Analysis of Extreme Wind Shear

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Wind-shear-induced ascent loads exceedances estimated in preflight simulations of Shuttle launches using sequential Jimsphere profiles are the basis for launch delays or postponements. Here, new methods using extreme-value statistical theory are applied in the analysis of the largest wind component shear in a wind profile as a function of shear-layer thickness and season. Seasonal variability of extreme shear decreases as the shear-layer thickness decreases. Wind-profile measurement system smoothing and its effect on extreme wind-shear statistics are simulated in this study by application of digital low-pass filters to Jimsphere wind profiles. Application of extreme-value analysis of wind shear on the day of launch is recommended.

Nomenclature

$DU(Z)$, $DV(Z)$ = zonal and meridional wind component shear at altitude Z
DZ = shear layer altitude interval
MDU, MDV = extreme zonal and meridional component shear within a wind profile for a selected shear layer interval DZ
mean = sample mean
n = sample size
$P(R)$ = cumulative probability distribution of reduced variate R
R = reduced (nondimensional) variate of the Gumbel distribution
$R(P)$ = inverse cumulative probability distribution
SD = sample standard deviation
$U(Z)$, $V(Z)$ = orthogonal wind components defined in the meteorological coordinate system in which U is the west-to-east (zonal) component and V is the south-to-north (meridional) component
VR = dimensional variable
Y_N = mean of reduced variate tabulated by Gumbel[3]
Z_1, Z_2 = lower and upper altitude bound of shear-layer interval
α = parameter of Gumbel distribution [Eq. (4)]
λ_c = low-pass filter cutoff wavelength
μ = parameter of Gumbel distribution [Eq. (5)]
σ_N = standard deviation of reduced variate tabulated by Gumbel[3]

Introduction

WIND-induced ascent structural loads on the Space Shuttle can be attributed to the entire range of wind-profile perturbation wavelengths. The contribution to loads by large wavelengths can be reduced significantly by using a launch trajectory that is biased with respect to a smooth wind profile that varies slowly with respect to time. It is not feasible to use a launch trajectory that minimizes loads relative to all of the significant perturbations in a wind profile obtained hours before launch. The common occurrence of an altitude (phase) shift of a critical perturbation can cause an increase in loads when the detailed trajectory based on the unshifted perturbation is used for the launch. Trajectory modification for loads alleviation is limited to large wavelengths that have an acceptable degree of persistence. The remainder of the wind-profile perturbation spectrum that is associated with wind shear is carefully monitored on the day of launch. Extreme wind shears that are associated with loads exceedances are identified from the prelaunch simulation analysis using sequential Jimsphere wind-profile data. Extreme wind shear is a cause of launch delays or postponements due to anticipated loads exceedances. In this paper, a new method for day-of-launch (DOL) analysis of extreme wind shear is proposed. Empirical and theoretical distributions of extreme wind component shear at the Shuttle launch site are described. The effect of wind-profile smoothing on extreme wind shear is analyzed and the capability of wind-profile measurement systems to measure extreme wind shear is discussed.

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Data

The analysis of extreme wind shear is based on samples of 150-per-month KSC Jimsphere wind profiles. A Jimsphere is a 2-m-diam balloon with a roughened surface to minimize self-induced motion that would lead to errors in the wind-profile measurement. Precision tracking of the balloon and smoothing of the position coordinates obtained at 0.1-s intervals yields wind data at 25-m intervals. The amplitude response of the Jimsphere system, defined by the ratio of the measured amplitude to the actual amplitude of a wind-profile perturbation at a given wavelength, decreases from 0.95 at 300 m, to 0.80 at 140 m, 0.50 at 90 m, and zero at 50 m.[1]

