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PROBLEMS OF ATMOSPHERIC WIND INPUTS FOR MISSILE AND SPACE VEHICLE DESIGN

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Foreword

A detailed discussion of the various aspects of the problems regarding wind inputs for missile and space vehicle design is obviously impossible in the available time for this presentation. We will, however, endeavor to discuss the subject with the hope that design personnel and meteorologists will acquire a better understanding of the complexities of this problem. Since we are associated mainly with the measurement, description, and presentation of wind data for design studies, the paper will be concerned primarily with this aspect of the wind input/vehicle response problem. The contributions on significance and examples of wind inputs to vehicle response are the result of numerous discussions and assistance provided by design personnel of the Marshall Space Flight Center. To these colleagues, and in particular to Dr. E. D. Geissler, we are indeed grateful. Also, we wish to acknowledge and thank Mr. Richard Allison, Chairman of the session, "Problems of Missile and Supersonic Flight in the Troposphere and Lower Stratosphere," for his invitation to present this paper.

I. Introduction

Wind input problems associated with the development of missiles and space vehicles result from the difficulties involved in measuring wind profile features with sufficient accuracy, establishing adequate wind design criteria, and integration of the criteria into the design to produce a required capability of the structural and control system. 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 regarding turbulence.

The primary areas of interest for wind inputs are the ground ($\lesssim$ 200 m) winds, mid-altitude (~ 8 to 15 km) winds, and high altitude (~ 50 to 85 km) winds. This paper will be concerned with the inflight or mid-altitude wind input problems. A brief review will be made of the overall influence of design philosophy on wind inputs plus examples of influence from the inflight or mid-altitude areas.

The concern regarding wind inputs to establish structural and control system designs is not new. The problem was present when the first experimental rocket was built. It has, however, become more complex as we have developed more sophisticated missile and space vehicles. In addition, where earlier designs were worked out using desk calculators and slide rules, we now employ high speed electronic computers which enable us to study in greater depth, and detail the features in design which previously were impossible.

There appears to be no one or simple solution to the wind input problem. In part, this is because there are no simple solutions to missile or space vehicle response and design problems. Also, wind input definitions depend upon accurate measurements, the statistical validity of the measurement samples, the representativeness of the statistical approximation of the wind inputs as employed in the design, and the design philosophy for a particular missile or space vehicle system.

II. Significance of Wind Inputs

A. Design Philosophy

The design philosophy adopted by the responsible organization for development of 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 versus unmanned[2], this may produce a major difference in design philosophy.

B. Types of Wind Inputs

There are currently several statistical descriptions of wind inputs employed in structural and control studies. All parameters derived from statistical samples are approximates and, therefore, the size of the statistical sample is important; generally, the larger the sample, the better the approximation. For example, some investigators maintain that it takes at least 10 years of wind profile records to provide a so-called "stable" sample. Figure 1 contains an interesting example of how "unstable" are individual wind profile samples. Another statistical problem which contributes to the cause for the variety of inputs involves defining the type of statistical distribution, i.e., Gaussian (normal), log-normal, etc., which represents the wind input. This problem, in particular, plagues the more sophisticated statistical wind input descriptions. Finally, the lack of large quantities of reliable detail 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.

Wind inputs are basically of three types: (1) Sample of measured profiles, (2) statistical distributions, and (3) discrete profiles. The first, consist of employing a specified number of individually measured wind profiles.[3] The second, involves the presentation and use of wind input statistics based on statistical models.[4] The third type is actually the so-called "synthetic" wind profiles constructed from empirical statistics

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to produce specific representations of the wind profile feature for given design studies.[5] Each wind input type has certain merits and the utility in design studies depends upon a number of considerations. Some of these are: (1) Accuracy of basic measurements, (2) tolerable complexity of input, (3) economy and practicability for design use, (4) representativeness of significant features of wind profiles, (5) statistical assumptions versus physical representativeness, (6) ability to insure control system and structural integrity with confidence, and (7) flexibility in design trade-off studies.

The oldest and most flexible of wind inputs involves the "synthetic" type. Here, various features of the wind profile, i.e., wind speed, shear, gusts, maximum wind layer thickness, etc., are described. Its major weakness is difficulty in establishing, with a definable confidence, the statistical properties of the overall vehicle response. The statistical distributions might be considered the more sophisticated type of wind input models. Certain assumptions are necessary regarding wind distribution types and the interpretation of the resulting vehicle response. Except for the more statistically inclined design personnel, the physical interpretation of the vehicle response for this type input in terms of the statistical assumptions, appears to be a significant problem. The sample of measured profiles approach for wind input definition is one of the more recently promoted suggestions and results from the general availability of high speed computers. Its major problem is computer time and flexibility for design studies, plus the problem of representativeness of the statistical sample size for design decisions.

