Some Aircraft Flight Conditions Relating to LO-LOCAT

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A model for atmospheric turbulence is presented for the low level environment below 1000 ft alt which considers a wide range of meteorological and topographical conditions for possible influence upon the intensity of the turbulence encountered. While altitude has long been recognized as relating to atmospheric turbulence, it will be shown that the low level environment is far more complicated in that a number of other conditions have been observed which have an even stronger influence upon turbulence. In particular, it was found that atmospheric stability defined as a function of temperature lapse rate had the strongest relationship to LO-LOCAT with such conditions as time of day, terrain type, season, and altitude also having a significant relationship to the turbulence encountered.

Nomenclature

A_{ji} = regression coefficient of the jth independent variable at the ith step, $i \geq j$
C_i = constant term in the regression model at the ith step
L = scale of turbulence
N_o = characteristic frequency of response
r_i = multiple correlation coefficient at the ith step of model
S_i = standard deviation of the least squares fit at the ith step
X_i = dichotomous variable representing the ith flight condition
$x_{\max}$ = maximum gust velocity encountered for the given leg, ft/sec
$x_{\min}$ = minimum gust velocity encountered for the given leg, ft/sec
Γ = temperature lapse rate, °F/1000 ft
σ_t = standard deviation of the gust velocity time history, ft/sec

Introduction

ALTHOUGH aircraft have been used for many years in an attempt to measure atmospheric turbulence, only recently has sufficient data become available to allow analysts to systematically study the turbulence environment. Early studies, although they provided a great deal of information about turbulence, lacked a comprehensive data base and therefore the resulting recommendations and conclusions were too often restricted to particular segments of the turbulence environment. The model presently under consideration was obtained using data from the ALL CAT Program,[1] a well-planned and comprehensive data collecting turbulence program established by the United States Air Force.

In Oct. 1964, the Air Force announced that an extensive low level turbulence program called Low Altitude Critical Air Turbulence (LO-LOCAT) was being established to determine the turbulence environment below 1000 ft above the ground utilizing statistically representative samples of turbulence data obtained over a wide range of meteorological, topographical, seasonal, and time of day conditions. A contract was subsequently awarded to The Boeing Co., who instrumented four C-131B aircraft assigned to the project and recorded turbulence data for about 8000 low level legs by Air Force crews from Sept. 1966 to Dec. 1967.

For each leg of 5½ min in duration, the gust velocity time history was recorded, filtered to eliminate drift and aircraft motion from the data, and finally decomposed into three orthogonal, space oriented gust velocity components. The component time histories were then used to obtain the following turbulence parameters for each leg: 1) σ_t, the standard deviation of the time history of the gust velocity components, 2) $x_{\max}$, the maximum gust velocity encountered in each component, and 3) $x_{\min}$, the minimum gust velocity encountered in each component. For a random sampling of 20% of the low level legs, a power spectral density (PSD) analysis was performed and for such legs the additional turbulence parameters recorded for each component were as follows: 4) N_o, the characteristic frequency of the turbulence components and 5) L, the scale of turbulence for the von Kármán model of turbulence.

The University of Dayton Research Inst. (UDRI) worked with a master tape containing the turbulence parameters for each leg which was supplied by The Boeing Co. at the request of the Flight Dynamics Lab. at Wright-Patterson Air Force Base. The work performed by The Boeing Co. in instrumenting the aircraft, collecting the data, and obtaining the turbulence parameters is documented in Refs. 2–5. The purpose of this article is to present a model for atmospheric turbulence which relates the turbulence parameters to altitude, terrain type, atmospheric stability, season, and time of day. Although the analysis was conducted on all of the turbulence parameters previously mentioned, this article will concentrate on the results obtained for σ_t and $x_{\max}$ at Edwards Air Force Base for the sake of brevity.

Low Level Flight Conditions

Associated with each low level leg is a code indicating the flight conditions under which the leg was flown. A listing of the flight conditions considered is given in Table 1. The conditions in atmospheric stability are defined as a function of the temperature lapse rate Γ. The atmospheric stability is defined to be very stable if $\Gamma < 2$, stable if $2 \leq \Gamma < 5$, neutral if $5 \leq \Gamma < 6$, and unstable if $\Gamma \geq 6$. All other conditions are self-explanatory.

Analytical Procedure

The model for atmospheric turbulence is to determine which of the flight conditions relate to the turbulence parameters and the strength of any such relationship. The first step was to represent each of the flight conditions by a dichotomous variable which is assigned a value one for those legs flown under the given condition and is assigned

Table 1 Aircraft flight conditions considered

Location—Edwards, Griffiss, Peterson, McConnell
Altitude—250 ft, 750 ft
Season—spring, summer, fall, winter
Time of day—dawn, midmorning, midafternoon
Atmospheric stability—very stable, stable, neutral, unstable
Terrain—high mountains, low mountains, plains, desert

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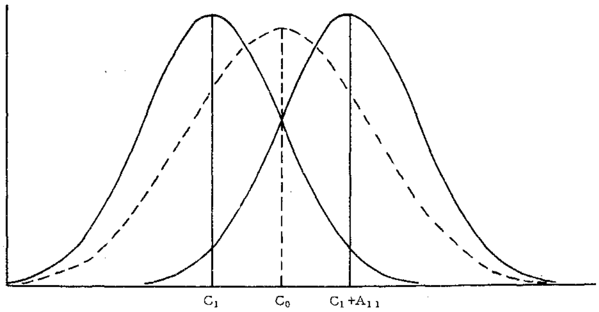

Fig. 1 Model decomposition at step 1.

