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DYNAMIC STABILITY OF SPACE VEHICLES

Volume VIII - Atmospheric Disturbances That Affect Flight Control Analysis

by B. A. Appleby and T. E. Reed

Prepared by
GENERAL DYNAMICS CORPORATION
San Diego, Calif.
for George C. Marshall Space Flight Center

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FOREWORD

This report is one of a series in the field of structural dynamics prepared under contract NAS 8-11486. The series of reports is intended to illustrate methods used to determine parameters required for the design and analysis of flight control systems of space vehicles. Below is a complete list of the reports of the series.

Volume I	Lateral Vibration Modes
Volume II	Determination of Longitudinal Vibration Modes
Volume III	Torsional Vibration Modes
Volume IV	Full Scale Testing for Flight Control Parameters
Volume V	Impedence Testing for Flight Control Parameters
Volume VI	Full Scale Dynamic Testing for Mode Determination
Volume VII	The Dynamics of Liquids in Fixed and Moving Containers
Volume VIII	Atmospheric Disturbances that Affect Flight Control Analysis
Volume IX	The Effect of Liftoff Dynamics on Launch Vehicle Stability and Control
Volume X	Exit Stability
Volume XI	Entry Disturbance and Control
Volume XII	Re-entry Vehicle Landing Ability and Control
Volume XIII	Aerodynamic Model Tests for Control Parameters Determination
Volume XIV	Testing for Booster Propellant Sloshing Parameters
Volume XV	Shell Dynamics with Special Applications to Control Problems

The work was conducted under the direction of Clyde D. Baker and George F. McDonough, Aero Astro Dynamics Laboratory, George C. Marshall Space Flight Center. The General Dynamics Convair Program was conducted under the direction of David R. Lukens.

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1/INTRODUCTION

The exit phase of flight must, by definition, originate on or near the earth's surface and terminate at some point in space, which will be above the sensible atmosphere. Therefore, all or part of the exit phase of flight occurs in the sensible atmosphere. The analysis of space vehicle systems for this phase of flight must necessarily include the affect of the atmosphere upon the launch vehicle.

The atmosphere is non-stationary with respect to the earth's surface and its properties (e.g., density and temperature) vary with respect to time and altitude. These deviations of the non-stationary atmosphere from the stationary position are termed atmospheric disturbances. This monograph is concerned with data on atmospheric disturbances, the criteria derived from the data, and the analyses to be performed to determine the vehicle and control system response to atmospheric disturbances. Specifically excluded from the monograph are the methods of determining loads on the space vehicle structure and the details of analyses. The loads on space vehicle structures, while of great significance, are adequately covered in other literature. The details of analyses are covered in another monograph (Reference 1). The intent here is to discuss what analyses are to be performed and what atmospheric disturbances are to be used, not to present methods of analysis.

The atmospheric conditions of the exit phase of flight usually dictate the amount of control capability designed into a launch vehicle. Aerodynamic lateral loads on the vehicle are dependent on the angle of attack (the angle between the vehicle centerline and the velocity vector). The lateral loads could cause the vehicle to tumble and/or break up if not compensated for by the control system. Thus, the basic function of a launch vehicle control system is to maintain control of the vehicle when it is subjected to aerodynamic forces and disturbances. Although part of the aerodynamic lateral loading is a result of programmed maneuvers, the major part of the maximum aerodynamic lateral loads are due to atmospheric disturbances. Therefore, an adequate analysis of control capability during exit flight requires accurate and extensive atmospheric disturbance data.

Atmospheric disturbances are categorized as winds and gusts. Winds are the large-scale movements of air occurring throughout the atmosphere, whose persistence or variation is expressed in terms of hours. Wind speeds at the ground are small (compared with wind speeds at altitude) and increase with altitude, reaching a peak in the 10- to 14-km altitude range. The wind speed then decreases to low levels from 19 km to 24 km and then increases again above 24 km altitude. A typical wind profile for the lower altitudes is shown in Figure 1. The data were obtained during the launch of Lunar Orbiter 2 on 6 November 1966 (Sounding 01469). The Rawinsonde AN/GMD-1 ballon system was used. Wind data have been gathered by several methods (balloon, anemometers, etc.) and by several different systems utilizing each of the basic methods.

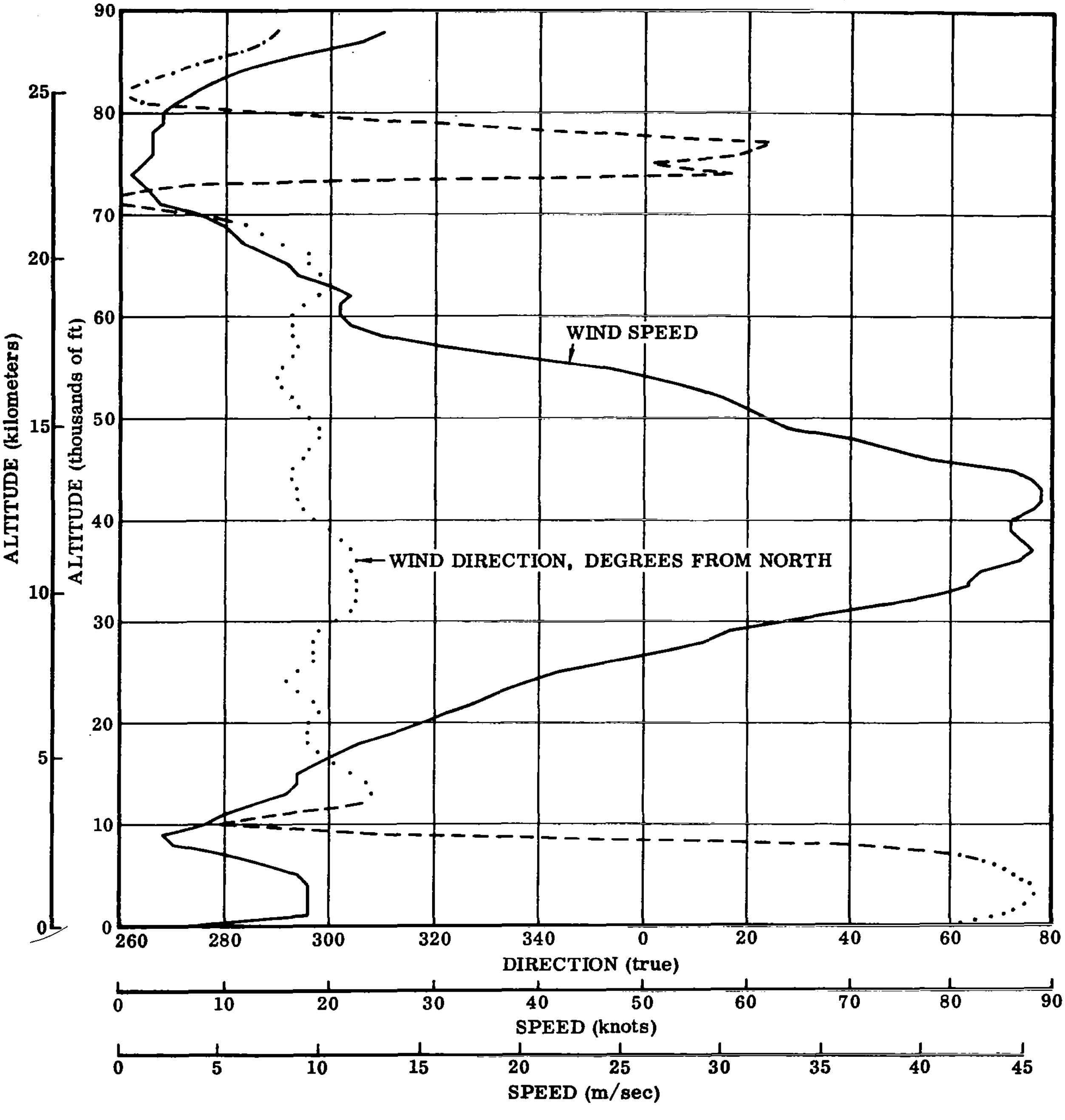


Figure 1. Wind Speed and Direction vs. Altitude

The type and amount of wind data available vary with location; the greatest amount of effort in obtaining wind data has been at the United States' Eastern Test Range and Vandenberg Air Force Base (VAFB), at altitudes up to 30 km. The data above 30 km are limited; however, because of low atmospheric density, loads due to winds above this altitude are quite small. Therefore, little need has developed for wind data above this level, and the data gathering efforts above 30 km have been restricted.

Various types of wind representation (synthetic profiles, series of wind soundings, and wind statistics) have been proposed and used successfully in launch vehicle design; however, an industry-wide consensus has not yet been reached as to which representation is best for all launch vehicles. On the other hand, methods of analysis are fairly consistent throughout the industry.

Gusts are the small-scale movements of air in the atmosphere. The persistence or variation is usually expressed in terms of minutes and altitude bands of less than 300 meters (for lower altitudes). Past efforts in obtaining data have been directed towards deriving gust data from aircraft response. With the advent of highly accurate wind sounding systems the fine detail of a wind profile is being measured. This detail is termed "turbulence" and is an overlap between the historical concepts of winds and gusts. Gust criteria have generally been of the "discrete (1-cosine) waveform" type and were considered to account for both discrete gusts and the profile detail (turbulence) not measured by wind sounding systems. With data on profile detail becoming available, this concept is undergoing modification.

