Space Shuttle Response to Ascent Wind Profiles

Orvel E. Smith*

NASA George C. Marshall Space Flight Center, Huntsville, Alabama

and

Lambert D. Austin Jr.†

NASA Lyndon B. Johnson Space Center, Houston, Texas

A parametric sensitivity analysis of the Space Shuttle ascent flight to the wind profile is presented. Engineering systems parameters are obtained by flight simulations using wind profile models and samples of detailed (jimsphere) wind profile measurements. The wind models used are the synthetic vector wind model, with and without the design gust, and a model of the vector wind change with respect to time. From these comparison analyses an insight is gained on the contribution of winds to ascent subsystems flight parameters and preflight launch-commit criteria.

Nomenclature

ET	= external tank
FPR	= flight performance reserves (propellant required to protect for in-flight dispersions)
H_0	= reference height for SVWP
h	= altitude of vehicle
Ma	= Mach number
MECO	= main engine cutoff
N_z, N_y	= vehicle axial accelerations
p, q, r	= vehicle roll, pitch, yaw rates
Q	= aerodynamic heat load indicator
$\dot{Q}$	= aerodynamic heat rate
q_∞	= dynamic pressure
SRB	= solid rocket booster(s)
SD	= standard deviation, a sample statistical parameter
SSV	= Space Shuttle vehicle
SSWP	= synthetic scalar wind profile
STS-1	= Space Transportation System (flight 1)
SVWP	= synthetic vector wind profile
u	= zonal wind component (positive west to east)
V	= vehicle relative velocity
v	= meridional wind component (positive to north)
w	= wind speed (scalar wind) or modulus of wind
α	= angle of attack
β	= angle of sideslip
αq_∞	= aerodynamic load indicator in pitch plane
βq_∞	= aerodynamic load indicator in yaw plane

u, v, w are defined in the standard meteorological coordinate system.

I. Background

ALTHOUGH the synthetic scalar wind profile (SSWP) model[1] has been used for aerospace vehicle design over the past 25 years, it was found to be inadequate for the Space Shuttle. This is because of the program requirements for a versatile Space Transportation System (STS) and the complexity of the Space Shuttle configuration, which has four main bodies, the external tank, two solid rocket boosters, and

the Orbiter. Some subsystems of the Space Shuttle vehicle (SSV) are more sensitive to ascent wind loads in the yaw plane than in the pitch plane. To reduce the requirements for ascent wind loads, a load alleviation technique is used for the SSV. This is done by shaping the ascent trajectory (wind biasing) to the profile of monthly mean wind components (vector mean wind) in the pitch and yaw planes. The flight control system is programmed to perform the wind load relief function through the altitude region of maximum dynamic pressure. The concern is now that of determining the contribution of wind dispersions with respect to the monthly vector mean wind to structural loads and performance parameters. Reference design missions were established for STS flights from Kennedy Space Center (KSC) and the Vandenberg AFB. The new wind profile model developed in this paper was required to permit the statistical treatment of wind as a vector quantity on a monthly basis for the two sites.

II. Winds for Aerospace Vehicle Flight

This section treats the following topics: 1) the development of the synthetic vector wind profile (SVWP) model, 2) the time conditional change in wind vectors which is used to construct the time conditional SVWP model, and 3) statistical data samples of detailed wind profiles as measured by the jimsphere system. The limitations of wind models and the recognition for improvements in gust modeling are discussed.

A. Synthetic Vector Wind Profile Model

The details of the SVWP model with several options treated by Smith[2] are lengthy; hence, only the fundamental principles of these models can be presented in this paper. The SVWP model uses the properties of the quadravariate normal probability distribution function. The 14 statistical parameters required to define this probability distribution function are estimated from long periods (11 years) of steady-state rawinsonde wind records for Cape Canaveral and Vandenberg AFB. These 14 sample statistics relate wind vectors at one altitude to those at another altitude through the quadravariate normal probability distribution. Because aerospace vehicle designers have historically been concerned with wind shear, the tabulations of the 14 parameters have been made in terms of the zonal and meridional wind components and the differences of the zonal and meridional wind components between two altitudes. The paired differences are repeated for all altitudes at 1-km intervals from 0 to 27 km. These 14 statistical parameters for wind vectors and vector wind shears have been tabulated by monthly reference periods for Cape Canaveral and Vandenberg AFB. The conventional statistical tabulations would be the complete variance-

