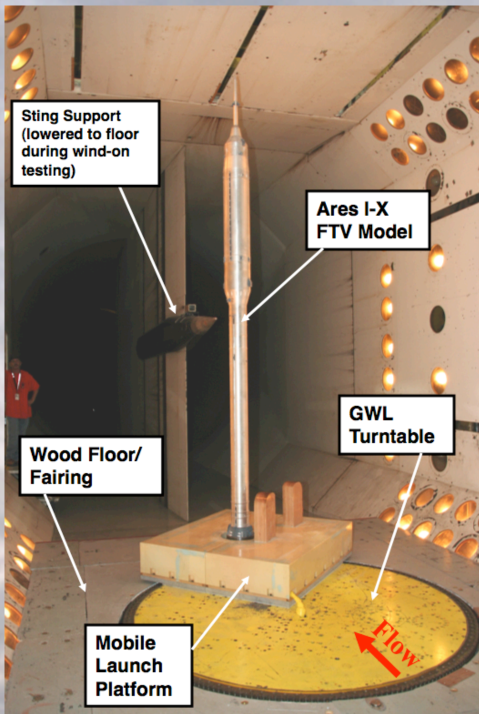
Launch Vehicle Ground Wind Loads - Test and Analysis

Perspective and recommendations from the Ares I-X GWL program



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November 17, 2011

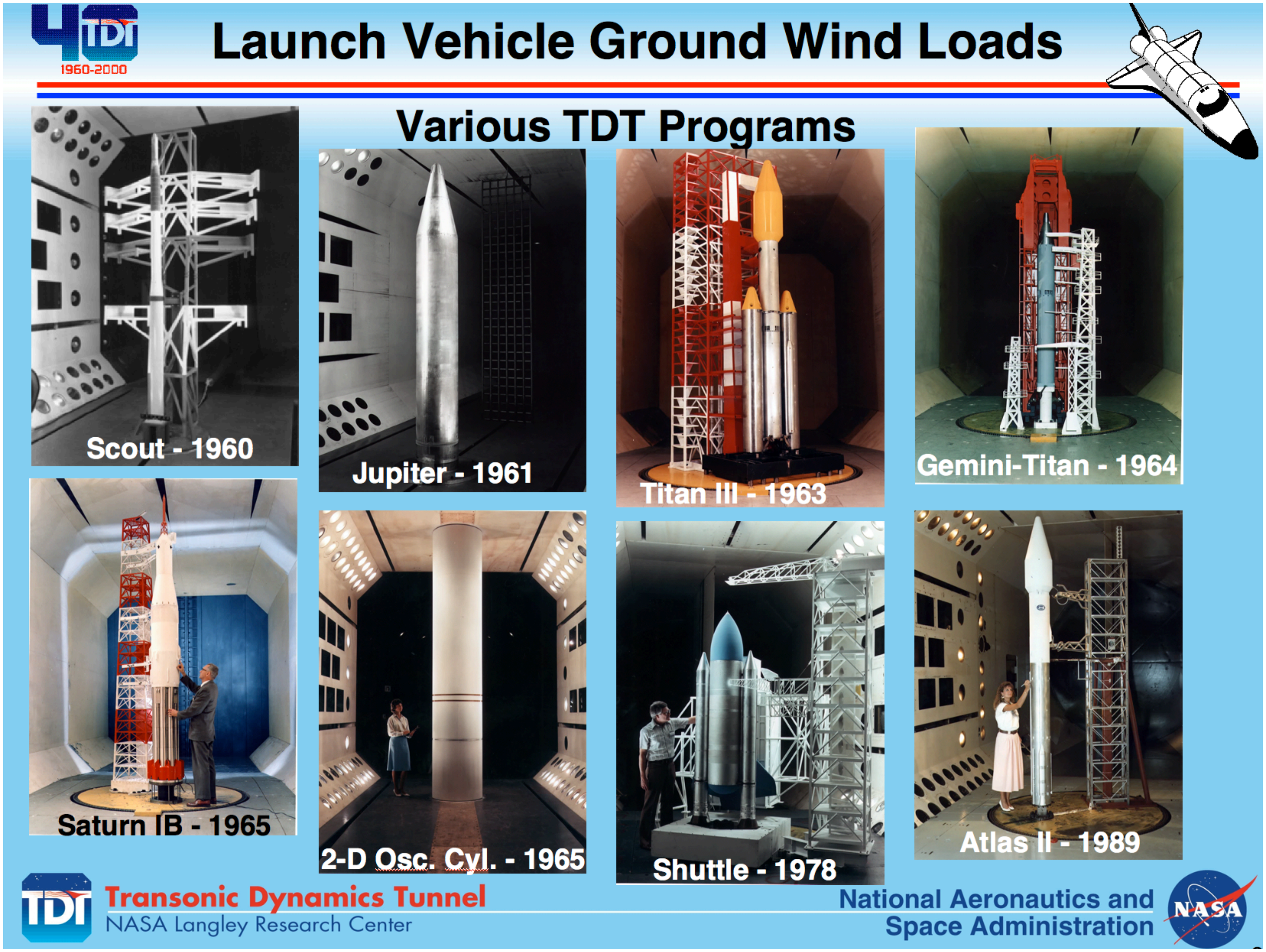
Outline

- Background
- Ground Wind Loads (GWL) – Steady and Dynamic
- Steady Loads – Analysis and Test
- Steady Loads – Lift-off Loads
- Dynamic Loads – Source and potential impacts
- Dynamic Loads – Analysis
- Dynamic Loads - Testing
- Ares I-X – Sample results
- Steady Loads – Recommendations
- Dynamic Loads – Recommendations
- Publications