Statistical Model

Zonal and meridional wind component shears DU and DV at altitude $Z2$ are defined by

$$DU(Z2) = U(Z2) - U(Z1) \tag{1}$$

$$DV(Z2) = V(Z2) - V(Z1) \tag{2}$$

where $Z2 > Z1$, U and V are the zonal (east–west) and meridional (north–south) wind components, and the shear-layer thickness DZ is $Z2$–$Z1$. The positive and negative extremes of DU and DV, defined as MDU and MDV, in the 3–16 km altitude band, were calculated for each profile of the 150-per-month sample of Jimsphere data base at the Shuttle launch site, Kennedy Space Center (KSC). The maximum altitude of

16 km was selected because Jimsphere profiles either terminate or become inaccurate above that altitude. Monthly observed probability distributions were derived from the 150 extremes for the four shear types [*MDU* (+ or −), *MDV* (+ or −)] and 11 shear intervals (100, 200, 400, 600, 800, 1000, 1500, 2000, 3000, 4000, and 5000 m). The decision to examine positive and negative shears separately was based on analysis that indicated large differences in the probability distributions of positive and negative extreme *u*-component shears. Even though the *v* component does not exhibit large differences, it was decided to proceed in a similar manner for both components because future application of this work will include specification of extreme shear with respect to the vehicle flight azimuth. When the vehicle coordinates are rotated with respect to the meteorological coordinates, the differences noted previously for the *u* component will appear in both of the vehicle components. These differences can be attributed to the maximum altitude limit of the data. Since the maximum wind vector often occurs at altitudes above 11 km, extreme negative shears for large *DZ* can be underestimated because the 16-km data cutoff does not permit adequate sampling of the decreasing wind in the altitude region above the maximum wind.

The distributions of positive and negative shears have a lower bound of zero and an upper bound that is related to physical limits imposed by turbulent dissipation of large shears; for *DZ* large the upper bound for negative shears is affected by the altitude cutoff of the data. It was not evident a priori that any of the theoretical extreme-value distributions could be used to fit the distributions of *MDU* and *MDV*. The Weibull and the Frechet probability distributions have a lower bound and the Gumbel is unbounded.[2] The Gumbel[3] distribution was selected because it yielded the best fit to the distribution for *DZ* less than 2000 m. For $DZ > 2000$ m, the observed distributions of *MDU*(+) tend to be asymptotic, suggesting that a Weibull would fit better than the Gumbel, which overestimates the largest extremes.

The parameters α and μ of the Gumbel distributions of *MDU* and *MDV* were calculated for the 11 shear intervals for each month. The Gumbel distribution is represented by a straight line on an extreme-value probability graph. Such a graph is linear for *VR* vs *R*, where *VR* represents *MDU*(+ or −) or *MDV*(+ or −). The variable *R* defined as the reduced variate is nondimensional and is defined by

$$R = (VR - \mu)/\alpha \tag{3}$$

where α and μ are calculated from the sample mean and standard deviation *SD*.

$$\alpha = SD/\sigma_n \tag{4}$$

$$\mu = \text{mean} - Y_n \tag{5}$$

for $n = 150$, $\sigma_n = 1.22543$, and $Y_n = 0.56461$ (tabulation by Gumbel[3]).

The cumulative probability distribution is given by the double exponential function of the reduced variate.

$$P(R) = \exp[-\exp(-R)] \tag{6}$$

The inverse probability function yields the value of *R* for a given probability.

$$R(P) = -\ln[-\ln(P)] \tag{7}$$

The variation of α and μ as a function of shear-layer thickness for November at KSC is illustrated in Figs. 1 and 2. The relatively small values of μ for *MDU*(−) attributed earlier to the data cutoff at 16 km are clearly indicated. The parameter μ appears asymptotic to 11 m/s for *MDV*(+ or −). The dispersion parameter α is largest for *MDU*(−) and *MDV*(+); the nearly asymptotic behavior of α for $DZ > 3000$ m for *MDU*(−) illustrated in Fig. 2 may also be attributed to data cutoff at 16 km.