2/STATE OF THE ART

The state of the art of atmospheric disturbance data, criteria, and methods of analysis has been and continues to be in an evolutionary stage. The old saying "necessity is the mother of invention" has often been true, especially with regard to criteria. Since need has generally preceded availability, meteorologists and analysts working in this area have usually been in the position of catching up to need rather than being able to anticipate and provide for needs. However, some consolidation in types of criteria has occurred and it appears likely that standardization of criteria and methods of analysis (at least in general terms) is possible in the future. This would alleviate the catch-up situation considerably.

2.1 ATMOSPHERIC DISTURBANCE CRITERIA

Atmospheric disturbance data and criteria have been constantly changing since the advent of the ballistic missile, and they will continue to change for some time. The following review of the past and present states of the art will summarize the recent history of the development of present design criteria.

2.1.1 DATA ON WINDS AND GUSTS

2.1.1.1 Wind Data. The obtaining of data on winds has been characterized by "abrupt" changes, due to introduction of new equipment capable of more accurate measurements. In spite of these changes, advances in the state of the art have a long lead time. This lead time is required because a set of wind soundings over an extended period of time (usually a minimum of 5 years) is necessary for the formulation of criteria.

Three of the agencies or groups most active in developing new equipment to measure winds and in analyzing the available data (from whatever source) are: the George C. Marshall Space Flight Center (MSFC), Air Force Cambridge Research Laboratories (AFCRL), and the Meteorological Working Group of the Inter-Range Instrumentation Group (MWG-IRIG). Raw data from wind soundings are kept at the National Weather Records Center, Asheville, North Carolina and are available on magnetic tape. Reduced data in the form of serially complete series of wind soundings are available from several sources, principally MSFC. A serially complete set of wind soundings is one in which missing data are filled in by extrapolation, interpolation, or substitution of data from nearby sites.

The Air Force sponsored a symposium on "Winds for Aerospace Design" in 1961, the proceedings of which (References 2 and 3) give a reasonably complete picture of the state of the art up to 1961. References 4 and 5 present a more recent look at the state of the art. The documents referenced above also have reference lists which may be helpful when more detail is desired.

The basic element of any wind-measuring system is the release of some object or material in the atmosphere and observation of its movement both in space and time. The balloon system is the only system that has been used extensively at numerous sites and for extended periods of time. In the operation of a balloon system a balloon is released at ground level and tracked, by some means, to obtain its position with respect to time. The time and horizontal distance traveled between any two data points can be calculated and the wind velocity and direction determined. Other systems utilize falling spheres or parachutes, easily dispersed material (such as smoke or chaff) or chemicals that will form a luminous cloud. The material or chemicals are quickly dispersed over a large altitude range and the movement tracked visually or by radar. By use of the movement over a given time period the wind velocity can be determined.

The balloon systems are the only ones that have acquired operational status. Their altitude range is from ground level to 30-35 km, which easily encompasses the important 10- to 15-km range. The first system to achieve wide use is the AN/GMD-1 system. This system uses data radioed from the balloon to compute altitude and then uses the cotangent of the elevation angle to obtain horizontal distance. At low elevation angles (which occur with high winds) the errors could be large — errors in wind shear sometimes approaching the value of the wind shear. Most of the data obtained in the 1950's were taken with this system. In the late 1950's the AN/GMD-2 system was developed to provide better data. In this system the slant range is obtained by a radio-ranging attachment, and sine and cosine are used to compute altitude and horizontal distance. This system is approximately six times more accurate than the AN/GMD-1 system. (Comparisons of the two systems are made in References 6 and 7.) However, wind soundings from both systems have 1000-ft (300 meters) altitude increments, which effectively filters much of the profile detail and precludes gust measurements entirely. The systems are capable of measuring at smaller altitude increments, but the accuracy problem is compounded since accuracy tends to decrease with a decrease in measurement altitude interval. To provide data at smaller altitude increments the FPS-16 radar/Jimsphere system was developed. With this system, position measurements of a passive target balloon possessing high drag and low mass are taken every 0.1 sec. The balloon's properties justify the assumption that changes in horizontal position between measurements accurately reflect horizontal air movements during the interval. To eliminate a spiral parasitic mode (period 4.0-4.5 sec) and to average out random measurement error, the raw data are smoothed over approximately 50 meters of altitude and given for successive 25-meter intervals. Since the balloon rise rate is approximately 5 meters/sec, some 100 measurements are reflected in each point of the detailed wind profile. This represents a vast improvement over the older Rawinsonde data which was averaged over approximately 800 meters. A typical comparison of data resulting from both systems is presented in Figure 2. An evaluation of the system is given in Reference 8.

For altitudes less than 35 km, two other systems have been tried on an experimental basis. These are the smoke-trail and chaff/Doppler radar systems. The smoke-trail system utilizes a continuous trail of smoke left by an ascending rocket. Photographs are taken at specified times and the dispersions of the trail analyzed to obtain wind

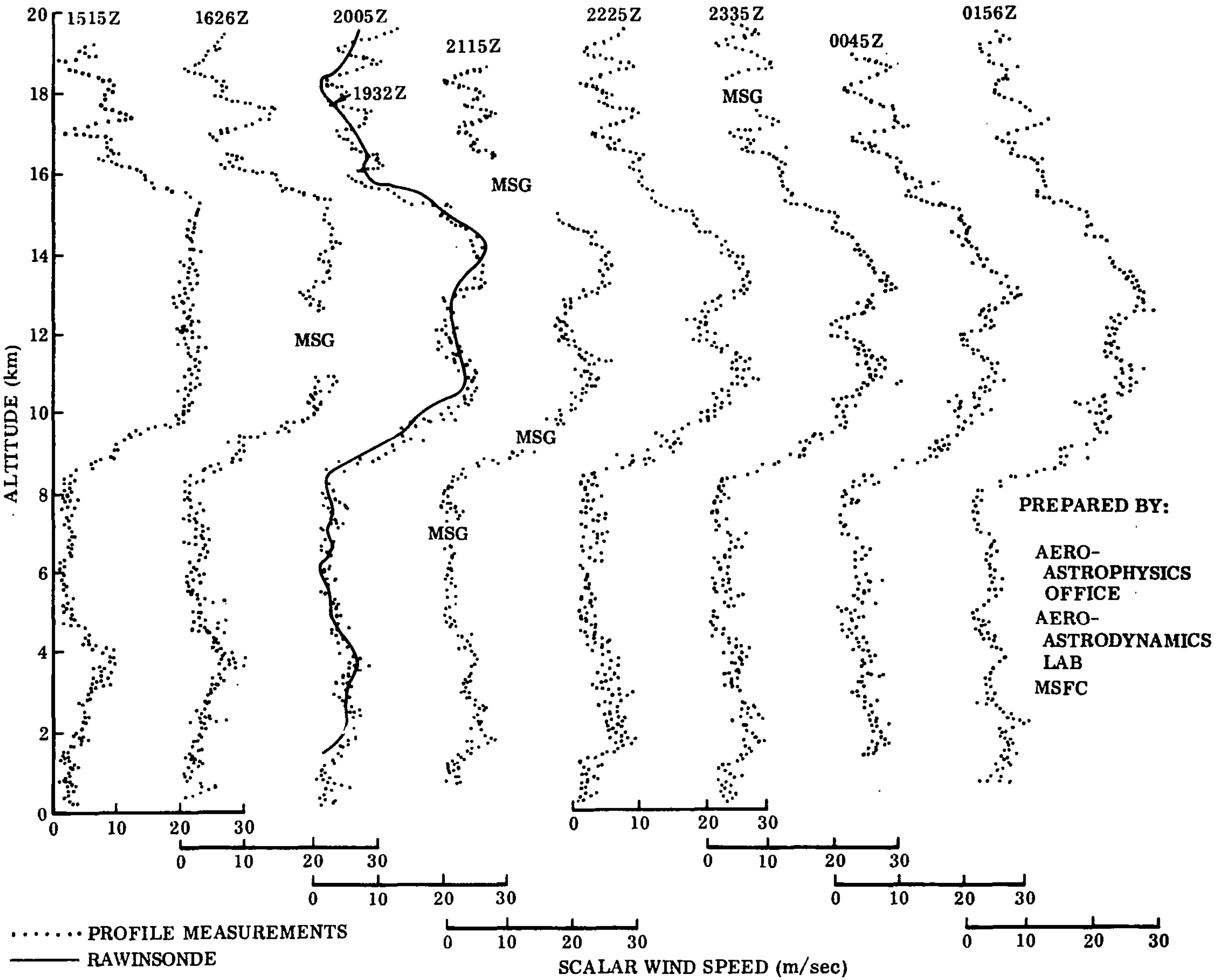


Figure 2. Composite of Eight FPS-16 Radar/Jimsphere Balloon Wind Profile Measurements, Point Mugu, August 20 and 21, 1963

profile data. Reference 9 discusses the application of the method and some experimental results. The chaff/Doppler radar system uses a column of chaff tracked by a Doppler radar system. The dispersions of the chaff column are used to obtain wind profile data. Reference 10 describes the method and some experimental results obtained from it. Neither system is, nor is planned to be, operational.

Above 35 km altitude a variety of wind sensing devices have been used. The rocketsonde method uses rocket-launched sensors such as spheres, parachutes, and chaff that are released and tracked by radar as they descend. Techniques have been developed whereby sodium, cesium, or other vapors or gases are released into the upper atmosphere from rockets. These techniques are especially useful in observing wind shear and turbulence. Rocket-grenades have also been used. Prior to 1959 the amount of data was small and was obtained sporadically.

The Meteorological Rocket Network (MRN) was established in 1959 to provide atmospheric data at several locations and for altitudes above 35 km on a regular basis. Several types of rocketsondes are utilized in the MRN. Several articles in Reference 3 discuss early results from the MRN. More recent results are given in Reference 5.