Background

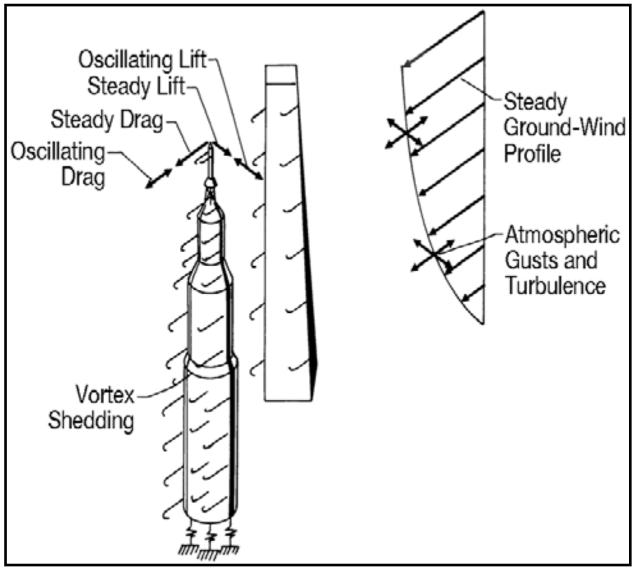
- **Perspective based upon:**
  - Ares I-X GWL effort at AB (2006 – 2009) and follow on reporting and analysis
    - Provide experimental data GWL/WIO data to support Ares I-X FTV program
    - Participate in and support risk assessment for rollout and on-pad stay
  - Review of available literature, data, and test reports for GWL's
  - Discussions with industry and government representatives
- **Challenges and limitations**
  - Lack of available electronic data for analysis development and correlation
    - especially full-scale data (limited to summarized data in few reports)
  - Lack of critical details and insight in many historical NASA and industry reports
  - Most NASA model testing was performed in the 1960's and 1970's – loss of expertise and memories
  - Proprietary issues – unclear what full-scale and test data exist for many launch vehicles
  - No consensus on analysis methods at start of Ares I-X effort – later came to conclusion that some being used were vehicle specific and/or incorrect or inadequate for dynamic GWL's
  - Mr. Keller and Mr. Ivanco (and AB) had very limited knowledge in the area of GWL's, especially dynamic wind-induced loads
    - Decided to start from scratch with open mind on model testing, and full-scale analysis and data acquisition
  - There was no shortage of opinions and entrenched ideas on the topic of GWL's
    - "No issue" "Analysis worked for Shuttle" "Need damper on rollout" etc…..

Background – Some Past GWL tests in TDT



Ground Wind Loads

- **Launch vehicle typically exposed to winds during rollout to and while at launch pad**
  - Large variation in exposure times and local structures
- **Three components**
  - Dynamic loads due to vortex shedding (WIO) (primary effort)
    - Most difficult to predict. Sensitive to many parameters
  - Steady loads: lift and drag due to steady winds (secondary)
  - Dynamic loads due to turbulence and gusts (analysis)



- **Vortex shedding (Von Karman vortex street)**
  - Flow separation and periodic vortices highly dependent on Re and Strouhal (S_t) number ($f_s D/V$)
  - Strouhal number typically assumed ≈ 0.2 – 0.3 (2-D cylinder) but can vary, especially at higher Re, where flow is more 3-D (tip), and during transition from laminar to fully turbulent flow
  - Important to simulate full-scale flow transition (subcritical=>transcritical=>supercritical)
- **Wind Induced Oscillations (WIO)**
  - Frequency of vortex shedding equal or close to vehicle bending mode (**typically** 1st bending)
  - Sometimes referred to as "lock-in" => Motion drives shedding frequency
  - Dynamic loads can be much greater than steady loads: fatigue, failure, operational concerns
  - Observed in wind tunnel testing and large full-scale structures (buildings, smokestacks, etc.)

