INSTITUTES FOR ENVIRONMENTAL RESEARCH
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Foreword

Data used in this study were selected from records obtained during 1965 Spring Operations of the National Severe Storms Laboratory. These operations were assisted by the cooperation and substantial support of the Aeronautical Systems Division, U. S. Air Force; the National Aeronautics and Space Administration; and the Federal Aviation Agency.

List of Symbols

D	differential operator denoting d/dt. A dot over a variable denotes a first derivative; a double dot denotes a second derivative
f	frequency (cps)
F_z	generalized force along aircraft Z-axis $\left(\frac{\text{slugs-ft}}{\text{sec}^2}\right)$
g	acceleration of gravity
$g(t)$	filter weight function
G	filter gain function
H	aircraft frequency response gain function
ℓ	distance from the accelerometer to the angle-of-attack sensor (ft)
m	aircraft mass (slugs)
n_z	norman acceleration (ft/sec^2)
N	number of filter weights
u, v, w	aircraft velocity along X, Y, and Z aircraft axes (ft/sec)
U	true airspeed (ft/sec)
w_e	indicated velocity error (from gust equation; ft/sec)
w_g	gust velocity (ft/sec)
X, Y, Z	aircraft body axes
α	angle-of-attack (rad)
δ_e	elevator control surface displacement (deg)
θ	attitude angle (pitch) (rad)
φ	roll angle (rad)
ψ	yaw angle (rad)
ω	circular frequency (rad/sec)

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A Preliminary Evaluation of the F-100 Rough Rider Turbulence Measurement System

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Response data for elevator control inputs are used as a basis for evaluating the F-100 aircraft gust measurement systems. The procedure involves 1) use of the gust equation to evaluate responses of the aircraft maneuvered in a zero-gust (nonturbulent) environment; 2) analysis of the separate responses, with the aid of calculated frequency response functions, to isolate probable instrumental problems, and 3) estimation of overall gust velocity measurement accuracies from estimates of equivalent gust velocities obtained from measured and calculated responses. The analysis indicates that with pitch dampers off, the overall error for the F-100 gust measurement system ranges from a threshold value of about 5 ft/sec to a maximum error of about 20 ft/sec. The accuracy estimates (error per unit gust velocity) range from a few percent to about 60 percent; the pitch damping system (in use during flights within thunderstorms) should reduce the maximum error to about 30 percent. Instrument improvements introduced in 1966 are expected to provide better measurements of the vertical component of atmospheric turbulence.

1. Introduction

Over the past 15 years, many aircraft gust measurement programs have been conducted by both government and private organizations. These programs have provided numerous samples of power spectrum measurements of atmospheric turbulence in storms and in clear air, but an experimental procedure is needed for evaluating the accuracy of gust velocity measurements in relation to frequency or wavelength.

In past test programs, control inputs in nonturbulent air have been used to provide some indication of the aircraft gust instrumentation behavior, but these programs have not been designed for detailed evaluations of gust measurement accuracies. The present study attempts to establish experimental and analytical procedures for determining the accuracy with which vertical components of atmospheric turbulence are measured. Data used were obtained by the F-100 thunderstorm penetrations (Rough Rider) aircraft, and the recommendations made are especially

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[1] This paper is based on the final report on Contract W66-170 between Turbulence Consultants, Inc., and the National Severe Storms Laboratory, ESSA.

tailored to present objectives of storm investigation. The basic approach, however, is generally applicable to all aircraft turbulence investigations.

2. General Procedures

To obtain data for estimating the accuracy of the F-100 aircraft gust measurement system, aircraft responses to control input motions were recorded in calm air. For instrument evaluation purposes, these responses provide data similar to those produced by atmospheric turbulence. The basic procedure described is referred to as Aircraft Gust Accuracy Determination (AGAD).

Two specific kinds of control motion inputs are considered important: 1) sinusoidal motions, covering the frequency range of pilot capability, and 2) random control motions intended to provide harmonic excitation in those frequencies that cannot be produced sinusoidally by the pilot.

The analysis of turbulence response data involves use of the gust equation:

$$w_g(t) = U\,[\alpha(t) - \theta(t)] + \int n_z(t)\,dt, \qquad (1)$$

where U is the true airspeed of the aircraft along the flight path, α, a small angle, is the angle of attack obtained from a vane mounted on a boom extending beyond the nose of the aircraft, θ is the angle of pitch obtained from an attitude gyro, and n_z is the normal acceleration given by an accelerometer near the center of gravity of the F-100 airplane. Equation (1) assumes that all measurements are at a single point. When, as in the case of the F-100, n_z is measured a considerable distance, ℓ, from the place where α is measured, a correction $\ell\,\dot{\theta}$ must be added to $\int n_z dt$ to allow for this difference. The time variables in (1) represent deviations from mean values. (See Appendix A for further discussion of gust equations.)

