhaps the greatest challenge is the definition and characterization of gust structure. Initial efforts to characterize gusts were as isolated discrete events; later efforts tended to concentrate on the random nature of atmospheric turbulence using the tool of power spectral analysis developed in the field of electronics and communications for dealing with random signals or noise. Neither of these representations is correct nor strictly in error.

The extreme gust encounters that a fleet of commercial aircraft experience only a few times over a decade of operation generally cannot be characterized as continuous turbulence, rather, they are usually sharp discrete events superimposed on a background of turbulence. The question is should design gusts be characterized as discrete events and the background randomness ignored, should a combination of the two characteristics be invented, or, should the character of both be used in separate analyses? The latter course is clearly the direction in which the aeronautical community is headed at the present time for lack of a more rational approach. Aeronautical engineers need to enroll the help and cooperation of meteorologists, atmospheric physicists, and statisticians to refine the concept of design gusts.

The general use of computers in engineering analysis and design has alleviated the former obstacle of analysis complexity. Now aircraft idealization as a dynamic system with multiple degrees of freedom (DOF) generally is not a problem, nor is the representation of reasonable unsteady airforces. The spanwise effects of turbulence are clearly present, but seldom considered, even in otherwise sophisticated analyses. Also, the assumption is nearly always made that the turbulence is frozen in space and that the airplane merely traverses this frozen pattern. This assumption, too, introduces a small error, turbulence is space- and time- dependent.

Analytical gust loads research aimed at improving airplane design criteria has, in recent years, focused on a baseline definition of atmospheric turbulence, namely that characterized by the von Kármán power spectrum with a fixed L of 2500 ft. Manipulating the von Kármán spectrum in various ways has led to the development of several procedures to ascertain internal structural loads at any arbitrary point in the aircraft structure and the associated balancing or equilibrium loads on nearby elements.

Recent Gust Methods Research

The statistical discrete gust procedure (SDG) was first proposed by Jones in 1967, and has been investigated, developed, and refined since that time.[15-21] The original intent was to define a unified procedure for gust analysis that would take account of the fact that the atmosphere contains both discrete events and local continuous turbulence. The basic assumption of the SDG approach is that atmospheric turbulence can be represented by a series of 1-cosine-shaped ramps applied in any order, ascending or descending. The amplitude of each element is adjusted to reflect equal probability of occurrence by scaling element amplitude according to the element gradient length H to a power: $H^{1/3}$ for low level events and $H^{1/6}$ for extreme amplitude events. In 1989 Jones generalized the statistical discrete gust method for continuous turbulence in a deterministic spectral procedure (DSP). The 1-cosine ramp constraint of SDG was replaced by a simple energy constraint on the whole input pattern; any gust pattern would be permitted provided it fell within the prescribed energy bounds. A direct solution is available for linear systems, but a numerical search is required for nonlinear systems, the design loads problem results in a search for the critical gust pattern unique to each separate load quantity.

In 1989 Pototzky and Zeiler presented results for time-correlated loads for linear systems subjected to continuous turbulence using matched filter theory (MFT).[22] Matched filters have their background in radar detection. In the gust application MFT will identify an unknown worst-case gust input for a given load quantity where the system dynamics are known. The most critical gust time history may be calculated from the impulse response function of the combination of a von Kármán filter and the aircraft. When the impulse response is normalized, reversed in time, and played back through the system, the most critical load and the associated correlated loads are obtained. NASA has studied MFT for linear systems and has also investigated the computation of maximum gust loads in nonlinear aircraft using a method based on the MFT approach with numerical optimization of the worst-case input.[23] If the response is nonlinear, then neither the equations of MFT nor random process theory are valid, and an explicit solution for worst-case input is not possible. Equally, the linear summation of 1-cosine ramps in the SDG method is no longer feasible.

The (DSP) was introduced by Jones and has been further developed by Noback.[24] It can be regarded as the translation of the continuous turbulence, power spectral density, method from the frequency domain into the space, or time domain. The critical gust profile, giving maximum response for any given load quantity and correlated associated loads, is obtained directly. Noback has compared the method with MFT and with direct simulation. It gives identical results to the power spectral approach for linear systems. Results have been obtained for a nonlinear system using equivalent gains to obtain the critical gust profile, and these results, also, have been compared with direct simulation.

