Engineering Notes

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Turbulence Variations during the High Altitude Clear Air Turbulence (HICAT) Program

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Introduction

ASHBURN and Waco[1] and Ashburn[2] discussed aspects of the High Altitude Clear Air Turbulence Program including size of turbulent regions and variations in turbulence associated with season, altitude, and terrain. These studies did not compare data from early HICAT flights (Phase I) with those collected after the program was extended (Phase II). In this report lengths of turbulence encounters (runs) are compared for the two phases while turbulence intensity, flight altitude, and terrain are included as added variables. Ratios of turbulent to total flight miles are also compared.

Program Description

The first series of 141 turbulence search flights (Phase I) was begun in November 1965, continuing until February 1967. Base locations were in California, Massachusetts, Alaska, Puerto Rico, Hawaii, Australia, and New Zealand. A redirected series of 106 flights (Phase II) were flown between March 1967 and March 1968 from California, Maine, Louisiana, Florida, Panama, and England. Several flights were ferry trips from one base to another. The program's aircraft, an Air Force U-2, flew over 500,000 miles between 45,000 and 70,000 ft altitude. Measurements of the aircraft c.g. normal acceleration form the basis for the analyses in this report. True gust velocities were obtained from gust probe measurements but the sample sizes were too small to be of use in a statistically significant comparison of the two phases.

Derived gust velocities (U_{de}) were available for nearly all the turbulence encounters (runs) and consequently are used in the comparitive analyses. The U_{de} gust velocities, derived from c.g. normal accelerations, are really fictitious values whose derivation requires several assumptions such as a rigid, nonpitching aircraft in steady, level flight prior to entry into turbulence and a fixed shape for the gust velocity profile. Although U_{de} gust velocities only approximate the true gust velocities which exist in the atmosphere, their use in the design of aircraft has been accepted for many years. This report contains comparisons of root mean square gust velocities ($RMS\ U_{de}$) computed from time histories of c.g. normal accelerations.

Results

The percentage of turbulence runs equalling or exceeding given distances are shown in Figs. 1–3 for the two HICAT phases. The distributions are for classes of intensity ($RMS\ U_{de} \leq 1$ fps or >1 fps), altitude ($<56{,}000$ ft or

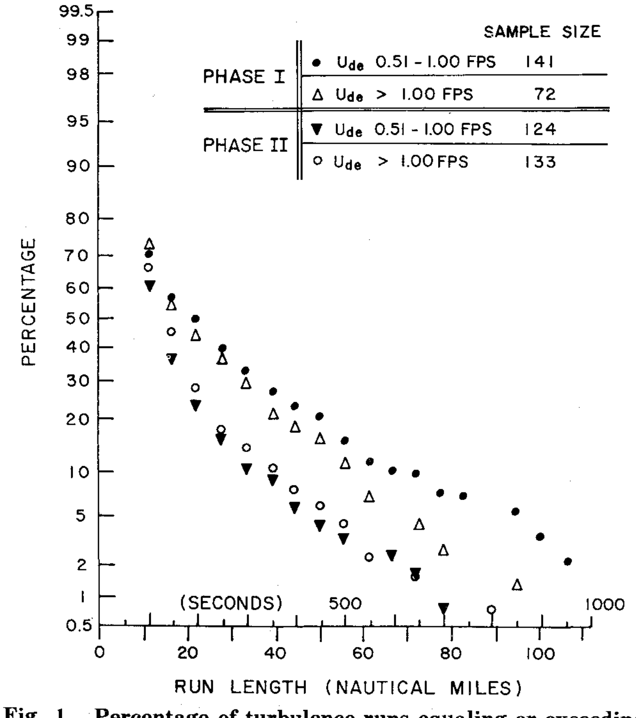

Fig. 1. Percentage of turbulence runs equaling or exceeding given lengths for HICAT Phases I and II and two intensity categories.

