# Problems of Atmospheric Wind Inputs for Missile and Space Vehicle Design

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**Three basic types of wind inputs are discussed: 1) samples of measured profiles, 2) statistical distributions, and 3) discrete profiles. The application and interpretation of these inputs for the design of vehicle structures and control systems require "judgment" on the part of the designer. Only two wind-profile measurement techniques even approach the desired accuracy and altitude resolution: photographic/smoke trail, and FPS-16 radar/spherical balloon. Larger quantities of accurate wind-input data and considerable study will be required to obtain accurate estimates of vehicle responses due to wind inputs. A critical analysis of techniques for employment of the wind-input data and interpretation of the vehicle response is needed; and the designer and meteorologist must work as a team to solve the wind input/vehicle response problem.**

## Introduction

THE purpose of this paper is to outline the significance of wind inputs, review current high-resolution wind measuring programs, and present some results of current investigations of high-resolution wind-profile measurements. The primary areas of interest for wind inputs are the ground ($\lesssim$200 m) winds, mid-altitude ($\sim$8–15 km) winds, and high-altitude ($\sim$50–85 km) winds. This paper will be concerned with the in-flight or mid-altitude wind input problems. A brief review will be made of the over-all influence of design philosophy on wind inputs plus examples of influence from the in-flight or mid-altitude areas.

## Significance of Wind Inputs

The design philosophy adopted for a particular missile or space vehicle is determined by the intended mission(s). Obviously, there exists a difference in attitude toward design of space vehicles in contrast to military missiles.[1] The latter are subject to military mission requirements that demand a continuous operational capability, subject to some acceptable loss probability, for various locations. Space vehicles are subject to requirements for operational capabilities which are dependent upon so-called "launch windows." Therefore, the design is often stated with respect to some acceptable launch delay probability. For certain missiles and space vehicles and between certain space vehicles, i.e., man rated vs unmanned,[2] this may produce a major difference in design philosophy.

There are currently several statistical descriptions of wind inputs employed in structural and control studies. All parameters derived from statistical samples are approximate and, therefore, the size of the statistical sample is important. The lack of large quantities of reliable detailed wind-profile measurements for various locations necessitates the combining of data on wind-profile features derived from various measurement samples to produce design wind inputs. Some investigators[3] maintain that it takes at least 10 years of climatic records to provide a so-called "stable" sample. Table 1 shows how "unstable" individual wind-profile samples can be. Another statistical problem which plagues the more sophisticated statistical wind-input descriptions is the definition of the type of statistical distribution [Gaussian (normal), log-normal, etc.] which represents the wind input.

Wind inputs are basically of three types: 1) samples of measured profiles,[4] 2) statistical distributions,[5] and 3) discrete profiles. The third type is actually the so-called "synthetic" wind profiles constructed from empirical statistics to produce specific representations of the wind-profile features for given design studies.[6, 21] Each wind-input type has certain merits, and its utility in design studies depends upon a number of considerations: 1) accuracy of basic measurements, 2) tolerable complexity of input, 3) economy and practicability for design use, especially for "nonnominal" design decisions, 4) representativeness of significant features of wind profiles, statistical assumptions vs physical representativeness, 6) ability to insure control system and structural integrity with confidence, and 7) flexibility in design tradeoff studies.

The oldest and most flexible of wind inputs is the "synthetic" type. Various features of the wind profile, wind speed, shear, gusts, and maximum wind layer thickness are described. Its major weakness is difficulty in establishing, with a definable confidence, the statistical properties of the over-all vehicle response. The statistical type is more sophisticated, but certain assumptions are necessary regarding characteristic distributions and the interpretation of the resulting vehicle response. Except for the more statistically inclined design personnel, the physical interpretation of the vehicle response in terms of the statistical assumptions appears to be a significant problem. The sample-of-measured-profiles approach to wind-input definition is a more recently promoted suggestion, which results from the availability of high speed computers; its major problems are computer flexibility for design studies and representativeness of the statistical sample size for design decisions. Each method has certain merits and shortcomings; just which is best depends upon the design problem and quality (and perhaps quantity) of the wind-profile measurements used to establish the design wind inputs. All require "judgment" on the part of the designer in establishing vehicle response design parameters.