The discussion to this point has centered on raw data. However, these data must be modified and analyzed in order to have the data in a form suitable for use in criteria definition or analyses. Much work has been done in this direction. As mentioned previously, MSFC (Reference 4) has a large amount of serially complete soundings taken at the Eastern Test Range and Vandenberg Air Force Base. These soundings can either be used directly in analyses or to develop criteria. References 11, 12, 13, 14, 15, 16, 17, and 4 give data on distribution and correlation of winds with respect to altitude and direction. References 18 and 19 discuss the persistence of winds with respect to time; a discussion on filtering and smoothing data is given in Reference 20; and a comprehensive summary of data above 35 km altitude is given in Reference 5.

2.1.1.2 Gust and Turbulence Data. Two essential features of the continuous atmospheric, four-dimensional environment of a launch vehicle are characterized by the concept of gusts and turbulence. Gusts are defined as short time-duration air movements whose occurrence at a specific time or place is unpredictable, whereas turbulence is considered to be a small-distance feature of the atmospheric motion missing from recorded wind data due to filtering by the measurement system.

Data pertinent to the problem of gusts and turbulence are not nearly as extensive or well organized as quasi-steady wind and wind-shear data. The recent introduction of the FPS-16 radar/Jimsphere balloon system mentioned earlier now provides data of a higher frequency content than was formerly available. A useful number of such soundings is, or will be, available from ETR. Analyses are currently being performed using such data. The statistical requirement for large sample sizes imposes a severe practical cost-per-measurement limitation, requiring compromise with respect to accuracy. The inability of a balloon to follow high-frequency components faithfully (Reference 21) remains a limitation (though a minor one with the Jimsphere). The use of smoke-trail chaff, or gas, in measurement systems mentioned earlier, provide much more detail over a much longer useful measurement time span than balloon techniques. Such data are so limited in quantity as to be of little statistical value at the present time.

A great deal of information has been collected over the years concerning direct-response measurements of gusts and turbulence by horizontally moving aircraft. References 22 and 23 are typical of such works. Unfortunately, the vehicle characteristics and operating characteristics preclude use of such data in any but a qualitative way for the design of vertically rising vehicles. In particular, aircraft data consisting of aircraft normal accelerations have been incorporated into space vehicle analysis by assuming atmospheric turbulence to be isotropic (Reference 24). Validity of such derivations of horizontal gust and turbulence properties is questionable (Reference 25). Additionally, aircraft data is generally obtained at relatively low altitudes. Another source of data is available in the form of flight data (consisting of strain, engine deflection, gyro, and acceleration measurements) obtained in the launch programs of the various vehicles developed to date. These data are in a highly unorganized state, being arranged in individual flight reports authored by contracting agencies.

2.1.2 WIND CRITERIA. The three basic forms of wind criteria are synthetic profiles, series of wind soundings, and wind statistics. Synthetic profiles were the first to appear and are widely used. Sissenwine put forth the first profile (Reference 26) in 1954 and revised it in 1959 (Reference 27). During the period 1958-1962 the companies needing wind criteria tended to develop their own versions of synthetic profiles. About 1961 MSFC began publishing synthetic profiles. Since then the use of the "Marshall winds" has become widespread, and the MSFC work now dominates the field of synthetic profiles. The latest MSFC information can be found in Reference 4.

The advantage of the synthetic profile is the ease and simplicity of its use. A few computer runs suffice (unless a large number of altitudes and directions are considered), and the output does not require interpretation.

The disadvantage of the synthetic profile is the difficulty of representing a set of random wind soundings by single or, at most, few wind profiles. Synthetic profiles are easily constructed using wind speed and shear values at given altitudes for the desired probability of being exceeded. Theoretically, the response to the profiles should be the same as that obtained from the set of random wind soundings (for the same probability of being exceeded). This is not generally true, however. As a result, uncertainty exists in the response obtained from synthetic profiles.

A series of wind soundings can be used as criteria by simulating the flight through each sounding, obtaining the response, and performing a statistical analysis of the responses. This approach is referred to as a statistical load survey. The original work with this approach was done by Kaman Avidyne and is reported in References 28, 29, and 30. The use of this approach is becoming more widespread as faster computer simulations are being developed. This topic will be discussed further in Subsection 2.2.

The advantage of this approach is obvious. The conditions of actual flights are accurately simulated, and the results are easily evaluated. The uncertainty between synthetic profile response and response to a set of wind soundings is eliminated. No assumptions are required and hence the most accurate results are obtained. The disadvantage is equally obvious. A fairly large sample is required, which means a large amount of computer time for the simulations. As a result, the costs are higher for this approach. To overcome this disadvantage faster computer simulations are being developed (see Subsection 2.2). If the set of wind soundings has been run for a vehicle, only the more severe winds need by used in subsequent analyses. This method alleviates the problem of computer time considerably and is another way to overcome the disadvantage of high cost.

The representation of wind data by wind statistics was proposed by Bieber and Trembath in Reference 3. Basically the approach is to develop wind statistics, obtain vehicle response corresponding to these wind statistics, and then determine vehicle response for the desired level of probability. This method has not had significant usage in the aerospace industry, probably due to the large amount of statistical analyses and data required.

2.1.3 GUST CRITERIA. Gust and turbulence characteristics are missing from the data sets on which wind criteria are based. Therefore, industry has defined distinctly separate gust criteria tailored to each specific vehicle. This step attempts to ensure minimum risk of vehicle loss and is formulated primarily on the basis of experience. Analysis of detailed wind soundings indicates an increase in frequency-of-occurrence of turbulence as wind shear increases. A correlation coefficient between vertical shear and turbulent gust intensity of approximately 0.5 has been noted (Reference 31). A quantity which is the product of wind speed and turning of the wind with height may be more closely related to turbulent intensity than vertical wind shear. It is also currently accepted that a low probability-of-occurrence wind shear may be accompanied by severe turbulence. The gust criteria are intended to provide an allowance for higher frequency turbulence not contained in wind sounding data due to instrumentation system filtering, and to account for transient air motions known to occur sporadically from time to time.

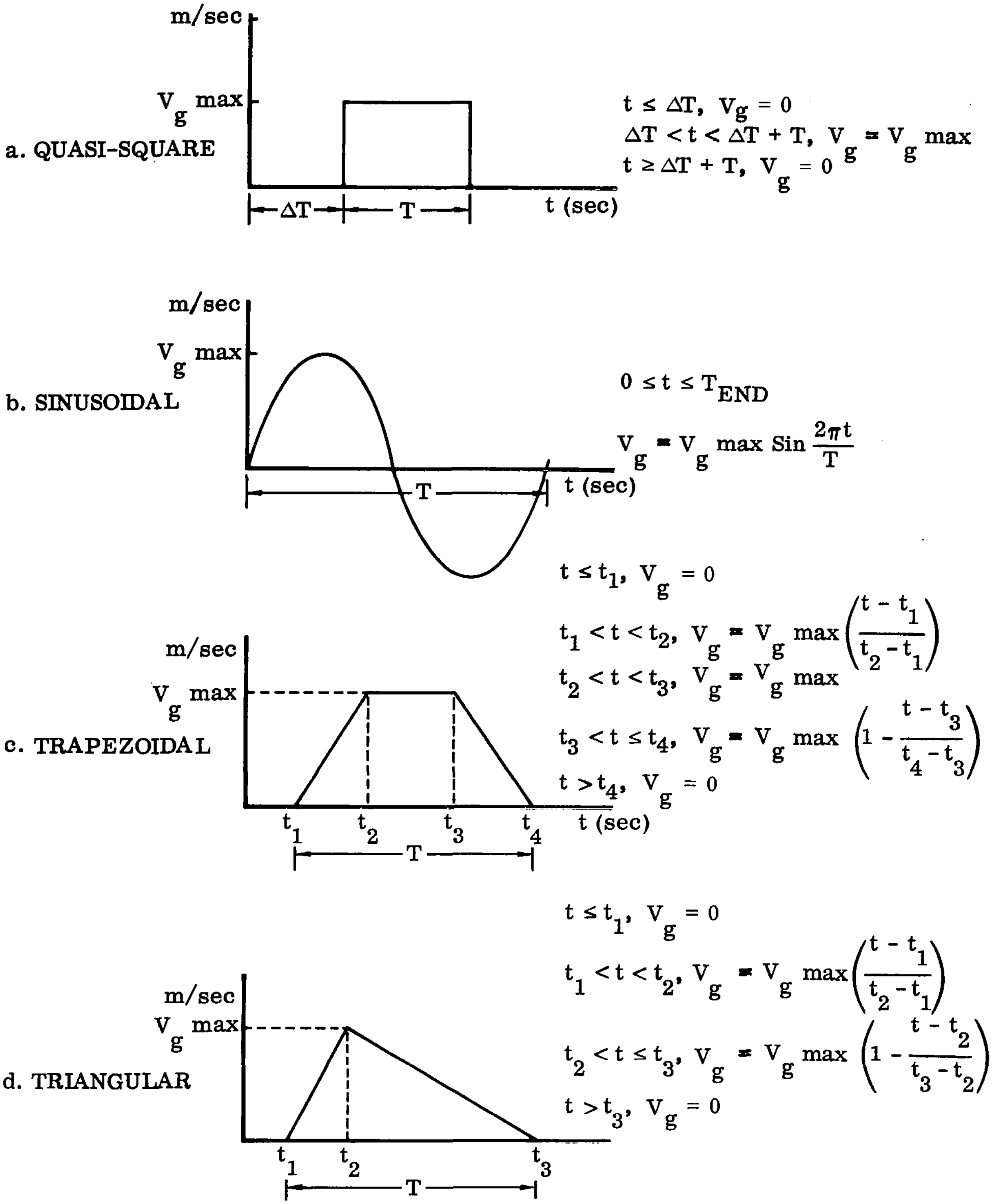
2.1.3.1 Discrete Gusts. The effect of gust phenomena on the vehicle is calculated by obtaining dynamic time response to arbitrary gust forcing functions. Such an analysis provides a rational basis on which structural and control adequacy may be assessed and permits development of an understanding of control system and structural system interactions. Discrete gust criteria continue to be recommended (References 21 and 4) and are generally used by the aerospace industry. Factors involved in the establishment of gust criteria are waveshape, wavelength, altitude, immersion rates, peak gust velocity, and vehicle orientation. It has been found that different vehicle configurations greatly affect the gust analysis results. Thus it is not possible to predict the impact of gust criteria upon a particular analysis. For this reason a range of discrete gusts is usually considered, with worst cases utilized for design. The considerable flight experience gained by the major design organizations indicates that this is a successful approach. The philosophy is to provide for the greatest integrity of the launch vehicle control and/or structural design, and gust and turbulence criteria may, therefore, greatly impact the resulting vehicle system (Reference 31).