Ground Wind Loads - Steady

- **Loads prediction/analysis suitable for many configurations**
  - Use or adjust existing test data for similar configurations
  - Textbook values for cylinder(s)
  - Use or adjust existing data for effects of launch towers as function of wind direction
  - CFD: Necessary? Practical? Confidence?
  - NASA SP-8008, Prelaunch Ground Wind Loads (1960's NASA Space Vehicle Design Criteria Series) is probably a good initial guide for values for "drag" coefficient
    - C_D = 0.6 (smooth cylinders), = 0.8 (cylinders with conduits), = 1.2 (clustered cylinder-type bodies
  - Estimates with reasonable margin (i.e. 25%) probably sufficient and conservative for steady GWL's analysis

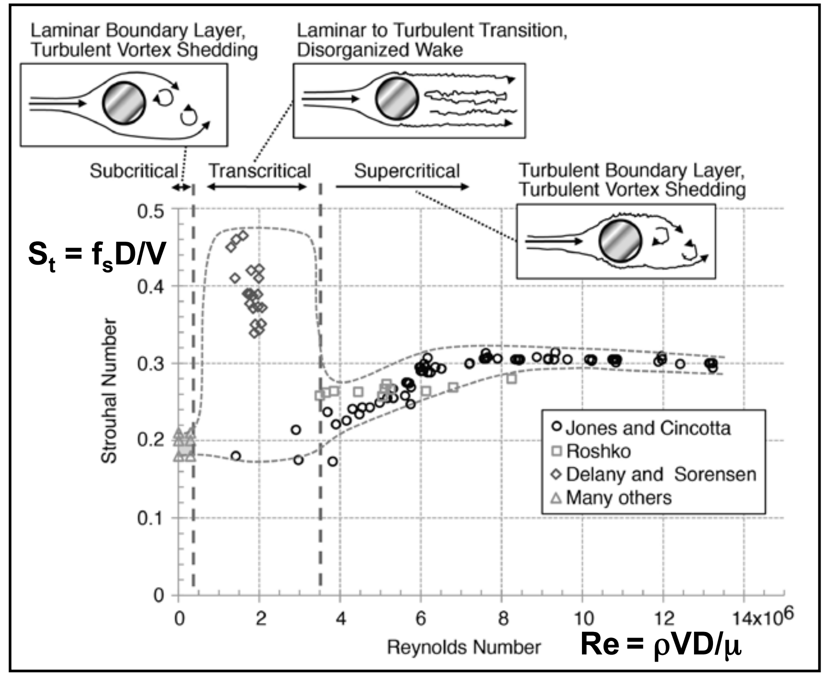
- **Wind-tunnel testing**
  - May be required for unique configurations and/or launch vehicles with small loads margins for wind requirements
  - Limitations: difficult to simulate potential ground wind profile(s) (boundary layer)
    - Wind velocity along length of vehicle can vary significantly from standard wind profile
  - Reynolds Number: Can probably simulate fairly well with proper grit sizing and large scale model. Need to keep flow velocity within incompressible regime ($\approx M < 0.3$)
  - Floor turntable required to vary flow angle efficiently
  - Low to moderate model cost for this type of testing
  - Accuracy: Good for improving confidence in data used for loads analysis
  - Lift-off loads - Can wind tunnel test properly simulate flow characteristics with sufficient accuracy to make this type of test worthwhile?

Ground Wind Loads - Dynamic

- **Concerns and Issues**
  - Wind-induced Oscillation (WIO) can be the largest load component and needs to be considered in design loads analysis
    - Dependent on damping, OML, support structures, and modal/structural characteristics
    - Results from periodic vortex shedding when a Karman vortex street forms in the wake of a launch vehicle – oscillatory "lifting" force perpendicular to wind direction
    - Vehicle response can be large when vortex shedding and vehicle structural mode (typically first bending) are at close to same frequency ("resonant WIO response")
    - Potential for higher oscillatory loads if "lock-in" occurs (structural response alters frequency and correlation of shed vortices)
    - Loads can be great enough to damage vehicle or affect ground support and guidance systems
    - Typically 1st bending modes of concern but examples exist for 2nd bending modes (Ares I-X)
    - How much of vehicle length is synchronized during vortex shedding??
    - Simple fix: **Stay/damper system**. Also - structural/aero asymmetries can limit critical wind angles
  - Potential concerns if:
    - Vehicle is long and slender
    - Long sections of constant diameter (potential for large regions of synchronized shedding)
    - Low damping ($< \approx 1\%$ C/Cc) in critical bending mode(s) (no issue if $>2\%$ to 3%)
    - Conduits/protuberances can fix shedding location and result in stronger oscillatory forces
    - Strouhal number ($St = f_s D/V$) at high Re wind conditions has value of 0.20 to 0.30.
  - Response to gusts and turbulence – dynamic response tends to be small and/or damps out fairly quickly. Response is more random in nature. Can be significant if combined with high steady and/or WIO induced loads.

