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Wingrove Parameter: A New Turbulence Metric

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This article discusses the development of a real-time turbulence metric called the Wingrove parameter. This metric is proportional to the turbulent kinetic energy of the vertical wind. It is computed from digital flight data recorder information after the application of a numerical filter to eliminate gust scales that do not contribute to aircraft turbulence. Preliminary results from this study show that the Wingrove parameter is able to eliminate long nonturbulent wave motions and to distinguish true atmospheric turbulence from maneuvering. There are some averaging problems because of the intermittent nature of turbulence events, and some simple procedures for eliminating them are presented. From these preliminary results it is concluded that the Wingrove parameter provides a substantial foundation for the development of a standardized, quantitative, real-time turbulence metric.

Introduction

TURBULENCE was a problem for pilots many years before the Wright Brothers' first flight. In 1896, Otto Lillienthal was fatally injured when his glider pitched up and stalled because of a turbulent gust.[1] Nearly 100 years after Lillienthal's death, aircraft still experience accidents because of unexpected encounters with turbulence. For example, between the years of 1964–1975, 183 (25%) of 729 air carrier accidents were turbulence related.[2] From 1981 to 1984, turbulence contributed to 24% of all accidents involving large commercial carriers and to 54% of all weather-related accidents.[3] In addition to accidents, turbulence has a broad impact on aircraft operations. Other effects include in-flight injuries, structural damage, crew fatigue, passenger discomfort, and increased costs because of late arrivals and in-flight diversions.[4–6] Research in turbulence has been directed toward three primary areas: 1) forecasting, 2) remote sensing, and 3) real-time turbulence reports. Results have not been completely satisfactory; meteorological observations and prediction models lack the temporal and spatial resolution necessary for accurate turbulence forecasts. Furthermore, systems for the onboard remote detection of turbulence are not yet adequate for operational use. In the meantime, real-time turbulence reports continue to be the primary method for avoidance.

Currently, most operational turbulence data are qualitative, based on verbal pilot reports (PIREPS). However, within the last 10 years, it has become clear that many airliners equipped with digital flight data recorder (DFDR) systems have enough information to estimate the turbulence intensity in a quantitative manner.[7] Modern computing technology now allows these computations to be made onboard and development of the Meteorological Data Collection and Reporting System (MDCRS) permits rapid dissemination of the results of these computations.[8] Although the technology to compute and automatically transmit aircraft data is available, it is not yet clear what turbulence information should be reported.

The purpose of this article is to present preliminary results of the work of scientists at San Jose State University and NASA Ames in the development of a standardized, quantitative turbulence measure (metric). In particular, we address the formulation and testing of the Wingrove parameter.

Background

The ideal turbulence metric should be quantitative, aircraft-independent, unaffected by maneuvering, and computationally efficient. Another desirable characteristic is ease of interpretation by pilots, forecasters, and other users.

The use of turbulence metrics is not new. Metrics such as vertical accelerations and airspeed fluctuations have been used for research purposes for many years.[9] Although quantitative, these particular metrics are either aircraft-dependent and/or can be influenced by maneuvering.

The derived gust velocity is an improvement.[10] Under the assumptions of the simple aircraft model it is based on, it can be considered aircraft independent. However, it is computed from vertical accelerations, and is therefore affected by maneuvering.

In 1964, MacCready[11] proposed that onboard estimates of the eddy dissipation rate be used as an aircraft-independent turbulence metric. Based on Kolmogorov's hypothesis,[12] the use of the metric assumes that the aircraft measurements are made within the inertial subrange. Kolmogorov showed that the power spectral density within the inertial subrange can be specified by a power law, i.e.,

$$\phi(k) = c\varepsilon^{2/3}k^{-5/3} \quad (1)$$

where $\phi(k)$ is the power spectral density of the vertical wind speed, c is Kolmogorov's constant, and k is wave number.[12] Although this method showed promise, it could not be easily implemented because of the requirement for special onboard equipment and at that time the inability to rapidly disseminate turbulence reports.