For vehicles of moderate length the vehicle may be assumed to be immersed in the gust. For very large vehicles, gust penetration characteristics must be considered, due to the variation in local angle of attack along its length. Waveshapes in common use include the one-minus-cosine, the quasi-square, sinusoidal, trapezoidal, and triangular functions illustrated in Figure 3. Wavelength ranges from 0 to 750 meters (a function of frequency content of wind profiles) and gust velocities range from 6 to 15 m/sec.

The current Marshall Space Flight Center criteria define the discrete gust to be a feature of the synthetic wind profile (see Figure 4). The definition provides a very definite phasing relationship to the steady-state wind peak. The gust (Figure 4) consists of the linear extension of the shear buildup envelope, the buildup to the peak gust speed (which is a one-minus-cosine curve with a half wavelength of 30 meters and an amplitude of 0.85 x 9 m/sec = 7.65 m/sec), the constant velocity plateau, and the tail-off (which is the second half of the one-minus-cosine wave). The gust is oriented vertically and is shifted so that the shear buildup extension is tangent to the one-minus-cosine curve. The gust-thickness varies from 30 to 275 meters. The factor of 0.85 approximates a statistical combination of 99 percent gust velocity and 99 percent wind shears.

Another discrete gust approach involves one-minus-cosine gust functions of varying gust velocity and wavelength assumed to act normal to the vehicle in both pitch and yaw at various flight times. An example of both this and the MSFC criteria and a comparison of results are presented in Reference 32. Here the peak gust velocity is a function of altitude and reaches a maximum of 40 ft/sec (12 m/sec). Non-random sinusoidal characteristics (Reference 33) have been observed. It may be very important to include such characteristics in the gust criteria since the higher degrees of freedom affected are included in the gust analysis.

Discrete gusts are analyzed as independent phenomena to construct a response envelope. No attempt is made to compute probabilities of occurrence. Rather, the conservative assumption is made that the worst gust will occur in the worst direction at



$t \le \Delta T,\ V_g = 0$

$\Delta T < t < \Delta T + T,\ V_g = V_g \max$

$t \ge \Delta T + T,\ V_g = 0$

$0 \le t \le T_{END}$

$V_g = V_g \max \text{Sin} \frac{2\pi t}{T}$

$t \le t_1,\ V_g = 0$

$t_1 < t < t_2,\ V_g = V_g \max \left(\frac{t - t_1}{t_2 - t_1}\right)$

$t_2 < t < t_3,\ V_g = V_g \max$

$t_3 < t \le t_4,\ V_g = V_g \max \left(1 - \frac{t - t_3}{t_4 - t_3}\right)$

$t > t_4,\ V_g = 0$

$t \le t_1,\ V_g = 0$

$t_1 < t < t_2,\ V_g = V_g \max \left(\frac{t - t_1}{t_2 - t_1}\right)$

$t_2 < t \le t_3,\ V_g = V_g \max \left(1 - \frac{t - t_2}{t_3 - t_2}\right)$

$t > t_3,\ V_g = 0$

Figure 3. Typical Discrete Gust Waveforms

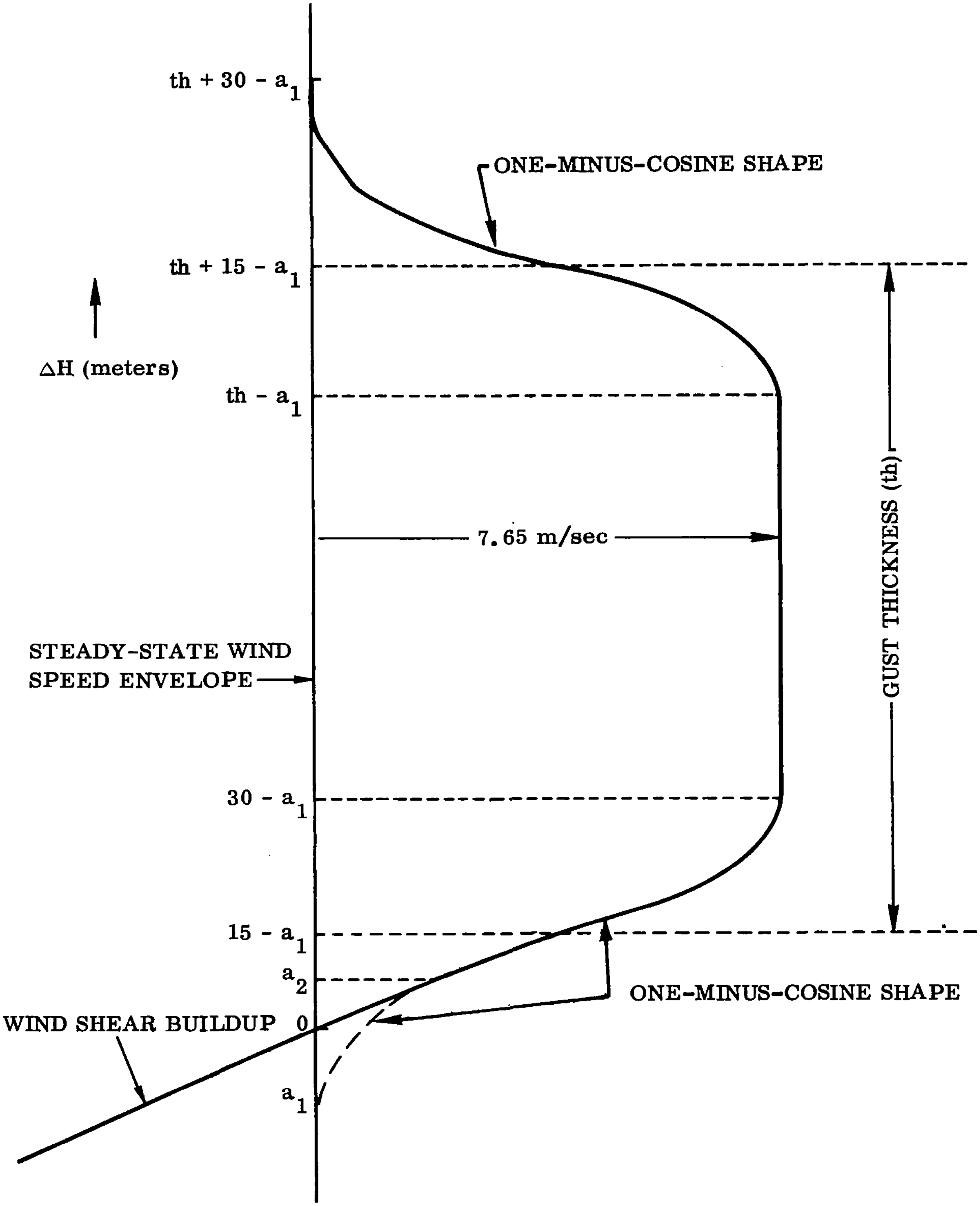


Figure 4. Modified Discrete Embedded Jet Gust As Defined By MSFC

the worst time. This assumption yields gust criteria consistent with the design philosophy.

2.1.3.2 Statistical Gust Treatment. The direct effect of the conservatism presently in use in treating discrete gust criteria is a penalty in payload, control-system capability, and launch availability. Attempts have been made to include probability-of-encounter data in the analysis through development of a statistical representation. The method suffers from considerable complexity, little significant data on which to base the analysis, and required simplifying assumptions.

The approach begins with the observation that continuous turbulence is characterized by the presence of many frequency components occurring in a random combination. Assuming availability of adequate data, the continuous gust turbulence may be analyzed by standard power-spectral-density techniques (Reference 21). Assuming an idealized theoretical model that is stationary, homogeneous, gaussian, and isotropic (valid to an unknown degree), the response statistics can then be computed. It is known that this approach is best at higher frequencies and poorest at the lowest frequencies. Unfortunately, the lowest frequencies are most important to the analysis. Turbulence spectra criteria do not, as yet, exist. A proposed definition of turbulence is the difference between Rawinsonde and FPS-16 radar/Jimsphere wind soundings. Such a definition results in random time functions from which spectra may be constructed. Empirical functions have been derived to represent aircraft data. A representative example of such a function is:

$$\Phi_w(\omega) = \sigma_w^2 \left(\frac{L}{\pi}\right) \left[\frac{(1 + 3\,\omega^2 L^2)}{(1 + \omega^2 L^2)^2}\right]$$

where

Φ_w = turbulence spectra (m^2/sec^2/cycle/m)

σ_w^2 = variance

L = vehicle length (meters)

ω = dimensionless frequency = $n\omega_o$

ω_o = sampling frequency = $\dfrac{2\pi}{h_i - h_{i+1}} \quad \dfrac{\text{rad}}{\text{meter}}$

It is recommended that the statistical approach be used with great care until more testing of concepts is available, as well as more adequate basic statistical data. With the large cost of modern launch vehicles and zero failure philosophy in mind, statistical gust and turbulence criteria are not recommended at the present level of the state of the art. The performance penalities associated with present gust criteria are less than the penalty of the loss of a complete mission.