In closing the remarks on types of wind inputs, it is evident that each method has certain merits as well as shortcomings. Just which is best depends, it seems, upon the design problem and quality (and perhaps quantity) of the wind profile measurements used to establish the design wind inputs. All require "judgement" on the part of the designer in establishing vehicle response design parameters.

C. Examples of Wind Input Influence on Design

Wind shear and turbulence affect the structural design for both ground and inflight conditions. As can be seen from Figure 2, which illustrates relative bending moment curves, the inflight winds establish structural requirements for most of the vehicles. A summary of the more important effects of wind upon an ascending vehicle is primarily: (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 control system in response to the phenomena under Item No. 4, if there is a feed-back mode with unsatisfactory damping. The most severe of these are Items 2 and 3, the limitation of the required control and structural deflection to reasonable values in the presence of wind and wind shears.

The parameters which contribute most significantly to the total structural requirements are the aerodynamic loadings due to dynamic pressure, angle-of-attack from causes other than wind (these are very small for most vehicles), etc., turbulence (gust), wind shear and the steady state wind magnitude. Frequently in current analyses the wind effects (wind magnitude, wind shear, and turbulence) are considered separate phenomena for analytical purposes and are combined, where applicable, to get the total effect. Their relative contributions to the vehicle response depend upon the configuration under study including the control system characteristics.

As a brief illustration on the response of a space vehicle or missile, Figure 3 shows the design versus an example of a specific flight test measurement for a selected SATURN configuration.[6] The larger bar graph represents the approximate relative contributions of various design parameters to the design limit for dynamic pressure-angle-of-attack product at 60 seconds range (flight) time. This product is proportional to the structural loading. The actual test results produced the relative contributions in the smaller bar graph. The solid line represents the design as a function of flight time, and the dots represent the actual observed values. It is emphasized that this example is for a selected configuration of the SATURN and the relative contributions of the design parameters, etc., may vary significantly for another configuration, control system, or a different space vehicle.

Uncertainty in the knowledge of wind shear and gusts used for design calculations precludes the derivation of very accurate total responses attributable to these features even for geographic locations such as Cape Canaveral, where we 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, an overly conservative approach on design is 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 results from the structure which is required for this type vehicle. Due to these factors, unless recognized in the basic design, a vehicle disturbed by turbulence could oscillate in a deformation mode for a relatively long period of time. Figure 4 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.[7] The three peaks represent the response in the first three bending modes. Note 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, if properly spaced, can excite and create large dynamic loads, unless the control system provides 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[8] 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.[9]

An example of the effect wind shear has upon control is given in Figure 5 for a large unstable vehicle configuration. The 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 overall vehicle system design.

III. Discussions Of High Resolution Wind Measuring Programs

It is rather well known that there is 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. From a space vehicle design viewpoint there is, obviously, a need for observational programs of the high resolution wind profile structure measurements at the various launch sites. This would then permit more reliable and accurate information with which to establish the design requirements for the complex vehicle structural and control systems. From a military missile viewpoint, there are numerous potential launching sites throughout the world for which design information and operating limits should be established. Unfortunately, current information of wind shear and wind profile turbulence produces design data whose accuracy and statistical validity are difficult to establish in a quantitative manner.

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. It is believed that these programs will contribute considerably to our understanding of wind inputs. Techniques currently employed are described below:

1. 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.[10] Positions of the spherical balloon are obtained at 0.1-second time intervals as the balloon rises. A statistical data reduction technique[11] has been developed for obtaining wind speeds at altitude intervals of 25 or 50 meters.

The RMS error in wind speeds was determined to be 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 meter altitude intervals. Vertical motions are assumed to be zero in the data reduction process. There still exist some question of balloon response and performance for measurement of the higher frequency ($\lesssim$ 75 m wavelengths). This is being currently studied by NASA and Air Force personnel.

An FPS-16 Radar facility for high resolution wind profile measurements has been programmed for and is to be installed at the Atlantic Missile Range. Through the cooperation of NASA and the Air Force Missile Test Center this facility is scheduled to be operational by the middle of 1964. Until then, measurements will continue on a limited basis (3 to 5 per week) using existing facilities on a time available basis. When the new facility becomes available, one or two detailed profile measurements are planned on a daily basis, 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. Plans are also being made by NASA to make measurements at the Pacific Missile Range to study time variability and the influence of mountains on small-scale motions. The Air Force is currently making extensive measurements at the Eglin Gulf Test Range, and the Army is planning similar measurements at the White Sands Missile Range.

2. Smoke Trail/Photographic Technique

Wind measurements are 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.[12,13] Currently, photographs of smoke trails are made at intervals of five seconds. 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-second time interval is required to obtain accurate wind data from this technique. Horizontal wind speeds are computed at 25-meter altitude intervals.