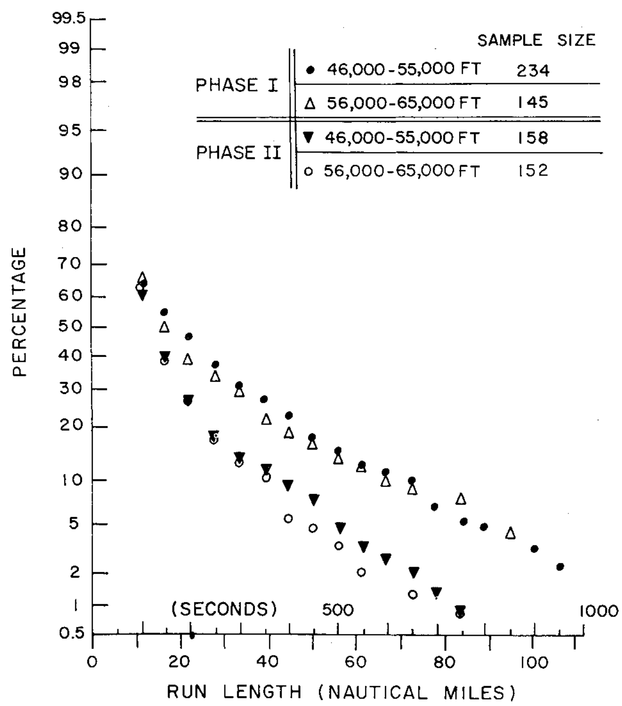

Fig. 2 Percentage of turbulence runs equaling or exceeding given lengths for HICAT Phases I and II and two altitude categories.

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Table 1 Ratio of turbulent to total flight miles (in percent) for Hicat Program phases, intensity, terrain and season

	Light					Moderate				
	All Flights	Water-Flat	Mountains	Summer	Winter	All flights	Water-flat	Mountains	Summer	Winter
Phase I	3.7	3.0	6.0	2.1	4.2	0.9	0.6	2.1	0.6	1.7
Phase II	2.3	2.1	2.8	1.8	2.9	0.6	0.4	1.2	0.2	1.3
Both phases	3.0	2.6	4.2	1.9	3.8	0.8	0.5	1.6	0.3	1.6

≥56,000 ft) and terrain (water-flatland or mountains). The obvious differences in the two distributions are related to the two phases. A distinct trend for shorter turbulence lengths is apparent in Phase II. There appears to be little dependence of run length on intensity, altitude, or terrain except in the case of Phase I where more intense turbulence is associated with shorter runs.

Several factors should be considered, possibly together, in describing the reasons for the phase differences. Seasonal and diurnal effects, weather patterns, or particular locations such as the lee of high mountains may influence the lengths of turbulent regions. It is possible that wind direction and speed affected the time required for a given flight trajectory through turbulence. To illustrate, 67% of Phase I turbulence time was in conditions where the wind had a component against the aircraft (53% in Phase II), perhaps due to the longer time required to traverse a stationary or nearly stationary patch at a given airspeed when flying against the wind.

It is the opinion of the authors that the similarity of geophysical, meteorological, and aircraft operational conditions in the two HICAT phases reduces the chances for these variables to have strongly influenced the turbulence length differences. Also, the likelyhood of five out of six distributions showing very small differences for varying terrain, etc, (Figs. 1–3) seems to support the adequacy of the sample size. Most likely, the variations are related to differences in editing of the original oscillograph records in the determination of the beginning and ending of turbulence runs. The editing differences resulted primarily from 1) changes in personnel from Phase I to Phase II and 2) increased experience in handling the data.

Another aspect of HICAT phase comparisons is the ratio of turbulent to total flight miles (Table 1). Turbulent/total mile ratios varied considerably for seasonal and terrain differences in contrast to the apparent lack of dependence of run lengths on these variables. The larger turbulent/total mile value in Phase I appears to be more the result of season rather than terrain effects. The ratio of winter (Dec.-Feb.) to summer (Jun.-Aug.) total flight miles was 3.4 in Phase I and only 0.7 in Phase II. On the other hand, 41% of the total flight miles in Phase II were over mountains compared to 29% in Phase I which appears to favor more turbulence in Phase II.