Probability Distributions

Observed and theoretical extreme-value (Gumbel) cumulative probability distributions of *MDU*(+) and *MDV*(+) at KSC during November are illustrated in Figs. 3 and 4. The Gumbel distributions fit the observed distributions closely for

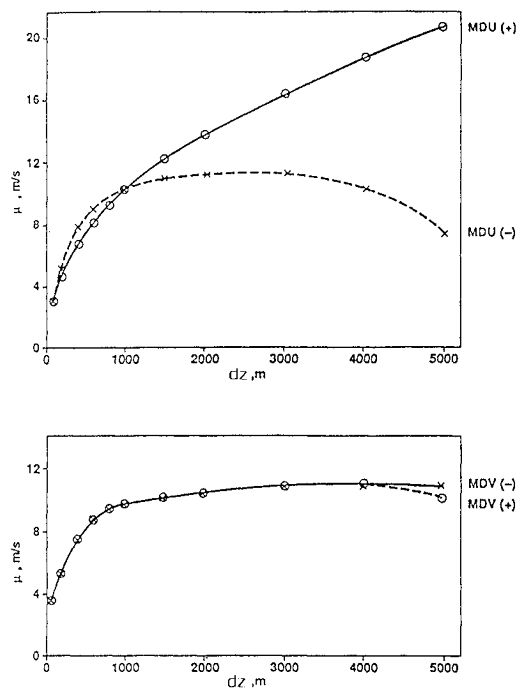

Fig. 1 Parameter μ of Gumbel distributions for extreme wind component shear as a function of shear-layer thickness *DZ* (KSC, November, 3–16 km).

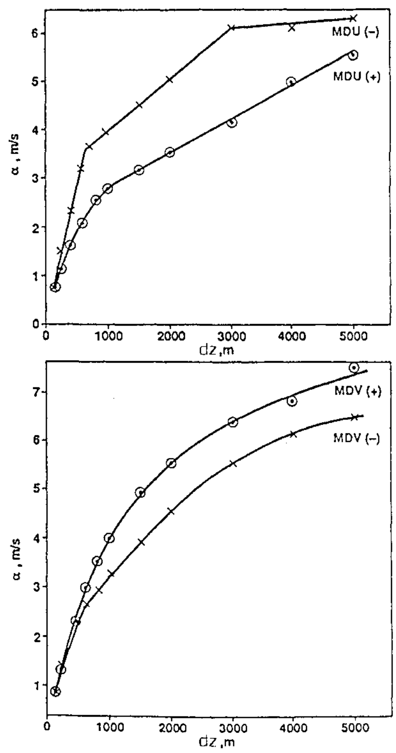

Fig. 2 Parameter α of Gumbel distributions for extreme wind component shear as a function of shear-layer thickness *DZ* (KSC, November, 3–16 km).

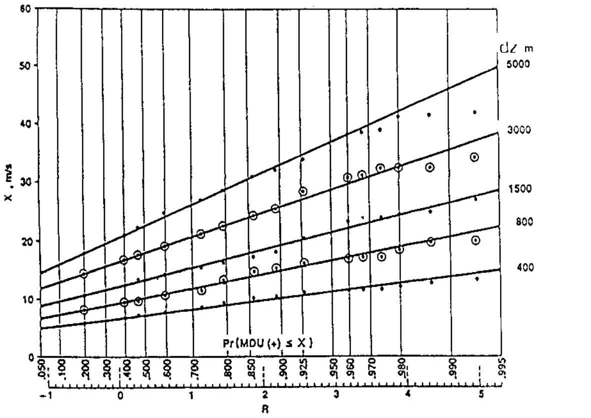

Fig. 3 Observed and theoretical (Gumbel) probability distributions of extreme positive *u*-component shear (KSC, November, 3–16 km).