The stochastic simulation method (SSM) begins with an approximation to Gaussian white noise with unity variance. The white noise source is applied to a von Kármán gust filter producing a stationary Gaussian signal with a von Kármán power spectrum. This turbulence time history is then applied to the linear or nonlinear aircraft model producing a load time history. Several simulations are performed. First, a search of the load time histories locates points in time where a peak load is within a specified range. A narrow response range is chosen for nonlinear systems to isolate the nonlinear nature of the airplane responses. Second, a sufficient amount of time prior to the peak load is selected, and the corresponding time history segments of excitation source profile, gust profile, and load response profile are extracted to form one data set. This process of extracting is repeated over a number of simulations, and the sets of excitation profiles, gust profiles, and response profiles are averaged, each being correlated in time relative to the peak load and a fixed time preceding the peak load. The number and duration of the simulations is selected to provide a sufficient number of extracted data sets to yield relatively smooth averaged waveforms. It has been demonstrated, by this experiment, that averaged waveform results agree between the stochastic simulation and matched filter methods for linear and nonlinear airplane models.[25]

European Industry View on Recent Gust Methods Research

The following was presented in March 1991 representing the collective opinion of the European Industry Panel for Loads and Dynamics.[26]

There is evidence that real atmospheric turbulence exhibits two types of characteristics that are best represented for airworthiness purposes by the following separate idealizations:

1) Continuous turbulence represented as a Gaussian process conforming to the von Kármán frequency spectrum is of particular interest where it excites low damped roots (including rigid body). It is best represented by the current form of continuous turbulence design envelope requirement, subject only to appropriate wording changes to clarify nonlinear applications and justifiable adjustments of amplitude.

2) Extreme discrete gusts of intermittent and non-Gaussian character that are best represented by limited complexity discrete events with a self-similarity coefficient of (perhaps) 1/6 (for H less than or equal to 350 ft, $U_{ds}(H) = (H/350)^{1/6}$). While recognizing the capability of the statistical discrete method to provide a more detailed model, we believe that the recent JAR tuned discrete gust proposal utilizing the 1-cosine gust shape is sufficient for airworthiness purposes and is unambiguous (the more complex gust patterns being addressed by continuous turbulence).

While it may be concluded that the statistical discrete gust method can succeed in its original objective of putting discrete gust analysis and continuous turbulence analysis within a single uniform framework, we do not foresee the statistical discrete gust method having a role to play within future airworthiness requirements. This is because continuous turbulence is more conveniently considered for linear dynamics within current continuous frequency plane analysis methods, both for design loads and for correlation (time correlated loads). For continuous turbulence with nonlinear dynamics, the statistical discrete gust method and related methods are untried and present obstacles to consistent solution that lead us to believe that they are unlikely to offer any significant benefit for airworthiness loads purposes over currently implemented time-plane stochastic simulation methods. It is recognized that the problem of correlation for time-plane stochastic simulation methods has yet to be resolved.

Matched filter theory and the deterministic spectral procedure are essentially more exact formulations of the statistical discrete gust method for Gaussian continuous turbulence, which for nonlinear dynamics have the same difficulties as the statistical discrete gust method and, therefore, lead to the same conclusion. In any case, neither the statistical discrete gust method, matched filter theory, nor the deterministic spectral procedure can represent extreme atmospheric events of nonGaussian character.

Encounter or Operation Statistics

The reduction of gust load data base statistics involving thousands of events with different airplanes and flight conditions requires a simple reliable procedure to translate peak gust-induced c.g. accelerations into terms of derived equivalent gust velocities. The revised gust load formula, devised by Pratt and Walker nearly 40 yr ago,[5] has most of the elements of a sensible conversion; however, the following additional concepts need to be considered:

1) Dynamic elastic effects can be large and should be accounted for by the inclusion of appropriate dynamic factors derived from a set of dynamic analyses for the airplane model using the reference gust gradient and waveform selected for the gust formula. Dynamic factors should be keyed to gust event flight conditions by regression analysis involving parameters such as weight, speed, and altitude.

2) A standard gust shape and gradient distance, not based on airplane dimensions, but on an agreed fixed standard needs to be adopted. Large airplanes tend to average out large peak gust velocities over their wing span; and so, at some point, airplane size effects also need examination.