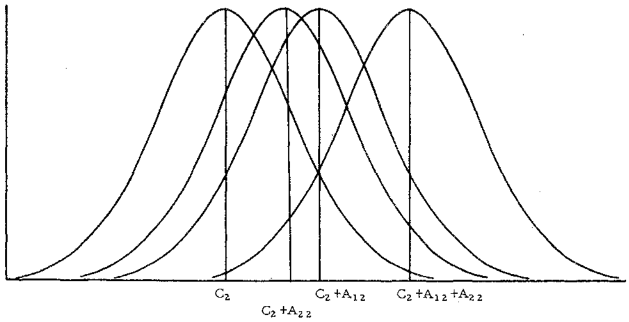

Fig. 2 Model decomposition at step 2.

a value zero for those legs not flown under the given condition. For example, the dichotomous variable representing the flight condition "dawn" would take a value one for those legs flown at dawn and take a value zero for those legs not flown at dawn. These dichotomous variables were then used as the independent variables in a stepwise regression routine with the various turbulence parameters used as the dependent variable. The routine BMD02R documented in Ref. 6 was used to establish a linear model relating the dichotomous variables to the turbulence parameters. As an example, suppose that a turbulence model is to be established for the turbulence parameter σ_t using data for n legs flown under a variety of flight conditions as indicated in Table 1. Define C_o to be the average of the n values of σ_t and define S_o to be the standard deviation of the n values of σ_t. The model at step 0 would indicate that the data is represented by a single normal distribution with mean C_o and standard deviation S_o. At step 1, each of the dichotomous variables X_i are correlated to the σ_t values and that variable chosen which has the strongest correlation to the σ_t values. Call it X_1. A least squares fit is then obtained to the linear model $\sigma_t = C_1 + A_{11}X_1$ resulting in values for the coefficients C_1 and A_{11} as well as a standard deviation S_1 and a correlation r_1. At this stage the model has broken the σ_t values into two normal populations with common standard deviation S_1. The mean for the σ_t values obtained under the flight condition represented by the dichotomous variable X_1 is defined to be $C_1 + A_{11}$ while the mean for the σ_t values not obtained under this condition is defined to be C_1 (i.e., the two values obtained in the linear model by replacing X_1 by zero and one). Pictorially, the decomposition is shown in Fig. 1. It should be noted that for the decomposition to be of value, S_1 should be less than S_o.

At step 2, the dichotomous variable with the strongest correlation to the yet unexplained variation in the σ_t values is added to the linear model resulting in a least

Table 2 Results of regression analysis on lateral σ_t at Edwards

i Step	c_i Constant	A_{1i} Very stable	A_{2i} Desert	A_{3i} Stable	A_{4i} 750 ft	A_{5i} Dawn	A_{6i} Unstable	A_{7i} Mid-afternoon	A_{8i} High mountains	A_{9i} Spring	r_i Correlation coefficient	s_i Standard deviation
0	2.77											1.243
1	3.24	−1.31									0.508	1.071
2	3.47	−1.31	−0.79								0.586	1.007
3	3.75	−1.57	−0.83	−0.71							0.626	0.970
4	3.90	−1.55	−0.84	−0.68	−0.30						0.638	0.959
5	3.92	−1.30	−0.84	−0.58	−0.31	−0.34					0.645	0.951
6	3.78	−1.17	−0.81	−0.45	−0.30	−0.34	+0.35				0.651	0.946
7	3.89	−1.18	−0.81	−0.45	−0.30	−0.44	+0.34	−0.22			0.655	0.942
8	3.83	−1.17	−0.74	−0.44	−0.30	−0.45	+0.31	−0.22	+0.15		0.657	0.940
9	3.80	−1.14	−0.75	−0.43	−0.30	−0.48	+0.28	−0.23	+0.16	+0.12	0.658	0.939

Table 3 Results of regression analysis on lateral x_{max} at Edwards

i Step	c_i Constant	A_{1i} Very stable	A_{2i} Desert	A_{3i} Stable	A_{4i} 750 ft	A_{5i} Dawn	A_{6i} Unstable	A_{7i} Spring	A_{8i} High mountains	A_{9i} Mid-afternoon	r_i Correlation coefficient	s_i Standard deviation
0	13.83											6.18
1	15.61	−5.48									0.416	5.63
2	17.08	−5.49	−4.87								0.551	5.16
3	17.89	−6.29	−4.89	−2.32							0.570	5.09
4	18.71	−6.18	−4.94	−2.19	−1.60						0.584	5.02
5	18.76	−5.18	−4.95	−1.83	−1.63	−1.34					0.589	5.00
6	18.24	−4.74	−4.80	−1.38	−1.60	−1.31	+1.18				0.592	4.99
7	18.11	−4.62	−4.81	−1.34	−1.59	−1.40	+1.10	+0.58			0.593	4.99
8	17.89	−4.60	−4.57	−1.31	−1.59	−1.45	+0.98	+0.59	+0.55		0.594	4.98
9	18.08	−4.60	−4.58	−1.30	−1.59	−1.64	+0.95	+0.61	+0.56	−0.39	0.595	4.98