2.2 ANALYSIS

The analysis of vehicle response to winds and gust has its foundation in aircraft response analysis. The analytical tools developed for aircraft analysis were adequate for and easily adapted to missile and launch vehicle analysis. In recent years statistical techniques have begun to be used for some analyses, but these have been developed in other fields (e. g. , communication, component vibration) and their use here only represents an application of known analytical tools. As a result there is nothing on the theoretical side that can be properly described as an advance in the state of the art. The state of the art in the application of analytical techniques has had some progress in the analysis of wind response. With the increasing use of large samples of wind soundings in simulations, efforts have been made to decrease the computer time required per wind. The advent of highly accurate wind soundings has renewed interest in elastic vehicle and propellant sloshing response to winds. Analysis of gust response has not changed significantly. The primary reason for the large lack of change in the analysis state of the art is that the methods of analysis have been considerably ahead of the state of the art of data and criteria. As a result, the data and criteria have seldom warranted refinements in methods of analysis.

Historically, the analyses of vehicle response to winds and gusts have been performed independently and the results then combined, in some rational manner, to obtain the total response. The vehicle response to wind (at a given flight time) depends upon the trajectory and wind from launch to the given flight time. Thus it is necessary to simulate the vehicle flight from launch to the time of maximum response. The gust analyses, however, are done at given flight times and do not depend upon the trajectory or wind history. They are time-slice analyses; i.e., trajectory parameters, aerodynamic coefficients, and vehicle characteristics are considered constant. The vehicle response to a discrete gust depends upon the gust waveform, amplitude, and length. If a statistical representation is used the response is governed by the gust spectrum. The basic elements of the analysis of vehicle responses to wind and gust are: 1) simulating the trajectory with wind, 2) determinating the time of maximum response, 3) obtaining the vehicle response to gust at this time, and 4) combining the two responses to obtain the total response.

2.2.1 WINDS. The analysis of vehicle response to winds depends upon the simulation of the vehicle trajectory from launch to the time of maximum response. The responses obtained are of two types: 1) structural loads (e.g., accelerations, shear, bending moment) and 2) control system behavior (e.g., engine gimbal angles). Thus both structural and control system analysts need to be concerned with vehicle response to winds. Historically, efforts in this area by the two groups of analysts have ranged from combined efforts to completely independent efforts (even to the extent of using different wind criteria). Clearly the need for close coordination and/or combined efforts is indicated.

The digital computer is, as a general rule, used in simulation of the vehicle trajectory with wind. The analog computer has been utilized on some occasions but has not yet found widespread acceptance for this purpose in the aerospace community. Some computations are suited to the digital computer, e.g., table lookup of variables such as aerodynamic coefficients and centers of gravity; while other computations are suited to the analog computer, e.g., integration of variables. While this sounds like an ideal use for the hybrid computer, there is a fundamental reason for the dominance of the digital computer in launch vehicle trajectory simulation. Once the digital computer data deck for a certain launch vehicle trajectory is assembled and checked out, digital computer runs can be made with very little setup time regardless of the number of runs. The setup and computer time required for each run is the same, however. On the analog computer, considerable setup time and effort are required, regardless of the number of runs being made. Once the runs are being made, large numbers of runs can be made quickly. The costs involved thus favor the digital computer for a small number of runs and the analog computer for a large number of runs. Since a considerable amount of trajectory simulation activity is conducted with a small number of runs at any one time, the digital computer has dominated as the tool for vehicle trajectory simulation. An additional advantage of the digital computer is in the area of repeatability. When repeat runs are made on the analog computer, and slightly different answers are calculated, the problem arises as to which one to use. Use of the digital computer avoids this situation.

2.2.1.1 Complete Trajectory Method. The most accurate simulation of the trajectory of a launch vehicle is one that takes into account all aspects that have an effect on the launch vehicle during flight. Such a simulation is necessarily quite detailed and the derivation of equations lengthy. The development of the equations for a complete simulation are well-documented and will not be presented here, since that would be unnecessary repetition and be considered outside the scope of this document. (Reference 34 is an example of the development of the equations.) Also, the various companies and agencies concerned with launch vehicle development have completed five- or six-degree-of-freedom simulations, and documentation of these are generally available.

A trajectory simulation is considered complete (or exact) if it meets the following qualifications:

a. The time derivatives of vehicle and control system positional variables are integrated in the simulation.

b. The autopilot and control system are simulated fairly accurately (at least in the low-frequency spectrum).

c. Approximations are not made in earth, atmospheric, or propulsion models which would cause trajectory parameters to differ appreciably from those obtained without the approximations.

d. Mass and aerodynamic properties are obtained by table lookup at all times, i.e., not held constant over certain intervals.

It is possible to reduce the complexity of a simulation without making any significant compromise in results. Two examples are: 1) leaving out the roll degree of freedom and 2) use of a flat non-rotating earth rather than a rotating spherical or spheroid earth. Also, nonlinear control systems can often be linearized. For any given vehicle further simplifications may be possible.

2.2.1.2 Approximate Trajectory Methods. The exact trajectory simulation previously discussed, while very accurate, takes a significant amount of computer time, and, for a large number of winds, the time tends to become excessive. To overcome this disadvantage attempts have been made to develop simplified and approximate trajectory simulations which take considerably less computer time yet yield results only slightly degraded in accuracy. As a rule, approximate trajectory simulations rely upon a reference trajectory and consider perturbations about this trajectory.

Clingan (Reference 3) tried a closed-form solution which neglected rotational acceleration and rate and considered only perturbations from a reference trajectory. This method was compared with a complete trajectory simulation (Reference 35) and found to give good agreement in some cases and poor agreement in other cases. Andrus (Reference 36) also proposed a closed-form solution.

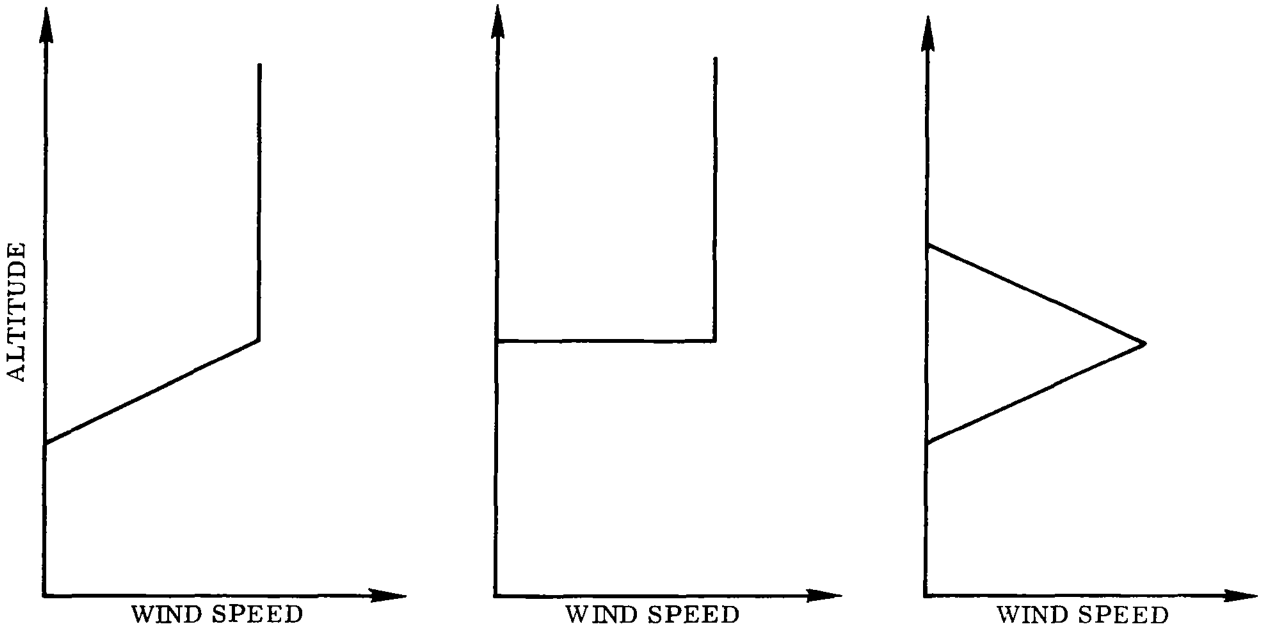
Van Der Maas used an alternate form of this approach (Reference 37) in obtaining an approximate trajectory simulation. Starting with the equations for a complete trajectory simulation, simplifing assumptions were made to reduce these to perturbation equations for a reference trajectory. Vehicle rotational acceleration and rate were retained and the autopilot/control system simulated. Laplace transforms were employed to obtain algebraic solutions. As shown in Reference 37, agreement between the approximate simulation and complete simulation is quite good.