3) The data base analysis procedure should be an international standard in order that gust statistics collected anywhere in the world can be pooled and used by all parties. It is clear that a data base must include over a million hours of airplane operation to provide reliable statistics at limit design levels for various altitudes. It is also clear that data bases are perishable in that aircraft systems, modes of operation, air traffic control procedures, and other factors affect the statistics, and all of these factors change over time.

The Pratt formula has been criticized for not including the effects of airplane pitching motion, but, this may not be a large real effect considering that most crews operate a large percentage of the time with the autopilot on, in fact, it may be as correct not to include pitch when determining the distribution of gust velocities in data base analysis. The effect of an autopilot on airplane c.g. acceleration response usually results in a response somewhere between the plunge only response and the pitch-plunge response.

All things considered, we are, no doubt, fooling ourselves with analytical oversophistication, therefore, periodic checks of actual flight test results against dynamic analysis results will continue to be required to properly scope design analysis efforts, particularly, with the advent of closely coupled and nonlinear flight controls and load alleviation systems and with new or novel configurations.

Proposed Research of Severe Gust Strike Events

A close examination of c.g. acceleration time histories from severe gust strike events generally indicates entry into more or less moderate random turbulence followed by severe larger scale effects, all within a time span of a few minutes. The severe design level gust environment generally cannot be considered as stationary random and Gaussian, neither can it be considered as isolated discrete gust strikes. It is possible, however, to obtain meaningful gust velocity time histories from c.g. acceleration records of severe design level gust strikes. The derived gust time histories can be used either individually in gust related accident studies or in some "averaged" form for design. The primary objective is to collect and study these rare events in order to characterize them and devise an improved design gust model or models.

This proposed approach uses simple Fourier series analysis of the c.g. acceleration time histories to derive the corresponding gust velocity time histories. As an example, a Fourier series representation for a more or less typical incremental c.g. acceleration data record from the CAADRP data base was determined, and the associated time history of gust velocity was developed. The Fourier analysis fit and the original c.g. acceleration time history are shown in Fig. 7. Figure 8 shows a portion of the record shown in Fig. 7 centered on the severe gust strike event. The proposed procedure is to determine the Fourier series coefficients a_n and b_n from a time series analysis of an appropriate section of the c.g. acceleration record. The corresponding Fourier series gust velocity coefficients g_n and h_n can be ascertained using a definition of the c.g. acceleration complex transfer function $T_n + iI_n$, normally developed for power spectral density gust analysis, together with the Fourier coefficients for c.g. acceleration:

$$a_n + ib_n = (T_n + iI_n)(g_n + ih_n)$$

g_n and h_n can be determined using the inverse transfer function coefficients.

$$g_n + ih_n = [(T_n - iI_n)/(T_n^2 + I_n^2)](a_n + ib_b)$$

Once the Fourier gust velocity coefficients are known, the gust velocity time history corresponding to the c.g. acceleration record can be constructed. Of course, if the gust velocity Fourier coefficients are available, then any airplane internal load, stress, or other response time history can be ascertained by using the appropriate complex transfer function.

The c.g. acceleration record from the CAADRP data base (Fig. 7) indicates a severe gust encounter with a peak incremental c.g. acceleration of 0.75 g for a 747-236 airplane enroute from Hong Kong to New Delhi in October 1988. The example airplane analysis conditions are given in Table 2. The total flight time covered by the analysis was 2 min. The total flight distance traversed in 2 min at a true airspeed of 415 fps was 49,750 ft, or 8.2 n.mi. The acceleration record covered only the central 60 s of the overall 120-s analysis record. The nongust record length was included to prevent the airplane dynamics generated in one period of the Fourier series from unduly influencing the next, thus simulating an isolated patch of rough air, not repeated patches.