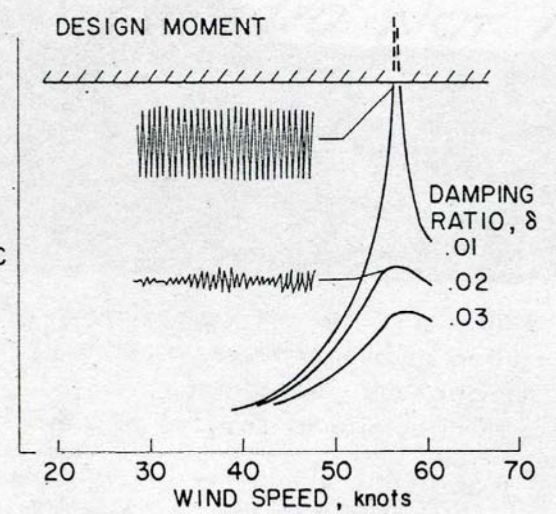
Strouhal Number and Damping

- **Strouhal number and vortex shedding**
  - Vortex shedding highly dependent on boundary layer at point of separation and therefore Re
  - Frequency of shedding described by Strouhal number (0.2<St<0.3 for high Re flows)
  - Stronger periodic shedding tends to occur at Re >3.5 x 10^6
  - Matching full-scale Re during sub-scale testing is important but often difficult
  - Grit can be applied to model to increase effective Re so full transition occurs at lower actual Re.



- **Importance of damping**
  - Experimental and full-scale data has clearly demonstrated that damping is critical parameter in determining vehicle response at or near resonant vortex shedding condition
  - Damping lower than 1% can be cause for concern
  - Damping greater than 2% - 3% will likely result in vehicle responding at resonant frequency but in random manner at lower amplitude
  - Inherent damping can be below 1% so damper is default recommendation for vehicle exposed to winds

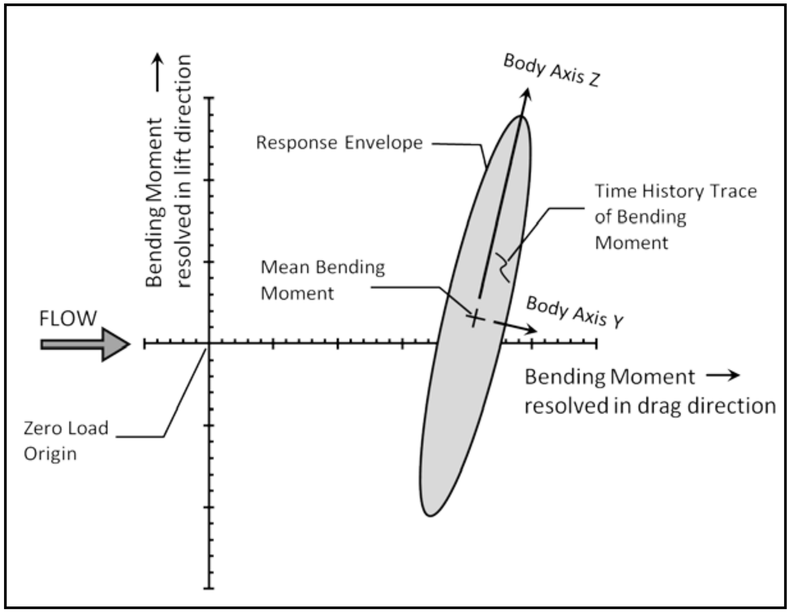
S-V GWL Data (1967)



Ground Wind Loads – Response Envelope

- Bending moments used to illustrate vehicle response due to lift and drag forces
- Response envelope illustrates load components viewed from above and typical of data from GWL test program
- Shaded area represents a notional time history trace of bending moment at base (or a point) of vehicle
- Can typically assume that this also represents a typical time history trace of deflection

Components of Bending Moment



- Important to realize that the magnitude of the dynamic bending moment loads do NOT equal the magnitude of the applied aerodynamic loads
- Dynamic loads (bending moments) result primarily from the inertia forces associated with the dynamic response of the structural modes of vibration
- For lowly damped structure, the resulting structural loads will far exceed the applied loads if the forcing function contains dynamic content close to the natural mode of vibration
- Due to structural asymmetries, a vehicle will respond in the modal axes and not in the direction of the dynamic lifting force being applied to the vehicle

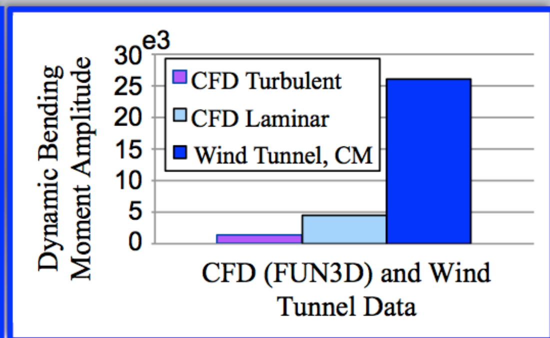
Dynamic GWL's - Analysis

- **Analysis options and challenges**
  - CFD is currently not up to the task due to the large regions of separated flow and critical nature of locating separation point/line along vehicle
    - Effects of conduits and protuberances, wind profile, turbulence all increase challenge
    - Launch tower and any other nearby structures
    - Large matrix of wind speeds and direction needed to be analyzed
  - MATLAB based method developed by Tom Ivanco may be able to "bound" the resultant wind-induced steady and dynamic loads
    - Result of requirement to be able to predict worst case WIO loads caused by vortex shedding
    - Vehicle dynamic structural model required
    - Aero forcing function based on experimental results for 2-D cylinders with corrections applied for 3-D tip effects
    - Wind profile and atmospheric turbulence can also be simulated
    - May have advantages over wind-tunnel testing due to inclusion of wind profile and turbulence effects
    - Good correlation with wind tunnel results from Ares GWL wind-tunnel tests in Transonic Dynamics Tunnel (TDT)
    - May be very useful in conducting trade studies to gain insight into potential launch restrictions or need for vehicle stabilization (stay/damper)
    - Similar methods known to be used or being developed by industry
    - Limited to fairly simple configurations – no modeling of conduits, protuberances, multiple cylinders, nearby structures, etc. (i.e. winged vehicle at top of vehicle)
    - IT IS A TOOL!! Know how it works and its limitations before use!