covariance matrix of these wind components as pairs over all altitudes. The end results for the SVWP model are the same because the sum and differences of normally distributed variates are normally distributed. Using the five component winds statistical parameters at a reference height, H_0, the practice is to compute the 95% probability ellipse. This ellipse contains 95% of the wind vectors at the reference height. Wind vectors on the 95% ellipse at the reference height are selected. The conditional distribution of vector wind shears is computed over successive altitudes for the given wind vector at H_0. In general functional notation, the conditional distribution is:

$$f(x_1,x_2 \mid x_3,x_4) = \frac{f(x_1,x_2,x_3,x_4)}{f(x_3,x_4)}$$

where x_1, x_2, x_3, and x_4 are quadravariate normally distributed variates. Here x_3 and x_4 are the components of the given wind at H_0, and x_1 and x_2 are the components of the wind shear. The joint conditional probability for wind shears is bivariate normally distributed. These conditional distributions are made bivariate circular normal to simplify the modeling. The locus of the envelope of conditional shear circles vs altitude in-plane with the given wind vector gives the largest shears. These conditional shears are subtracted from the given wind vector. The resulting locus gives one of several options for the SVWP model. Hence, the SVWP is formed as the distribution of wind shears which varies with the given wind vector at a reference height, altitude, month, and launch site. Because this model is based on the properties of the multivariate normal distribution, it can be made completely general for any probability level. By convention, the 99% conditional shears are used in the SVWP. The classical 9 m/s^2 gust[1] is reduced by a factor of 0.85 when used with the SVWP.

A statistical analysis of the SVWP for the design reference missions reveals that the February SVWP for Cape Canaveral and December SVWP for Vandenberg AFB would establish the range for design requirements. The design objective is to have not more than a 5% chance of launch delay due to ascent winds in any month for the design reference missions.

To illustrate the principles of the SVWP, an example for the December winds at Vandenberg AFB is given. The reference height H_0 is 10 km (Fig. 1); the given wind vector has the direction from 330 deg with a magnitude of 57.8 m/s which intercepts the 95% vector wind ellipse. This wind vector represents a right-to-left quartering wind for a mission flight azimuth of 195 deg. (The flight azimuth is measured in degrees clockwise from true north.) The 99% conditional shear circles are computed for all altitudes for the given wind vector. A scale plot of the conditional shear circles subtracted from the given wind vector (Fig. 2) infers that 99% of the wind vectors are contained in these circles given the wind vector at 10 km is from 330 deg with a magnitude of 58 m/s. The locus of the conditional circles in-plane with 330 deg is called the SVWP. It is represented by the continuous line in Fig. 2. The dashed line in Fig. 2 that passes through the center of the circles is the conditional mean vector. Another illustration of this example is shown as Fig. 3. In Fig. 3 the curve labeled 1 is the SVWP, and the curve labeled W_E is the expected value (mean) of the conditional wind vectors. The curve labeled 2 has two branches: they are the two intercepts of the 330-150 deg plane with the 95% wind vector ellipses vs altitude. The curve labeled W_A is also a SVWP, but because it lies outside the envelope of the 95% ellipses it has not been adopted for use in the Space Shuttle program. Selections of several wind vectors at the reference height are used in the construction of SVWP, and several reference heights in the altitude region where the vehicle is most sensitive to winds are applied in the analysis. The vehicle system analysis may be made using the SVWP with or without gust.
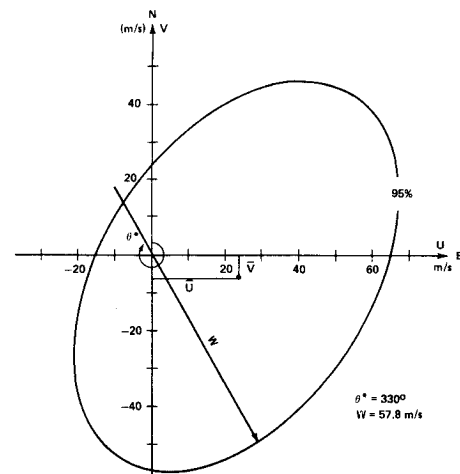

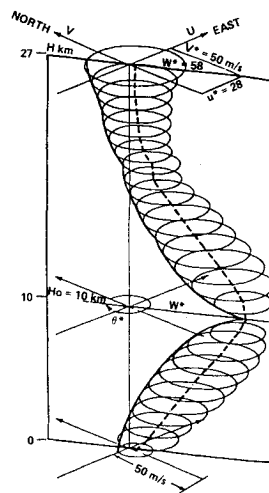Fig. 1 A 95% vector wind ellipse 10-km altitude, December, Vandenberg AFB.