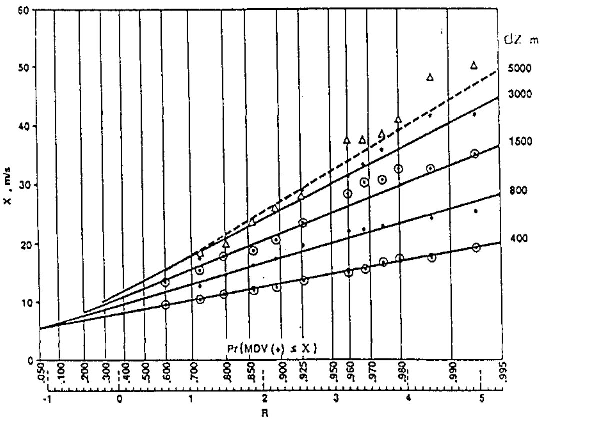

Fig. 4 Observed and theoretical (Gumbel) probability distributions of extreme positive *v*-component shear (KSC, November, 3–16 km).

$DZ<$ 3000 m. For $DZ>$ 3000 m, the Gumbel tends to overestimate $MDU(+)$ and underestimate $MDV(+)$ at the large percentiles of the probability distribution function.

Seasonal variability for selected shear intervals of $MDU(+)$ is illustrated in Fig. 5. For $P=0.99$ and $DZ=3000$ m, $MDU(+)$ is nearly twice as large in February than it is in July; in contrast, for $DZ=400$, $MDU(+)$ increases from 13 m/s in July to 17 m/s in February at $P=0.99$. From this we conclude that seasonal variation of extreme shear increases as DZ increases. The reason is that large-scale shears are associated with the maximum speed in the profile, which has a strong seasonal variation at KSC.

Probability Distributions for Filtered Wind Profiles

Wind-profile measurement systems have varying degrees of capability to measure perturbations with small wavelengths. The degradation of system response for small wavelengths can be simulated by application of a smoothing or "low-pass" filter to wind-profile data that cover a wide range of wavelengths. Progressive amounts of smoothing in conjunction with analysis of wind-shear distributions derived from the smoothed data sets was used to study how system response to small wavelengths influences the measurement of extreme wind shear. For this study, the 150 Jimsphere profiles for November at KSC were digitally low-pass filtered to remove perturbations with wavelengths less than 500, 1500, 3000, 6000, and 9000 m. The filters have zero phase shift and have a cosine response function. The filters were derived according to methods described by DeMandel and Krivo.[4] Gumbel probability distributions of extreme wind shear were calculated from the five filtered versions of the data base according to the

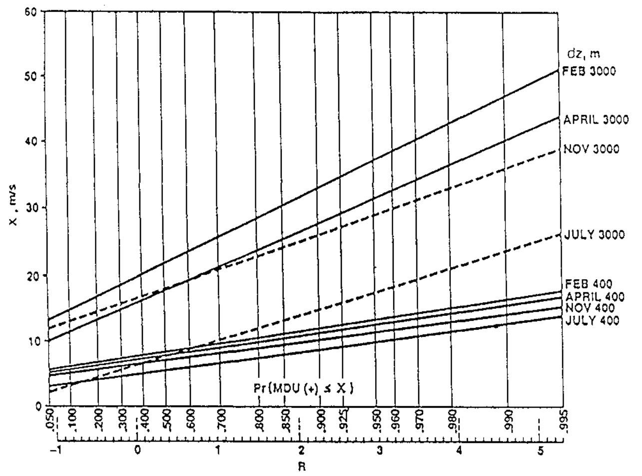

Fig. 5 Monthly Gumbel probability distributions of extreme positive *u*-component shear (KSC, 3–16 km).

