Certain remarks on the description of atmospheric turbulence as related to loads on gliders

By Dipl. Ing. Ludomir Laudanski, Technical University of Warsaw

Presented at the XI OSTIV Congress, Leszno 1968

1. Introductory Remarks

The problem of loads on gliders caused by atmospheric turbulence can be presented in the following way:

$$\boxed{\vec{u}(\vec{r},t)} \longrightarrow \boxed{O_{diff}} \longrightarrow \boxed{\vec{a}(\vec{r},t)} \qquad \begin{array}{l}\vec{r}\text{ - radius vector}\\ t\text{ - time}\end{array}$$

In this diagram, the input is a random field of turbulent velocities $\vec{u}$ and the output is a random field of acceleration $\vec{a}$ of a glider center of gravity. The field $\vec{a}$ is the result of superposition of an operator O_{diff} modelling the dynamic properties of the glider structure, on the field $\vec{u}$ considered.

It is well known that so far the problem of loads on gliders, treated in the above general way, is extremely difficult to solve.

This is the case because we are at the very beginning of development of the theory of turbulence, especially the theory of atmospheric turbulence, that would give us a probability-based description of the field $\vec{u}$. On the other hand, the similar, although slightly easier, problem exists with respect to an operator describing the dynamical properties of a flying object. So far we know nothing about this operator, even in the case when the influence of the surrounding medium is neglected. For these reasons, it seems, that it is almost impossible to obtain a solution of the problem so formulated.

It seems that, in practical applications, the most important question is: how realistic is the model actually considered? To give an answer to this question is the main purpose of this paper. The closer the model is to the description of the atmospheric turbulence, the more precisely the problem of loads can be treated.

2. Yudin model

Since the beginnings of aeronautics, the danger of a 'sudden gust' has forced us to study continuously atmospheric turbulence. In this field there exist meteorological as well as aeronautical aspects of the problem (see: 1). For many years aeroplanes (and also helicopters and gliders) are used as a tool for the systematic collection of experimental data for the theory of atmospheric turbulence. (See: (2), (3), (4), (5)).

Among others, in the study of turbulence the measurements are made of the accelerations of the centre of gravity of the flying object. This leads to a new general problem, being partially the reverse of the above formulated one:

$$\boxed{\vec{a}(\vec{r},t)} \longrightarrow \boxed{O_{int}} \longrightarrow \boxed{\vec{u}'(\vec{r},t)}$$

But, although the way from $\vec{u}$ to $\vec{a}$ is unique, the way from $\vec{a}$ to $\vec{u}$ is determinated only up to certain constants. In other words, instead of the information on the whole field $\vec{u}$, we obtain only the information on its 'most disturbed' part $\vec{u}'$. To explain it, let us consider a glider flying in a steady vertical stream (in a thermal, for example). In such a case the accelerometer reading will be zero, and this will give us no information about the existing up gust, in which we are interested.

Although this gives only limited information about the whole field $\vec{u}$, it gives the full information about the loads encountered. If we could collect the necessary quantity of data describing the field $\vec{a}$, we would have all the data necessary to solve the problem considered. It means, that if we were able to build an appropriate operator O_{diff} for each new glider structure, we would have the full answer to the question of loads, which the particular glider could meet during its 'life'.

However for this, it is necessary to have good computing facilities. (See: (6), (7).)

3. Gust model

The other way of making use of the acceleration measurements (except for the qualitative estimations of the atmospheric turbulence, based on the pilots reports) is the determination of the so called 'gust model'. Briefly, this method is based on the idea of replacing the information on the atmospheric turbulence by a single gust of appropriate 'shape' and amplitude. This quantity has no real physical analogue in the atmosphere. On the other hand—our information about the dynamic properties of a glider is limited only to a single parameter. It is understood, that such a description of the field is very rough. (See: (8)).

4. Spectral gust model

Let us pay more attention to the spectral model of the problem (see: (9), (10), (11)). For simplification of the treatment let us reduce the random fields of turbulent velocities considered to a random function of vertical components of velocity of the 'most disturbed' part of the field $\vec{u}'$.

The problem is considered under following assumptions:

(a) The field of atmospheric turbulence is a composition of the time-space 'volumes' (time and space are connected according to Taylor's hypothesis) having finite dimensions inside which the turbulence is a stationary, homogeneous and isotropic random field. Thus the description of the random field $\vec{u}'$ is reduced to the determination of a random function, W (x) describing the changes of vertical velocity components, along an arbitrarily chosen direction.