Fig. 2 Conditional bivariate normal vector wind given the wind vector at H_0 is 330 deg at 58 m/s, Vandenberg AFB, December.

B. Temporal Vector Wind Change and Time Conditional SVWP

For the launch operation of the Space Shuttle it has been proposed by Moote[3] to wind bias to the day-of-launch measured wind profile to further reduce the contribution of winds to the structural loads and performance requirements. To support such a procedure, a knowledge of not only the temporal variability of the wind is required, but also how much the ascent wind loads and performance parameters will vary with time. There is a requirement to make some allowance for wind loads and performance variation with respect to time during the countdown for key prelaunch operational decisions and also from the last time it is operationally feasible to perform a prelaunch flight simulation using a measured wind profile.

The statistical variation of winds with respect to time at discrete altitudes has been modeled using the properties of the quadravariate normal probability distribution. The 14 statistical parameters for this distribution have been tabulated[4] for each month at 1-km altitude intervals from 0 to 27 km for Cape Canaveral. The time conditional distribution of wind vectors for 12-h change of time for a given wind vector is illustrated by the small ellipses in Fig. 4 for five selected wind vectors. The given wind vectors I-IV are selected to be on the 95% April probability ellipse. The given wind vector labeled V is selected to coincide with the monthly vector mean wind. Note that all of the conditional ellipses (small ellipses) have the same size and orientation. The centroid of the small ellipses is the conditional mean. The size of the conditional ellipse decreases with decreasing time. The
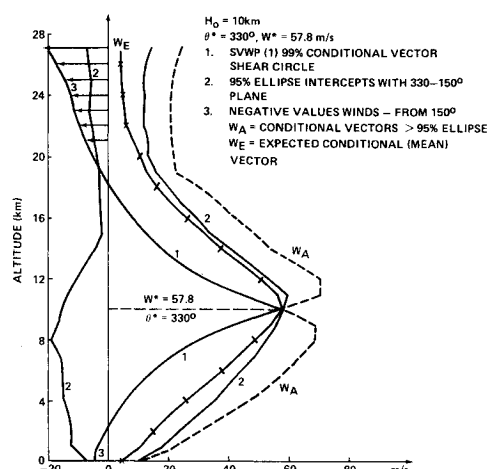
Fig. 3 Synthetic vector wind profile for given wind vector at 10 km, Vandenberg AFB, December.
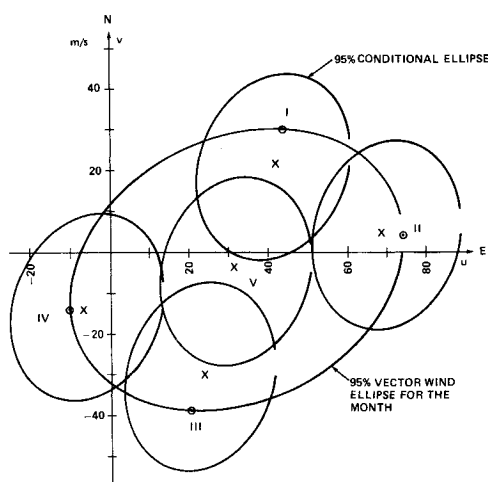

Fig. 4 The 12-h time conditional wind vectors for five given wind vectors, 12-km altitude, April, Cape Canaveral.

size of the 95% conditional ellipses approaches that of the monthly 95% ellipse as the time interval increases. Selected values on the 95% time conditional ellipses are used as given values at a reference height, and the SVWP is constructed as described in the previous section. In Sec. III performance parameters resulting from the time conditional SVWP and a sample of sequential wind profiles are compared.

C. Samples of Jimsphere Wind Profiles

It was recognized early in the Space Shuttle program that all wind models have limitations. This is particularly true in depicting the structure of the wind profile as it occurs in nature. Detailed high-resolution wind profiles as measured by the jimsphere system show many gust, shear, and wave-type oscillations that are not understood and hence are not subject to detailed modeling, nor are they predictable for aerospace vehicle launch operations. For these reasons a sample of 150 jimsphere wind[5] profile measurements for each month was made available for Cape Canaveral for the Space Shuttle ascent design verification. These samples are also used for wind load performance assessments for the scheduled launch month of the Shuttle.