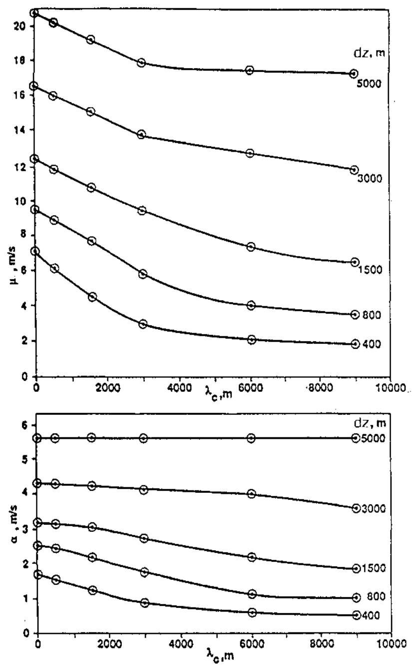

Fig. 6 Parameters α and μ of Gumbel distributions for extreme positive *u*-component shear as a function of low-pass filter cutoff wavelength λ_c (KSC, November, 3–16 km).

theory described earlier in the Statistical Model section. The parameters α and μ for $MDU(+)$ are plotted in Fig. 6 as a function of DZ and low-pass filter cutoff wavelength λ_c. A comparison of the capability of Rawinsonde and Jimsphere data to measure extreme wind shear was made by assuming that application of a 2000-m smoothing filter to a Jimsphere profile yields a realistic simulation of a Rawinsonde profile. From the curves in Fig. 6, we can estimate α and μ for the five shear intervals for $\lambda_c=2000$ m (Rawinsonde) and $\lambda_c=0$ (Jimsphere). The choice of a probability level of 0.99 for the comparison yields a value of 4.6 for R from Eq. (7). Substitution of R and the appropriate values of α and μ into Eq. (3) yields solutions for $MDU(+)$ at the 0.99 probability level that are illustrated in Fig. 7. The 99 percentile of $MDU(+)$ for Jimsphere data can be expressed as a power of shear-layer thickness:

$$MDU(+)99=0.994(DZ)^{0.451} \tag{8}$$

The effect of the 2000-m smoothing filter is clearly illustrated by the increasing deviation of the dashed curve from the

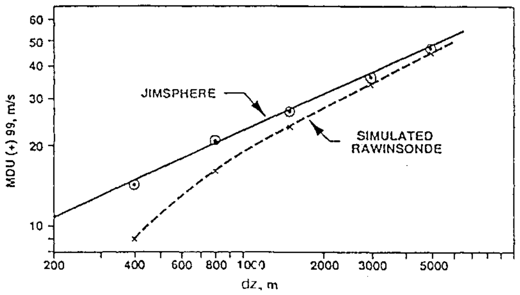

Fig. 7 The 99 percentile extreme positive *u*-component shear as a function of shear-layer thickness *DZ* (KSC, November, 3–16 km).

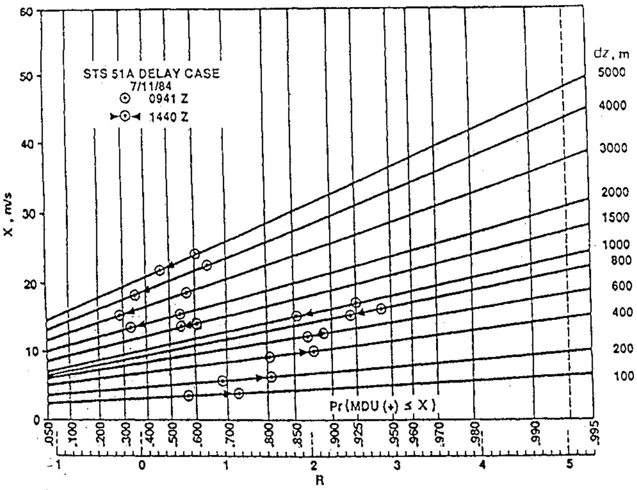

Fig. 8 Gumbel extreme-value distribution of extreme positive *u*-component shear for November at KSC, 3–16 km, and observed shears for STS 51A launch delay.