One useful interpretation of (1) is that it is a relative velocity statement, where $U\alpha$ is representative of the vertical velocity of the air relative to the airplane, and $\int n_z dt - U\theta$ is the velocity of the airplane center of gravity relative to inertial space (or ground reference). This interpretation permits a relatively simple explanation of why control motion inputs (deliberate or inadvertent) do not affect the gust velocity w_g deduced from (1). The explanation is that the control motions are of a self-canceling nature, i.e., the incremental change in one variable is balanced by changes in the others. This characteristic of the gust equation is useful for estimating system accuracy, since control inputs in calm air must produce a null condition ($w_g = 0$) when the responses are added. Any nonzero value represents an error of the measurement system.

Although (1) provides a basis for testing system error in calm air, it alone does not provide accuracy information, i.e., gust velocity error per unit gust velocity. To obtain such information for calm air measurements, it is necessary to relate values of gust velocity error w_e deduced from (1) in calm air to the value of the gust velocity that would produce the aircraft responses obtained for control inputs. For this purpose, the airplane transfer functions for the F-100 (sometimes called compliance or frequency response functions) have been determined [6]. The procedure used to estimate the gust velocity error per equivalent unit gust velocity is described in Appendix B. These functions and the results obtained by applying (1) to the calm air flight data provide the basis for AGAD.

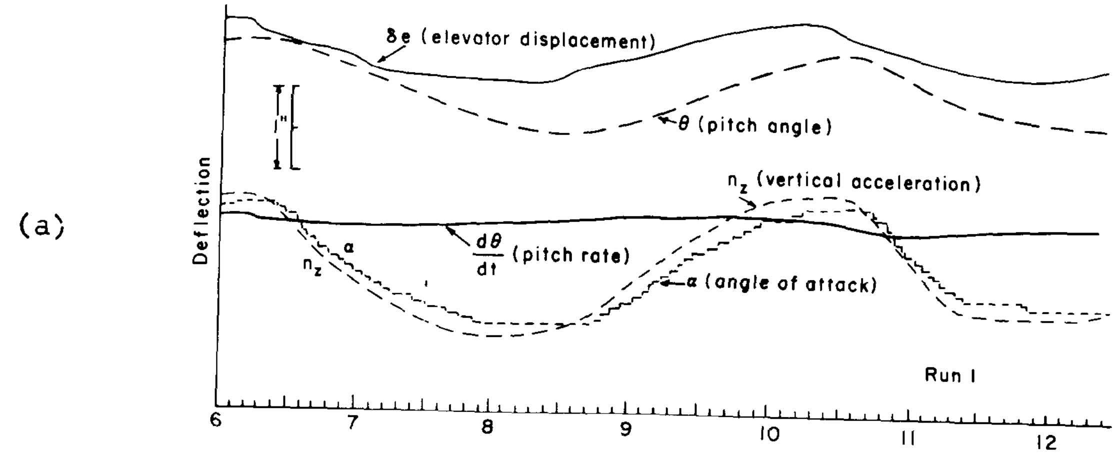
A meaningful analysis of atmospheric turbulence data must, in addition to AGAD, also consider the importance and limitations of filtering unwanted or questionable frequencies in the turbulence data. It is important to know which components should be filtered (by AGAD) and to have effective filters. The recent introduction by Ormsby [5] and Graham [2] of extremely sharp general purpose (low-pass, high-pass, band-pass) numerical filters is of great value in this connection. The combination of AGAD procedures and appropriate filtering techniques should provide important means for interpreting aircraft measurements of atmospheric turbulence.

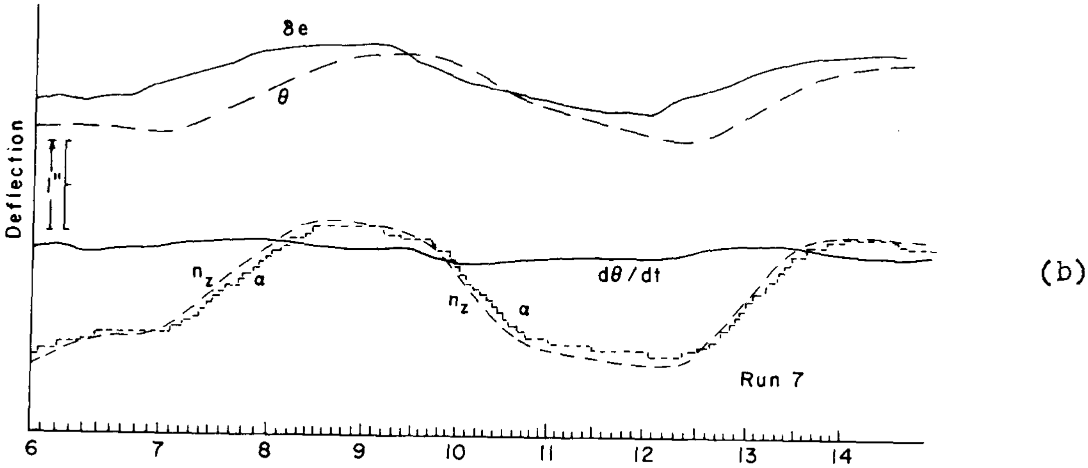
The sections that follow describe the application of AGAD procedures to specific elevator control input data obtained with the F-100 airplane during 1965; in section 6, the characteristics of the Ormsby-Graham numerical filters are considered from the standpoint of Rough Rider program requirements.