To determine the wind loads and performance changes with respect to time for the purposes given in the previous section, a limited sample of sequential jimsphere wind profile measurements is available for Cape Canaveral. These measurements are approximately 3-h intervals. For Vandenberg AFB the available sequential data sample of jimsphere wind profiles is even more limited.

D. Wind Gust Model

The 150 jimsphere wind profiles have been used in the development of an improved gust model. A new concept of a vector wind gust model is reported by Smith and Adelfang[6] in which the gust amplitude and gust lengths for wind components are modeled using a bivariate gamma probability distribution function. The wind gust varies with the defining filter function, with altitude, and with season. The goal is to replace the 9 m/s design scalar wind gust which is invariant with altitude and season, by this new gust model for ascent flight performance and load assessments that are done on a monthly basis.

III. Ascent Systems Analysis

In this section statistical comparisons are presented for the SSV performance parameters and ascent wind load indicators as derived from flight simulations using the SVWP model and a sample of 150 jimsphere wind profile measurements. Also presented is a comparison of performance statistics derived from a time conditional SVWP and a sample of sequential jimsphere wind profiles. These comparisons are illustrated from analyses for the STS-1 ascent flight using April wind models and samples of jimsphere wind measurements for Cape Canaveral. These comparisons are summarized from more complete analyses (such as Austin[7]) to identify the contribution of winds to the ascent subsystem flight parameters.

Table 1 provides a descriptive summary of the STS-1 ascent flight profile for reference purposes. It is important to note that ascent winds during 30-85 s of flight time (9-60 kft altitude) not only make significant contributions to the vehicle parameter variations in this flight period but also contribute to variations in the SRB staging conditions, aerodynamic heating, and flight performance reserves which occur later in flight.

A. Performance Parameters

The wind profile makes a significant contribution to the ascent flight performance parameters (Tables 2 and 3). The column heading "nominal ascent" in the tables gives the performance requirements for STS-1 wind biased to the April mean wind, and the last column is the dispersion of these parameters from all sources (i.e., the vehicle systems uncertainties combined with the wind contribution). The extreme range of performance parameters due to the wind profile as derived from the 95% SVWP with 99% conditional shears and gusts reduced by the 0.85 factor and the sample of 150 April wind profiles (Tables 2 and 3) not only illustrate the contribution of the wind profile to performance variation, but also show good agreement between the two methods. These performance parameters vary with the launch month due to different characteristics of the wind profile. Comparisons of flight parameters using the SVWP and the sample of 150 jimsphere profiles for September and December have resulted in equally good agreement.

Another factor of significance with respect to these parameter variations is their reflection of the integrated effects of the wind profile during ascent. These integrated effects are representative of the steady-state nature of the wind profile and, therefore, can be alleviated through the implementation of wind biasing techniques such as those discussed by Moote[3] for day-of-launch operations. While the vehicle dynamic response as sensed by the angle of attack α and sideslip β excursions are somewhat alleviated by the use of a load relief scheme in the ascent flight control system (N_z and N_y feedback), the vehicle system response characteristics are such that large α and β dispersions still occur as a result of in-flight wind shears and gusts. Unfortunately, these wind characteristics are random and not predictable by deterministic methods and, therefore, are not amenable to wind biasing techniques.

Table 1 STS-1 ascent flight profile

Time, s	Altitude kft	Altitude km	Mach No.	Description
0	0	0	0	SRB ignition and liftoff
0-7	0.4	0.012	0.1	Vertical rise
7-22	5	1.52	0.1-0.4	Tilt maneuver and roll to flight azimuth of 60 deg
30-85	9-60	2.74-18.29	0.6-2.5	Peak wind environment: maximum dynamic pressure and aerodynamic loads region
90-160	80-240	24.39-73.17	2.5-5.0	Maximum aerodynamic heating
120-130	159-170	48.48-51.83	3.7-4.0	SRB tailoff and staging
130-510	–	–	–	Optimum guidance to maximize performance at selected MECO targets