A number of the problems faced by MacCready have been overcome with technological improvements in measurement, recording, and communication of airliner data. Recently, Cornman et al.[13] showed that vertical accelerations measured onboard airliners can be used to compute the eddy dissipation rate. His method employs the use of a two-degree-of-freedom rigid body aircraft model. Data are preprocessed with a band-

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pass filter to eliminate "nonturbulent contaminants: pilot, autopilot, and/or low-frequency atmospheric inputs."

More recently the F-factor has been developed to diagnose the intensity of downbursts.[14] Since this metric depends strongly on wind shear information along the aircraft track, it is not appropriate for quantifying many other turbulence phenomenon [e.g., mountain wave turbulence and clear-air turbulence (CAT)].

Rodney Wingrove[15] suggested another metric based on wind information. In studies conducted at NASA Ames, Wingrove and Bach[5,7] have shown that three-dimensional winds can be computed accurately from information collected onboard modern airliners. When the procedures that they have developed are combined with recent improvements in aircraft instrumentation and DFDR technology, in-flight computations are now possible. He proposed that onboard calculations of the vertical wind velocity be used directly as the basis of a metric. It is well-known that the variation in the vertical wind component is the major contributor to aircraft turbulence (e.g., see Ref. 16). The vertical wind velocity is then to be processed "using a high-pass filter-smoother in order to eliminate long term waves in the vertical wind that do not contribute to turbulence G-loads."[14] Subsequently, the Wingrove parameter has been defined as

$$Wi \equiv \overline{w_h'^2} \tag{2}$$

where w_h is the vertical wind velocity, the prime indicates high-pass filtering and the overbar indicates an average along the aircraft track. Ideally, vertical wind velocity computations are not contaminated by aircraft motions, therefore, the effects of maneuvering are eliminated. Notice that Wi is the variance of w_h' along the aircraft track ($\overline{w_h} = 0$) and is proportional to the turbulent kinetic energy of the vertical wind.

In the following, we present preliminary results of the development and testing of the Wingrove parameter and describe its application.

Methodology

The Wingrove parameter is being tested on DFDR data from several severe turbulence incidents. These cases are part of an archive of data from airliners involved in turbulence incidents summarized by Wingrove et al.[7] Preprocessing of airliner data includes wildpointing, aircraft performance calculations, and vertical and horizontal wind estimations.[17]

Prior to computing the Wingrove parameter, the Earth-fixed vertical wind speed w_h was linearly detrended to remove biases. Next, a fourth-order Butterworth high-pass filter was applied to the data to determine w_h'. The cutoff frequency of 0.1 Hz was selected on the basis of experimental and computational studies of large multiengine aircraft response to gusts felt at the aircraft's center of gravity[9,18] (Fig. 1). This cutoff is identical to the low-frequency cutoff of the bandpass filter used by Cornman et al.[13]; it corresponds to a scale of about 2500 m using typical airliner true airspeeds.

To determine Wi, $w_h'^2$ must be averaged over an interval that is proportional to the scale of the turbulence phenomenon. The purpose of averaging is to provide a stable statistic of the turbulence intensity along the aircraft track. However, the selection of the averaging period is somewhat arbitrary because of observed variations in turbulence scale, variations in airspeed, and the localized structure of turbulence layers. Many turbulence patches reported as severe by the aircrew are typically moderate or less over 99% of the patch. For example, in the examination of seven severe turbulence incidents reported from airliners, Lester et al.[19] found that the median duration of severe or greater turbulence to be about 4 s.

Cornman et al.[13] recommended that both peak and average values of eddy dissipation rate be used to characterize turbulence patches. They averaged over 10 s, arguing that this interval will satisfy the local-stationarity assumption and provide enough data values for statistical stability.

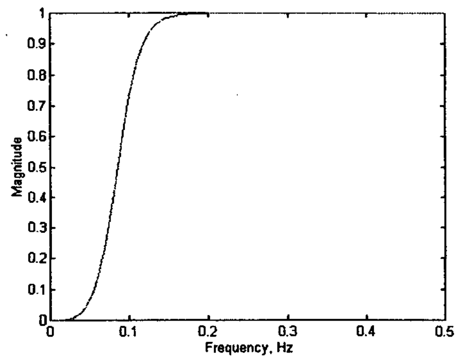

Fig. 1 Frequency response for a high-pass fourth-order Butterworth filter used in this study.