3. Description of Data and Data Reduction

Data for the AGAD procedures were obtained with the F-100 Rough Rider aircraft in the spring of 1965. They reflect sinusoidally applied displacements of the elevator control surface at frequencies varying from approximately 1/5 cps to nearly 1 cps.

The aircraft response motions were obtained under calm air conditions at pressure altitudes of about 26,000 and 35,000 ft. True airspeeds were estimated to be about 700 and 800 ft/sec, respectively. The response variables, described in the preceding section, were oscillographically recorded for periods of approximately 30 sec. Small portions of three of the 12 data runs obtained are shown in fig. 1a; only the elevator traces and the response quantities needed in (1) are indicated. The 12 records were digitized semiautomatically on punch cards at 0.1-sec intervals and later transcribed to magnetic tape. The linear calibration factors used to convert the response variables to engineering units are listed in table 1.





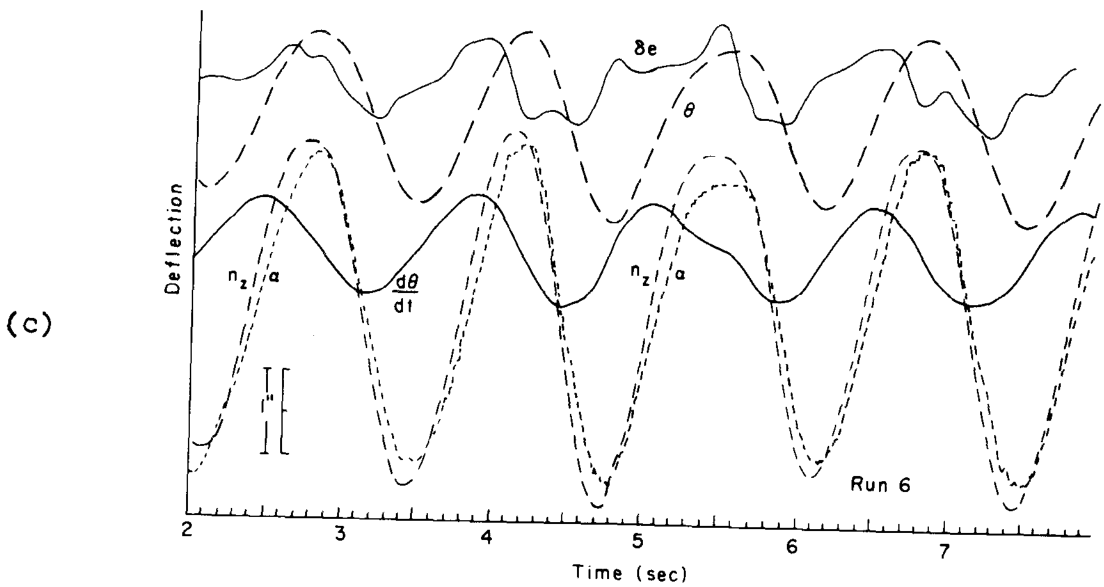


Figure 1. Portions of oscillograph traces showing aircraft response variables used to determine gust velocities for the wavelengths indicated.

Table 1. Calibration Factors

Variable		Calibration factor
Angle of attack	α	4.4 deg/in
Attitude angle (pitch)	θ	8 deg/in
Rate of change of pitch angle	$\dot{\theta}$	19 deg/sec/in
Normal acceleration	n_z	0.86 g/in
Elevator control surface displacement	δ_e	6 deg/in

The separate velocity terms obtained from the response variables, as defined by (1), are shown in figs. 2 through 4 for the portions of the three runs selected for presentation in figs. 1a, b, and c. Note that $\dot{\theta}$ for runs 1 and 7 (figs. 1a and b) is not significant and $\ell\dot{\theta}$, therefore, is not large enough to be considered in the w_e equation of these runs. The corresponding resultant time histories of the indicated velocity error w_e are seen in fig. 5.

