ATMOSPHERIC TURBULENCE AND ITS RELATION TO AIRCRAFT

A ONE-DAY symposium on "Atmospheric Turbulence and its Relation to Aircraft" was held in the Royal Aircraft Establishment, Farnborough, on November 16, 1961, under the chairmanship of the director of the Establishment, Mr. M. J. Lighthill. The object of the symposium was two-fold: first, to bring together people interested in turbulence from a meteorological point of view and those people interested in turbulence in relation to aircraft engineering, and secondly, to review existing knowledge (or lack of knowledge) about atmospheric turbulence from the points of view of the meteorologist and aircraft engineer.

Altogether eleven papers were presented, of which six were concerned with meteorological and five with aircraft aspects.

The introductory paper on "Atmospheric Turbulence and Aircraft", by J. K. Zbrozek (Royal Aircraft Establishment, Bedford), gave a broad review of aircraft engineering problems where knowledge of atmospheric turbulence is of paramount importance. It was shown that the static strength and the fatigue life of an airframe are often determined by atmospheric turbulence considerations. A case was presented for more detailed knowledge of atmospheric turbulence in relation to stability and control, stability augmentation and passenger comfort studies. The effect of a vertical gradient of wind on the stability of a high-speed aircraft was described.

The author discussed the merits of the two models of atmospheric turbulence used by the aircraft engineer. One model is based on the discrete gust concept, and describes the turbulence in terms of the frequency-of-occurrence distribution of 'equivalent' gusts (gusts per mile). The second model treats the turbulence as a continuous random process and describes it by spectral density functions and the probability distribution of turbulence r.m.s.'s. The range of turbulence wave-lengths of interest to the aircraft designer was defined, the importance being stressed of the long waves in the application to more advanced designs. Some examples of spectral densities of atmospheric turbulence measured by use of an aircraft as a measuring probe were given. The validity of Taylor's hypothesis, the importance and difficulty of a satisfactory definition of the turbulence scale, and possible peculiarities of high-altitude turbulence were briefly discussed.

Prof. P. A. Sheppard (Imperial College of Science and Technology) in his paper "The Incidence of Atmospheric Turbulence" gave an overall picture of meteorological phenomena which are basic sources of atmospheric turbulence with a scale compatible with aircraft dynamics. The patterns of atmospheric motions and of heat-flow on a global scale were described and turbulence-generating processes discussed. This broad picture of atmospheric turbulence was followed by descriptions of more specific turbulence phenomena.

The turbulence in the Earth's boundary layer was related to the turbulence-generating phenomena of the lapse-rate and wind-shear, and the concept of the Richardson number, the most important parameter in the turbulence of stratified fluids, was introduced. Clear-air turbulence and its relation to jet streams, and the jet streams themselves, were described. Other types of turbulence, such as storm turbulence with its possibility of penetrating deep into the stratosphere and turbulence due to the topographical features of the ground, as distinguished from the effect of surface roughness, were discussed also.

Dr. T. H. Ellison (University of Manchester), in his paper entitled "Mechanism of Atmospheric Turbulence", approached the problem from the fluid mechanics point of view. He outlined the theoretical ideas concerned with the action of a density gradient on turbulence, introducing the flux form of Richardson number and suggesting an explanation of the existence of turbulence at Richardson numbers greater than one. The theoretical aspects of the turbulence in the Earth's boundary layer, including heat-flux effects, were expounded, and an interesting theory relating the Earth's boundary layer parameters to the geostrophic wind was outlined. Discussing the turbulence outside the boundary layer, Dr. Ellison explained the origins of wind shear at higher altitudes and pointed out the difficulties of determining the turbulence scale.

It was shown, on dimensional grounds, that for wave numbers intermediate between that of the generation of energy and that where viscosity is important, the spectral density of turbulence must follow Kolmogoroff's $-5/3$ relationship. This relationship was confirmed by experimental evidence, but the scale of the turbulence generating large eddies is still an open question.

Dr. Ellison introduced many new and stimulating theoretical ideas and his outline of further research deserves serious consideration by the experimental worker in the field of atmospheric turbulence.

A very comprehensive review of present knowledge of certain statistical properties of atmospheric turbulence at heights below about 1,000 m. was given by Dr. F. Pasquill of the Meteorological Office in a paper entitled "The Statistics of Turbulence in the Lower Part of the Atmosphere". Dr. Pasquill introduced his paper by first defining some of the functions describing the statistical properties of turbulence and outlining the techniques of measuring turbulence and their limitations. The available data on the three velocity components of turbulence were analysed in terms of the intensity, the scale and the shape of the energy spectrum, and the results of analysis were tabulated. It was shown that in the inertial sub-range the decay of a turbulence spectrum with wave number does not always follow the $-5/3$ law, but deviations from this law were not systematic enough to draw any firm conclusions. The scale of turbulence was found to be proportional to the height above the ground-level, decreasing with increasing thermal stability of the air. The intensity of the three components of turbulence was given as the ratio of the turbulence standard deviation to the mean wind-speed and the effects of thermal stability of air were demonstrated. The analysis suggested also that the ratio of the standard deviation of the vertical component of turbulence to the friction velocity is constant and independent of height, in agreement with theoretical predictions (as, for example, Ellison's paper). Finally, Dr. Pasquill presented ten examples of comparisons between turbulence spectra as measured from an aeroplane and from a 'fixed point'.