2.2.1.3 Influence Coefficient Matrix Method. The use of influence functions was considered fairly early in the history of wind response studies (e.g., Trembath in Reference 3). Out of this emerged the influence coefficient method in which an influence coefficient matrix describing the vehicle response to a series of basic profiles is generated. By representing any particular wind or a composite of the basic profiles, a wind vector may be constructed. Multiplication of this vector and the influence coefficient matrix yields the total vehicle response to winds. The influence coefficient matrix needs to be generated only once for a particular reference trajectory;

thereafter, the response to a wind requires only a matrix multiplication. Thus the computer time is considerably reduced when analyzing a large number of winds. The method was evaluated in Reference 35 in comparison with other approximate methods and an exact trajectory simulation. The accuracy was found to be good and the method was recommended for preliminary design. Reference 38 documents studies to improve the method. The basic profiles used in Reference 35 are shown in Figure 5. The profiles are used at altitudes from ground to some altitude above the expected maximum wind response altitude. The modified ramp is the most widely used profile.

2.2.1.4 Static Aeroelasticity and Elastic Modes. The previous subsections have discussed the analysis of the response of a rigid vehicle to winds. However, launch vehicles are usually sufficiently flexible to have significant deflection under design loads. These elastic deflections can be classed as static aeroelastic deflections and modal deflections.

Static aeroelastic deflections, or static aeroelasticity, are those deflections which occur when an air load is applied for a sufficiently long period of time that transients decay (or are small) and the vehicle assumes a static deflected position. The wind profile variation is of a long period nature, and hence static aeroelastic deflection does occur. If at some time instant the vehicle has an angle of attack, the



a. Modified Ramp b. Step c. Triangular Spike

Figure 5. Basic Profile Shapes

resulting air loads cause deflections which change the local angle of attack and, in turn, the load distribution on the vehicle. The change in load distribution again changes the local angle of attack. Thus an iterative process is begun which rapidly converges on a suitable airload distribution. When a vehicle is flying through a wind the static aeroelastic response approximately follows the wind loading. The static aeroelasticity of a vehicle is of interest to the control system analyst because it increases the aerodynamic moment on the vehicle, which means an increase (over rigid body) in the required control system capability. Experience indicates that this increase is in the range of 5 to 20 percent. Reference 39 gives two methods for obtaining the effect of static aeroelasticity upon loads and control system capability. Also, methods for combining these effects with the results from the rigid body trajectory simulation are given.

The effects of static aeroelasticity can be considered to be applicable to wind profile variations whose period is significantly greater than the period of the first bending mode. If the wind profile variation has a period near or less than the period of the first bending mode, the elastic modes of the vehicle may be excited. In this case the elastic modes (usually first bending mode) would need to be included in the trajectory simulation in order to completely account for elasticity of the vehicle. However, the inclusion of an elastic mode in the trajectory simulation has received little attention for three reasons. First, most of the wind data available are in 1000-ft altitude increments and thus of a long-period nature. Second, the inclusion considerably increases the complexity of the simulation; hence computer time increases. Third, flight data indicate that response to elastic modes has not been a significant item. The gust loads used in design have generally more than accounted for modal oscillations seen in flights. With more accurate wind data becoming available (e.g., FPS-16 radar/Jimsphere data) and large launch vehicles with first bending mode frequencies of 1 to 2 Hz becoming operational, more attention may be given to inclusion of elastic modes.

2.2.1.5 Propellant Sloshing. Propellant sloshing has, in one important respect, received scant attention. While considerable effort is expended to demonstrate that the vehicle will be stable if sloshing occurs, virtually no effort has been expended to determine which wind profile characteristics tend to induce sloshing. In at least one case (Reference 40) sloshing was included in a trajectory simulation; however, no systematic study was made of sloshing response with regard to wind. Sloshing has seldom been included in simulations for the same three reasons given for elastic modes. Since sloshing frequencies are generally less than 1 Hz, studies should be made to determine the importance of sloshing in trajectory simulations.

2.2.1.6 Selection and Optimization of Autopilot Design. The autopilot design (including gain and filter values) can influence the vehicle response to winds. It is therefore necessary that consideration be given, with regard to wind response, to the autopilot design. The following example will illustrate one aspect of autopilot design. For an attitude control autopilot, the displacement gain is the amount of control capability commanded per degree of vehicle rotation from the desired attitude. The effect of this parameter upon bending moments on the vehicle is shown in Figure 6. The impact of displacement gain upon bending moment is readily seen. The solid line represents the response to a steady (constant) wind shear and the dashed line represents the response to time-varying winds and gusts. For low gain, a large angle of attack occurs (due to low control moment) causing large air loads. For high gain the autopilot commands excessive control moment, which results in large vehicle accelerations. The low point of the combined curve is the optimum point for wind and gust effects; however, the stability of the autopilot/control system/vehicle system must also be considered. The above example graphically illustrates the need to jointly consider the vehicle response to wind and gust and vehicle stability in the design of an autopilot. Results of studies of various types of autopilots and effects of autopilot parameters are given in Reference 41.

2.2.2 GUSTS AND TURBULENCE. Gust analysis is normally performed as an independent step in vehicle design — for reasons previously given. Analytic techniques employed vary widely as functions of vehicle type, control scheme employed, and design phase. Fundamental to all gust analysis is the time-slice approach, in which all slowly varying vehicle parameters are assumed to be constant over the computational interval. The analysis is repeated for various flight times throughout

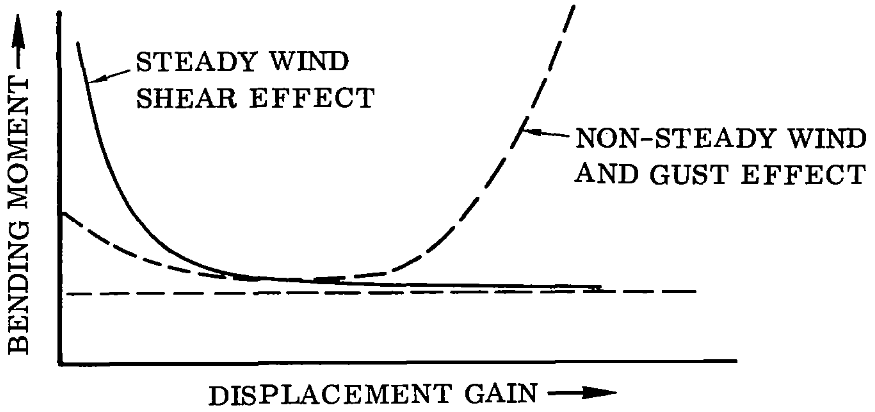


Figure 6. Bending Moments vs. Displacement Gain

the maximum aerodynamic loading regime. Analysis methods employed may be conveniently grouped into discrete gust and statistical gust methods. The primary concern of the control analyst is the study of the effect of various control schemes and parameters on structural loads and system response. The short-duration wind disturbances are significant to both control system and structural system design. Short-period atmospheric disturbances are envisioned as resulting from two distinctly different sources. Turbulence is considered to mean atmospheric motion not present in wind soundings, by virtue of measurement system filtering. Accounting for turbulence is best done statistically. Gusts, however, are the occasional transient bursts of wind that are known to occur from time to time.

It should be recognized that meaningful interpretation of vehicle reaction to short-duration gusts can be made only if an adequate definition and isolation of the disturbing function can be made. Such isolation is uncertain, and, in fact, separate gust and turbulence analyses are made only in lieu of wind measurements of satisfactory frequency content in sufficient number. An adequate gust definition has not as yet been developed. A good definition for one vehicle is not necessarily good for another.

2.2.2.1 Discrete Gust Methods. Discrete gust analysis is performed in a classical manner wherein a mathematical model comprised of the system equations is solved for the dependent variables, with assumed analytic gust forcing functions. Formulations vary in complexity (depending upon design phase) from closed-form solutions involving a few degrees of freedom to complex analog and digital simulations involving great detail. Since most launch vehicles are highly symmetrical, planar analysis involving 3-degree-of-freedom rigid body perturbation equations is usually used. If the pitch and yaw properties of the vehicle being studied are significantly different, both planes are analyzed. Vehicle elasticity is very important in gust studies and is usually handled by using normal mode vibration theory. Occasionally, however, direct integration schemes are used. Detailed autopilot representation and propellant sloshing (in the case of liquid-fueled vehicles) must also be included. Since typical gust response for vehicles and control schemes now used is only of the order of 20 percent of the vehicle response to winds, a greater degree of approximation is permissible (Reference 21) than that employed in wind studies. Some control laws result in gust response approaching wind response, however (Reference 41). Aerodynamic force distributions are generally linearized at an estimated or calculated angle of attack value corresponding to the design wind-plus-gust condition. Local angles of attack resulting from the gust produce local forces which are assumed to change faster than the structural system can respond (i.e., additional aerodynamic forces due to local structural motion is ignored). This is a reasonable assumption since the predominant component of local angle of attack is the relative wind term. The aerodynamic forces produce accelerations which ultimately result in control forces according to the control law and system concept. Since the use of modal analysis is widespread, engine system dynamics are usually also linearized. Thus the state of the art is linear, planar, lumped-parameter, time-slice analysis. Digital programs written for gust analysis at this level represent capacity utilization of existing large-scale computers.