There exist some subjectivity in reading position coordinated from film and, therefore, the exact accuracy of wind data measured by this technique is difficult to determine. It is estimated, however, that 20- to 30-second average wind speeds measured by this method have an RMS error between 0.3 and 1.0 m/sec. It should be pointed out that limitations do exist at present in the smoke trail data reduction process. When the smoke trail assumes a "peculiar" configuration, large errors may occur in the data reduction. Peculiar configurations refer, for example, to loops which appear on the profile that are caused by a change of wind direction with altitude or from rocket motions. 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.

3. Other Methods of Measurement

The only two operational methods for measuring detailed wind profiles are the FPS-16 radar/spherical balloon and the smoke trail/photographic methods described above. Preliminary work has been done on at least two other methods employing different principles.[14,15] One of these employs the idea of establishing a column of chaff by means of a small rocket and tracking the chaff with doppler radar to obtain wind data. Experimental results from this investigation indicated that this technique was not capable of providing data with the desired altitude or spatial resolution. The other method employs the idea of attaching two sonic anemometers to a balloon and measuring very small-scale wind shears as the balloon rises. Preliminary error analysis results also indicate that this technique will not be able to provide the required accuracy and altitude resolution data without a rather complex measuring and data reductioı system.

Studies on doppler radar-acoustic techniques, radar back-scatter measurements, laser techniques, etc., for possible use as indirect atmospheric measurement devices are being accomplished by various governmental and private organizations.[16] Although promising, no development systems have been produced which meet the requirements for high resolution wind measurement systems.

IV. Comments and Concluding Remarks

At this time, it is difficult to determine how much effect high resolution wind profile measurements may have on resolving the problems of wind input definitions. 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.[19] These measurements will certainly enable more accurate vehicle response studies to be performed. Through these analyses the extent of our current statistical approximations may be established in terms of the risk we are assuming in the vehicle design. Future problems concerning: (1) Expressions for wind inputs with known risks, (2) influence of integrated detail wind profile on vehicle response, and (3) techniques for employment and interpretation of high resolution wind input statistical data in vehicle response studies, and other problems are certainly evident. The solutions will be a function of the understanding of: (1) The designer for the physical limitation of the analytical representations of the wind inputs, (2) 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 which involve atmosphere wind inputs.

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Maximum Upper-Level Wind Speeds as Observed by Rawinsonde
(Based on Serially Completed Data Records)

Year	No. of Cases WS ≥ 50.0 m/sec			Total No. of Cases	Max. WS (m/sec) and Month of Occurrence
	January	February	March	(J, F, M)	
1956	39	13	31	83*	109-M*
1957	5	12	35	52*	107-M*
1958	54	53	52	159	101-J
1959	37	16	52	105	95-J
1960	28	42	46	116	91-F
1961	46	26	24	96	88-F
Average	35	27	40	102	99

*NOTE: It is interesting to note that the three month period which totaled the least number of extreme wind speed cases contained the highest wind speeds that were measured.

Figure 1. Yearly Variations of High Wind Speed Observations, Cape Canaveral, Florida

SCOGGIN-5

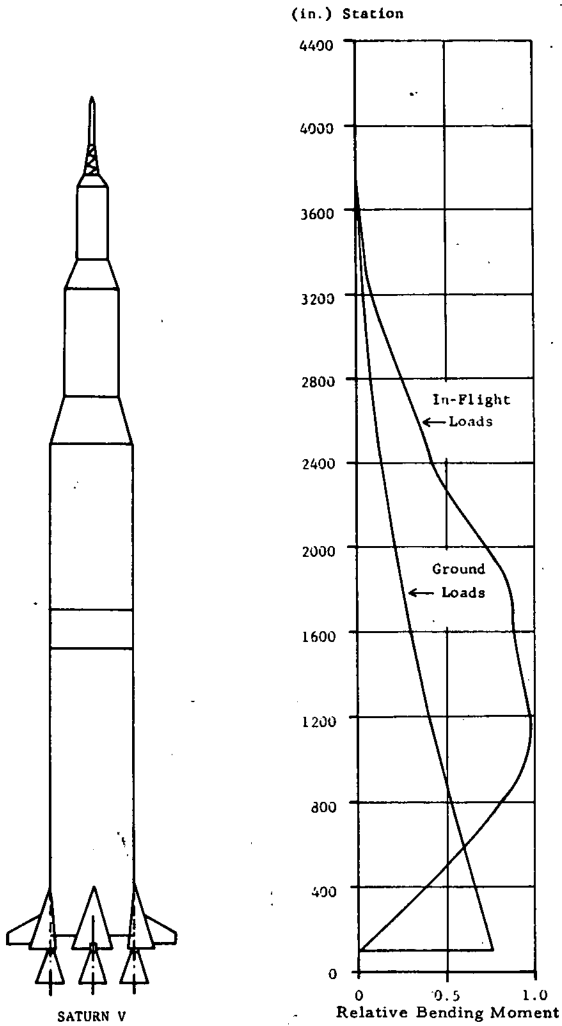

Figure 2. SATURN V (Selected Configuration) Relative Bending Moments Due to In-Flight and Ground Wind Loads as Function of Vehicle Station.