squares fit to the model

$$\sigma_t = C_2 + A_{12}X_1 + A_{22}X_2$$

which yields values for the coefficients C_2, A_{12}, and A_{22} in addition to the values S_2 and r_2. This representation is pictured in Fig. 2 with $A_{12} > 0$, $A_{22} > 0$, and $A_{12} > A_{22}$. The decomposition continues until all dichotomous variables having a regression coefficient significant at the 1% level of significance have been entered into the linear model. All other variables are not considered useful in the prediction of the turbulence parameter and their regression coefficients are considered to be zero. Since the dichotomous variables take only values of zero and one, this regression routine reduces to a decomposition of low level legs into classes represented by the presence of various combinations of the flight conditions. Furthermore, the regression coefficients give a measure of the effect produced in the turbulence parameter by the flight conditions under consideration.

Results of Statistical Analysis

The results of the stepwise regression analysis for 1265 low level legs at Edwards Air Force Base with lateral σ_t as the dependent variable are given in Table 2. At step 0 the mean lateral σ_t for the 1265 legs is given as 2.77 ft/sec. At step 1 the legs are decomposed into two groups, those flown in very stable air having a fitted mean lateral σ_t of $3.24 - 1.31 = 1.93$ ft/sec while those not flown in very stable air have a fitted mean 3.24 ft/sec. The flight condition "very stable air" was considered first because the dichotomous variable representing this condition was most strongly correlated to the dependent variable in the regression procedure. Additional flight conditions are considered in their order of influence upon the residuals of the dependent variable after the effects of the dichotomous variables already considered had been removed. In this case the condition "desert" produced the next strongest effect upon the lateral standard deviations of the 1265 legs. At this stage the legs have been decomposed into four groups with, for example, the predicted mean lateral σ_t for legs flown in very stable air over the desert given as $3.47 - 1.31 - 0.79 = 1.37$ ft/sec, and for legs flown over the desert not in very stable air as $3.47 - 0.79 = 2.68$ ft/sec. The process continues similarly with the final correlation coefficient of 0.658 indicating that the decomposition presented explains $100\ (0.658)^2 = 43.3\%$ of the total variation in the lateral standard deviations of the 1265 Edwards legs. The final step in this table presents a set of regression coefficients reflecting the relationship of each flight condition to the component σ_t values. The intermediate steps are of value only in that they provide the best (in the least squares sense) predictive linear model for the turbulence parameter based upon the given number of dichotomous variables entered.

While the quantity σ_t provides much information about the turbulence encountered on each leg, the quantity $x_{\max}$ also contains information about the intensity of the turbulence. Therefore, $x_{\max}$ for the lateral component of the gust velocity for $n = 1265$ low level legs at Edwards Air Force Base was used as the dependent variable in the stepwise regression procedure in an attempt to relate the various flight conditions to this parameter. The results of this analysis are given in Table 3. A comparison with the results in Table 2 reveals that the regression coefficients are roughly the same in relative magnitude with the flight conditions entering into the linear model in about the same order and with the same sign. This consistancy indicates that the two turbulence parameters contain much the same information about the turbulence environment. However, it should be noted that the correlation coefficient for the final step of the $x_{\max}$ regression is smaller than the corresponding correlation coefficient for the σ_t regression (0.595 for $x_{\max}$ to 0.658 for σ_t) indicating that the latter turbulence parameter has a stronger relationship to the flight conditions. This is not surprising since σ_t is a more comprehensive measure of the intensity of the turbulence encountered over the entire leg.

Conclusions

Military specifications have long recognized the importance of altitude as a significant factor in the determination of the turbulence encountered by an aircraft. Analysis of the LO-LOCAT data reveals that in addition to altitude, such factors as atmospheric stability, terrain, season, and time of day also have a significant influence upon the intensity of turbulence encountered at altitudes below 1000 ft. In fact, at the low altitudes the results of Tables 2 and 3 indicate that atmospheric stability and terrain are of greater significance than altitude in predicting turbulence. It would therefore seem imperative that a rather complex model for the prediction of atmospheric turbulence is needed to explain the turbulence environment encountered by aircraft. This paper attempts to establish such a model by recording several turbulence parameters which are reflexive of the turbulence encountered for a series of low level legs. The flight conditions of each leg are recorded and the model established through the application of a stepwise regression routine. While other recent studies have succeeded in relating various turbulence parameters to the flight conditions considered in the LO-LOCAT study, the present model goes beyond their findings in that a systematic and statistically sound procedure has been developed to rank the flight conditions in their order of influence upon the turbulence environment. In addition, the regression coefficients in the model provide a clear and concise notion of the influence of each of the flight conditions upon turbulence.

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