The overall procedure can be illustrated by using a c.g. acceleration transfer function based on the plunge-only DOF. For this purpose, the same representation of the unsteady lift functions were employed as were used in the development of the Pratt gust load formula.[5] Of course, the results could be improved if a fully elastic airplane analysis were used including both pitch and plunge and autopilot effects. Figure 9 shows the real and imaginary transfer function coefficients T_n and I_n to convert gust velocity to c.g. acceleration, and Fig. 10 shows the inverse coefficients to convert c.g. acceleration to gust velocity. Figure 11 shows the derived true gust velocity time history for the full 120-s analysis period. Figure 12 shows

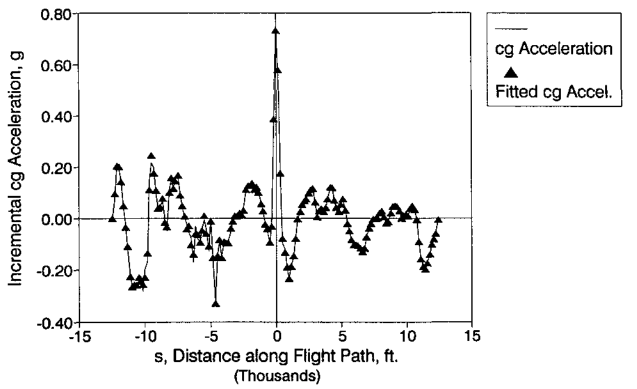

Fig. 7 Gust strike event, c.g. acceleration (747-200, 239 KIAS, 1812 ft, 751,700 lb).

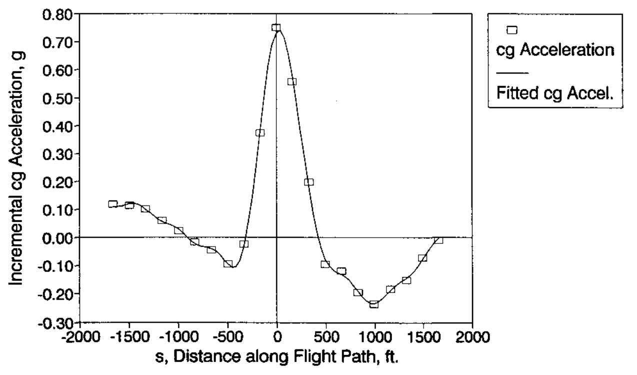

Fig. 8 Portion of gust strike event, c.g. acceleration (747-200, 239 KIAS, 1812 ft, 751,700 lb).

Table 2 Example airplane conditions

Gross weight, lb	751,700
Speed, KIAS	239
Altitude, ft	1812
Flap setting, deg	10
Total c.g., acceleration, g	1.75
μ_g	23.38
K_g	0.717
U_{de}	46.6
U_{dt}	47.8
U	48.5

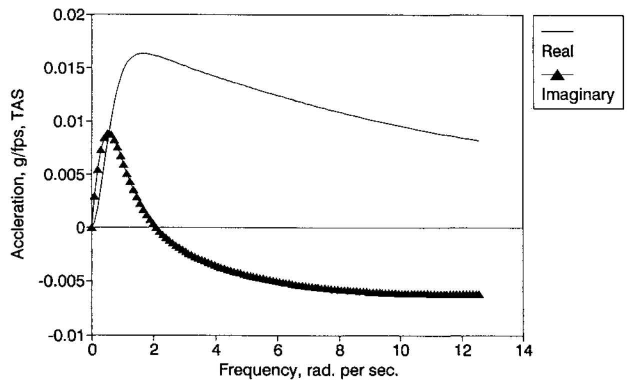

Fig. 9 Transfer function for c.g. acceleration (Kussner-Wagner functions, plunge only).

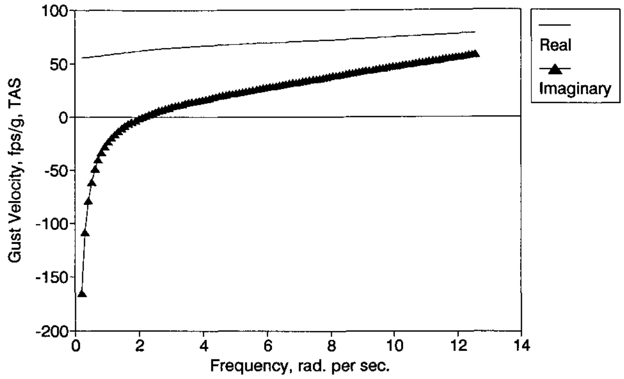

Fig. 10 Transfer function for gust velocity (Kussner-Wagner functions, plunge only).