4. Analysis of Aircraft Data

Of the 12 elevator control response time histories obtained with the F-100 airplane, six were selected for detailed analysis; of these, five are used here. These runs represent wavelengths ranging from about 1000 to 4000 ft, or frequencies of about 1.2 to about 5 rad/sec. Although these frequencies are near the limits of a pilot's capability, as far as sinusoidal inputs are concerned, an attempt should be made to obtain somewhat longer wavelength data. Random, rather than sinusoidal, control motions may be necessary in practice to extend the frequency range - especially to higher frequencies.

For each of the five runs analyzed (only runs 1, 6, and 7 are illustrated), estimated values of the maximum velocity error and the velocity error per unit gust velocity are presented in table 2 and are shown as accuracy estimates in fig. 6. Each of the three runs of figs. 2 through 4 is considered in more detail below.

Table 2. Summary of Accuracy Estimates

Run	ω (rad/sec)	w_e	$U\alpha_{meas}$	$U\theta_{meas}$	$H_\alpha(\omega)$	$H_\theta(\omega)$	EG_α	EG_θ	GA_α	GA_θ
7	1.2	10	40	50	0.38	1.30	130	38	7.7	26
1	1.6	12	50	55	0.82	1.70	62	32	19	37
5	2.0	18	90	90	1.90	2.70	47	38	38	47
2	2.6	12	50	55	2.40	1.50	21	37	57	32
6	5.0	15	100	100	1.26	0.24	80	420	19	3.5