The intent of the analysis is to compute the response of the coupled system of vehicle elastic airframe and autopilot, including predominant effects using multi-degree-of-freedom analysis. Principal response is generally near the first elastic bending mode frequency, so zero coupling with the wind shear is assumed. Conservative assumptions are made when combining gust response with wind and wind shear in lieu of accuracy in both analysis and data. Peak responses calculated using discrete gust analysis generally are some 20 percent larger than spectral analysis responses for the same vehicle. This is a reflection of the conservative assumptions made. The simplest discrete gust analysis possible involves the solution of the following equations based on the relationship illustrated in Figure 7. This is a rigid body with elastic bending representation in one plane.

$$I_{cg}\Delta\ddot{\theta} = T\,(x_g - x_{cg})\,\delta_1 + q\,S\,C_{z_\alpha}\sum_{i=1}^{n}\bar{C}_{z_{a_1}}\,(x_{cg} - x_i)\,\Delta\alpha_i \tag{1}$$

$$M\,\Delta\ddot{z}_b = T\,\delta_1 + q\,S\,C_{z_\alpha}\sum_{i=1}^{n}\bar{C}_{z_{\alpha_i}}\,\Delta\alpha_i \tag{2}$$

$$\Delta\alpha_i = \Delta\theta + \frac{w_{gi} - \Delta\dot{z}_b}{V} \tag{3}$$

$$\delta_1 = k_1\,(\Delta\theta - \theta_c) + k_2\,\Delta\dot{\theta} + k_3\int_0^t \Delta\theta\,dt \tag{4}$$

$$\begin{aligned} BM_k &= q\,S\,C_{z_\alpha}\sum_{i=1}^{k}\bar{C}_{z_{\alpha_i}}\,\Delta\alpha_i\,(x_k - x_i) \\ &\quad - \sum_{i=1}^{k} m_i\,(x_k - x_i)\,[\ddot{z}_b + (x_{c_g} - x_i)\,\Delta\ddot{\theta}\,] \end{aligned} \tag{5}$$

$$M_r\,\ddot{q}_r + M_r\,\omega_r^2\,q_r = Q_r \tag{6}$$

M_r generalized mass in rth mode

ω_r frequency in rth mode

q_r displacement of the normalized station in the rth mode

Q_r generalized force in rth mode

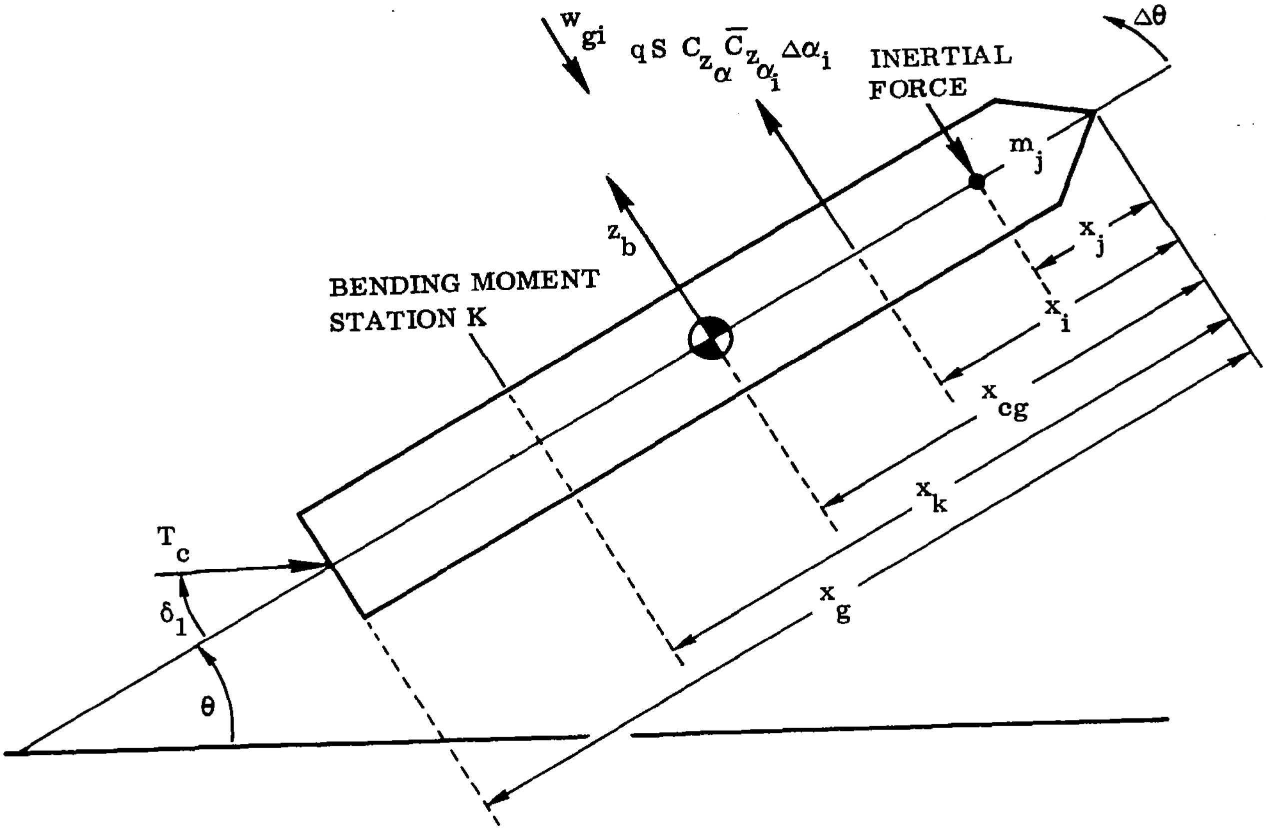


Figure 7. Rigid Body/Elastic Bending Representation

$$M_r = \sum_s m_i \left[\phi_s^{(r)} \right]^2 \tag{7}$$

$$Q_r = \sum_i F_i \left[\phi_i^{(r)} \right]^2 \tag{8}$$

These equations may be expanded to account for additional detail such as engine limiting, propellant sloshing, autopilot filters, etc.

2.2.2.2 Statistical Turbulence (Gust) Methods. The development of random process theory has led to applications to the problem of turbulence. Most of this work has been of a theoretical nature. That is to say, actual vehicle design loads have not generally been so established. This is due to the limited nature of available data and the assumptions required in the analysis mentioned earlier. A primary difficulty is that the very definition of gusts is significant in the determination of the statistical distribution of the turbulence field and strongly influences the interpretation of analysis results. This is because the gust representation is of equal importance with vehicle dynamics and control system characteristics.

The statistical approach generally fails to predict extreme conditions (1 percent) which are of most interest. Statistical representations can greatly influence design and hence should be used with care until more experience is available. Recent analysis (Reference 4) led to the following conclusions.

a. Spectral methods cannot account for important turbulence features observed to exist that are highly organized rather than random in nature (i.e., sinusoidal properties, embedded jets, etc.).

b. Turbulence does not appear to be homogeneous, and hence is non-stationary with respect to the moving vehicle.

c. Some small-scale motions are highly persistent in time.

These observations constitute important defects in the application of harmonic analysis. Also of great significance to the control analyst is the fact that statistical approaches to gust or turbulence analysis obscure physical relationships that provide insight essential to a design synthesis. Changes occurring in the course of design or parameter variations require recalculation of the vehicle mechanical admittance functions and repetition of the entire analysis. This computational effort is of great practical significance. The required assumptions of isotropy, linearity, and gaussian are of unknown validity and present another fundamental problem.

Thus the state of the art of statistical gust analysis is currently in a developmental stage. It offers great promise as a design analysis tool that would permit a rational overall design approach embodying considerably more information than is now the case.

2.2.2.3 Optimization of Control System Parameters. Consideration should be given by the control analyst to the problem of minimizing gust response when designing flight control systems or establishing parameters. Gust response depends equally upon the frequency content of the gust waveshape and the modes of the system. It is possible to control the distribution of energy to the system modes by varying the control law in such a way that a desirable phasing relationship exists. Such considerations are of necessity secondary to such items or stability, however. A straightforward universal procedure for optimization does not exist. Success depends upon a thorough understanding of the system and intuition, with a certain amount of trial and error. A reduction in gust response through optimum control increases confidence in the success of the vehicle. It has been found (Reference 41) that no one control law is superior to any other from the viewpoint of giving the smallest loads or required control capability, for all vehicle stations, vehicles, launch sites, and separation ratios. Changes that improve wind shear response normally degrade gust response and vice versa. Assessment of vehicle response to atmospheric turbulence cannot be generalized to one vehicle parameter. Complex relationships require that all parameters of interest for a particular vehicle be analyzed.

A property of the more detailed wind soundings becomes available in the presence of small-scale shears (0 to 300 meters) whose effect cannot be properly accounted for by the rigid body analyses employed. There, effects should be included in the gust analysis by analyzing vehicle response to triangular waveshapes of small wavelengths.

The probable development of less expensive digital computers, with larger data storage capability in core, will make feasible complete coupled trajectory and gust analysis simulations in the near future. Use of such simulations with large samples of detailed winds in extended load surveys will yield statistics of much greater confidence level for use in design than is now possible.

3/CRITERIA

The atmospheric disturbance environment during the exit phase of flight shall be included in the autopilot and control system design of a launch vehicle. The autopilot and control system shall be designed to maintain vehicle control and remain stable when subjected to the expected atmospheric disturbances. The determination of the control capability requirements shall consider all characteristics of atmospheric disturbances including wind, wind shear, gust and turbulence. This capability shall be included for design in combination with the control capability requirements for programmed maneuvers and with autopilot and control system dispersions. The analyses shall be performed in conjunction with and/or in coordination with analyses to determine structural loads induced by atmospheric disturbances.