Wind shear and turbulence affect the structural design for both ground and in-flight conditions. As can be seen from

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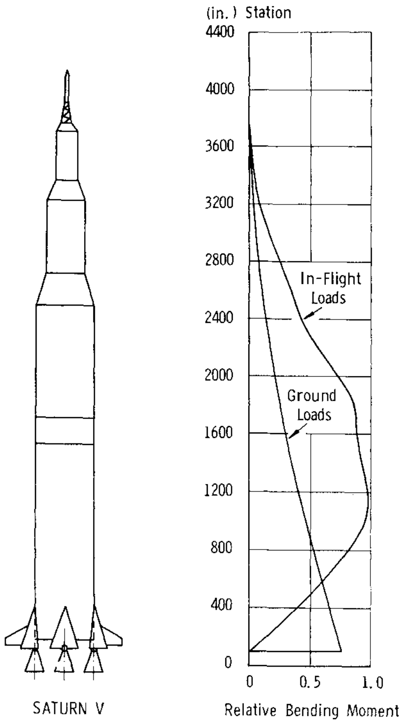


**Fig. 1 Saturn V (selected configuration) relative bending moments due to in-flight and ground wind loads as a function of vehicle station.**

Fig. 1, which illustrates relative bending moment curves, the in-flight winds establish structural requirements for most of the vehicles. The more important effects of wind upon an ascending vehicle are: 1) drift of the vehicle from a standard flight path, 2) steady and quasi-steady loads exerted upon the structure through primary aerodynamic lift forces, 3) loads exerted upon the fuselage from control deflections in response to wind inputs, 4) vibratory loads created through excitation of structural modes and sloshing resonance in the tanks, and 5) vibrator deflections of the control system in response to the latter phenomena, if there is a feed-back mode with unsatisfactory damping. The most severe of these are 2 and 3, which require the limitation of the required control and structural deflection to reasonable values in the presence of wind and wind shears. Frequently, in current analyses the wind effects (wind magnitude, wind shear, and turbulence) are considered separate phenomena for analytical purposes and, where applicable, are combined to get the total effect. Their relative contributions to the vehicle response depend upon the configuration under study, including the control system characteristics.

Figure 2 illustrates the $Q\alpha$ pitch response of a selected Saturn configuration,[7] and compares design vs measured (flight) values. The larger bar graph represents the approximate relative contributions of various design parameters to the design limit for dynamic pressure angle-of-attack product (which is proportional to the structural loading) at 60 sec range (flight) time. The smaller bar graph shows the test results. It should be emphasized that this example is for a selected configuration of the Saturn, and the relative contributions of the design parameters *may vary significantly* for other configurations and control systems.

Uncertainties in wind shears and gusts used for design calculations precludes the derivation of very accurate total responses, even for geographic locations such as Cape Kennedy where NASA recently began a program to obtain more accurate measurements. As a result, a danger exists that the vehicle may experience a total bending moment which exceeds its design capability or, alternately, that an overly conservative approach on design may be employed which restricts the vehicle's payload and operational capabilities.

The lack of significant lifting surfaces on a space vehicle results in low aerodynamic damping. In addition, low structural damping is provided by the structure for this type of vehicle. If these factors are not recognized in the basic design, a vehicle disturbed by turbulence could oscillate in a deformation mode for a relatively long period of time. Figure 3 illustrates the frequency response function where the nose deflection of a large vehicle is plotted against the input frequency of a unit amplitude sinusoidal gust.[8] The three peaks represent the response in the first three bending modes. The response at lowest mode is about 10 times that of the steady-state response (steady-state response = 1). Thus, a number of small gusts, properly spaced, can excite and create large dynamic loads, if the control system does not provide active damping.

Control systems for vertically rising vehicles must also be designed with respect to wind shear expectations in the atmosphere. The most stringent requirements[9] upon control systems result from changes in wind speeds which are large and occur relatively fast (high shear). In cases where a very stiff attitude control is exercised, the vehicle is accelerated by lift forces in the direction of the wind until it drifts with the wind. In this case, total control forces and loads depend upon transients as a function of prior history of the wind profile. If, however, the vehicle is controlled to zero angle of attack, it will accelerate against the wind, and loads will depend mainly upon wind shear. If given sufficient time, such a flight path would turn completely against the wind as with an uncontrolled stable vehicle. A combination of attitude and angle of attack may be used as input in the control system. It is difficult to generalize the reaction of a vehicle structurally to wind inputs, since it can be quite different depending upon the mode of control.[10]

An example of the effect of wind shear upon control of a large unstable vehicle configuration is given in Fig. 4. The