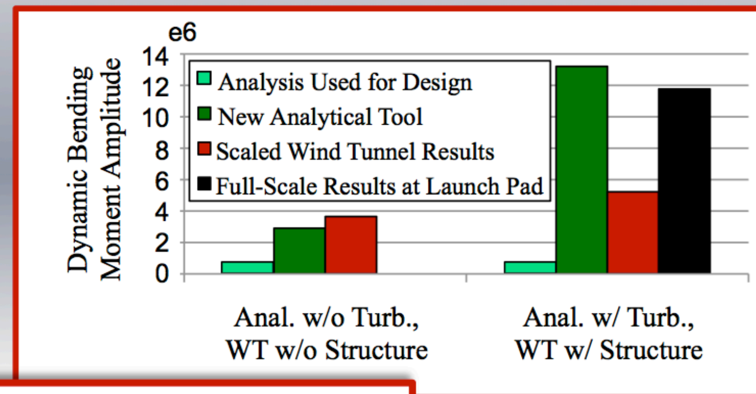
Analysis Method - Highlight DRAFT

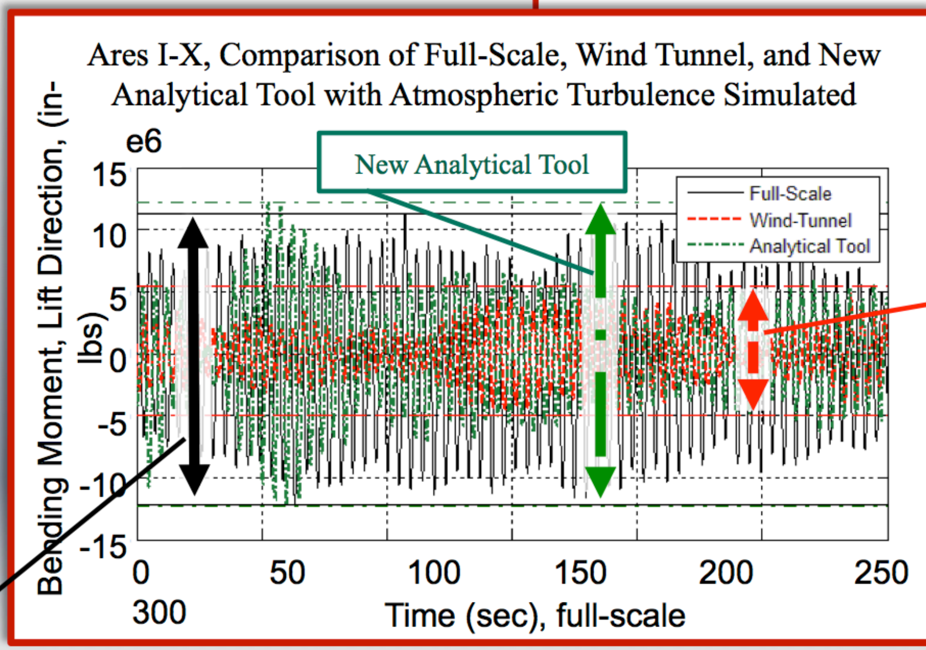
DEVELOPMENT OF AN AEROELASTIC GROUND WIND LOADS ANALYSIS TOOL AND COMPARISON WITH WIND TUNNEL AND FULL-SCALE DATA

Checkout Model, Comparison of Traditional CFD and Data



Ares I-X, Comparison of Analysis and Data





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Analysis Method - Text

DEVELOPMENT OF AN AEROELASTIC GROUND WIND LOADS ANALYSIS TOOL AND COMPARISON WITH WIND TUNNEL AND FULL-SCALE DATA

DRAFT

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Research Objective: The objective of this research was to create and validate an aeroelastically-coupled ground wind loads (GWL) analysis tool for launch vehicle design. Space vehicle design criteria specify simple analysis techniques to use for preliminary design. These simple methods do not provide adequate resolution to gain insight into launch restrictions or needs for vehicle stabilization (damper). The goal of this research effort is to provide an accurate prediction of wind induced oscillation (WIO) loads caused by vortex shedding. An accurate prediction enables identification of launch restrictions or stabilization needs during design of the vehicle prior to the availability of wind tunnel data.