In the current study, several experiments were performed with different averaging intervals. Ten s was selected as a compromise to provide details of the turbulence patches while giving enough data values for statistical stability.

This article presents results of W_i for four cases.

1) On Jan. 22, 1985, a B-747 encountered a series of strong vertical oscillations while cruising at 33,000 ft over the western slopes of the Greenland icecap. At the end of the event the aircraft suddenly gained 1000 ft. Analysis of the flight and meteorological data indicated that the aircraft intersected a turbulent region near the trough of a mountain lee wave. This incident resulted in 13 injuries.[20]

2) On April 7, 1986, a DC-10 reported severe turbulence just after it began descending from a cruising altitude of 41,000 ft over Jamestown, New York. Analysis of the data indicates that the aircraft descended through a strongly sheared layer in the lower stratosphere. Although some turbulence was present, the largest vertical accelerations were caused by maneuvering. Twelve injuries resulted from this incident.[19]

3) On Sept. 27, 1987, an L-1011 encountered severe turbulence while flying from San Juan, Puerto Rico to New York. The aircraft was flying at an altitude of 33,000 ft and dropped several thousand feet into the vicinity of a thunderstorm. This turbulence near the thunderstorm incident resulted in injuries to four passengers and one flight attendant.[21]

4) On Nov. 3, 1975, a DC-10 encountered severe turbulence 50 nm west of Calgary, Alberta, Canada, at 33,000 ft while enroute from London to Oakland, California. The turbulence occurred simultaneously with a severe surface windstorm in the same area. Analysis revealed that this incident was the result of breaking Kelvin–Helmholtz waves in a complex mountain lee wave system. This incident resulted in nine injuries.[22]

Results and Discussion

In the Greenland case, as the airliner flew into the mountain wave, it initially experienced smooth downward motions that reached −15 m/s. The aircraft subsequently crossed the trough of the lee wave and entered an updraft where it encountered severe turbulence. The lee wavelength was about 25 km.

Vertical accelerations, vertical wind speed, and corresponding Wingrove parameter are shown in Figs. 2a, 2b, and 2e, respectively. Figure 2c illustrates the effect of averaging on the high-pass filtered data; Fig. 2d shows the effect of omitting the high-pass filtering step. The influence of the longer (nonturbulent) waves on the computations is obvious.

The correlation between Wi and vertical accelerations is weak in the vicinity of the smooth wave action as shown in Fig. 2. The influence of the lee waves has been eliminated by high-pass filtering. In contrast, there is a strong correlation between the Wingrove parameter and vertical accelerations

