1. INTRODUCTION
On-pad launch vehicle wind induced translation and structural response are the subject of engineering design analyses and operational planning. The NASA ARES-1 may have to be constrained, to prevent contact with pad infrastructure, to reduce loads and to insure that the projected on-pad exposure period is within the estimated fatigue life of attachments to the launch pad. The ARES-1 solid rocket booster (SRB) needs to be protected from extreme loads because its re-usable base (the "aft-skirt") is attached to the launch pad. Detailed engineering analysis of launch vehicle wind induced translation, structural loads and fatigue life require a detailed definition of wind forcing functions at locations along the vehicle. Kennedy Space Center (KSC) near-pad wind measurements at 18.3m elevation are below the elevation of the base of on-pad Shuttle and ARES launch vehicles. The near-pad wind measurement system currently sampled at 1/sec has an effective frequency response that begins to roll-off at frequencies less than the nominal maximum frequency of 0.5Hz. This does not satisfy the need for engineering analysis to define wind forcing functions to at least 5 Hz.

The power spectrum density (PSD) model (Fichtl and McVehil, 1970) that is an essential component of the simulation process described herein is based on wind measured at five elevations on the KSC 150-m meteorological Tower 313. The wind data sampled at 10/sec are from relatively light cup anemometers more suitable for turbulence research and PSD modeling compared to current sensors that have reduced frequency response, but have the capability needed for long-term exposure for range support of Shuttle launches. The methodology for application of PSD and coherence models described in this paper permits simulation of wind time series at any desired location on launch vehicles for a user selected frequency range suitable for engineering design applications. Although this paper describes a process that does not require measurements to simulate wind, the process can be adapted to simulate wind along the launch vehicle, given a measured wind at 18.3m. This is the subject of ongoing work.

2. BACKGROUND
Ground wind time series are simulated based on PSD model for the longitudinal and lateral components of turbulence and a coherence model for the reduction of correlation between wind components at two locations as a function of temporal frequency, wind speed and distance between locations (Anon, 2000). Short distances reduce correlation only at high frequencies; as distances increase correlation is reduced over a wider range of frequencies. The longitudinal component is oriented in the direction of the mean wind; the lateral component is perpendicular to the direction of the mean wind.

Current applications of simulated ground winds time series

| (*) E-mail: Stanley.I.Adelfang@nasa.gov |

3. GROUND WIND PSD MODEL FOR ATMOSPHERIC TURBULENCE
The PSD model (Eq.1) for ground wind turbulence was developed for engineering applications (Fichtl and McVehil, 1970) from horizontal wind measurements at the NASA 150-m meteorological tower at Cape Canaveral, FL. The model is specified in Shuttle design documentation (Anon, 1999 and in somewhat different form in Anon, 2000).

$$\text{psd}_{k, kk} = \frac{d_1 (\frac{x_{kk}}{18.3})^d_3}{1 + d_2 \left[ \left( \frac{18.3}{x_{kk}} \right)^{d_5} \frac{u_{183}^2}{ux_{kk}} \right]^{d_4}}$$

Where,
- \( \text{psd} \) = power spectrum density, \((m^2/s)/1/sec\)
- \( d_1, d_2, d_3, d_4, d_5, d_6 \) are non-dimensional constants for the longitudinal and lateral components of turbulence
- \( x \) = elevation (m)
- \( u_{183} \) (m/sec) = mean wind speed at 18.3m elevation
- \( ux \) = mean wind speed (m/sec) at \( x \)
- \( n \) = temporal frequency (1/sec)
- \( k \) = index for frequency variable
- \( kk \) = index for selected variable and related variables, in this case \( ux \) calculated from \( u_{183} \) and \( x \)

The PSD model and the mean of 20 simulations are illustrated in Fig. 1. As the number of simulations increase the deviations of the mean from the model decreases.
Fig. 1 Mean PSD (perturbed) of the 20 Simulated Series Versus the PSD Model (smooth) at elevation 102.5 m and mean wind speed 9.871 m/s

4. BASIC ELEMENTS OF WIND SIMULATION AT ELEVATION X AND MEAN WIND SPEED UX

- Selection of the frequency range for the application and the simulated wind time series
- Integration of the PSD to obtain the variance and standard deviation (SDPSD) of the time series to be simulated
- Generation of n-values of Gaussian distributed white noise with zero mean and SD = 1; "n" is chosen such that the fast Fourier transform (FFT) is at the same frequencies defined for the PSD model
- Calculation of the FFT of the Gaussian series (FFTGA)
- Low-pass filtering of FFTGA by multiplying each Fourier component of FFTGA by the square-root of the normalized PSD
- Calculation of the un-adjusted simulated time series, S, which is the inverse transform of the low-pass filtered FFTGA
- Calculation of the adjusted simulated time series SA such that it has the standard deviation calculated from the PSD model, i.e., 
SA = S * SDPSD/SD

5. SIMULATION PROCESS FOR CONCURRENT WIND COMPONENT TIME SERIES AT SELECTED LOCATIONS

Simulation of a wind component at the nearest adjacent location (and all other succeeding next nearest locations) is based on a coherence model (Anon., 2000) for the coherence decay between winds at two locations as a function of temporal frequency f, and distance, d, (Eqs. 2 and 3); where the adjacent locations are displaced vertically or horizontally.