Approach: The newly developed analysis tool was constructed within MATLAB with the vehicle structure represented by a sum of modal contributions. Externally applied aerodynamic forcing is calculated based upon wind tunnel results of two-dimensional cylinders with corrections applied for three-dimensional tip effects. Aerodynamic forces are then normalized by mode to form generalized forces, and the generalized coordinate response solution is determined in the time domain through the use of a state-space Runge-Kutta routine. A time history of dimensional displacement is output from the modal analysis. Vehicle loads are then derived by converting dimensional modal displacement into loads through the use of FEM analysis or beam theory. Atmospheric turbulence and boundary layer distributions can also be simulated through the appropriate modules. If enabled, turbulence simulation is achieved by altering the bandwidth and spectral content of the oscillating lift forces.

Accomplishment Description: The newly developed analysis tool is easily configurable to various vehicles with various geometries and Reynolds numbers exposed to smooth flow or atmospheric turbulence and boundary layers. Run times vary depending upon the level of detail simulated, but range from several minutes to several hours when run on desktop or laptop computers. Therefore, trade studies in early design can be easily accomplished to produce a "GWL friendly" vehicle or enable early identification that stabilization is required. As demonstrated in the graphics, when compared to wind tunnel and full-scale experimental data this analytical tool provides the most accurate results of all analysis methods applied to the Ares vehicles to include sanctioned analyses used for vehicle design and Navier-Stokes CFD attempts. Furthermore, this tool is more accurate at predicting the full-scale Ares I-X WIO response in actual turbulent environments than wind tunnel data acquired in smooth air. The analytical tool results shown in the graphics were calculated prior to vehicle rollout.

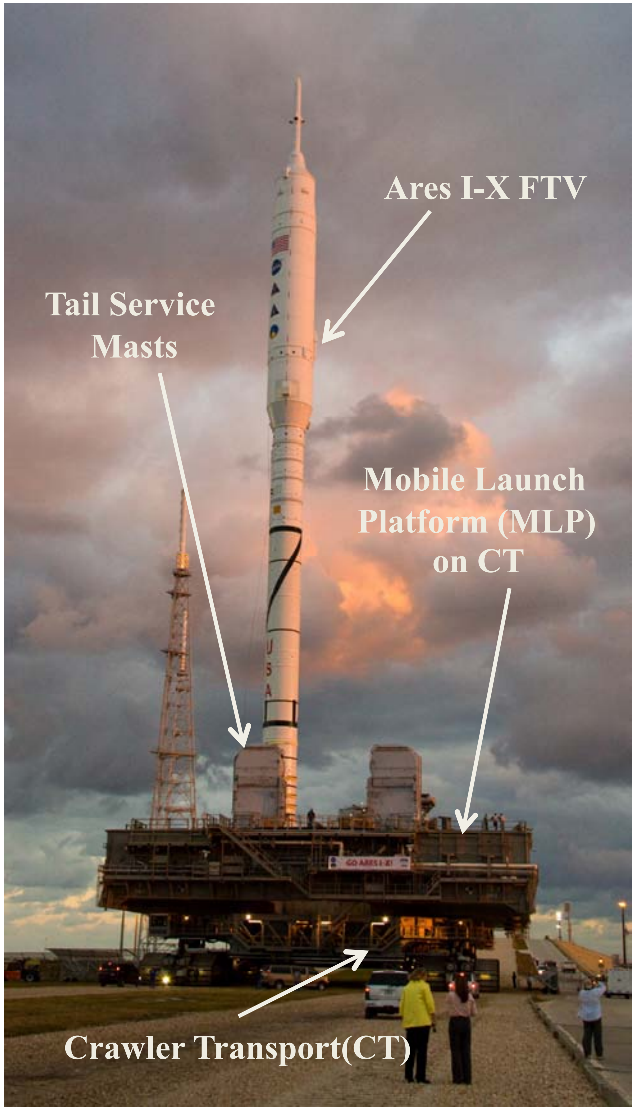
Significance: This newly developed analytical tool can be refined in order to be available to NASA and US Industries for future launch vehicle designs. Availability of this tool will enable rapid low-cost analysis and trade studies early in design cycles when solutions to such problems are still economically viable and will impose minimal schedule impacts. Additionally, availability of this tool could have prevented the "11th hour" changes to the Ares I-X operational environments resulting from inaccurate and un-conservative WIO design loads. Furthermore, turbulence modeling within this new analytical tool offers a quantitative explanation to discrepancies observed between full-scale data and scaled wind tunnel results.

Future Plans: Future plans include additional refinement of the prediction code to optimize low amplitude displacement at high Reynolds numbers indicative of the launch vehicle problem. Additionally, code refinement and documentation will enable external distribution.