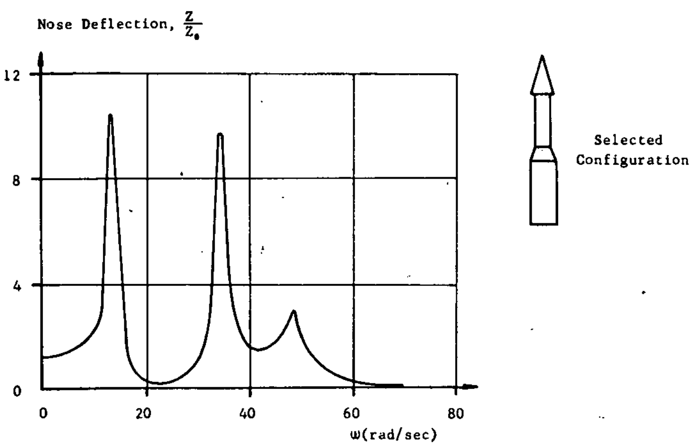

Figure 4. Frequency Response Due to Sinusoidal Gust

SCOGGW-6

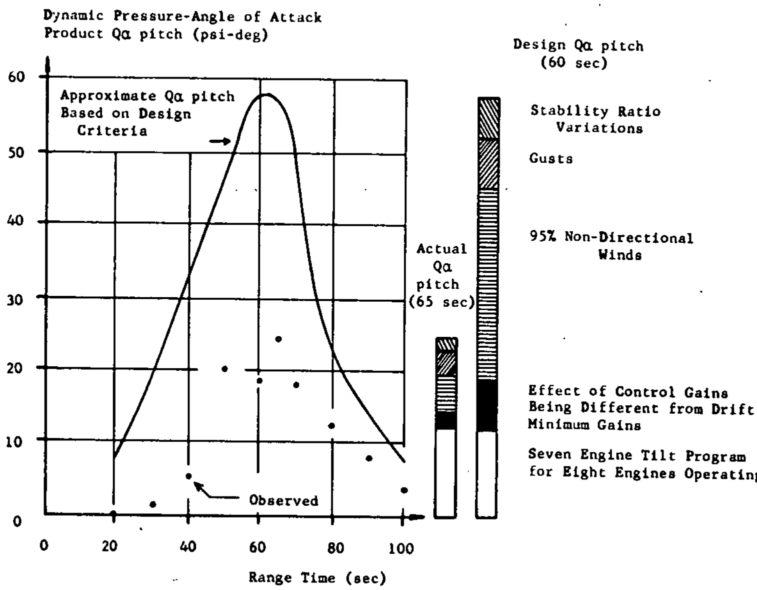

Figure 3. Example of Relative Vehicle Response Design Contribution

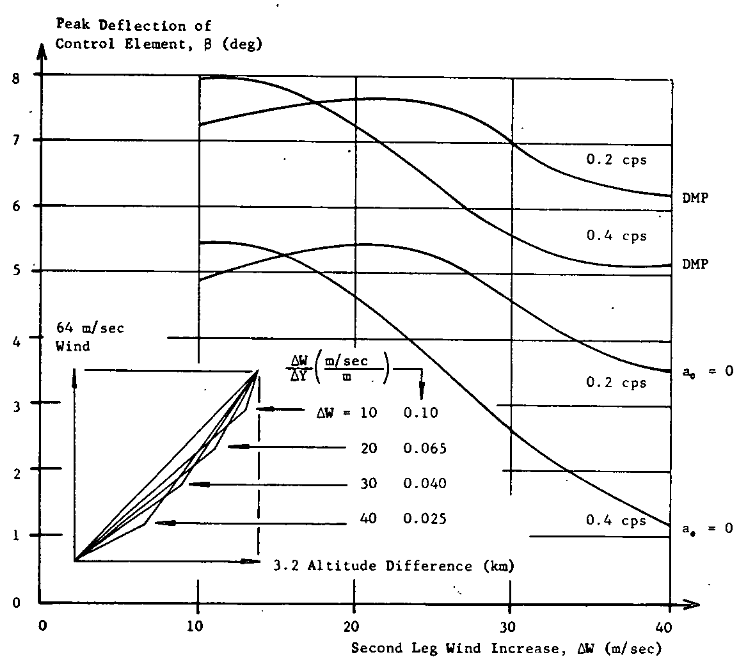

Figure 5. Peak Values of Required Control Deflections for Unstable Missile (Selected Configuration) in Presence of Strong Wind Increase