The trajectory shall be examined for critical conditions. As a general rule, for purposes of determining total control capability, the effects of trajectory, control system, and autopilot dispersions may be root-sum-squared with the gust effects. The resulting effect is then directly added to wind effects and to programmed maneuver effects. The no-wind nominal trajectory is the basis for determining each effect. Examination for criticality shall include, but not be limited to, the following conditions.

a. Transition Turn. This condition is not usually critical, but severe pitch program maneuvers combined with high wind speeds could be significant. The condition covers a period of about 20-30 seconds commencing with program initiation.

b. Maximum Wind Effect. This condition generally occurs in the 10-15 km altitude range and produces the largest amount of required control capability.

c. Programmed Maneuvers. This condition covers planned pitch and yaw programs and guidance steering to correct for trajectory dispersions. Critical times may occur anywhere in the flight, depending on where they are employed. The wind, gust and dispersion effects should be added to the maneuver effects as discussed above.

d. Staging. This condition covers a period starting with initiation of staging and ending when stable control of the next stage is achieved.

The specific wind criteria to be employed for autopilot and control system analysis are based on the particular launch site and launch azimuth which are intended to be used for the launch vehicle. The preference of the contracting agency or contractor generally determines the type of wind representation used. The associated probability of launch (probability of being able to launch at a given time without exceeding the structural and control capabilities) is dictated by the mission and performance requirements for the particular space program. Where a launch vehicle is to be used with upper stages for which it was not designed, the contracting agency may accept the resulting probability of launch rather than modify the launch vehicle.

4/RECOMMENDED PRACTICES

The history of a launch vehicle generally begins with feasibility studies to determine approximate characteristics, advantages, disadvantages and potential problems. If development of the vehicle is ordered the preliminary design begins, leading eventually to a final design. The vehicle then moves into the hardware and flight phases. As the vehicle becomes operational, the desire to use the launch vehicle for more missions results in feasibility and compatibility studies with upper stages and/or payloads not considered in the initial design. Feasibility studies are undertaken to determine if it is feasible and practical to utilize the launch vehicle in the desired application. Generally, the modifications required come from or are an outgrowth of the feasibility study. Compatibility studies are undertaken when the new application is so similar to previous applications that it is known that the mission can be performed and all that is needed are the minor modifications peculiar to the mission.

The practices employed vary with the phase of launch vehicle development and use. To facilitate the discussion the launch vehicle development will be separated into two phases. These phases are the initial design phase (up through final design of the original vehicle) and the modification design phase (further applications not considered in the initial design).

The analyses mentioned in the following discussions will necessarily also be performed by structural dynamics analysts to obtain bending moments, shears, and accelerations for structural design. Therefore, close coordination by control system analysts and structural analysts is required to avoid unnecessary duplication of effort.

4.1 INITIAL DESIGN PHASE

The practices followed during design studies of a launch vehicle, from first concept through final design verification, vary as the design progresses. Also, the criteria and methods of analysis are subject to change due to advances in the state of the art. For these reasons, broad guidelines rather than specific rules must be given.

The vehicle response to winds and gusts needs to be determined early in conceptual design in order that the required control capability can be estimated. The first analysis can be done using a "trimmed vehicle" simulation; i.e., autopilot/control system dynamics and vehicle rotational accelerations are neglected, as the autopilot and control system characteristics are usually not available at this point. Synthetic wind profiles should be used because of their simplicity of use. Currently, the MSFC wind criteria (Reference 4) are recommended as the best available. The gust response can be estimated by applying the peak gust angle of attack to the "trimmed vehicle" and adding 20 percent to the response, rather than using the MSFC gust definitions.

As the preliminary design of the vehicle begins, a tentative autopilot and control system should be available. The vehicle response to gusts should be immediately determined to check the original estimates, using a MSFC discrete gust definition. Of particular importance is the gust effect on upper stage and payloads. Also, variations in autopilot design and parameters should be performed at this point to assist in optimization and final design of the autopilot and control system. The analysis for response to wind will depend on the wind criteria to be used for final design verification. For criteria using synthetic profiles, a complete trajectory simulation should be used. As stated previously, the MSFC criteria are recommended (which includes a gust waveform as a distinct feature of the profile). For criteria using a statistical load survey, an approximate trajectory simulation (Subsection 2.2.1.2) or the influence coefficient matrix method (Subsection 2.2.1.3) should be used in conjunction with an appropriate set of wind soundings.

The sample size of the set should be a minimum of 50 winds for any one month and should extend over a minimum period of 5 years. The set should also be serially completed by meteorologists. If the design is critical, the more severe winds should be run in a complete trajectory simulation. Discrete (one-minus-cosine) gusts tuned to the first elastic bending mode should be investigated at this stage.

The final design verification should be conducted as soon as the design is finalized to the extent that further changes will not have a significant effect on vehicle response to winds and gusts. Ideally, this will be prior to design freeze so that changes can still be made easily. Where the synthetic wind criteria are being used, the critical winds from the preliminary design study should be rerun with final data. Where a statistical load survey is being done, the more severe winds should be run with a complete trajectory simulation and final data. Responses should be ranked at stations of interest and for small time intervals throughout the maximum aerodynamic loading flight regime.

The gust simulations should be rerun with final data in a complete analysis including sloshing, at least two rigid body degrees-of-freedom, three bending modes, and the complete control system and engine vectoring dynamics. Various discrete gust shapes should be checked, including a (one-minus-cosine) function of peak gust velocity normal to the vehicle of 9 to 12 m/sec and wavelengths varying from 30 to 450 meters. If the vehicle is very large or has wings or fins, both immersion and penetration effects should be analyzed. Gust factors should be based upon worst-case results as a conservatism.

4.2 MODIFICATION DESIGN PHASE

The practices followed during the modification design phase depend largely upon those followed in the initial design phase. The desire to avoid major redesign orients many of these studies towards determining what can be accomplished with existing hardware, i.e., existing control capability. Often the cognizant agency will accept a lower launch probability rather than redesign the various stages and payloads.

When it is desired to use payload/fairing configurations significantly different from those used in initial design or upper stages not considered initially, feasibility studies are usually performed to determine the problems involved, the nature of modifications required, and the costs. Basically, the practices previously given for preliminary design through final design verification should be used. The factor of launch probability does, however, enter into the choice of wind criteria. For launch probabilities of 95 percent or higher the use of synthetic profiles is reasonable. However, for launch probabilities less than 95 percent, the statistical load survey is recommended because of its superior accuracy in determining vehicle response vs. launch probability. This becomes quite important when the study is conducted on the basis of using the existing structural and control capabilities and obtaining the resulting launch probability.

If the use of a payload/fairing configuration quite similar to a configuration previously studied is desired, compatibility studies are usually performed to determine the minor modifications needed to accomplish the mission. These are usually in the nature of changes in programmed maneuvers, autopilot gains, and the payload interface. The practices previously given for final design verification should be used, with the change noted above.

5/RECOMMENDATIONS FOR FUTURE ACTIVITIES

Past recommendations have generally emphasized the need for better data. However, better data are becoming available and ground work can now be laid for standardization of criteria. The following recommendations will outline the direction that the standardization should take and the work necessary to accomplish the task. Methods of analysis requiring further work are also indicated.

5.1 WIND CRITERIA AND ANALYSIS

It is recommended that a standard set of FPS-16 radar/Jimsphere soundings be obtained for ETR and for VAFB, as well as for any other regions contemplated for launches. Each set should be serially completed and used as standard wind criteria, utilizing the statistical load survey approach. Much of these data are already available for ETR; however, the FPS-16 radar/Jimsphere system is not currently in use at VAFB. It would be highly desirable if the system could be installed and put into operation at VAFB in the near future.

In conjunction with the above, the continued development and dissemination of high-speed trajectory simulations is needed. This will facilitate the rational, rapid, and inexpensive use of the above criteria at all design phases.

The effect and importance of sloshing and/or elastic modes in trajectory simulations are not well defined. It is recommended that systematic studies be undertaken to determine the quantitative effect of their inclusion for a wide range of vehicles. The studies should also result in guidelines for determining when sloshing and/or elastic modes should be considered in trajectory simulations.

5.2 GUST CRITERIA AND ANALYSIS

It is recommended that gust criteria, consistent with the wind criteria recommended in Subsection 5.1, be established. The criteria should take into account wind profile detail and "discrete" gusts and indicate methods of analysis and combinations of wind and gust effects.

Knowledge of the correlation between gusts and wind speed, the frequency of occurrence of gusts, the gust waveform, and the gust amplitude all are inadequate. Therefore, efforts to improve gust definition should be continued. One area that needs more study is the correlation between gusts and change in wind direction.

The recent advent of slightly unsymmetrical payloads requires the development of six-degree-of-freedom gust analyses to properly account for cross-coupling and torsional effects, which is now feasible due to recent computer advances.

5.3 WIND-GUST INFORMATION SERVICE

It is recommended that a Wind-Gust Information Service be established to provide a regular interchange of published material throughout the aerospace and meteorological communities concerned with winds and gusts. The Service would be staffed by one person, or perhaps a small group. Personnel would be selected from government agencies, such as MSFC and AFCRL. A copy of each article, note, report, paper, etc. published on the subject of wind and/or gust, whether concerned with data, criteria, or analysis, would be sent to the Service. The Service would review each document and prepare an abstract (if not already available). Bulletins containing the abstracts would be published at regular intervals and distributed to all persons working with, or interested in, winds and gusts. The regular interval should be in the range of 3-6 months. The Service would not be responsible for furnishing copies of the published material itself, only the bulletins.

The bulletin would also contain the status of data gathered about winds and gusts. This would be a list of all wind soundings obtained during the previous bulletin interval. The list would give site, equipment, date, time and altitude range covered, and where the sounding can be obtained. The actual sounding would not be given. Summaries could also be given of available data collected over several years at certain sites.

The bulletin could discuss study contracts, new data-gathering methods under development, or any other matter of general interest. This would keep those working in the field abreast of anticipated developments.

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