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SPACE VEHICLE
DESIGN CRITERIA

PRELAUNCH GROUND WIND LOADS

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FOREWORD

NASA experience has indicated a need for uniform design criteria for space vehicles. Accordingly, criteria are being developed in five areas of technology, outlined as follows:

Volume I — Environment
Volume II — Material Properties and Processes
Volume III — Structures
Volume IV — Stability, Guidance, and Control
Volume V — Chemical Propulsion

The individual components of this work are regarded as being sufficiently useful to justify publication separately in the form of monographs as completed. This document, Section 1 of Volume III, Part B, Chapter 2, is one such monograph. The planned general outline of Volume III is set forth on page ii.

These monographs are to be regarded as guides to design and not as design requirements, except as may be specified by NASA project managers or engineers in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, will eventually become uniform design requirements for NASA space vehicles.

Comments from addressees concerning the technical content of the monographs are solicited. Please address such comments to the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RVA), Washington, D. C. 20546.

November 1965

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PLANNED OUTLINE OF VOLUME III: STRUCTURES

PART A: DESIGN PRINCIPLES

Chapter 1 - General Criteria
Chapter 2 - Detail Design Practices

PART B: LOADS AND STRUCTURAL DYNAMICS

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Chapter 2 - Prelaunch
Chapter 3 - Launch and Exit
Chapter 4 - Space Flight
Chapter 5 - Entry and Atmospheric Flight
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PART C: STRUCTURAL ANALYSIS

Chapter 1 - General Criteria
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PART D: TESTING

Chapter 1 - Model Tests
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Volume III: Structures
Part B: Loads and Structural Dynamics
Chapter 2: Prelaunch

SECTION 1: GROUND WIND LOADS

1.1 INTRODUCTION

Space vehicles, while free-standing prior to launch, are exposed to steady winds and gusts and to the turbulent wake from umbilical mast, gantry, or other nearby structures. The response of a vehicle to winds and turbulence produces oscillatory loads which must be accounted for in the design of the vehicle.

The magnitudes of the steady winds and gusts to be considered in the design of a particular vehicle will depend on such factors as the atmospheric environment at the launch site and the length of free-standing time anticipated. The response of the space vehicle and the loads on the structure depend on the winds and gusts to which it is exposed, the frequency and damping of the combined vehicle and support-system vibration modes, the vehicle shape, the number and location of external protuberances, the nearness and type of umbilical mast and other structures, and the propellant loading condition.

Related problems, such as transient loads associated with ground handling operations, thrust buildup and release, and guidance alinement problems caused by wind-induced oscillations, are treated in other monographs.

1.2 STATE OF THE ART

The problem of ground wind loads on space vehicles is related to the problem of wind loads on slender structures such as towers, masts, and smoke stacks. Significant material relating to wind loads on structures, including space vehicles, may be found in references 1, 2, and 3.

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It is convenient to consider the total load due to winds as being composed of steady loads, vortex-shedding loads, and gust loads. Of these, the steady loads are the most readily evaluated. On simple clean bodies of revolution the steady drag loads can be calculated by strip analysis, using drag coefficients for two-dimensional cylinders or cone-cylinder combinations obtained at appropriate Reynolds numbers. For more complex configurations, such as clustered cylinders, cylinders with external conduits and protuberances, or those influenced by the presence of adjacent tower structures, steady loads may be estimated from wind-tunnel tests of rigid models. In most instances, however, the estimates of steady loads are determined in conjunction with the unsteady vortex-shedding loads on aeroelastically scaled models as discussed in the following paragraphs.

The unsteady aerodynamic forces associated with vortex shedding are not well understood. Studies conducted by Fung (ref. 4), Humphreys (ref. 5), Roshko (ref. 6), and Scruton (ref. 7) on two-dimensional cylinders have contributed to an understanding of the mechanism of vortex shedding, but have not produced data applicable to actual space vehicles. Wind-tunnel investigations of dynamically scaled models have therefore been resorted to for quantitative estimates of the effects of ground winds. References 8 to 18 are examples of investigations wherein response measurements (such as bending moments or accelerations) on a model in a wind tunnel are related through scaling factors to corresponding responses on the full-scale vehicle in a steady wind. References 19 to 22 are examples of an alternate method of load prediction, wherein the aerodynamic forces associated with vortex shedding are obtained from high-frequency pressure measurements.