Gust accuracy (percent) given by $GA = \frac{w_e}{EG} \times 10^2$

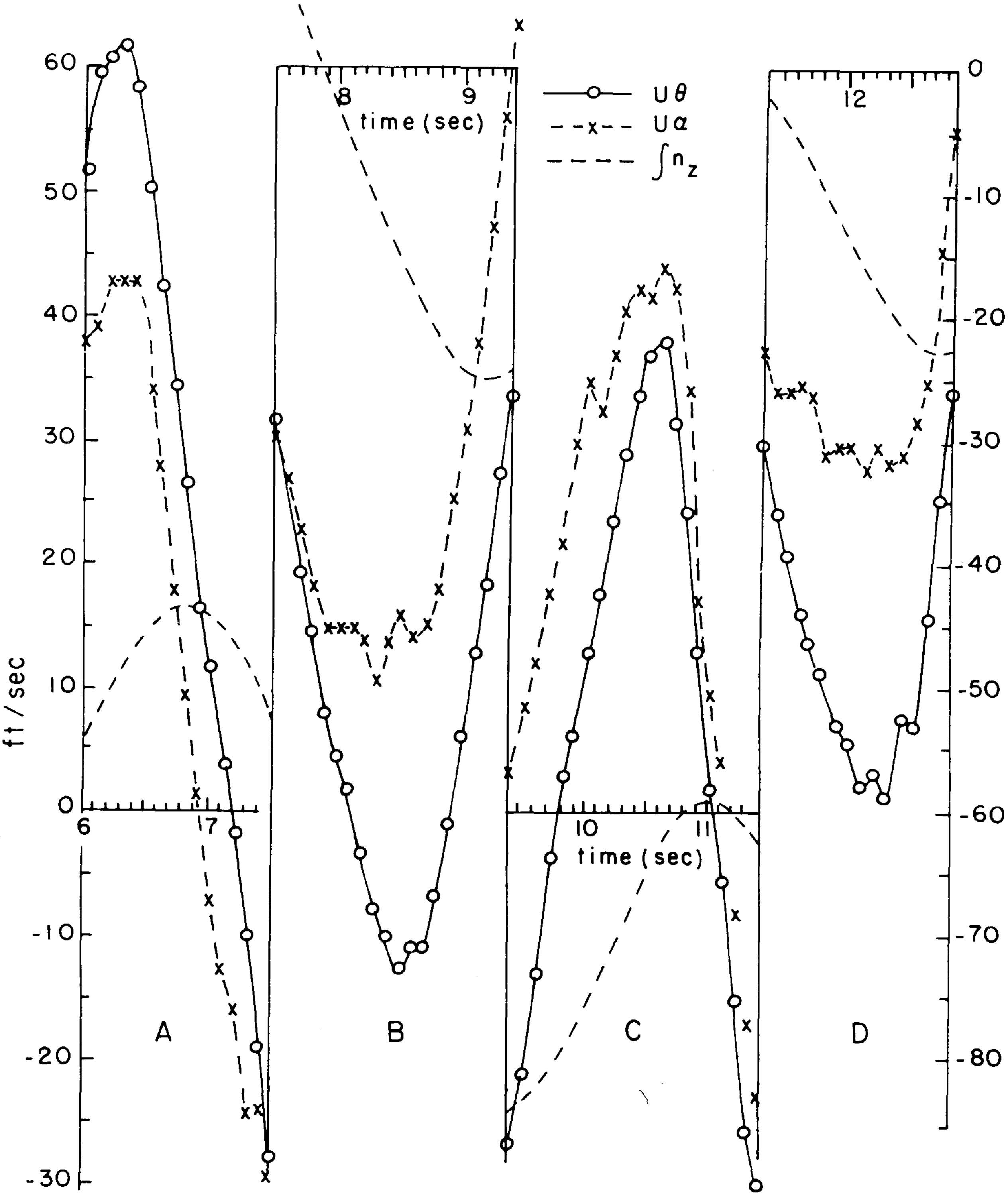


Figure 2. Computed velocities for run 1. Read left ordinate for A and C, right ordinate for B and D.

Run 1 (fig. 2) - This run has a basic wavelength of about 3000 ft (4-sec period). The phase difference between $U\alpha$ and $U\theta$ at this frequency ($\omega \approx 1.6$ rad/sec) is about 15 deg (≈ 0.2 sec). Figure 2 indicates some approximation to this, although distortion occurs at $t \approx 9.5$ sec and $t \approx 11$ sec. The larger errors occur near the peak values of $U\alpha$ and $U\theta$. At $t = 10.5$ sec there is reasonably close agreement between $U\alpha$ and $U\theta$; here the error, as shown in fig. 5, is near zero. The calculated responses of figs. 7(a), 7(b), 8(a), and 8(b) also indicate about a 10 percent difference between the $U\alpha$ and $U\theta$ amplitude responses. An attempt was made to reduce this error by using the alternate gust equation (A9) in Appendix A which does not contain U_α explicitly, but this procedure gave no improvement.

Run 7 (fig. 3) - Here the wavelength is slightly more than 4000 ft (6-sec period). At this frequency the calculated phase difference between $U\alpha$ and $U\theta$ is about 20 deg (≈ 0.3 sec). Figure 3 indicates obvious wave-form (and phase) distortion between $U\alpha$ and $U\theta$; the average phase shifts, however, are 0.3 to 0.4 sec/cycle, or close to the calculated value. For this run there is a considerably greater non-linear trend in the integrated acceleration trace than in run 1. Use of the equivalent n_z (A9) again brought insignificant results.

Run 6 - For this run the wavelength is a little more than 1000 ft ($\omega \approx 5$ rad/sec). The calculated phase difference is only about 5 deg, which is less than 0.1 sec. Figure 4 does not show a discernible phase difference between $U\theta$ and $U\alpha$. Substitution of n_z for $U\alpha$ in this run, however, and in run 5 with wavelength about 2500 ft, significantly reduced the velocity errors indicating that angle-of-attack phase distortion is the principal source of error for wavelengths between 1000 and 2500 ft. No data are available for wavelengths less than 1000 ft.

In summary, at the low frequencies some pitch angle (θ) distortion occurs, while at the higher (or intermediate) frequencies the angle of attack α does not have the proper phase relation to the pitch angle. The general characteristics of the velocity errors w_e reveal: (a) an approximate relation between the input frequency of elevator displacement, δe, and the velocity error, and (b) a residual of about ± 5 ft/sec superposed on the larger and more regular w_e components of $(\bar{a})$. The systematic error (a) is more serious and should be eliminated if possible; (b) is the basic resolution (or threshold) of the system representing the resultant of resolution inaccuracies of each component velocity measurement. This threshold error can probably be reduced by relatively small refinements in the recording and analysis procedures.

The conversion of the w_e values to accuracy estimates will now be considered. The velocities used for the accuracy estimates are the originally computed values. Only the mean values have been removed from these data, none of the slowly varying trends.