Turbulence and total flight miles were determined by adjusting for data collected in areas where the U-2 made repeated passes through turbulent regions. The adjusted figures, which are presented in Table 1, are considered more representative of routine rather than search flights. Turbulence was considered present when peaks of 0.1g or greater occurred frequently on the acceleromter trace. Moderate or severe turbulence (peaks ≥0.25g) occurred in roughly 25% of the turbulent miles in both phases. All of the 32 severe turbulence encounters occurred in Phase II, most during four winter flights over the Rocky Mountains. The lack of severe encounters in Phase I was largely because high mountain flights were usually in summer when mountain wave activity was at a minimum. Many of the Phase I flights over low mountains were in winter and resulted in large amounts of moderate turbulence. A rather pronounced case was the eleven winter flights over Australia, which included 7300 flight miles over low mountains. Moderate turbulence occurred in 8% of these miles. The winter jet was especially strong with winds often between 150 and 200 knots (near 100 knots at flight level). At the other extreme there was no turbulence recorded in 10,000 winter miles flown over the Alaskan mountains (Phase I) related no doubt, to the highly stable atmospheric conditions resulting from extreme cold near ground level.

Conclusions

The HICAT Program, which produced perhaps the greatest collection of turbulence data for altitudes above 40,000 ft, had as one of its main purposes the establishment of a world-wide climatology of turbulence at high altitudes. The occurrence of turbulence was highly irregular as expected, depending upon terrain effects and weather conditions, the latter being in turn strongly dependent upon season. Irregularities in Phases I and II distributions of turbulence lengths could conceivably have been related to the relatively small number of flights as compared to commercial or military operations at lower altitudes. On the other hand, the sample size appeared to be adequate in showing that turbulence lengths were not highly dependent on the same factors which affected the amount of turbulence per given flight distance. The optimum sample size needed to produce a statistically significant distribution of turbulence lengths remains in doubt, however, be-

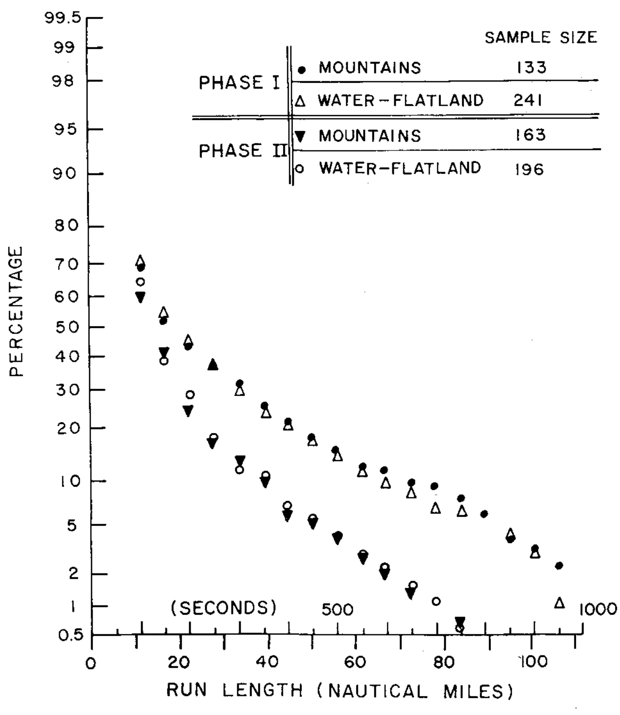

Fig. 3 Percentage of turbulence runs equaling or exceeding given lengths for HICAT Phases I and II and two terrain categories.

cause of the critical dependence of turbulence start-stop points on subjective editing procedures.

An important consideration for future commerical aviation flights in the stratosphere is the impact of meteorological conditions, such as the Australian winter jet, on route structure. Will the threat of moderate or severe turbulence result in costly rerouting around areas prone to strong winds? It is possible that commercial aviation routes in use today at lower altitudes will not be acceptable for supersonic flights in the stratosphere if low frequency, large amplitude turbulence is prevalent over certain regions. Some of the apparent difficulties facing the supersonic aircraft may be better understood with further analysis of the HICAT data. Flight data tapes are available for all turbulence encounters, along with oscillograph records of each flight. Future tasks could include analysis of the variance of the first and second most important parameters controlling the distribution of turbulence.

References

[1]Ashburn, E. V. and Waco, D. E., "Ratio of Turbulent Flight Miles to Total Flight Miles in the Altitude Range 45,000–65,000 Ft," *Journal of Aircraft*, Vol. 8, No. 2, Feb. 1971, pp. 127–128.

[2]Ashburn, E. V., "Distribution of Lengths of High Altitude Clear Air Turbulence Regions," *Journal of Aircraft*, Vol. 6, No. 4, Jul.-Aug. 1969, pp. 381–382.