Because unsteady vortex-shedding loads are associated with flow behavior in the boundary layer, seemingly small changes in the surface features of the body can precipitate large effects. For example, a thin strip of tape stretched axially along the surface of a circular cylinder in a wind tunnel has been known to result in an order-of-magnitude change in the unsteady loads. Similar effects have been observed when small changes are made in the nose shape of wind-tunnel models of launch vehicles. Umbilical towers or other structures near the vehicle can significantly affect the response. Configuration details which might otherwise be considered aerodynamically unimportant become significant factors with regard to vortex-shedding loads. Unfortunately, only a meager quantity of suitable full-scale data is available for correlation with wind-tunnel data (see refs. 23 to 26).

Despite this lack of quantitative full-scale data on which to base comparisons, a phenomenon that can lead to catastrophic structural oscillations has been observed both in wind tunnels and on large structures in the atmosphere. These oscillations, which can lead to loads that are an order of magnitude greater than those associated with steady drag forces, have all the earmarks of a self-excited aerodynamic instability. The response is usually periodic at the fundamental natural frequency of the structure and occurs over a narrow range of wind

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velocities. The Strouhal number associated with the oscillation is usually in the vicinity of 0.2 ($fD/U = 0.2$, where f is the frequency of response in cps, D is the maximum diameter of the vehicle, and U the wind velocity). This phenomenon has been observed over virtually the entire Reynolds number range of interest in the present problem, including values above 10 million.

A major objective of wind-tunnel tests of aeroelastic models is, therefore, to determine whether the configuration under study is susceptible to large-amplitude self-excited oscillations, and, if so, to find a means of suppressing these oscillations to an acceptable level. This may involve adding artificial damping to the structure or attaching aerodynamic spoilers that will break up the flow features contributing to self-excited response. A paramount consideration in selecting a mechanical or aerodynamic means of suppressing these oscillations should be the avoidance of adding weight which will be carried by the vehicle after lift-off.

Dynamic loads due to atmospheric turbulence must be determined analytically and combined with the steady-drag and vortex-shedding loads. Since little is known regarding the possible effects that atmospheric turbulence may have on vortex shedding, it is generally assumed that loads resulting from these two phenomena occur independently. An analysis of response to gusty winds requires a description of the wind input and a transfer function which relates this input to a response. It can be seen that lifting-body payloads tend to increase the severity of gust loads. Both discrete gusts and continuous random gusts have been assumed as wind inputs; the latter form is considered to be the more realistic representation of the atmosphere. Methods for analyzing the response of launch vehicles to random unsteady winds, together with some mathematical models of ground wind spectra, are presented in references 12, 27, and 28. Additional information on the spectra of ground winds can be found in references 29 and 30; however, these measurements are in general obtained at frequencies below the fundamental cantilever frequencies of most launch vehicles. Improved fast-response anemometers are required to extend the frequency range of existing data. A recently developed fast-response anemometer is described in reference 31.

1.3 CRITERIA

Space vehicles shall be designed to withstand the structural loads resulting from exposure to the peak winds expected to be encountered while free-standing in the prelaunch condition.

The 99.9% probability-of-occurrence[1] peak winds[2] for the launch site should be considered as the design winds when space vehicles are expected to remain

[1]The probability-of-occurrence values cited here do not establish an operational risk level. Risk level is a function of exposure time, and the likelihood of encountering a given probability-of-occurrence wind value will increase as exposure time increases. Reference 32 gives data on risk levels for various exposure periods at Cape Kennedy.

[2]Peak winds are the quasi-steady winds multiplied by 1.4 to account for gusts. Windspeed data for use in the design of NASA space vehicle systems are available in reference 33.

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free-standing and unsheltered for time periods of 1 hour or longer. The 99% probability-of-occurrence peak winds should be considered as the design winds when free-standing and when unsheltered time periods are less than 1 hour.

Wind-tunnel tests of models, geometrically and dynamically similar to the full-scale vehicle, should be made to evaluate the response of the vehicle to steady winds. Analyses should be made of the effect of wind profile gradient, gusts, and turbulence on the dynamic response of the vehicle. In evaluating the vehicle response and structural loads, consideration should be given but not limited to the following:

a. Vibration modes and damping of the combined space vehicle and launcher system

b. Vehicle nose shape, protuberances, and surface roughness

c. Proximity and shape of umbilical masts and other large structures

d. Vehicle propellant loading and tank pressurization condition

1.4 RECOMMENDED PRACTICES

1.4.1 PRELIMINARY DESIGN

In the early stages of design the mass and stiffness properties and the geometric shape of the vehicle, including protuberances, will not be accurately known. As a consequence, only rough estimates of ground wind loads should be attempted. For this purpose it is recommended that the loads be estimated by multiplying the steady drag loads computed by using the peak windspeed profile by the factor 1.5. This factor represents an allowance for the dynamic response associated with vortex shedding and gusts. If steady-state drag coefficients for the particular configuration under consideration are not available in such documents as references 8 to 18, the following values are suggested: $C_D = 0.6$ for smooth circular-cylinder sections; $C_D = 0.8$ when the surface has corrugations or conduits exposed to the wind; and $C_D = 1.2$ for clustered-cylinder-type bodies.