**Table 1 Yearly variations of high-wind speed observations, Cape Kennedy, Fla. (Maximum upper-level wind speeds as observed by Rawinsonde based on serially completed data records, two observations per day)**

| Year | No. of cases WS ≥ 50 m/sec Jan. | Feb. | March | Total no. of cases Jan., Feb., March | Max. WS (m/sec) and month of occurrence |
|---|---|---|---|---|---|
| 1956 | 39 | 13 | 31 | 83[a] | 109-March[a] |
| 1957 | 5 | 12 | 35 | 52[a] | 107-March[a] |
| 1958 | 54 | 53 | 52 | 159 | 101-Jan. |
| 1959 | 37 | 16 | 52 | 105 | 95-Jan. |
| 1960 | 28 | 42 | 46 | 116 | 91-Feb. |
| 1961 | 46 | 26 | 24 | 96 | 88-Jan. |
| Average | 35 | 27 | 40 | 102 | 99 |

[a] Note that the three-month period which had the smallest number of extreme wind speed cases contained the highest wind speeds that were measured.

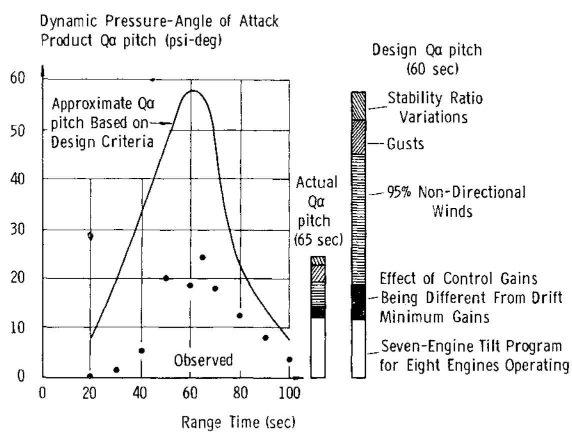


**Fig. 2 Example of relative vehicle response design contribution.**

peak control deflections are shown for various cases of wind shear. The upper two control deflections are for a drift minimum controlled vehicle with a control frequency of 0.2 and 0.4 cps. The lower two are for a vehicle with angle of attack control only. It may be seen that the presence of small-scale and large-scale wind shears are important in control system analysis and for over-all vehicle system design.

## High-Resolution Wind-Measuring Programs

It is rather well known that there are not sufficient data or knowledge of the physics of wind shear and turbulence associated with vertical wind profiles. Neither is there enough information to permit the establishment of completely reliable criteria for design of space vehicle structural or control systems. Furthermore, the sample size is not large enough to even determine seasonal or year-to-year variations of turbulence and wind shear at any given location, much less on a geographic basis. There is obviously a need for high-resolution wind-measuring programs at various launch sites. More knowledge of time and geographic variations of wind shear and turbulence, as well as a better understanding of the physical causes and interrelationships, will certainly contribute to the improvement of our design techniques. NASA, the U. S. Air Force, and the U. S. Army currently are engaged in, or have plans for, high resolution wind-profile measurements. Techniques currently employed are described below.

### FPS-16 Radar/Spherical Balloon Technique

Wind measurements are made by releasing a super-pressure, semirigid, constant-volume, radar-reflective Mylar balloon and skin tracking it with a high-precision ground-based radar.[11] Positions are obtained at 0.1 sec time intervals as the balloon rises. A statistical data reduction technique[12] has been developed for obtaining wind speeds at altitude intervals of 25 to 50 m. The rms error in wind speeds is approximately 0.8 m/sec to an altitude of about 10 km. The accuracy of wind data measured by this technique depends upon the wind-speed profile and wind direction, and the release point of the spherical balloon relative to the tracking radar. Therefore, wind data can frequently be measured with an rms error smaller than 0.5 m/sec for 50-m altitude intervals. Vertical motions are assumed to be zero in the data reduction process. There exists some question of the current spherical balloon response[13] and performance for measurement of the higher frequencies ($\lesssim$200-m wavelengths). This is being investigated by NASA in an effort to eliminate this error source either by application of an appropriate filter function or redesign[14] of the spherical balloon.

An FPS-16 radar facility for high-resolution wind-profile measurements is to be installed at the Atlantic Missile Range (through the cooperation of NASA and the Air Force Missile Test Center) by the middle of 1964. Until then, measurements will continue on a limited basis (3–5 per week) using existing facilities on a time available basis. When the new facility becomes available, one or two detailed profile measurements per day are planned, plus employment in prelaunch monitorship for go no-go decisions. In addition, special measurements will be made to study time variability of small-scale motions and special features. NASA also plans to make measurements at the Pacific Missile Range to study time variability and the influence of mountains on small-scale motions. The Air Force plans to make extensive measurements at the Eglin Gulf Test Range, and the Army is planning similar measurements at the White Sands Missile Range.