Model Tests on Unsteady Rotor Wake Effects

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Nomenclature

t = nondimensional time
β = blade flapping angle, positive up
θ = blade pitch angle, positive nose up
β_I, β_{II} = forward and left rotor tilting angle
θ_I, θ_{II} = forward and left cyclic pitch angle
θ_o = collective pitch angle
μ = rotor advance ratio
ω = nondimensional frequency of progression or regression in airframe fixed reference system

Introduction

STEADY-STATE wake asymmetrics have been shown to result in large reductions in hingeless rotor cyclic control effectiveness[1] and in substantial changes of hingeless rotor static derivatives not only at low but also at high advance ratios.[2] Unsteady substall rotor aerodynamics, recently summarized by Pierce and White[3] are usually based on the rigid vortex wake concept, where the spacing of the wake vortices is preselected independent of blade motions. This concept appears to be ill-suited for the conditions of the model tests to be reported on here, where low frequency progressing or regressing flapping modes are excited at low lift. Related rotor model tests and supporting analysis reported by Kuczynski, Sharpe and Sissingh[4] used single-axis harmonic excitation of the cyclic controls. Unsteady wake effects may have been present but were not identified, possibly because of compensating influences of the neglected blade flexibility and the neglected wake in the analysis. Test results to be presented in the following were obtained with progressing and regressing cyclic control excitation. One reason for selecting this form of excitation was the desire for simplicity of the rotor model which did not require actuators nor a swashplate nor control links with their unavoidable play, but which used instead actuation of the feathering motion by an excentric. Another more basic reason was that dynamic instabilities caused by interblade coupling occur in the form of advancing or regressing blade flapping[5] so that it is of particular interest to find out what unsteady wake interactions exist for such modes.

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A Qualitative Model of Unsteady Asymmetric Wake Effects

We first consider a progressing blade flapping mode in which each blade flaps in a rotating frame of reference with the non-dimensional period $2\pi/(1 - \omega)$ which is longer than the period of rotation 2π and which is also longer than the natural blade flapping period. The sum of elastic, centrifugal and inertia flapping moments about the rotor center is directed opposite to the flapping deflection β. To sustain an advancing flapping mode the aerodynamic flapping moment on each blade at the phase of maximum up β must be directed upward, causing a dynamic downwash. The opposite blade will have at the same time its maximum down β and will cause an upwash. We thus have a progressing asymmetrical wake. Because of wake inertia the wake will lag the blade oscillation. Thus each blade when passing the neutral position on its way up, will encounter a downwash which is equivalent to an increased aerodynamic damping. In a regressing blade flapping mode the wake will lead the blade flapping oscillation in a rotating frame of reference. We have now two cases. Either the blade operates below resonance, then we have downwash at the phase of maximum up blade flapping, and, because of the lead of the wake, a decreased aerodynamic damping. Or the blade operates above resonance, then we have upwash at the phase of maximum up blade flapping and because of the lead of the wake increased aerodynamic damping. When the blade is in resonance and has zero mechanical damping, no aerodynamic moment is required to sustain the flapping oscillation and no wake occurs. Since in most rotor designs, the blade resonance frequency is only slightly above the rotational frequency, the unsteady wake effect will mostly increase blade aerodynamic damping and will thereby decrease the airframe damping which is important for whirl flutter, air resonance and flying qualities.

Test Equipment and Calibration

The rotor model used for the tests is two bladed with 16 in. diam and 1-in. blade chord. The airfoil is NACA 0012. The blades are attached to the hub with soft flexures, giving first flap bending frequencies of 11.6 and 24.3 *cps* at 0 and 20.3 *rps* rotor speed, respectively. Second flap bending frequency, first torsional frequency and first chordwise frequency at 20.3 *rps* are 161, 184, and 200 *cps*, respectively. The blade Lock number is 4.0. Fig. 1 shows a schematic of hub and pitch control with blade flexure *F*, feathering shaft *S* oscillated by a bending spring *B* from an excentric *E*, driven by an internal shaft *I*. A feathering amplitude of ±1.5° was used for the tests. The internal shaft *I* is driven by a set of exchangeable gears from the rotor shaft and can rotate with 0, ±0.05, ±0.1, ±0.2, ±0.6, ±0.8 times rotor speed. Both shafts carry magnetic pickups to measure the azimuth angles and shaft speeds. One blade flexure is strain gauged for blade flap bending, the other