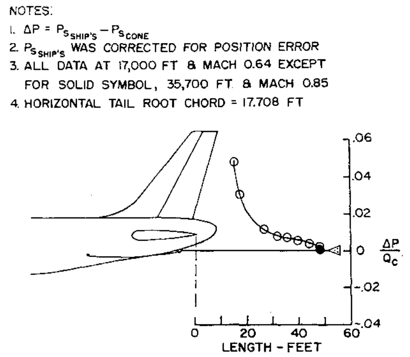

Fig. 3 Variation of $\Delta P/q$ with static tubing length on DC-8 aircraft.

behind the aircraft at constant airspeed and representing as true zero pressure the value that is asymptotically approached as a limit as the cone is extended. Figures 3, 4, and 5, showing the results of these surveys, are presented both as an indication of cone static system performance and as fundamental data concerning the extent of the pressure field of an aircraft in subsonic free flight.

In normal use the trailing cone is assumed to be a zero static pressure error source. The most desirable method for measuring static error for airspeed system static source development or calibration, is simply to use an accurate differential pressure gage or manometer between the cone source and the system being calibrated. For measurement of airspeed and altitude, the appropriate instrument is connected directly to the cone source. Lag of the system (0.2 to 1.0 sec time constant dependent on instrument volume) should be accounted for.

Several elements of trailing cone use require further study and test. Although the cone has been trailed immediately below a jet engine exhaust wake without temperature problems or power effects on static error, the unit has not been flown on an afterburner-powered aircraft where problems could arise from high temperatures and static pressure variations from under-expanded jet wakes.

The cone has been dragged during takeoff and landing on the aircraft centerline with good results, except that occasionally large-scale cone motions occur at aircraft rotation when it is emersed in the jet wake reflected from the runway.

There has been an indication of possible negative pressure error with flaps extended on one aircraft configuration. Such error is difficult to establish with certainty, for its magnitude is generally less than 0.02 $\Delta P/q$ between 65 and 150 knots airspeed, which corresponds to a measured ΔP value equivalent in magnitude to the error that the best of airborne instrumentation experiences. If the negative pressure field exists at large distances behind an aircraft, one possible explanation of its source could be that a vortex pattern is being generated by the inboard end of each flap and that the cone static pressure orifices lie in a small magnitude negative pressure field formed by the trailed vortex cores with flaps extended.

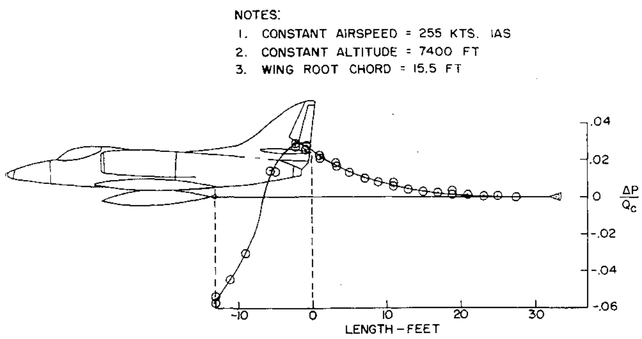

Fig. 4 Variation of $\Delta P/q$ with static tubing length on A4E aircraft.

At the present state of development, it may also be in order to avoid the area of the vortices trailing from the wing tips. These vortices generally are rolled up in approximately 2 to 4 chord lengths behind a low-aspect ratio wing and trail one-fifth to one-third of the half-span inboard from the wing tip. Periodic rotational motion of the trailing cone may be generated by the same phenomenon.

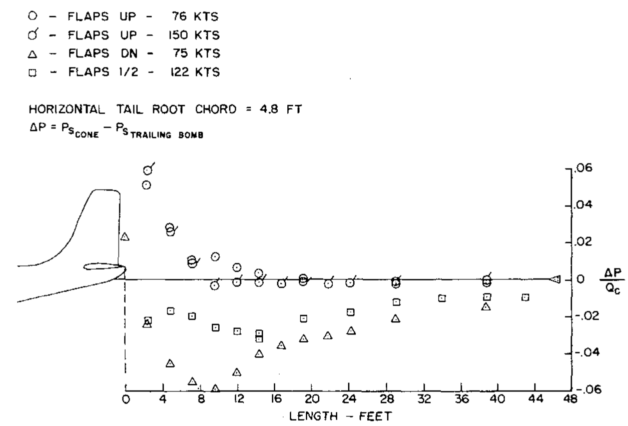

Fig. 5 Variation of $\Delta P/q$ with static tubing length on Aero Commander.