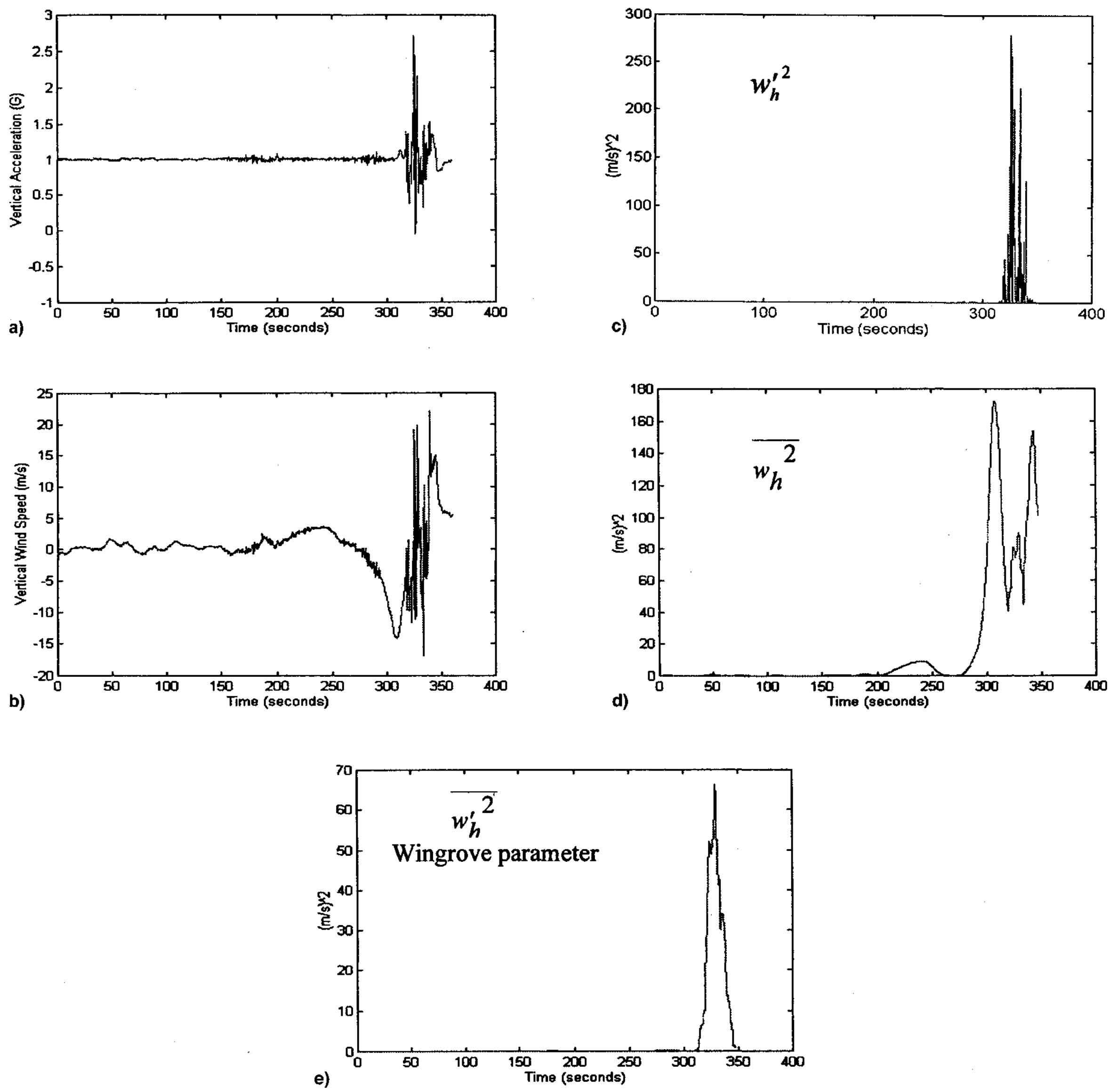

Fig. 2 PAA 125 turbulence encounter over Greenland, January 1985.

near the region of maximum G-load (+1.5 *g*). That is the location of severe turbulence in agreement with the pilot report.

In the Jamestown case (Fig. 3), the aircraft was descending into a region of increasing tailwind when it encountered a shallow sheared layer (25 kn/1000 ft) and the tailwind suddenly decreased. Consequently, an increase in pitch was induced by the pilot or autopilot in an attempt to reduce the airspeed. As a result, there were additional sharp downward elevator control inputs leading to additional pitch angle changes and large changes in vertical acceleration.

Figures 3a and 3b show the vertical acceleration and vertical wind speed for Jamestown. There are three noticeable features in the vertical wind record:

1) A high-frequency oscillation with an amplitude of about 1 m/s that is apparently from noise in the vertical acceleration record.

2) A large-amplitude oscillation with a period of about 35 s. This may be contamination caused by extreme angle of attack when the aircraft stalled.

3) A sharp decrease in vertical wind to −13 m/s. However, at this point, the aircraft was stalling, which puts into question the accuracy of this vertical wind calculation.

Figure 3d, the Wingrove parameter, clearly shows the elimination of the 35-s oscillation mentioned previously. The main turbulence spike is flanked by insignificant values of Wingrove parameter that correspond with the high-frequency noise shown in Fig. 3b. As in the Greenland case, relatively high Wingrove parameters are associated with maximum vertical accelerations; the maximum change in vertical acceleration again indicates severe turbulence (−1.3 *g*). In this case, however, the highest Wingrove parameter is only 12 m^2/s^2. We attribute the small Wingrove parameter in the Jamestown case to a weak turbulent burst of short duration. Preliminary examination of other cases shows similar results. High Wingrove parameters are correlated with large vertical accelerations in nonmaneuvering cases and short duration turbulence events are not captured well by the 10-s average.