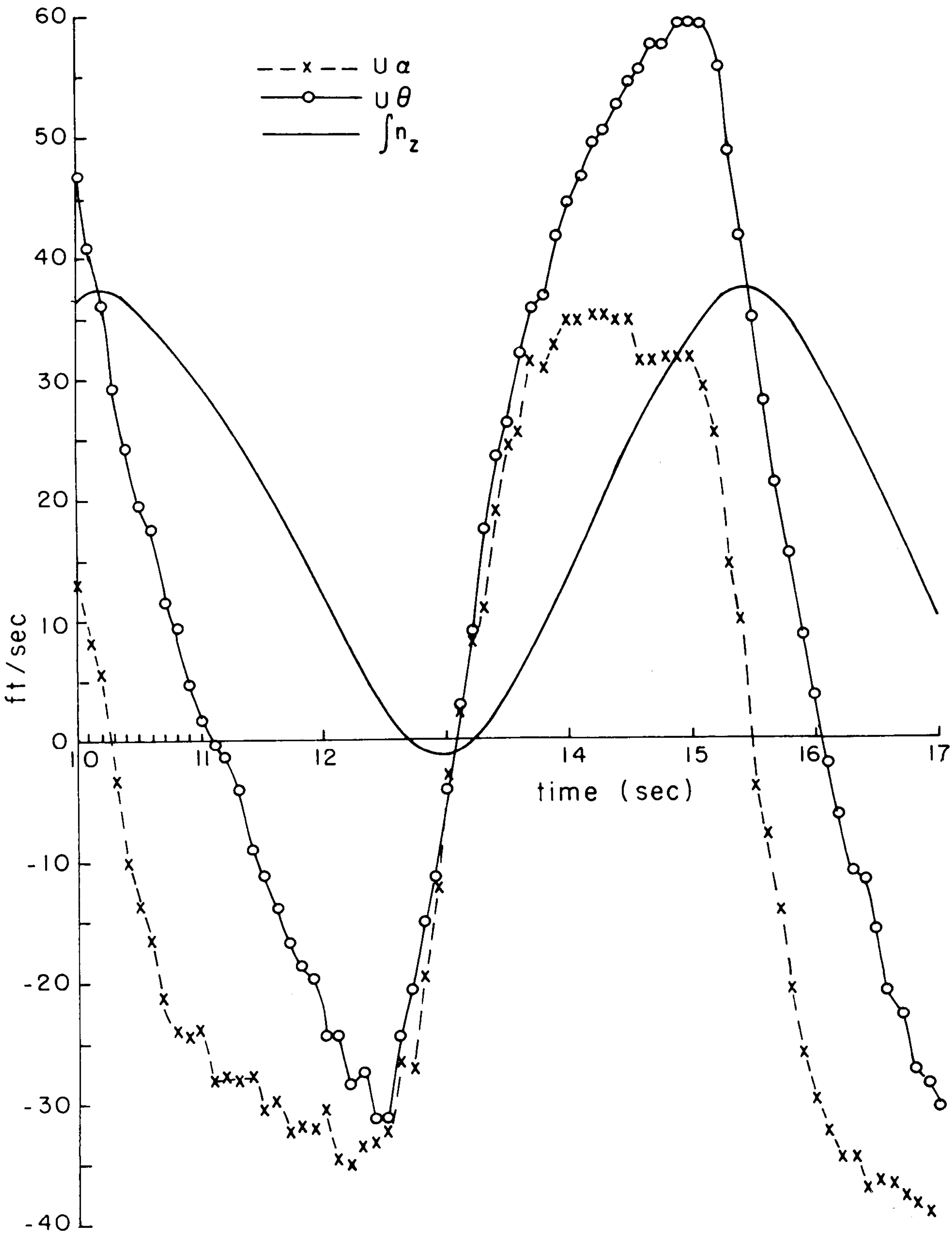


Figure 3. Computed velocities for run 7.