Table 2 STS-1 performance parameter variations for April winds

Parameter	Nominal[a] ascent	Extreme range from SVWP with gust[b]	Extreme range from 150 April jimsphere	All dispersion sources
FPR, lb	13,465	+ 1750	+ 1215	− 8700
max q_∞, psf	575.9	− 3080	− 3145	
		+ 81	+ 77	+ 140
		− 36	− 46	
max $\dot{Q}$, Btu/ft^2/s	2.0	± 0.5	± 0.4	+ 1.1
Q SRB staging, Btu/ft^2	84.5	± 20	± 15	+ 45

[a] Nominal trajectory wind biased to April mean wind.
[b] SVWP—Synthetic vector wind profile.

Table 3 STS-1 SRB staging parameter variations for April winds

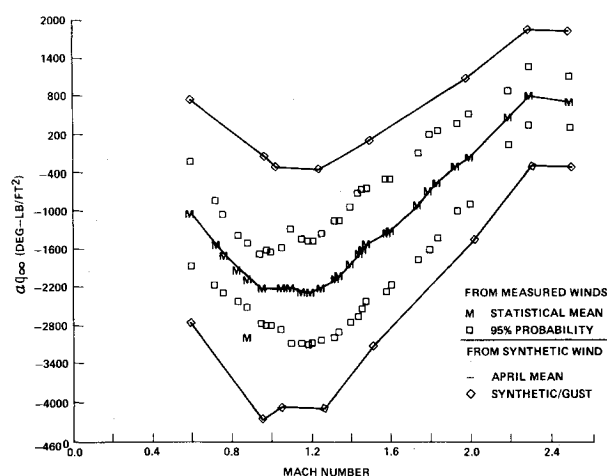| Parameter	Nominal[a] ascent	Extreme range from SVWP with gust[b]	Extreme range from 150 April jimsphere	All dispersion sources
q_∞, psf	16.4	± 4	± 1.4	± 15
α, deg	0.62	± 3	± 1.5	± 15
β, deg	− 0.41	± 3	± 1.5	± 15
h, ft	167,266	± 7000	± 7000	± 17,000
V, ft/s	4195	± 90	± 100	± 200
p,q,r, deg/s	− 0.6, − 0.1, − 0.16	± 0.20	± 0.25	± 5, ± 2, ± 2

[a] Nominal trajectory wind biased to April mean wind.
[b] SVWP – synthetic vector wind profile.

Fig. 5 STS-1 wind load indicators in pitch plane from April winds, Cape Canaveral.

Fig. 6 STS-1 wind load indicators in yaw plane from April winds, Cape Canaveral.

B. Ascent Wind Load Indicators

Aerodynamic load indicators are the product of angle of attack α and dynamic pressure q_∞ and of sideslip angle β times dynamic pressure. For the purposes of trajectory design and mission assessments, these indicators have been found to be reliable representatives of the wind effects on the SSV
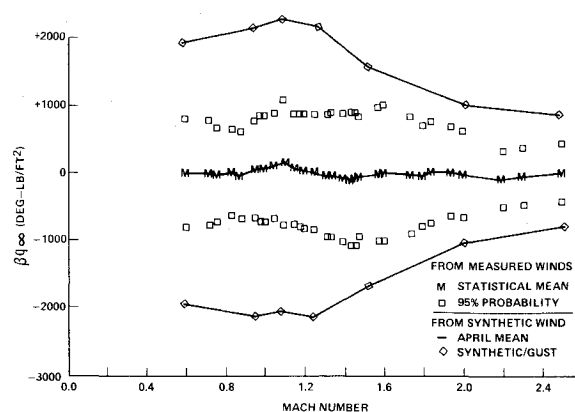
structural loading in the maximum dynamic pressure flight regime. The load indicators, αq_∞ and βq_∞, for specific Mach numbers (Figs. 5 and 6) have been derived using the April 95% SVWP with and without the 9 m/s design gust. The solid line in these figures is the result from the April mean wind. The statistical mean values (denoted by the letter "M") obtained from 150 flight simulations using the April jimsphere measured winds for Cape Canaveral are identical to