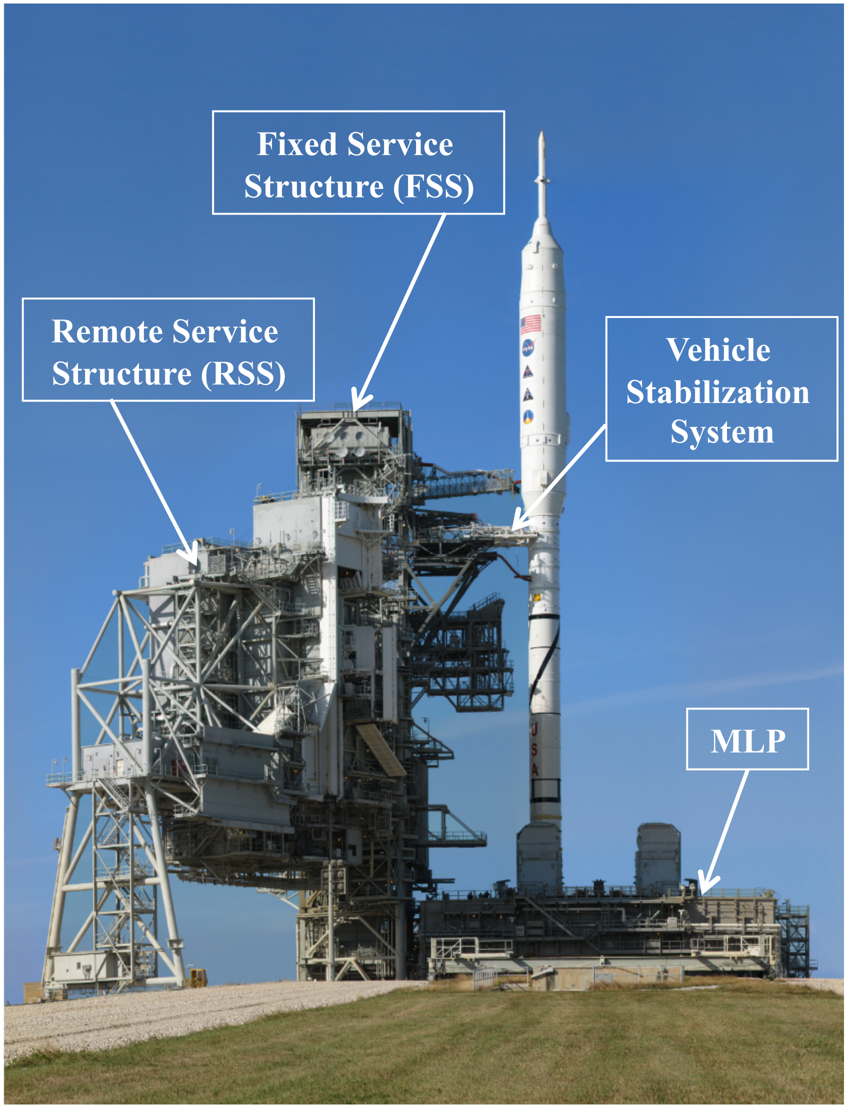
Dynamic GWL's – Wind-Tunnel Testing

- **Advantages**
  - Wind-tunnel model can be dynamically aeroelastically scaled to reasonable simulation of actual vehicle
    - Typical method for scaling dynamic aeroelastic models (except flow incompressible)
    - Mass and stiffness distribution, OML and protuberances
  - Can include simplified rigid simulation of launch tower and/or other nearby structures
  - Ability to test a wide variety of wind speeds and directions (floor turntable in TDT)
  - Measure steady and dynamic loads/moments/response as well as steady/unsteady pressures
  - Identify potential critical wind speed and angles
  - Variable damping is possible with internal damper or even simulation of external damper
  - Simulate full-scale Re thru full surface gritting (Re limited by incompressible flow constraint)
  - May have significant value for evaluating critical parameters and correlation/validation with analysis method(s)
  - Steady loads data as well (balance that can measure steady and dynamic loads), strain gauges?
- **Disadvantages/Limitations**
  - May not be possible/practical to simulate wind profile and/or atmospheric turbulence
    - Can have significant effect on strength and broadband nature of vehicle response
    - Wind profile – can effect length of vehicle with synchronized shedding (although actual wind profile is variable and ever changing)
  - Limitation on simulation of launch towers and nearby structures
  - Wall effect and tunnel blockage issues?
  - Cannot simulate variability of wind speed and direction that occurs in nature – actual wind speed and direction can change significantly within a few cycles of vehicle oscillation
  - Cost effective and necessary if stay/damper is planned for full-scale vehicle??
  - Use an analysis method instead - if confident can be applied to configuration?