High-altitude turbulence, excluding the turbulence in large cumulus, was described by Mr. J. K. Bannon of the Meteorological Office, in a paper entitled "Turbulence in the Stratosphere and on the Upper Troposphere". A tentative distribution of discrete gusts per mile and the percentage prevalence of rough air were given for altitudes up to 75,000 ft. It was pointed out that clear-air turbulence is usually found in comparatively shallow layers and the typical size of turbulence patches was indicated. The possible origins of high-altitude turbulence, with special reference to jet streams, were discussed, but it was pointed out that the forecasting of this type of turbulence is not yet possible.

A new model of the air-flow in severe convective storms was described by Dr. F. H. Ludlam (Imperial College of Science and Technology) in his paper "Air Flow in Cumulonimbus". The gist of the paper can best be given by quoting the author's summary: "A new model of the air-flow in severe convective storms is described. It is suggested that strong wind shear in the vertical organizes the flow, and makes more efficient the release of kinetic energy. Consequently, in the severe storm, up- and down-draught speeds of 50–100 m./sec. may be attained. The organized flow permits the growth of hailstones of 2–3 in. diameter. Strong draughts and intense precipitation occur over regions up to 10 miles across, surrounded by more extensive weaker precipitation and draughts which can be discriminated by the quantitative use of radar".

In the paper "Clear Air Stirring Motions Induced in Stably Stratified Airstreams by Flow over Mountains", Dr. R. S. Scorer (Imperial College of Science and Technology) described many possible phenomena like billows and rotors of air motion when flowing over ground undulations, and illustrated them by photographs of corresponding cloud formations. One was very impressed by the profusion and beauty of these natural phenomena, but was left with the feeling that there is still a long way to go before it would be possible to forecast and estimate the magnitude of the phenomena in the way needed for engineering applications. Although the author himself said: " . . . the atmosphere is so complicated that we are not going to elucidate its behaviour by theorizing or even experimenting", he made some attempt to put theoretical reasoning into the dynamics of the problem.

The aircraft designers' point of view on atmospheric turbulence was put forward by Mr. G. F. H. Hemsley (Vickers-Armstrong, Ltd.) in his paper "Consideration of Air Turbulence in Aircraft Design". The author outlined the problem areas in civil airframe design, emphasizing the effect of turbulence on the useful life of the aircraft. The difficulties were pointed out of achieving satisfactory handling characteristics on modern aircraft when the maximum usable lift is often determined by the balance between controllability and stability from one side and the response to gusts from the other. The author stressed the importance of weather forecasting in the flight planning of the modern jet transport, as the fuel reserves are a large percentage of the pay-load and even a small reduction in these could have a considerable effect on the operating economics. This problem will be even more acute on the future of supersonic transport.

In the field of military aircraft design, the author discussed a relatively new problem of high-speed, low-altitude flight. In this flight condition, atmospheric turbulence has to be seriously considered not only in structural aspects but also in many others, such as comfort of crew, displays, weapon system, etc. In his conclusions, the author summarized the designers' view on the present state of knowledge of atmospheric turbulence by saying, "We are striving for two things, safety and efficiency. These tend to be opposing objectives and only by detailed and accurate data can the optimum be achieved. Arbitrary definitions of the atmosphere are used as design criteria and we know from experience that the safety standards are acceptable. Can relaxations be made consistent with safety ?"

A very thorough review of existing knowledge of atmospheric turbulence as seen by an aircraft engineer was given by Mr. N. I. Bullen (Royal Aircraft Establishment, Farnborough) in a paper "Gust Loads on Aircraft". The author discussed the 'discrete gust' concept, its limitations and its relation to present requirements. A comparison was made between counting accelerometer data collected in Britain and the data based on V–g–h recorders from the United States, and attention was directed to the areas where information is scarce.

In his paper "Aircraft Response to Turbulent Air", Mr. J. Burnham (Royal Aircraft Establishment, Bedford) discussed in some detail the relationship between the 'discrete gust' and 'continuous turbulence' approaches to the assessing of aircraft response to atmospheric turbulence. It was pointed out that, for a large family of more orthodox aircraft, both approaches lead essentially to the same answer; however, the extension of this conclusion to more advanced designs is hampered by the lack of information in the low-frequency band. More information is required about the long-wave components of atmospheric turbulence and the effects on human or automatic pilots at low frequencies should be studied.

The main role of the Air Registration Board is to formulate design requirements with the view of ensuring a satisfactory level of safety. Among other things, the environmental conditions dictated by the motions of the atmosphere have to be specified. The atmospheric motions encompass not only the 'gusts' which affect the airframe design but also other components of motion which lead to stability and control requirements, take-off procedure, speed margin requirements, etc. The above aspects of airworthiness were expounded by Mr. W. Tye (Air Registration Board) in his paper "Atmospheric Turbulence Considerations in Civil Aircraft Airworthiness". In his concluding remarks, Mr. Tye presented a list of problems which require further exploration to satisfy the needs of the engineer concerned with airworthiness. This list can be regarded as a research programme for both meteorological and aeronautical workers in the immediate future.

It is thought that the symposium fulfilled its original aims by bringing together meteorological and aeronautical research workers in the field of atmospheric turbulence. Each side has now a better picture of the aims and objectives of the other, and by pooling existing knowledge from both sides a somewhat better picture of atmospheric turbulence is emerging. Lack of time prevented full discussion of some of the papers, but it is hoped that it will be possible to organize further similar symposia when more restricted ranges of problems of atmospheric turbulence will be more extensively discussed.

The proceedings of the symposium will be published by H.M. Stationery Office in book form.

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