Table 4 STS-1 temporal performance dispersions for April winds

Parameter	3 standard deviations systems dispersions	Monthly dispersion from 95% SVWP[a]	3 standard deviations changes vs time			From time conditional SVWP[a]
			From sequential jimsphere winds			
			$\Delta t = 3$ h	$\Delta t = 6$ h	$\Delta t = 9$ h	$\Delta t = 24$ h
FPR, lb	6500	1870	335	500	924	1440
max q_∞, psf	59	75	13.5	22.5	33	56
q_∞, SRB staging, psf	10	4	1	2	3	3
max $\dot{Q}$, Btu/ft²/s	0.7	0.4	0.2	0.2	0.3	0.3
Q SRB staging, Btu/ft²	30	15	6	8	12	12

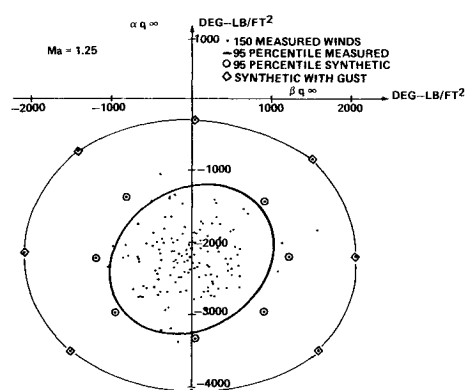[a] SVWP—synthetic vector wind profile without gust.

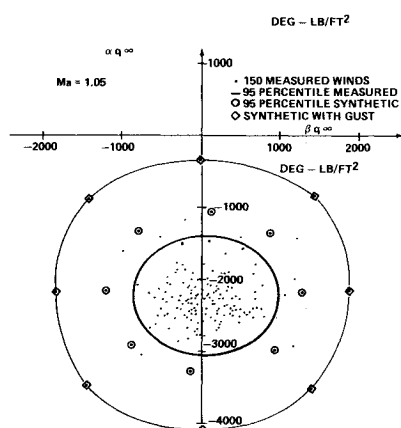Fig. 7 STS-1 pitch and yaw load indicators $Ma = 1.05$ from April winds, Cape Canaveral.

Fig. 8 STS-1 pitch and yaw load indicators $Ma = 1.25$ from April winds, Cape Canaveral.
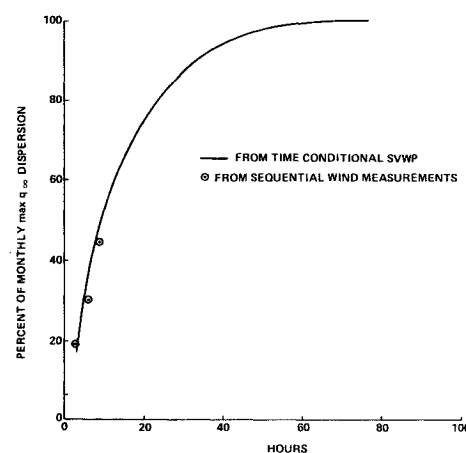

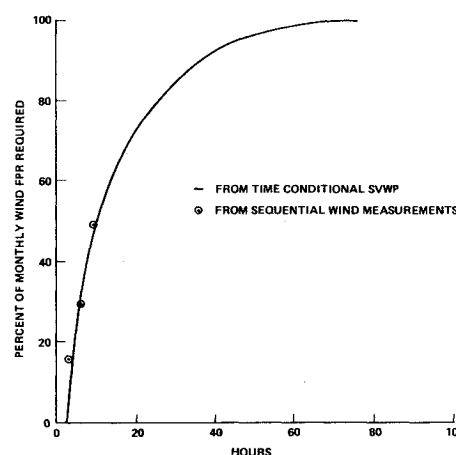Fig. 9 STS-1 three standard deviation change in max q_∞ relative to monthly dispersion, April winds, Cape Canaveral.

Fig. 10 STS-1 three standard deviation change in FPR relative to monthly dispersion, April winds, Cape Canaveral.

those derived from the monthly mean wind. Also shown in Figs. 5 and 6 is the 95% dispersion with respect to the sample mean for the jimsphere data sample. The large differences between these load indicators for the 95% sample estimates and those derived from the 95% SVWP model are attributed to the differences in the two methods. The 9 m/s design gust is applied at each Mach number for the SVWP, whereas the data samples of jimsphere wind profiles have gust amplitudes less than 9 m/s for gust lengths less than 300 m.