The time-space 'volumes' are distinguished from one another by the intensity σ_W^2.

(b) All the time-space 'volumes' have the same normalised spectral density function of velocities with a so called scale parameter L.

(c) We know the frequency of occurance of time-space 'volumes' with intensities σ_W^2 in the form of a probability density function $f(\sigma_W)$.

(d) A random function of vertical component velocities $W(x)$ is a gaussian process.

5. *Kolmogoroff model*

According to the above approach we will try to compare assumptions of the spectral model with the appropriate theory of atmospheric turbulence, particularly Kolmogoroff's local turbulence structure theory.

We will start from Kolmogoroff's hypothesis (see: (12), (2)) that if turbulence is locally isotropic then for a description of the time-space 'region' it is sufficient to have the mean value $\bar{\varepsilon}$—i. e. the mean portion of energy supplied to unit volume in unit time by the mean flow which is an infinite source of energy (called here 'energy flow rate'). The consequence of the above statement is that a power spectral density function of velocities has a form depending only on the quantity called 'energy flow rate' and frequency of turbulent fluctuations. For a so called inertial subrange—i. e. for a wide enough range of frequency k variations $\bar{\lambda}$ we will have the so called 'law of minus five-thirds':

$$f_w = f_w(\bar{\varepsilon}, k) = C \cdot (\varepsilon)^{2/3} (k)^{-5/3}$$

Although it would seem that the quantity called 'energy flow rate' has a clear physical sense, in the general case there is no expression given for it by the theory of turbulence (see: (2), (13)).

Certain attempts of surmounting this difficulty, having perhaps more general value, is based on the fact that there exists a qualitative dependence between the power spectral density function of, in this example, the vertical velocity component, and variation of stratification. This problem was solved (by (14)) for the case close to the ground (between 1 and 4 m), that is in the range where the Monin-Obuchov similanty theory is relevant.

This approach allows an easier interpretation of copious experimental results having wide scatter. The results have moreover shown, that in normalised spectral function, the variation of Richardson's number involves an appropriate variation of the pulsation components in the spectrum. On the base of these results it can be shown that for the unsteady stratification ($Ri < 0$) the frequency of maximum power input of the process is f_{max}, for the stratification of $Ri = 0$ it is I, 3 f_{max} and for the steady stratification ($RI > 0$) it is 4 f_{max}.

6. *Comparison of the two models*

Comparing the above with assumption (a) it is easy to see that the agreement between the time-space 'volumes' and the time-space 'region' occurs only when the unique relation between so called 'energy flow rate' and intensity σ_W exists. In Kolmogoroff's concept however one value of 'energy flow rate' $\bar{\varepsilon}$ can correspond to several values of intensity. Thus taking of the values of intensity σ_W as a distinguishing parameter for different time-space 'volumes', leads to another composition of the field, than 'energy flow rate' $\bar{\varepsilon}$ taken as a parameter for the time-space 'region'.

In addition the 'universal' spectral functions are not the same for the two cases considered—this bring out the fundamental difference between Kolmogoroff's and Press Steiner's models.

Detailed considerations concerning the Gaussian properties are given in ref (15). Here we discuss only one point i. e. the number of zeros of the random function.

The simplicity of the expression used for the number is due to the assumption, that the function is Gaussian. The simpler assumption, that the one-dimensional distribution of the velocity gradient should be Gaussian can be made (this is necessary but not a sufficient condition). Whereas, from considerations based on the theory of turbulence on the transport of energy in one direction from large scale turbulence to the small scale ones, it results that this type of transport is possible only if the gradient distribution is non-symetric and hence not Gaussian.

Therefore the use of the expression for the number of zeros appears inaccurate and as is noted in paper (16) gives always higher values.

The discussion on the spectral model can be concluded nothing that, if Kolmogoroff's hypothesis is retained, then this model is no less arbitrary than the single gust model, remembering the similar roles played by the gust shape and the density intensity repartition in those cases.

The most developed model of Lappi (17) where the turbulence scale parameter is variable with height and the turbulence intensity with wind velocity and ground geometry, and in addition the wind velocity with stratification, does not solve the difficulties connected with relating Kolmogoroff's ideas and the assumptions of the spectral model.

