Temporal Coherence in Wind Simulation and Atmospheric Data

J.M. Rinker, H.P. Gavin (Duke University)
A. Clifton (NREL)

NAWEA 2015 Symposium
June 10, 2015
Wind is (incorrectly) assumed to be stationary

Simulation

Time-invariant statistics

Reality

Time-varying statistics
Nonstationary inflow increases wind turbine design loads

Wind Turbine Design Loads

1. Simulated Wind
2. Turbine Model
3. Load Extrapolation

Effect of nonstationary inflow on dynamical system

Design load with stationary input

Design load with nonstationary input

Frequency vs. Load
Nonstationary inflow increases wind turbine design loads

Wind Turbine Design Loads

Effect of nonstationary inflow on dynamical system

Neglecting nonstationarity could lead to non-conservative turbine design loads.
Nonstationary inflow increases wind turbine design loads

Wind Turbine Design Loads

1. Develop nonstationary simulator
2. Quantify effects on design loads

Effect of nonstationary inflow on dynamical system

Neglecting nonstationarity could lead to non-conservative turbine design loads.
Proposed solution: simulator with temporal coherence

Developing a stochastic simulator that produces nonstationary fields

Instead of

produces
Proposed simulator modifies standard simulation method

**Phases**

Stochastic from a uniform distribution:

\[ X(f) = \frac{S(f)}{2\Delta f} \]

**Magnitudes**

Deterministic from Kaimal spectrum:

\[ |X(f)| = \frac{\sqrt{S(f)\Delta f}}{2\Delta f} \]

**Vees method**

Stationary time history

\[ U, \sigma_u, L \]

None

\[ X(f) = \frac{S(f)}{2\Delta f} \]

IFFT

\[ |X(f)| = \frac{\sqrt{S(f)\Delta f}}{2\Delta f} \]
Proposed simulator modifies standard simulation method

**Phases**
- Stochastic from a uniform distribution:
- Deterministic from Kaimal spectrum:

\[ U, \sigma_u, L \]

\[ |X(f)| = \frac{\sqrt{S(f)}/2\Delta f}{\text{Kaimal Spectrum, } S(f)} \]

**Independent phases create stationary simulations**

**Veer's method**

\[ X(f) = U \cdot \sqrt{S(f)}/2\Delta f \cdot \exp(i2\pi f) \]

Stationary time history:

Wind Velocity

\[ \text{Time} \]

**Stationary time history**

\[ \text{Stationary time history} \]
Correlate phases using phase difference distributions

Phase difference distributions (PDDs)

Phase difference $\Delta \phi_k$ is difference in phases at $f_{k+1}$ and $f_k$

$$\phi_2 = \phi_1 + \Delta \phi_1$$

Higher distribution concentration increases phase correlation

Non-uniform distribution on $\Delta \phi_1$  Phases $\phi_1$ and $\phi_2$ are correlated

No phase correlation: $\rho = 0$
Nonstationary simulator samples phase differences

Nonstationary time history

Modified Veers method

**Magnitudes**

Deterministic from Kaimal spectrum:

\[ |X(f)| = \frac{\sqrt{S(f)/2\Delta f}}{\rho_u \sigma_u \sqrt{N_0}} \]

**Phases**

*Phase differences* from a non-uniform distribution, cumulatively sum

\[ \text{Prob. Density} \]

Wind Velocity

Time

\[ U, \sigma_u, L \]

\[ \rho, \mu \]
Nonstationary simulator samples phase differences

**Magnitudes**
Deterministic from Kaimal spectrum:

\[ |X(f)| = \frac{\sqrt{S(f)}/2\Delta f}{X(f)} \]

**Phases**
Phase differences from a non-uniform distribution, cumulatively sum

**Simple, only two new parameters**

**Modified Veers method**

**Nonstationary time history**

\[ U, \sigma_u, L \]

\[ \rho, \mu \]
PDD parameters have direct effect on time domain behavior

- Probability Distribution
  - $\rho = 0.00$, $\mu = 0$
  - $\rho = 0.50$, $\mu = \pi/2$
  - $\rho = 0.70$, $\mu = \pi/2$
  - $\rho = 0.70$, $\mu = 3\pi/2$