Summary

Use of the trailing cone for aircraft static system calibrations and for minimum error static reference systems can appreciably reduce the time, cost, and complication of flight test. With one system, and simplified recording and data reduction techniques, an aircraft may be completely calibrated from stall speed to dive speed in a single flight without imposing maneuvering or geographic flight area restrictions on the aircraft. Advanced developments of this device should extend the useful operational range of the calibration technique to the high Mach number regime and to slow-speed flight by helicopters and VTOL machines.

Nature and Observation of High-Level Turbulence, Especially in Clear Air

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Introduction

EVER since the development of fast-flying jet aircraft there has been increasing concern about clear-air turbulence (CAT). The importance of research in this field may be stressed by various considerations:

1) First of all, the aircraft engineer would like to have as detailed information as possible on gust loads to be expected with specific types of aircraft under design. From these data he will be able to compute stresses as well as aerodynamic behavior under average and extreme atmospheric conditions.

Presented as Preprint 63-81 at the IAS 31st Annual Meeting, New York, January 21–23, 1963; revision received January 27, 1964.

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2) Of no little concern to airlines is the "passenger comfort." It can be considered a function inversely related to frequency and amplitude of accelerations, and to length of time exposed to turbulent conditions. Crew performance is also decreasing with similar correlations. This factor, however, may be of more concern in missile operations than in regular aircraft flights.[1]

Observational Evidence of CAT

Quite to the contrary of earlier assumptions, experience from aviation and research shows that the stratosphere is not nearly so "stratified" as its name might lead us to believe. Although some statistical evidence gained from U-2 data indicates that the frequency of severe gust encounter decreases as we go beyond the tropopause,[14] we by no means can be certain of the absence of turbulence at flight levels of supersonic transport aircraft. According to these statistical findings a frequency maximum of CAT occurrence will have to be expected near tropopause level. It will have to be borne in mind that the U-2 does not acquire supersonic speeds. It reacts to a different portion of the spectrum of disturbances which might exist at these altitudes than does a supersonic transport. Therefore, we must be cautious in generalizing the findings presented in Fig. 1 to other aircraft types.

From data accumulated so far it may be seen that cases of extremely severe turbulence may occur, albeit not very frequently. Accelerations of 0.25 g will be considered uncomfortable when lasting over some length of time; 0.5 g already constitutes heavy turbulence. Cases with 2–3 g have been reported, usually in connection with mountain waves when observed in clear air. Turbulence observed in thunder storms may be of the same magnitude. Needless to say, such heavy turbulence may cause the loss of control over the aircraft and may even result in structural damages.[8]

According to statistical evidence, most turbulent regions show a rather small horizontal and vertical extent. Most of the turbulent patches observed over *continents* extend less than 30 miles horizontally. This is confirmed by recent measurement flights of Project TOPCAT over South Australia.[12]

A study by Clodman et al.[2] shows that over the *oceans* the frequency of CAT occurrence is at least one order of magnitude less than over the continents, being approximately 0.2% of the miles flown. On the other hand, however, the average horizontal extent of turbulence regions of about 100 km observed over oceans exceeds by far what has been reported over the continents.

Nature of Clear-Air Turbulence

In searching for mechanisms that might cause bumpiness in flight, we will have to be aware of the fact that the aerodynamic and elastic properties of the traveling vehicle in itself may, under certain circumstances, set off vibrations which may appear as CAT, although the ambient atmosphere may be only partly responsible for the observed effects. Presently, we will concern ourselves only with possible atmospheric causes of turbulence. These may be classified into two categories: convective motions in an unstable atmosphere, and perturbation motions in a stable atmosphere.