The time histories for the Bermuda (Fig. 4) case are similar to the previous incident. Figure 4a shows a single turbulence spike corresponding to a change in vertical acceleration greater than 1.0 *g* (severe turbulence). The maximum vertical wind speed within the turbulence region exceeds 20 m/s (Fig. 4b). As with the Bermuda case, the duration of significant turbulence is quite short, lasting only a few seconds. The primary difference in the two cases is that a majority of the large vertical accelerations experienced by the Bermuda case were most likely from turbulence, while in the Jamestown case, they were clearly caused by maneuvering. These characteristics are reflected in Figs. 4c and 4d. The relatively low Wingrove pa-

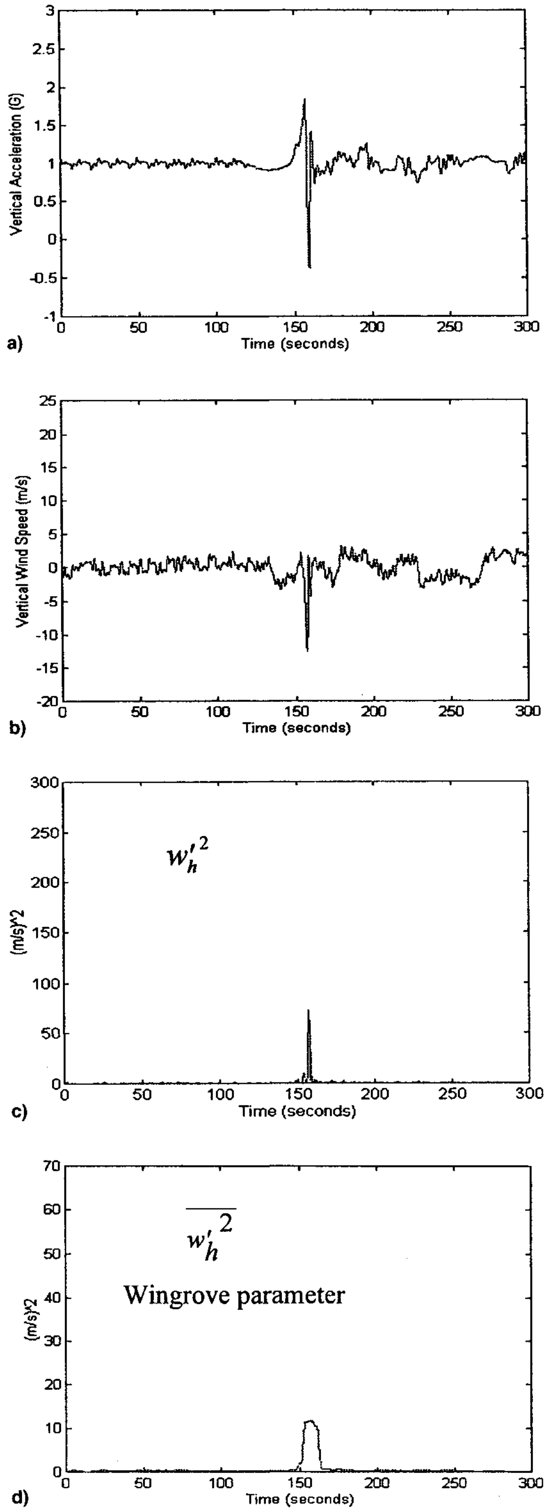

Fig. 3 SA 534 turbulence encounter over Jamestown, New York, April 1986.

rameter for Bermuda is the result of the short duration of the turbulence as compared to the averaging period.

The Calgary case is shown in Fig. 5. The turbulence duration, approximately 225 s, is much longer than the previous cases. As illustrated in Fig. 5a, the turbulence is highly intermittent. It is composed of a series of bursts of moderate turbulence (0.5–1.0 *g*) with a spike of severe turbulence at approximately 300 s. The vertical wind speed (Fig. 5b), reveals that the turbulence is imbedded within an organized wave pattern. These are mountain lee waves with a wavelength of approximately 17 nm. As indicated in Figs. 5c and 5d, the influence of these nonturbulent waves has been removed by high-pass filtering.