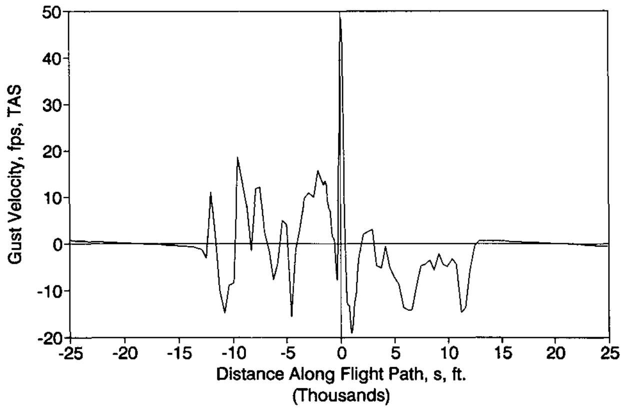

Fig. 11 Fourier series fit to the gust strike event (747-200, 239 KIAS, 1812 ft, 751,700 lb).

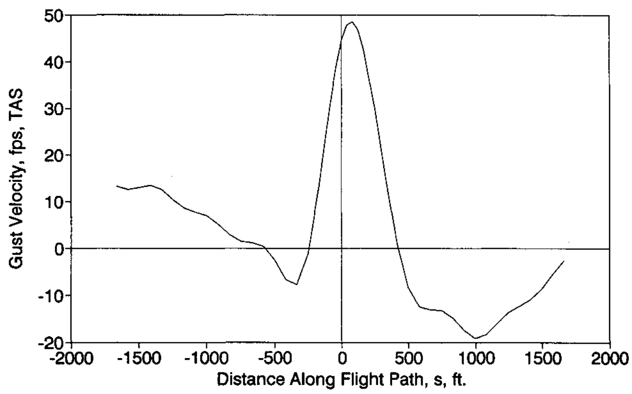

Fig. 12 Portion of gust strike event (747-200, 239 KIAS, 1812 ft, 751,700 lb).

an expanded view centered on the event peak with maximum gust velocity equal to 48.5 fps, TAS.

Conclusions

Continual improvements have been made in the development of airplane gust loads design criteria since the subject was first seriously discussed in 1915; however, troublesome questions remain, particularly, concerning the characterization of gust structure for deriving design gust loads.

The modern digital flight data recorder has made possible the collection of rare severe gust strike event time histories. Available severe gust strike records should be converted to gust velocity time histories, and efforts should be made to characterize these time histories to develop an improved gust design model of models. The lead in this effort should be taken by the national aeronautical laboratories who, with the aid of atmospheric physicists and meteorologists, would characterize the gust structure, conduct fluid flow wind- or water-tunnel experiments to simulate the rare gust events, and characterize the gust structure in design criteria form.

Gust loads data bases from routine commercial flight operations worldwide should be pooled and periodically updated to reflect changes in aircraft equipment and flight operations. Also, a uniform method of converting incremental c.g. accelerations to derived equivalent gust velocities should be established based on the gust characterization discussed above. Perhaps this could be accomplished by adjusting K_g in a Pratt-type gust load formula to account not only for μ_g, but also for additional important effects. The gust shape and spatial extent should be independent of the airplane, and elastic dynamic effects of the data gathering airplanes should be used in the data reduction. The establishment and maintenance of the data base should reside with an international organization supported by the national airworthiness authorities.

Studies are continuing in the U.S. to develop a commercially viable high-speed civil transport airplane, HSCT. The HSCT is envisioned to be produced early in the next century and will cruise at supersonic speeds at altitudes in the neighborhood of 70,000 ft. The currently revised discrete gust criteria are defined to 50,000 ft, and are based on gust encounter operational statistics gathered in the 1980–1990 time period from subsonic commercial aircraft operations covering the altitude range from sea level to about 40,000 ft. The gust environment definition should be extended to higher altitudes to include the HSCT cruise altitude range. Aircraft gust statistics for the higher altitudes should be gathered from all available sources; these sources might include operations of the Concorde, U.S. military high-altitude aircraft, such as the U2 and the SR71, and European and former Soviet bloc civil and military aircraft. In addition, high-altitude meteorological balloon tracking data should be examined in order to supplement the meager high-altitude aircraft data.

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