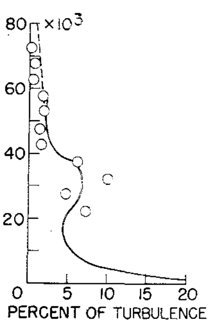

Fig. 1 Turbulence occurrence from U-2 data: Coleman and Steiner[3] (circles), and from data presented by Press and Steiner[6] (solid line), and by Coleman and Stickle[4] (dashed line).[14]

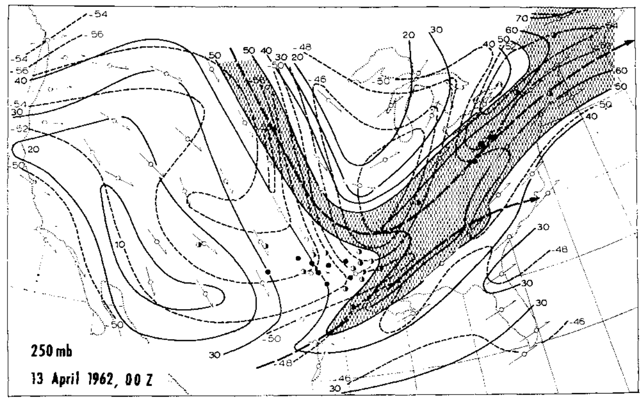

Fig. 2 250-mb isotachs (m/sec, solid lines, heavy numbers) and isotherms (°C, dashed lines, light numbers) of April 13, 1962, 00 GCT. Areas with winds > 50 m/sec are shaded. Jet axes are indicated by heavy dashed lines. Reports of severe CAT within ±6 hr of map time are entered with fully black circles, reports of moderate CAT with half-black circles. Reports of light CAT have been omitted.

Turbulence in an unstable atmosphere

This type of turbulence will be found within the friction layer of the atmosphere near the ground, and underneath, in, or near convective cloud systems. Although this type of turbulence may occur in clear air, it usually is excluded from clear-air turbulence considerations, mainly because its occurrence is expected by the experienced pilot.

Turbulence in a stable atmosphere

It is believed that this type of turbulence is responsible for most CAT cases observed in the upper troposphere and in the stratosphere.[9, 10, 13]

Most of the cases of moderate and severe turbulence seem to occur either in a region of strong horizontal temperature gradients and vertical wind shears, indicating the intersection of a sloping stable zone with this pressure surface, or they occur in the region of merging between two jet branches, or over mountainous terrain.

With this evidence in mind, we will have to look for a physical process that may result in bumpiness in flight. This can be found easily in gravity-wave-type disturbances on stable interfaces. Cloud studies by Conover[5] as well as aircraft measurements[7] reveal the existence of helical vortices in air-particle trajectories as they travel through such disturbances. These wave motions may be visible at times in a rather spectacular way in cirrus-cloud patterns. Gravity waves in a shearing current do possess the correct wavelength to which an aircraft of present design would respond with typical CAT accelerations.

From the foregoing it appears that we will have to keep a watchful eye on stable regions in the atmosphere which, at the same time, show a vertical wind shear. (This is equivalent to their being "baroclinic.") We know of three processes that tend to stabilize an atmospheric layer: 1) differential sinking motion, 2) differential temperature advection, and 3) decrease of absolute vorticity.

Referring to Fig. 2 we find that the streamline and isotherm configuration suggests strong sinking motion in the confluent region between the two "jet fingers" over northern Texas and Oklahoma. Offhand, this would qualify mechanism 1 to be effective. Figure 3 shows a rapid turning of winds with height which indicates differential temperature advection to be active.[15] Therefore, process 2 will also play a role in the generation of the observed CAT. Young and Corwin[19] report on the occurrence of CAT in a weakly rising current off the U. S. Northeast Coast, near the inflection point upstream from a high-pressure ridge. Since in these cases the vorticity