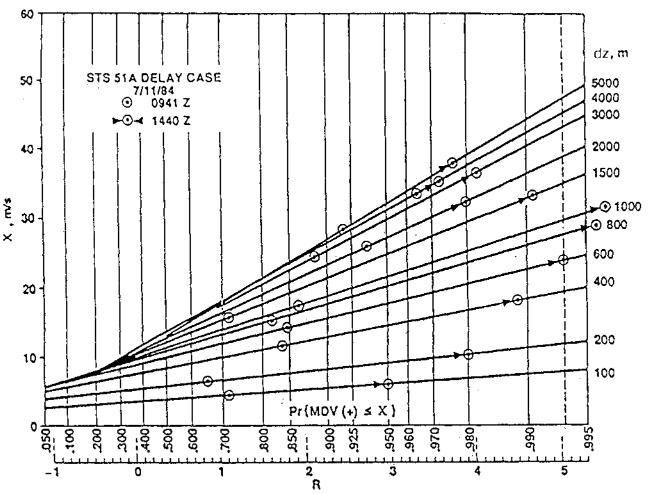

Fig. 9 Gumbel extreme-value distribution of extreme positive *v*-component shear for November at KSC, 3–16 km, and observed shears for STS 51A launch delay.

straight line as the shear-layer thickness decreases. For $DZ = 400$ m, the simulated Rawinsonde "measures" 65% of the extreme shear measured by the Jimsphere.

The approach can be used to evaluate the wind-shear measurement capability of other wind-profile systems that have an amplitude response roll-off at small wavelengths that is approximated by a Martin-Graham smoothing filter.[4]

Day-of-Launch (DOL) Application

The purpose of the theoretical treatment of extreme wind shear in this context is the establishment of a convenient method for summarizing the historical data at the launch site. Extreme wind shears that are larger than those in the historical data base will be identified on the DOL with the procedure to be described.

The parameters of the monthly Gumbel distributions of extreme wind component shear are derived a priori from the sample of 150 per month Jimsphere data at the launch site. Graphs containing the straight lines that represent the Gumbel distributions for various shear-layer thicknesses for the appropriate month will be available for display at a computer terminal. As sequential wind-profile data become available on DOL, the probabilities of the maximum shears observed in these profiles are calculated from Eq. (6), after calculation of R from Eq. (3), using the parameters α and μ. An extreme probability >0.9934 indicates that the DOL extreme shear exceeds the theoretical upper bound of the extreme shears that have been observed at the launch site during that month. An example of this process is illustrated in Figs. 8 and 9, which contain the Gumbel distributions for the month of November for extreme positive $u-$ and $v-$ component shears and the extreme shears observed in two Jimsphere wind profiles obtained during the Shuttle launch delay (51A) on November 7, 1984; the plotted circles represent the DOL data. The arrow points toward the most recent observation. The observed $MDV(+)$ shears illustrated in Fig. 9 increase substantially during the 5-h period between the profiles; the 600, 800, 1000, and 1500 m shears all exceed the theoretical bounds of the November data base.

Discussion

The basis for extreme-value statistical theory is that the data sample is a set of independent observations that are identically distributed (homogenous).[2] Such an ideal is not achieved for the data sets used in this study and is rarely achieved for any set of climatic data. However, extreme-value analysis of nonhomogenous data using any of the three distributions (Gumbel, Wiebull, and Frechet) may yield adequate results. Perhaps the greatest deficiency of the data sample used in this study is the altitude limit imposed by the Jimsphere measurement system that does not permit proper sampling of negative shears for large shear-layer thicknesses. On the DOL, it is conceivable that a particular Jimsphere profile measurement may extend well beyond the 16-km limit established in this study. In that case, some care should be exercised in the assessment of the extreme negative shears from such a profile because they may be larger than those observed with the 16-km cutoff. Consideration should be given to imposing a 16-km cutoff on DOL for proper comparison of extreme negative shears to the historical data at the launch site.

Acknowledgment

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