- Wind Velocity

- Phase Difference

- Time
PDD parameters have direct effect on time domain behavior

\[ \rho \text{ controls nonstationarity} \]
# How to choose simulation parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>High-frequency time series available?</th>
<th>Calculation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard wind parameters</td>
<td>Yes</td>
<td>From time series</td>
</tr>
<tr>
<td>$(U, \sigma_u, L)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporal coherence parameter</td>
<td>Yes</td>
<td>From time series</td>
</tr>
<tr>
<td>$(\rho)$</td>
<td></td>
<td>$(\frac{1}{N} \sum_{k=1}^{N} e^{i\Delta \phi_k} \approx \rho e^{i\mu})$</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>...</td>
</tr>
</tbody>
</table>
### How to choose simulation parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>High-frequency time series available?</th>
<th>Calculation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard wind parameters ((U, \sigma_u, L))</td>
<td>Yes</td>
<td>From time series</td>
</tr>
<tr>
<td>Temporal coherence parameter ((\rho))</td>
<td>Yes</td>
<td>From time series</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>IEC 61400-1</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>??</td>
</tr>
</tbody>
</table>

\[
\frac{1}{N} \sum_{k=1}^{N} e^{i\Delta \Phi_k} \approx \rho e^{i\mu}
\]
## How to choose simulation parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>High-frequency time series available?</th>
<th>Calculation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard wind parameters ((U, \sigma_u, L))</td>
<td>Yes</td>
<td>From time series</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>IEC 61400-1</td>
</tr>
<tr>
<td>Temporal coherence parameter ((\rho))</td>
<td>Yes</td>
<td>From time series</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>???</td>
</tr>
</tbody>
</table>

Use dataset to determine what values of \(\rho\) are realistic, correlations with other parameters
High-frequency sonic anemometer data from NWTC

Site - National Wind Technology Center
Highly turbulent, non-neutral conditions

Sonic Anemometer on Tower M4
- About 3 years of data
- 20 Hz sampling
- Measurement heights:
  - 15 m, 30 m, 50 m,
  - 76 m, 100 m, 131 m

Quality control
- Cleaning: Spike removal
- Screening:
  1. Mean wind speed
  2. Wind direction
  3. Precipitation
Characterize $\rho$ using joint probability distribution

**Joint distribution ($U, \sigma_u, L, \rho$)**

- Probability density function for multiple random variables
- Probability is area under curve

**1. Marginals**

- Distribution single random variable
- Frequency of occurrence of values
- Model or empirical

**2. Correlations**

- Linear relationship between different random variables
- Organized in matrix
- Direct calculation

<table>
<thead>
<tr>
<th></th>
<th>$X_1$</th>
<th>$X_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.7</td>
<td>1</td>
</tr>
</tbody>
</table>
Characterize $\rho$ using joint probability distribution

Joint distribution $(U, \sigma_u, L, \rho)$

- Probability density function for multiple random variables
- Probability is area under curve

Can draw samples from joint distribution

1. Marginals
- Distribution single random variable
- Frequency of occurrence of values
- Model or empirical

2. Correlations
- Linear relationship between different random variables
- Organized in matrix
- Direct calculation

<table>
<thead>
<tr>
<th></th>
<th>$X_1$</th>
<th>$X_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>1</td>
<td>0.7</td>
</tr>
<tr>
<td>$X_2$</td>
<td>0.7</td>
<td>1</td>
</tr>
</tbody>
</table>

J.M. Rinker, H.P. Gavin, A. Clifton
Important that marginal models match data at high values

Tail data

Larger $U, \sigma_u, \rho$ produce larger system responses

Generalized Pareto (GP) distribution

Probability of values above a specified threshold

"Composite" distribution

Optimize parameters to minimize sum of CDF error

Multiple main distribution candidates

Quantile cutoff $Q$

"Main" distribution

GP distribution

Probability

Parameter

Probability

Parameter

J.M. Rinker, H.P. Gavin, A. Clifton
Information from wind parameter distributions/model fits

Main distribution models:

<table>
<thead>
<tr>
<th>Distribution</th>
<th>15 m</th>
<th>30 m</th>
<th>50 m</th>
<th>76 m</th>
<th>100 m</th>
<th>131 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U</td>
<td>σ_u</td>
<td>L</td>
<td>ρ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>GG</td>
<td>GEV</td>
<td>GG</td>
<td>GG</td>
<td>GG</td>
<td>GG</td>
</tr>
<tr>
<td>C2</td>
<td>GG</td>
<td>GEV</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW</td>
<td>GEV</td>
<td>GG</td>
<td>LN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>GEV</td>
<td>GG</td>
<td>GG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LN</td>
<td>EW</td>
<td>GEV</td>
<td>GG</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B: Beta, C2: Chi-Squared, EW: Exponential Weibull, GEV: Generalized Extreme Value, GG: Generalized Gamma, LN: Lognormal
Information from wind parameter distributions/model fits