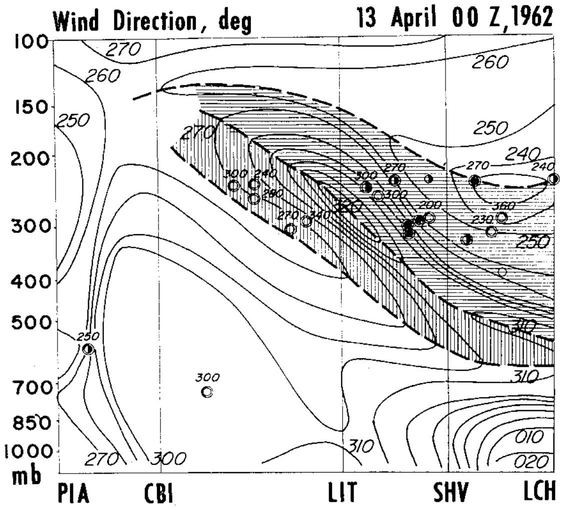

Fig. 3 Cross section of wind directions (deg) through the CAT area of Fig. 2 from Peoria, Ill. (PIA) to Lake Charles, La. (LCH). Aircraft reports of severe CAT, fully black circles; of moderate CAT, half-black circles; of light CAT, open circles. The blacked-in outer portions of the circles indicate time of observation: black half-circle to left or right—6 hr before or after map time. Areas of sharp turning of wind with height are shaded. The cases of moderate and severe CAT seem to be concentrated where winds are backing rapidly with height. Aircraft reports on wind direction have been entered numerically.

of the current seemed to be decreasing, mechanism 3 might have been prevalent. More detailed research will be needed, however, to make any definite statements on this point.

Clodman's[2] findings indicate that standing gravity waves are one of the main reasons for CAT occurrence over mountains and hill ranges. The cases of severe CAT reported in Fig. 2 over the Allegheny Mountains may qualify in this category. Over level terrain, as well as over oceans, traveling wave disturbances might be the dominating feature.

The information contained in Fig. 1 for supersonic transport flight levels has been obtained mainly from U-2 aircraft and should not be extrapolated to aircraft flying at supersonic speeds. In order to estimate the impact of atmospheric gusts upon vehicles that are still in the planning stage, we would have to know more about the atmospheric structure on a horizontal scale of about 2000 m, rather than 200 m to which our present jet aircraft are reaching. None of our present aircraft-instrument packages provide adequate information in this range of resolution.

Turbulence problems in supersonic transport operations

A further problem arises from the fact that temperature discontinuities affect the speed of sound and thereby the Mach number at which a supersonic aircraft is flying. This, in turn, influences the drag coefficient. A supersonic aircraft might therefore experience CAT by "skimming" along a temperature discontinuity that is "warped" into waves, without any direct action of atmospheric gusts. Some of this detailed structure of the upper atmosphere is slowly emerging from acoustic and other research,[18] but we are still far from being able to estimate all effects that this structure might have, and far from understanding the processes that lead to the formation of this microstructure.

Turbulence problems in missile operations

Detailed wind measurements with the smoket-rail photographic technique and with the FPS-16 radar reveal details of vertical wind shears that have not been known before.[16, 17] A vertically rising vehicle, in passing through these shears of alternating sign and/or magnitude, might respond with vibrations, especially if these shears are spaced at critical response frequencies.

Preliminary studies of such detailed wind shears show that at times they may persist for several hours, thus indicating a rather stable and by no means random nature. They also seem to be reflected, to a certain degree, by the thermal stratification of the atmosphere.[11] More research will have to be done in this field before forecast of these wind shears can be attempted.

Conclusions

CAT for horizontally flying as well as for vertically rising vehicles is a small-scale phenomenon. Our large-scale radiosonde network at best permits an estimate of gross flow conditions in the upper-wind field. In order to arrive at reliability forecasts of CAT, much more will have to be known about the detailed structure of the atmosphere. This means primarily better instrumentation for more special measurement programs. Once we know precisely which factors are responsible for the formation of microstructural details, even our routine radiosonde data will help us in assessing CAT probabilities more accurately than is presently possible.

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