For vertical separation, the coherence squared is,

$$\text{coh}_k^2 = \exp \left( -0.693 f_k \frac{u_{x_2}}{u_{x_2-d}} \right)$$

(2)

Where, $u_{x_2}$ and $u_{x_2-d}$ are the mean wind speeds (m/s) at adjacent locations along the vertical x-axis and d is the vertical distance between adjacent nodes.

For horizontal separation, the coherence squared becomes,

$$\text{coh}_k^2 = \exp \left( -0.693 f_k \frac{d}{u_x(0.036)} \right)$$

(3)

Where, d is the absolute value of the y coordinate difference (m) between the two locations at elevation x. An example is illustrated Fig. 2.

Fig. 2. Coherence squared (Eq. 2) for d = 5.5 m at elevation 102.5 m and mean wind speed 9.871 m/s

- The coherence function is used to model the Fourier components $A_k^*$ and $B_k^*$ of the wind at a selected location, given the Fourier components $A_k$ and $B_k$ of the simulated time series at an adjacent location and another set of essentially uncorrelated Fourier components $AA_k$ and $BB_k$ calculated at the selected location. The coherence weighted Fourier components at the selected location are:

$$A_k^* = \text{coh}_k A_k + \sqrt{1 - \text{coh}_k^2} AA_k$$

(4)

$$B_k^* = \text{coh}_k B_k + \sqrt{1 - \text{coh}_k^2} BB_k$$

(5)

The coherence weighted FFT, cohFFT is

$$\text{cohFFT}_k = A_k^* + B_k^* i$$

(6)

The coherence weighting in Eqs. 4 and 5 is analogous to the correlation weighting used to derive a correlated
Gaussian distributed data base $G_3$ from uncorrelated Gaussian distributed data bases $G_1$ and $G_2$ with zero mean and standard deviation $X$, where the target correlation between $G_3$ and $G_1$ is $C$.

$$G_3 = G_1 \cdot C + G_2 \cdot (1-C)$$ (7)

The coherence modeled time series is the inverse Fourier transform of $cohFFT$. The inverse transform produces a 27.31-minute time series of 32,768 values at intervals of 0.05 seconds with frequency resolution to 10 Hz.

- The procedure is straightforward for all additional adjacent nodes displaced horizontally (y-coordinate) and vertically ($x$).
- A two-step simulation process first simulates an intermediate time series for the vertical component of the separation vector ($dx = (x_2-x_1)$) and then simulates the required time series for $dy = abs(y_2-y_1)$.

The simulation process has been documented for potential ARES-1 users. Test cases have been developed that provide random number input series and simulated time series output for ARES-1 user independent code development and verification.

6. SIMULATION CASE

A simulation case was developed for this paper to illustrate longitudinal component time series at 18.3, 20.3, 35.3, 60.3, 100.3 and 200.3m. The values for the parameters of the PSD model are: $d_1=1.35, d_2=29.035, d_3=-1.1, d_4=1.972, d_5=1$ and $d_6=0.845$. The simulation is initiated at 18.3m for $ux=1.42$m/s and peak wind speed=17.21m/s (Eq.2, Anon., 1999). Mean wind speeds (11.65, 13.57, 15.65 and 17.86 m/s) at 20.3, 35.3, 60.3, 100.3 and 200.3m elevation are calculated from peak winds at those altitudes (17.55, 19.49, 21.57, 23.76, and 27.08m/s) according to Eqs. 1 (for peak wind speed at elevation $x$, given peak wind at 18.3m) and 2 (for mean wind at $x$ from peak wind at $x$) in Anon., 1999. The frequency range for the PSD is $1.52588 \times 10^{-4}$ to $5$Hz. Each 109.23 minute time series consists of 65,536 values sampled at 10/s. The coherence functions for the distances between adjacent elevations (2, 15, 25, 40 and 100m) are illustrated in (Fig.3), right to left respectively. The coherence is less than 0.5 for frequencies greater than 0.58, 0.090, 0.058, 0.042 and .020 Hz for $d=2, 15, 25, 40$ and 100m.