Main distribution models:

- B: Beta
- C2: Chi-Squared
- EW: Exponential Weibull
- GEV: Generalized Extreme Value
- GG: Generalized Gamma
- LN: Lognormal

Approximately 94% of data are nonstationary with 99% confidence.
Information from wind parameter distributions/model fits

**Main distribution models:**
- B: Beta
- C2: Chi-squared
- EW: Exponential
- GEV: Generalized Extreme Value
- GG: Generalized Gamma
- LN: Lognormal

**Approximately 94% of data are nonstationary with 99% confidence**

![Graphs showing CDF and CDF Error for Mean Wind Speed U, 10-Minute Standard Deviation \(\sigma_u\), Kaimal Length Scale \(L\), and Concentration Parameter \(\rho\).](image)

...so what? Does it matter?
Use SDOF to calculate increase in extrapolated ultimate load

Extrapolating SDOF maximum response

3 cases:
1. IEC 61400-1 (WT II, TC B)
2. Distribution, \( \rho = 0 \)
3. Distribution, \( \rho \neq 0 \)

1. Sample wind parameters
   2. Simulate turbulent wind
      3. Calculate SDOF response
         4. Extract maximum response
   5. Extrapolate 50-year load

Maximum response distributions

- IEC
- Dist-No TC
- Dist-TC

\[ p_{ext} = 3.8 \times 10^{-7} : \quad F_{IEC} \approx 449 \]
\[ F_{NoTC} \approx 21 \]
\[ F_{TC} \approx 27 \]
**Use SDOF to calculate increase in extrapolated ultimate load**

### Extrapolating SDOF maximum response

3 cases:
1. IEC 61400-1 (WT II, TC B)
2. Distribution, $\rho = 0$
3. Distribution, $\rho \neq 0$

1. Sample wind parameters
2. Simulate turbulent wind
3. Calculate SDOF response
4. Extract maximum response
5. Extrapolate 50-year load

### Maximum response distributions

- **Frequency**
  - $f_n = 0.66\, \text{Hz}$, $\zeta = 0.01$

- **Probability Density**

  - $p_{\text{ext}} = 3.8 \times 10^{-7}$: $F_{\text{IEC}} \approx 449$
  - $F_{\text{No TC}} \approx 21$
  - $F_{\text{TC}} \approx 27$

- **Increase** 28.3%
Use SDOF to calculate increase in extrapolated ultimate load

Extrapolating SDOF maximum response

3 cases:
1. IEC 61400-1 (WT II, TC B)
2. Distribution, $\rho = 0$
3. Distribution, $\rho \neq 0$

1. Sample wind parameters
   2. Simulate turbulent wind
   3. Calculate SDOF response
   4. Extract maximum response
   5. Extrapolate 50-year load

Maximum response distributions

$\rho_{ext} = 3.8 \times 10^{-7}$: $F_{IEC} \approx 449$
$F_{NoTC} \approx 21$
$F_{TC} \approx 27$

Nonstationarity in “normal” wind conditions matters

28.3% increase

Wind
Response

5,000 samples/case

$f_n = 0.66 \text{ Hz}, \quad \zeta = 0.01$
Summary

Simulator

Data Analysis
Summary

Simulator

Data Analysis

Nonstationary, stochastic

Wind Velocity

Time

Wind Velocity

Time
Summary

Simulator

Nonstationary, stochastic

Data Analysis

Temporal coherence via PDDs
Summary

**Simulator**

- Nonstationary, stochastic

**Data Analysis**

- Fit joint dist. to NWTC data

**Temporality coherence via PDDs**

- Wind velocity vs. time
- Phase difference distribution
- Concentration distribution
Summary

**Simulator**

- Nonstationary, stochastic
- Temporal coherence via PDDs

**Data Analysis**

- Fit joint dist. to NWTC data
- SDOF loads extrapolation
- 28.3% increase
Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 1106401; by the U.S. Department of Energy (DOE), Office of Science (OS), Office of Workforce Development for Teachers and Scientists, OS Graduate Student Research (SCGSR) program; by the U.S. DOE under Contract No. DE-AC36-08GO28308 with NREL; by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.
Thank you! Questions?

Simulator

- Nonstationary, stochastic
- Temporal coherence via PDDs

Data Analysis

- Fit joint dist. to NWTC data
- SDOF loads extrapolation

28.3% increase
Empirical histograms don’t match IEC distributions