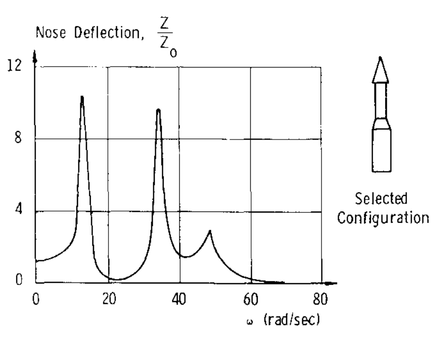


**Fig. 3 Frequency response due to sinusoidal gust.**

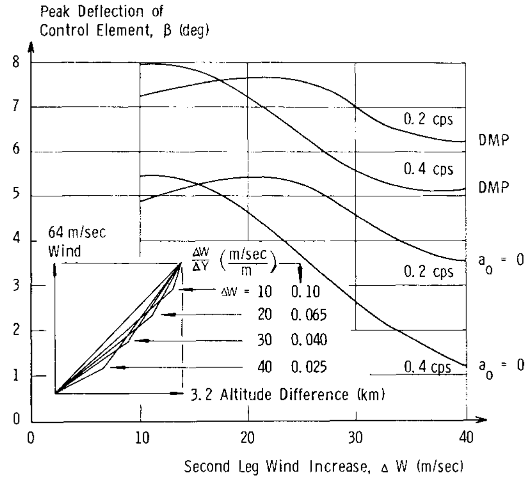


**Fig. 4 Peak values of required control deflections for unstable missile (selected configuration) in presence of strong wind increase.**

### Smoke Trail/Photographic Technique

Wind measurements can be made by establishing a vertical column of smoke (vapor) by means of a small rocket and photographing the trail at predetermined intervals of time to obtain motions of the trail.[15, 16, 20] Horizontal wind speeds are computed at 25-m altitude intervals. Currently, photographs of smoke trails are made at intervals of 5 sec. In some cases, because of the width of the trail, it is difficult to measure the exact center. For this reason it has been determined that at least a 20- to 30-sec time interval is required to obtain an rms error of 0.3 to 1.0 m/sec by this technique.

The exact accuracy of measurements by this technique is difficult to determine, due to the subjectivity in reading position coordinates from film. When the smoke trail assumes a "peculiar" configuration (e.g., if it has loops caused by a change of wind direction with altitude or by rocket motions), large errors may occur in the data reduction. Although most errors can be eliminated, there are cases where errors are difficult to detect during the data reduction process. NASA currently has modest measurement programs at Wallops Island and the Atlantic Missile Range using this technique.

### Other Methods of Measurement

Preliminary work has been done on at least two other methods employing different principles.[17, 18] One of these employs the establishment of a column of chaff by means of a small rocket and tracking the chaff with doppler radar. Experimental results from this investigation indicated that this technique was not capable of providing data with the desired altitude or spatial resolution. In the other method two sonic anemometers are attached to a balloon to measure very small-scale wind shears as the balloon rises. Error analysis results indicate that this technique will not provide the required accuracy and altitude resolution without a rather complex measuring and data reduction system. Studies on the use of doppler radar-acoustic techniques, shearsondes, radar back-scatter measurements, and LASER techniques for indirect atmospheric measurements are being done by various governmental and private organizations,[19] but no development systems have been produced which meet the requirements for high resolution wind measurement systems.

## Concluding Remarks

It is apparent that we are rapidly learning more about the detail features of wind profiles. To establish the features with confidence will take many more measurements and considerable study. These measurements will certainly permit more accurate vehicle response studies. Through these analyses the validity of our current statistical approximations may be established in terms of the risk we are assuming in the vehicle design. Areas requiring effort are: 1) expressions for wind inputs with known risks, 2) influence of integrated detailed wind profile on vehicle response, and 3) techniques for employment and interpretation of high resolution wind input statistical data in vehicle response studies. The solutions will depend upon: 1) the understanding of the designer for the physical limitation of the analytical representations of the wind inputs, 2) the understanding of the meteorologist for the physical limitations of the analytical representations of the vehicle response functions, and 3) the degree to which the two work as a team to answer missile and space vehicle design problems related to wind inputs.

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