Fig.4 Simulated longitudinal wind component at 18.3m repeated in each panel, and at 20.3, 35.3, 60.3, 100.3 and 200.3m

7. DISCUSSION

A desirable characteristic of the simulation model is that it can be included in a Monte Carlo process that will output a sufficient number of simulations that would mimic the original data used in the derivation of the NASA ground wind model (GWM, Anon., 2000). The GWM was used for calculation of the peak wind and associated mean wind values listed in Sec.6; thus the GWM gust factors (GF, the ratio of peak to mean) are known for comparison to those calculated from multiple outputs of the simulation model.

Note that only the mean wind is required in the PSD model of the simulation process. To mimic the process used in the derivation of the GF of the GWM, the GF of the simulation process is defined as the mean of 200 simulations at each of
the six elevations. The GF calculated from the simulation model (dashed upper curve in Fig. 5) with revised values of constants \(d_1\) and \(d_3\) (discussed below) is in good agreement with the GWM values (solid upper curve); the lower curve is based on the original values of constants \(d_1\) and \(d_3\).

![Gust factor as a function of elevation](image)

**Fig. 5 Gust factor as a function of elevation**

The gust factors (upper curve in Fig. 5) were obtained with adjusted values of \(d_1\) and \(d_3\) in the PSD model for the longitudinal and \(d_1\) for the lateral component. The published values (Anon., 1999) for \(d_1\) are based on an unrealistic value of the surface roughness parameter \(z_0\) for KSC. Where, \(z_0\) can be "back calculated" using Eq. 8 for the longitudinal component or Eq. 9 for the lateral component.

\[
\begin{align*}
z_0 &= \frac{18.3}{\exp\left(\frac{6.198(0.4)^2}{d_1^*0.03}\right)} \quad (8) \\
\end{align*}
\]

\[
\begin{align*}
\frac{z_0}{18.3} &= \frac{18.3}{\exp\left(\frac{3.954(0.4)^2}{d_1^*0.1}\right)} \quad (9)
\end{align*}
\]

For \(d_1\) equal to 0.807 in Eq. 8 or \(d_1\) equal to 0.154 in Eq. 9, \(z_0\) is 0.030. A more realistic average value of \(z_0\) equal to 0.13 is closer to but somewhat less than the values in Fichtl and McVehil (1970) yields the values used herein (\(d_1=1.35\) for longitudinal and 0.256 for lateral) obtained by solving for \(d_1\) in Eqs. 8 and 9.

The constant \(d_3\) for the longitudinal component influences the rate of decrease of GF as a function of elevation. The revision of the published value of \(d_3\) (-1.63, Anon., 1999) is suggested in correspondence from Fichtl (unpublished, 2004) based on a literature search of research studies completed since 1970. Examination of the formulation of Fichtl's 1970 PSD model indicates that \(d_3\) in the simplified but equivalent formulation used herein from Anon. 1999 is obtained by multiplication of Fichtl's equation for \(\beta\) by \((z/18.3)^{-1}\). Thus the variation of gust factor with elevation is described by FZ in Eq. 10.

\[
FZ = \left(\frac{z}{18.3}\right)^{-63-1} \quad (10)
\]

Where, \(d_3\) is the exponent (-1.63). Fichtl's recent discussion suggests various choices for increasing the "-63" value; the value chosen (-0.10) yields the revised value of \(d_3\) (-1.1) that produces good agreement with the rate of decrease in GF predicted with GWM.

8. CONCLUSION

A simulation process has been developed for generation of the longitudinal and lateral components of ground wind atmospheric turbulence as a function of mean wind speed, elevation, temporal frequency range and distance between locations. The distance between locations influences the spectral coherence between the simulated series at adjacent locations. Short distances reduce correlation only at high frequencies; as distances increase correlation is reduced over a wider range of frequencies.

The choice of values for the constants \(d_1\) and \(d_3\) in the PSD model is the subject of work in progress. An improved knowledge of the values for \(z_0\) as a function of wind direction at the ARES-1 launch pad is necessary for definition of \(d_1\). Results of other studies at other locations may be helpful as summarized in Fichtl's recent correspondence. Ideally, further research is needed based on measurements of ground wind turbulence with high resolution anemometers at a number of altitudes at a new KSC tower located closer to the ARES-1 launch pad. The proposed research would be based on turbulence measurements that may be influenced by surface terrain roughness that may be significantly different from roughness prior to 1970 in Fichtl's measurements. Significant improvements in instrumentation, data storage and processing will greatly enhance the capability to model ground wind profiles and ground wind turbulence.

ACKNOWLEDGEMENTS

The author appreciates the numerous technical discussions with his colleagues Frank B Leahy and Steve Hahn.

REFERENCES