The joint relationship between αq_∞ and βq_∞ serves as an important load indicator for the SSV subsystems analysis. Comparisons of the joint relationships for these load indicators for Mach numbers of 1.05 and 1.25 are shown in Figs. 7 and 8, respectively. In these figures the dots represent the 150 pairs of αq_∞ and βq_∞ obtained from the April jim-

sphere sample. The ellipse (heavy solid curve) is the 95% ellipse from this sample. This ellipse, indeed, contains 95% of the paired sample data points. The eight circled dots are the results from the 95% SVWP with the 99% shear without gust. The outermost values are for the 95% SVWP, 99% shear, and with the 9 m/s design gust reduced by the 0.85 factor. As shown, the 95% ellipse from the sample of wind measurements is very close to that given by the SVWP without gust. In addition, the significant impact of a wind gust on the SSV aerodynamic loads is seen by the approximately 850 deg/psf increase in the αq_∞ and βq_∞ resulting from the application of the design gust criteria. The gust contribution

to the vehicle dynamic response envelope has been shown by other analyses to be approximately equal to that of all other sources of vehicle uncertainties.

The comparison of flight simulation results from wind models with those from a sample of detailed wind profiles as presented in this section is for discrete altitudes. The reader is cautioned not to conclude that the SSV is over-designed due to the use of the 9 m/s design gust criteria. These parametric analyses do not give the percentage of successful SSV flights when considering independent wind profile effects at all altitudes for the accumulation of all indicators. This subject is beyond the scope of this paper.

C. Temporal Performance Variations

The sensitivity of the various ascent system indicators to in-flight winds and the significant contribution of these winds to the SSV design requirements suggest a potential for increased subsystems performance margin through the implementation of a trajectory biasing concept based on a near-launch time wind environment. As a result of SSV response characteristics and the potential for a severe wind shear or gust to occur at any time during ascent, only those indicators which reflect the steady-state nature of the wind will be significantly affected by a near-launch time frame trajectory design effort. However, the viability of such an effort depends upon the time frame required to accomplish the trajectory profile design, associated subsystem assessments, and software updates to the SSV prior to launch.

Table 4 summarizes the requirements levied on several STS-1 subsystem indicators as a result of ascent wind dispersions attendant with a trajectory profile design time frame. Current STS trajectory profiles are designed for a monthly wind dispersion since no software updates are planned near launch time. As a result, an STS-1 FPR of 1870 lb was required to protect against a launch hold for April wind uncertainties. Similarly, dynamic pressure and aerodynamic heating allowances had to be provided for the potential occurrence of near worst case April winds on launch day. However, analyses to identify the gains associated with reducing the impact of in-flight wind dispersions on SSV and trajectory design requirements indicate only 335 lb of FPR required to protect for April wind uncertainties by designing the STS-1 trajectory profile for wind measurements taken 3 h prior to launch.

As with the results presented in the previous section, the statistical analyses were made with a time conditional SVWP model and with a sample of jimsphere wind profile measurements. The parameter variations for STS-1 presented in Table 4 were obtained from a statistical assessment of 144 jimsphere wind profiles sequentially measured at 3-, 6-, and 9-h intervals. The synthetic time conditional wind model has been used to identify parameter variations for various launch months (February, April, September, and December) and trajectory profile design time frames (6, 9, 12, 24, 48, and 72

h). Figures 9 and 10 give the time variation for the SSV dynamic pressure dispersion and FPR. These parameters have been normalized to their monthly wind variation levels to provide a more generalized assessment of the impact of changes in these parameters due to temporal changes in the wind. While these results show the good agreement between the synthetic and measured winds, they also indicate a potential to reduce the wind dispersion allowance to 50% of the monthly requirement by shaping the ascent trajectory profile for a wind measured approximately 10 h prior to launch.

IV. Conclusions

Using STS-1 as an example, the results presented herein indicate the significant role played by the ascent wind environment in the design and launch-commit criteria of the SSV. While the steady-state and dynamic (discrete gusts) nature of the wind profile combine to contribute to the vehicle design requirements, some alleviation of the SSV launch-commit uncertainty is possible by biasing for steady-state winds measured in the near-launch time frame.

In addition, analysis results summarized in this report indicate extremely good agreement between the available synthetic wind profile models and jimsphere measured winds. It is important to understand both the quality and applicability of the synthetic wind models so as to enhance our capability to provide detailed subsystem assessments when budget constraints and STS operational flight schedules do not permit the engineering support required by a measured wind data base.

References

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