The effect of averaging is also illustrated in Figs. 5c and 5d. In Fig. 5c, a value of $w_h'^2$ exceeding 150 m^2/s^2 occurs at approximately 210 s. Because this value is surrounded by much smaller values, the result of averaging is a relatively small Wingrove parameter (Fig. 5d). In contrast, at approximately 300 s in Fig. 5c, there are sustained $w_h'^2$ values of less than 60 m^2/s^2, which result in the largest Wingrove parameter for this incident. Despite these uncertainties with the averaging process, the largest Wingrove parameters correspond with the most intense turbulence.

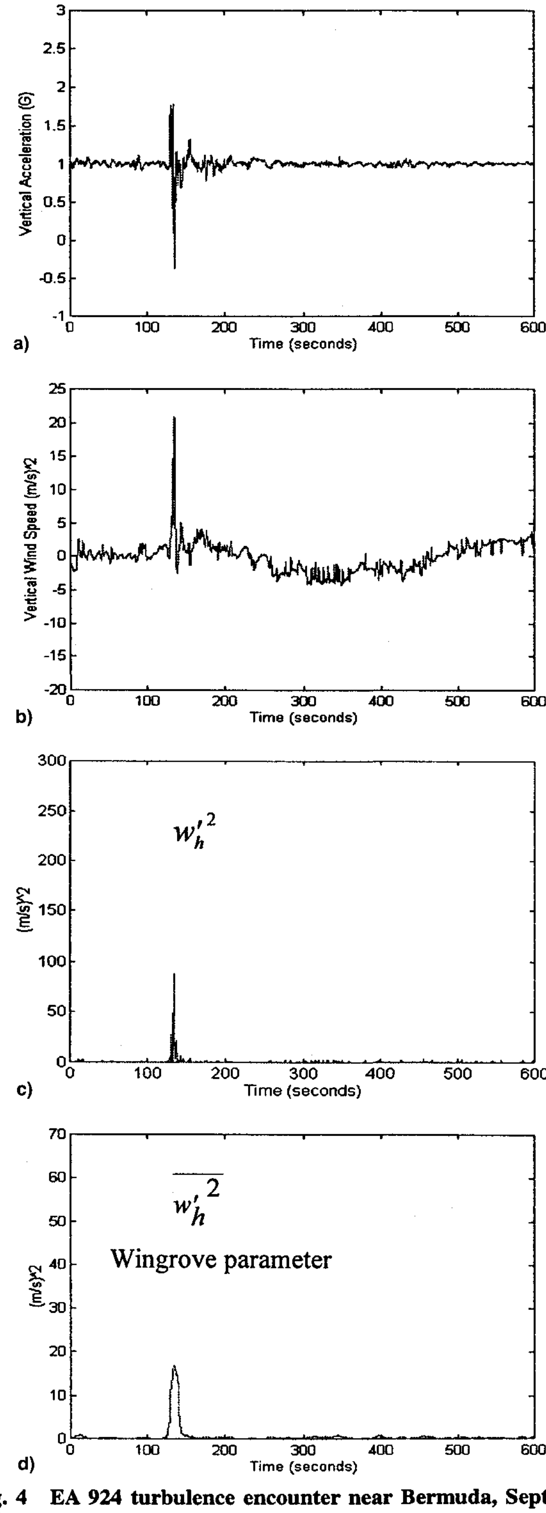

Fig. 4 EA 924 turbulence encounter near Bermuda, September 1987.