7. *Pinus model*

To end these remarks about different models of turbulence I would like to mention one more theory due to Pinus (18) as this shows a relation between Richardson's (stratification) number and the large scale turbulence which is responsible for loads on aircraft. Pinus proposes to determin the loads due to gusts by the following expression:

$$a = 4c \frac{V\delta}{b} (a_i + b_i \lg Ri) \qquad \begin{array}{l} a - \text{accel. of c.g.} \\ \delta - \dfrac{\rho}{\rho_0} \end{array}$$

where: $c = (u^2+v^2)^{1/2}$—wind velocity, V—aircraft velocity, b—constant depending on type of aeroplane, a_i and b_i—constants depending on the meteorological region considered, Ri—Richardson's number.

8. *Final Remarks*

I think, that the most complete model describing aircraft loads is the spectral model. This model takes advantage of recent progress in mathematics and uses advanced experimental techniques, for example measurements of correlation functions, spectral and propability distributions. All this is of great advantage.

On the other hand I think that the relation between this model and the basic ideas of the universal structure of turbulence remain unknown.

The main aim of my paper was to call attention to these disturbing facts, which need further clarification.

Literature

(1) *H. A. Panofsky*, *H. Press*, (1962), Meteorological and Aeronautical Aspects of Atmospheric Turbulence, Progress In Aeronautical Sciences, *3*, Pergamon Press, Oxford.

(2) *A. S. Monin*, *A. M. Jaglom* (1965, 1967), Statisticeskaya Gidromechanika (v. 1, v. 2), Nauka, Moskwa (in rus.).

(3) *J. L. Lumley*, *H. A. Panofsky* (1964), The Structure of Atmospheric Turbulence, Interscience Publishers, New York.

(4) *P. A. Woroncov* (1966), Turbulentost i vertikalnyje toki w pogranicnom sloje atmosfery, Gidrometeoizdat, Leningrad.

(5) *A. T. Matveev* (1965), Osnovy obscey meteorologii, Gidrometeoizdat, Leningrad.

(6) *M. I. Yudin* (1946), Voprosy teorii turbulentnosti i struktury vetra s prilozenijem k zadace o kolebanijach samoleta, Trudy NIU GUGMS, ser. 1, wyp. 35.

(7) *A. S. Dubov* (1958), K voprosu opredelenija vertikalnych skorostej vetra po dannym samolotnego akselerografa, Trudy GGO, wyp. 72.

(8) *J. Zbrozek* (1965), Atmospheric Gusts—Present State of the Art and Further Research, JRAS, 649, *69*.

(9) *H. Press*, *R. Steiner* (1958), An approach to the problem of estimating severe and repeted gust loads for missile operationg, NASA *TN 4332*.

(10) *J. Taylor* (1965), Manual on Aircraft Loads, Pergamon Press, Oxford.

(11) *L. Laudanski* (1967), Loads on Gliders in Turbulent Atmosphere, S. Aero-revue, 4.

(12) *A. N. Kolmogoroff* (1941), Lokalnaja struktura turbulentnosti w neszimajemoj zidkosti pri ocen bolsich cislach Reynoldsa, Dokl. AN SSSR, *30*, 4.

(13) *S. Pancev* (1967), Slucajnyje funkci i turbulentnost, Gidrometeoizdat, Leningrad.

(14) *A. S. Gurvich* (1960), Eksperimentalnoje issledowanije castotnych spektrov i funkcii raspredelenija verojatnostej vertikalnych komponent skorostej vetra, Izv. AN SSSR, ser. geof. 7.

(15) *L. Laudanski* (1968), Pewne uwagi o gaussowskosci funkcji losowych – unpubl.

(16) *H. W. Liepmann*, *M. S. Robinson* (1953), Counting Methods and Equipment for Mean Value Measurement in Turbulent Research, NASA TN 3037.

(17) *U. O. Lappi* (1966), Low Altitude Turbulence Model for Estimating Gust Loads on Airrcraft, J. Aircraft, *3*, No. 1.

(18) *N. Z. Pinus* (1957), Turbulentnost soizmerimaja s razmerom samolota, Izv. AN SSSR, ser. geofiz. No. 3.

Zusammenfassung

Es ist bekannt, dass das Problem der Belastung von Segelflugzeugen durch die atmosphärische Turbulenz sehr schwer zu lösen ist: Die wichtigste Frage ist: Wie realistisch ist das angenommene Modell der Turbulenz?

Der Bericht erörtert das Yudin-Modell, das sogenannte Böenmodell, das Spektralböenmodell, das Kolmogoroff-Modell und das Pinus-Modell sowie die Schwierigkeiten, einige von ihnen mit den anderen in Einklang zu bringen. Der Autor betrachtet das Spektral-Böenmodell als das vollständigste.

Zacher

Swiss Aero-Revue 4/1969