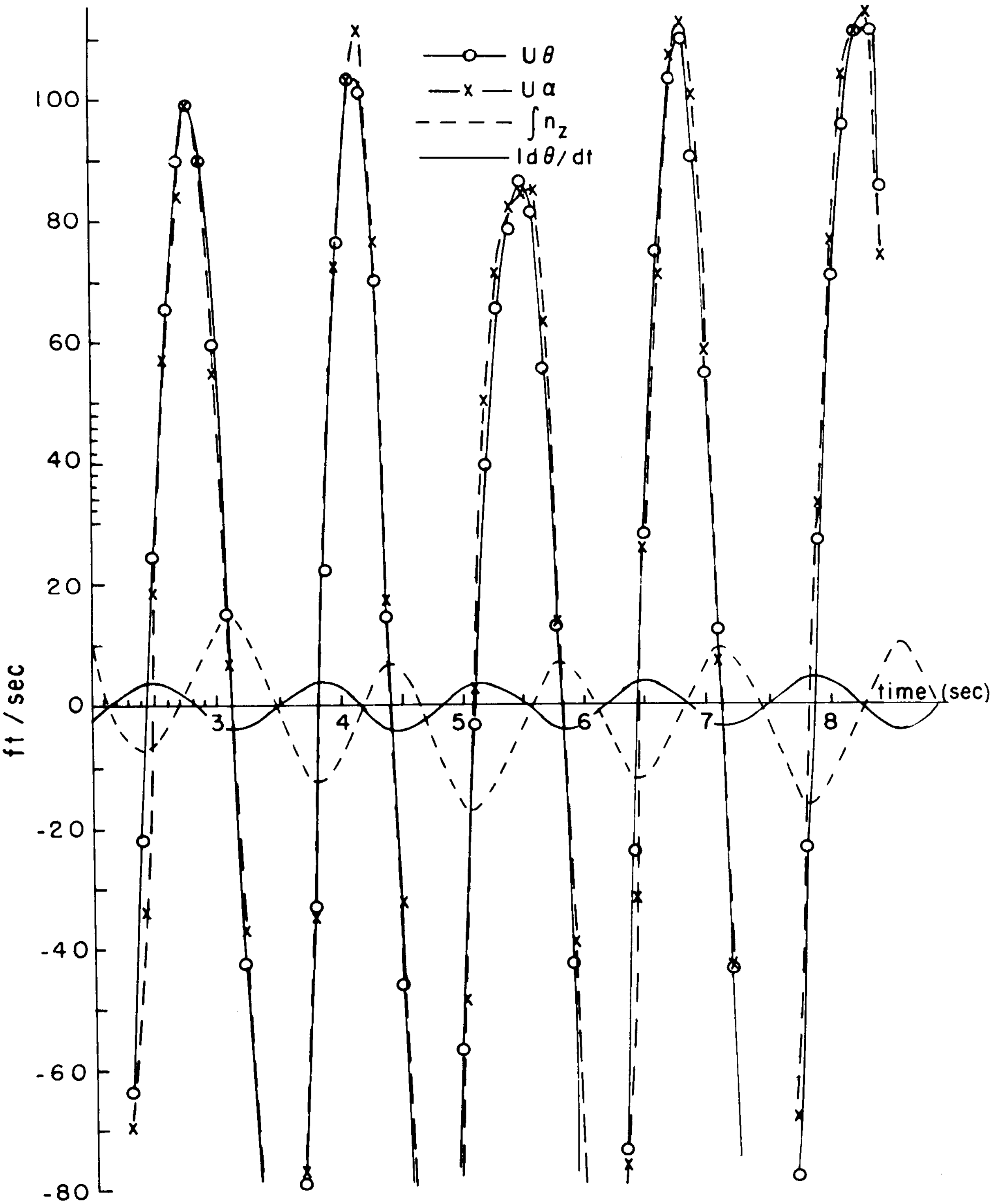


Figure 4. Computed velocities for run 6.

The procedure described in Appendix C is used to relate the error velocities w_e, to equivalent gust velocities. In this procedure, the EG and w_e estimates are used to obtain an estimate of the accuracy of the system. Note that since α and θ response characteristics are different, it is necessary to treat the source of w_e as being the result of α or θ individually; as the response variable α or θ is assumed to be in error for a particular frequency range, the corresponding EG values change accordingly

The error procedure is based on the assumption that the recorded data are approximately sinusoidal, and the airplane response to sinusoidal gust velocities can be represented by the calculated transfer (gain) functions, $H_\alpha(\omega)$ and $H_\theta(\omega)$. A more exact procedure would involve a harmonic analysis of the response data before applying the error procedure. For the present, however, it is assumed that this refinement would not change the results significantly.