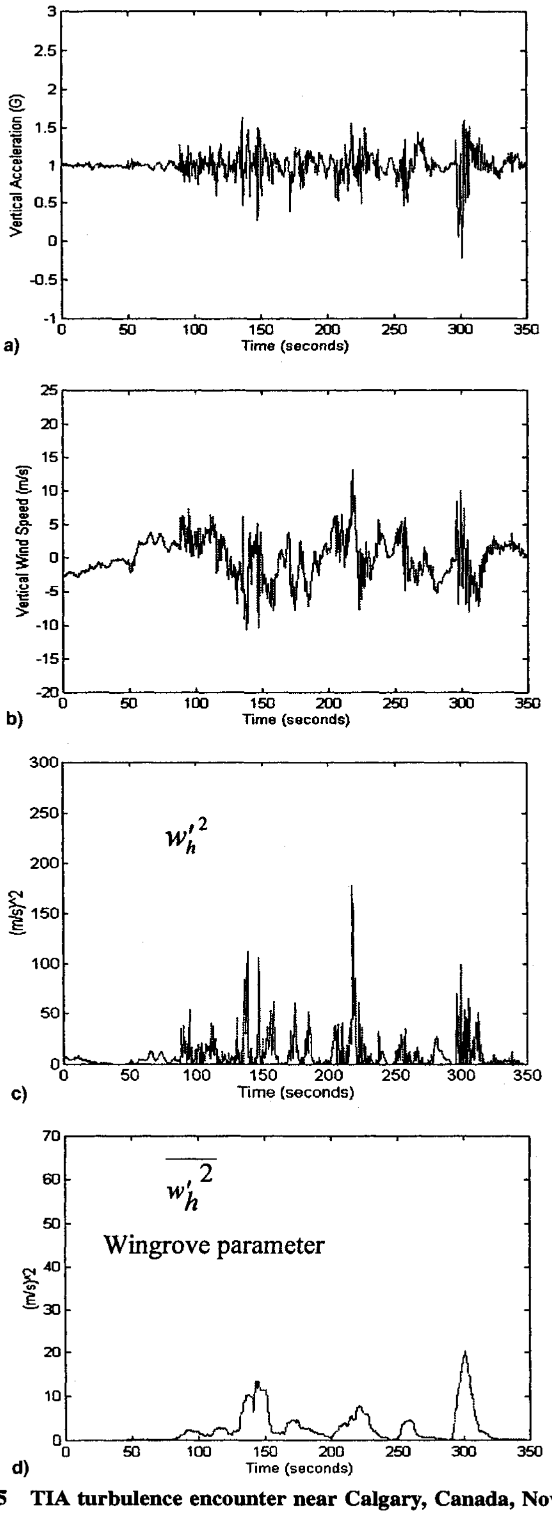

Fig. 5 TIA turbulence encounter near Calgary, Canada, Nov. 3, 1975.

Summary and Conclusions

The Wingrove parameter has been introduced to quantify turbulence observations in a standardized format that is simple to understand. The Wingrove parameter *Wi* is a turbulence index proportional to the turbulent kinetic energy of the vertical wind. It is intended for use with DFDR information to quantify turbulence intensities automatically, leading to an increase in the frequency of turbulence reports.

In this article, the Wingrove parameter was applied to data derived from four airliner turbulence encounters. All cases were reported as severe turbulence at or near the tropopause. There was a wide variation of causes, including mountain waves, convection, and maneuvering.

Preliminary tests have shown that the Wingrove parameter is able to eliminate the influences of nonturbulent waves and maneuvering. However, the burst-like nature of turbulence encounters causes some problems when averages are taken along the aircraft track. For example, the magnitude of a single turbulence spike that may have been sufficient to cause passenger injury will be suppressed by averaging over a longer period. Because of wide variations in durations of turbulent bursts, standard turbulence thresholds (light, moderate, and severe) cannot be specified for *Wi* at this time. This is not a new problem, the computation of other metrics such as the eddy dissipation rate are also greatly affected by intermittency of turbulence encountered by aircraft. Intermittency problems may be reduced in a number of ways including 1) reducing the averaging period, 2) increasing airliner data sampling rates, 3) reporting the extreme raw value of $w_h'^2$, 4) reporting duration of turbulence above some threshold, and 5) reporting a statistic related to intermittency, such as kurtosis.

In addition to the need for further study to resolve these intermittency problems, studies to improve the filter cutoff should also be conducted to reflect the dynamics of specific aircraft. Finally, attention should be given to the development of a more comprehensive metric to account for horizontal turbulent gusts. For example, we are currently studying the expansion of the Wingrove concept to total turbulent kinetic energy.

It is concluded that the Wingrove parameter provides a substantial foundation for the development of a standardized, quantitative, real-time turbulence metric.

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