1.4.2 REFINED DESIGN

Once the geometric and structural dynamic characteristics of the vehicle and its mounting system are defined, refined analytical procedures and wind-tunnel tests should be employed to predict vehicle response to steady winds and gusts.

1.4.2.1 Calculation of Response to Vortex Shedding

As a refinement over the factor 1.5 used in preliminary design (section 1.4.1), the aerodynamic forcing function due to vortex shedding in a steady wind should be estimated from wind-tunnel data obtained on configurations most like the one in question. Such data, in the form of nondimensional dynamic bending-moment coefficients or power spectra of integrated pressures, are

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presented in references 16 and 18. Calculations such as described in references 16 and 18 should be performed for the fundamental bending mode of the vehicle for appropriate values of structural damping, fuel weight, and tank pressurization. The possible contribution of fuel slosh to response should also be considered analytically. In order to account approximately for the design ground wind profile shape, it is recommended that the wind-tunnel data be scaled to an equivalent uniform wind speed chosen so as to produce the same steady-state base bending moment as does the design wind profile.

1.4.2.2 Wind-Tunnel Tests

Wind-tunnel tests should in general be conducted only after the final design, including location and configuration of protuberances, is established. Experience indicates that the wind-tunnel model should, insofar as possible, have the following parameters scaled:

Reynolds number, $\rho VD/\mu$

Reduced frequency, $f_n D/V$

Outside geometry, including surface roughness and shape of conduits or other external appendages

Ratio of air density to structural density, $\rho D^3/M_n$

Structural damping, ζ_n

Mode shape, ϕ_n

Umbilical tower; general shape, porosity, and location relative to the vehicle

Definition of the symbols is as follows:

ρ	air density
V	equivalent speed (see section 1.4.1)
D	maximum diameter of vehicle
μ	air viscosity
f_n	cantilever frequency for the nth mode
M_n	generalized mass in the nth mode
ζ_n	ratio of damping in nth mode to critical damping
ϕ_n	ratio of local deflection to deflection at specified station in nth mode
n	modal number

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With regard to the number of vibration modes that should be simulated by the model, it is usually necessary to consider only the fundamental mode (n = 1).

It may not be possible, with large vehicles, to match in existing wind-tunnel facilities the Reynolds number corresponding to strong wind conditions. It is usually possible, however, to test a wind-tunnel model in the same Reynolds number regime as its full-scale counterpart — that is, subcritical, supercritical, and transcritical (see Roshko, ref. 6) — and this should be done when the Reynolds number corresponding to the design wind condition cannot be achieved in the wind tunnel.

In most instances the structural damping of the full-scale vehicle will not be known at the time of the wind-tunnel tests. A range of damping values should therefore be investigated. (A damper device for varying the damping of a structure is described in ref. 12.) Sufficient wind azimuth angles should be covered to establish critical load conditions. The Mach number in the wind tunnel should not exceed 0.4 to avoid compressible-flow effects not found on the full-scale vehicle.

1.4.2.3 Gust Loads

Recommended methods of gust-load analysis, based on power-spectra techniques, are presented in references 12 and 27. In the case of very tall vehicles, consideration should be given to the correlation of gust velocities along the length of the vehicle as illustrated in reference 12. Also, horizontal wind components perpendicular to the direction of the mean wind should be included in the response calculations. A procedure for obtaining the combined response due to steady drag, vortex shedding, and turbulence is discussed in reference 34.

1.4.3 FULL-SCALE MEASUREMENTS

In view of the uncertainties that exist in the estimation of ground wind loads by presently available techniques, it is recommended that full-scale measurements be made on new vehicle configurations to establish the validity of wind-tunnel tests and analysis. These measurements should include vehicle response, such as bending moment or accelerations, and simultaneous measurements of the wind velocity at various elevations near the vehicle. In addition, the frequency and damping of the relevant vibration modes of the vehicle on its launch pad should be measured.

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