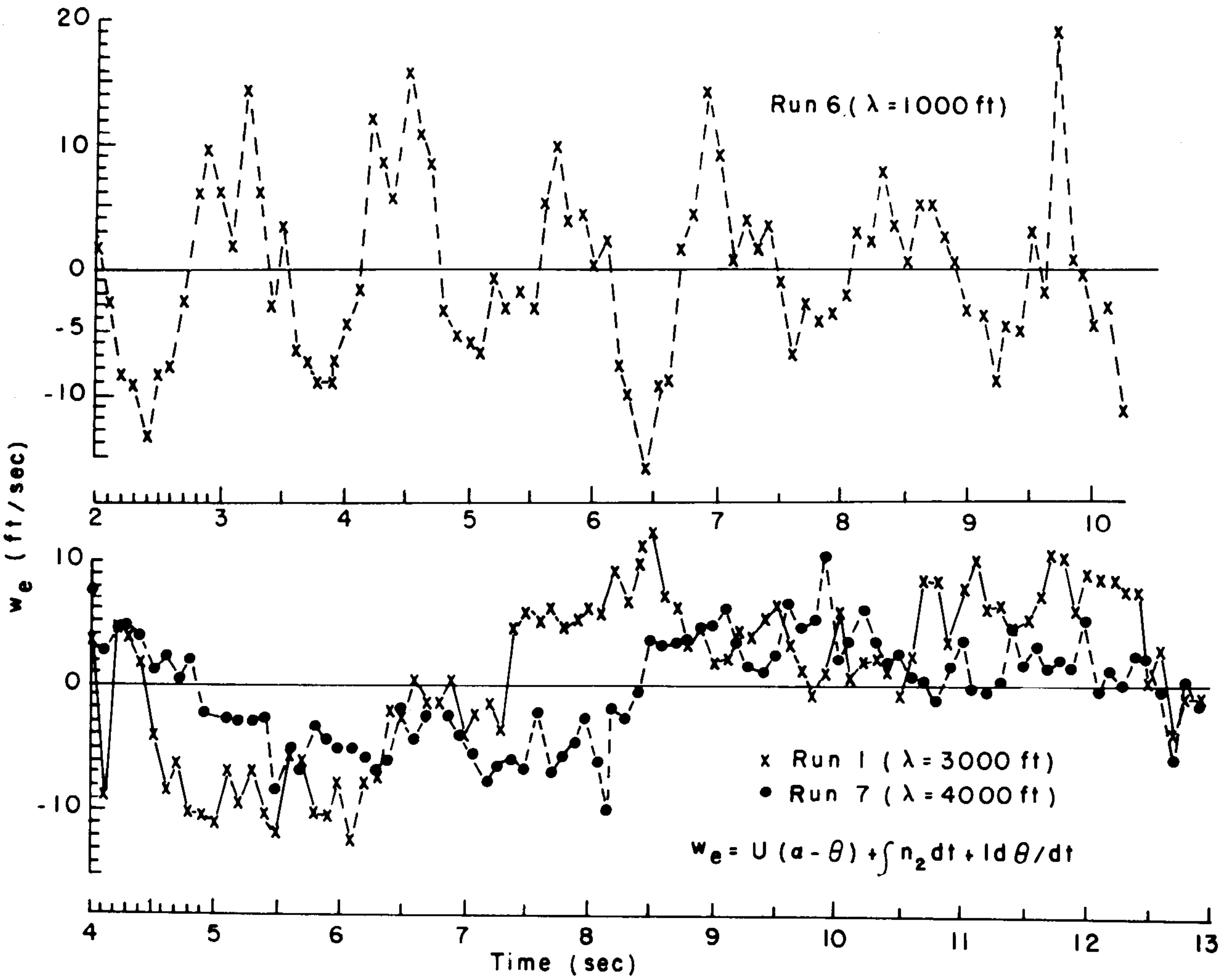


Figure 5. Indicated gust velocity error as a function of time.

Referring to table 2, the w_e values obtained from the flight data vary from about 10 ft/sec for the longer wavelengths to nearly 20 ft/sec for the shorter ones. The equivalent gust velocities were estimated from the average $U\alpha$ and $U\theta$ response peaks for each run by dividing these values by the corresponding $H_\alpha(\omega)$ and $H_\theta(\omega)$ transfer functions. Table 2 also presents the average peak values, w_e values, equivalent gusts, transfer functions, and gust accuracy (GA) values obtained.

5. Numerical Filtering Aspects

The use of numerical filtering in the power spectrum analysis of aircraft gust velocity estimates is not new. Some form of both low-pass and high-pass filtering procedures has been employed generally for the past decade. The filters (numerical smoothing procedures), however, have not possessed particularly sharp frequency attentuation characteristics. This has been a severe limitation, for not only must the spectrum estimates be compensated for the filter gain function, but the filtered time history frequently cannot be assumed to represent the filter-gain corrected spectrum characteristics. For this reason, use of numerical filters has been primarily restricted to "pre-whitening" the time series to reduce the effects of computational leakage of energy from frequencies of large energy to frequencies of less energy (see Blackman and Tukey [1]).

Recent work by Ormsby [5], Graham [2], and others has resulted in procedures by which numerical filters of extremely sharp frequency gain characteristics can be designed. Specific advantages of these filters in aircraft turbulence work are: 1) spectrum estimates need no correction for the filter characteristics and provide close fidelity between the time series and spectrum estimates; 2) data can be numerically filtered to provide any desired frequency band-pass time history, which for spectrum analysis eliminates pre-whitening and gives much greater flexibility in frequency resolution and improved statistical reliability; 3) the excellent phase-shift characteristics of these filters permit individual components of the gust velocity to be filtered, if necessary, without alteration of the final time series by phase distortion.

A brief summary of the filter design characteristics programmed in the present study is presented in Appendix D, with an example of the application of this class of filters to tower data supplied by New York University.

6. Discussion

A discussion of the indicated velocity errors presented in table 2 and summarized as accuracy estimates in fig. 6 should include an appraisal of the factors contributing to the errors, a discussion of the accuracy estimates, and prospects for reducing these errors.