Ares I-X Flight Test Vehicle



Rollout to KSC LC-39B



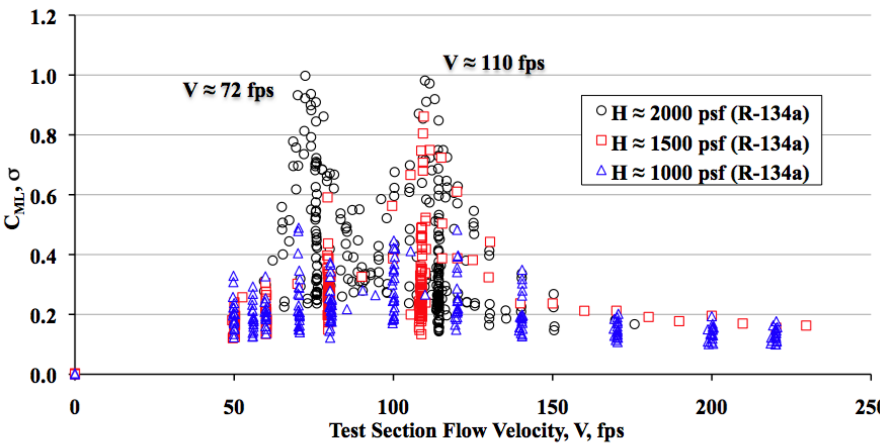
On Pad at KSC LC-39B

GWL Checkout Model

- **Model design based on early Ares I OML and FEM**
  - Simple, all metal construction. Internal ballast weights.
  - 4.05% length scale (Length ≈ 13 feet)
  - 5.26% diameter scale => match full-scale Re
    - Assumed minimal effect on aero
  - Dynamically AE scaled for 1st bending mode WIO
  - Simplified protuberances
  - No asymmetric base stiffness
  - Designed for minimal inherent structural damping (<1%)
  - Simulated rollout (no launch tower)
  - Research oriented test – effects of Re, protuberances, grit, flow azimuth
  - Instrumentation; base bending moments, accelerometers, steady/ unsteady pressures

GWL Checkout Model in TDT

- **Test Results**
  - 2 strong WIO conditions (16 Hz)
    - 10 and 15 knots full-scale wind velocity
  - Stronger WIO response at higher Re
  - WIO related to protuberance orientation wrt flow
  - "Lock-on" observed for WIO
  - Orthogonal 1st bending modes (16.1 and 16.6 Hz)
  - "C_D" = 0.4 – 0.8 depending on flow azimuth



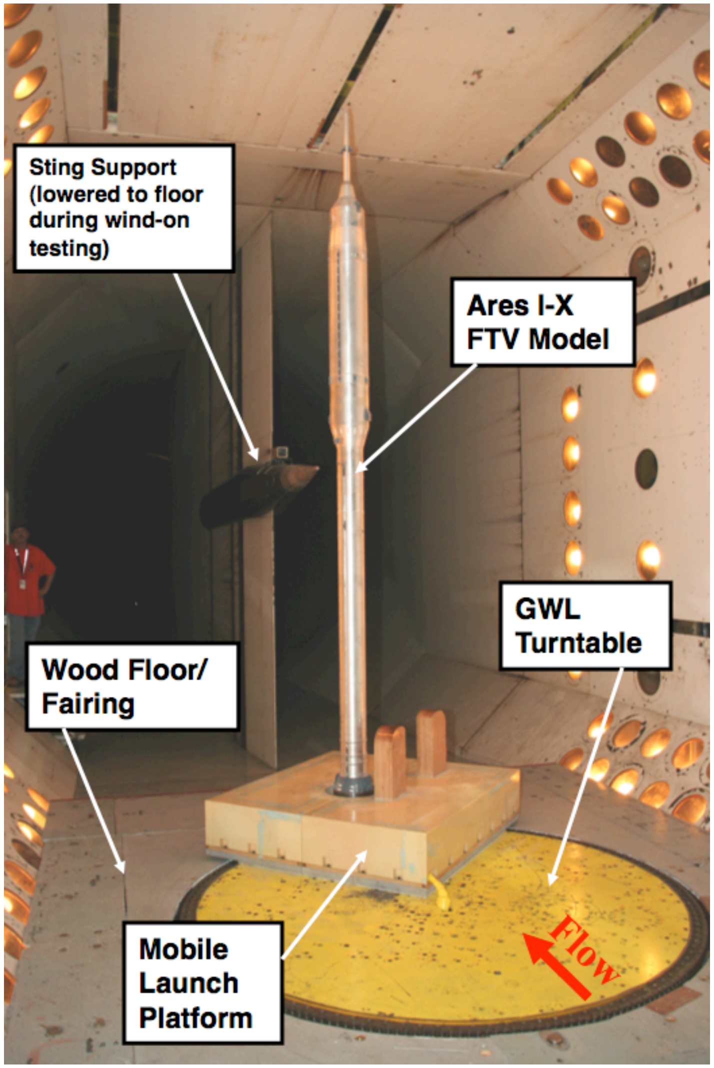
- **Test Conducted in TDT: March/April 2007**

Ares I-X GWL Model

- **Model design based on Ares I-X OML and FEM**
  - Planform and layout very similar to GWL CM
  - Aluminum tube construction. Internal ballast weights.
  - 4.05% length and diameter scale (Length ≈ 13 feet)
  - Reynolds number ≈ 30% of full-scale at critical conditions
    - Surface grit applied to model surface to simulate full-scale Re flow conditions (based on Szechenyi, J. Fluid Mech (1975)
  - Dynamically AE scaled for 2nd bending mode WIO
  - Increased details on all components
  - Asymmetric base stiffness simulation - balance
  - Minimal damping targeted (internal variable damper)
  - Included KSC Pad 39B launch structures and MLP
    - Rigid. Aerodynamic interference only
  - Rollout, and On-pad configurations (stay and launch)

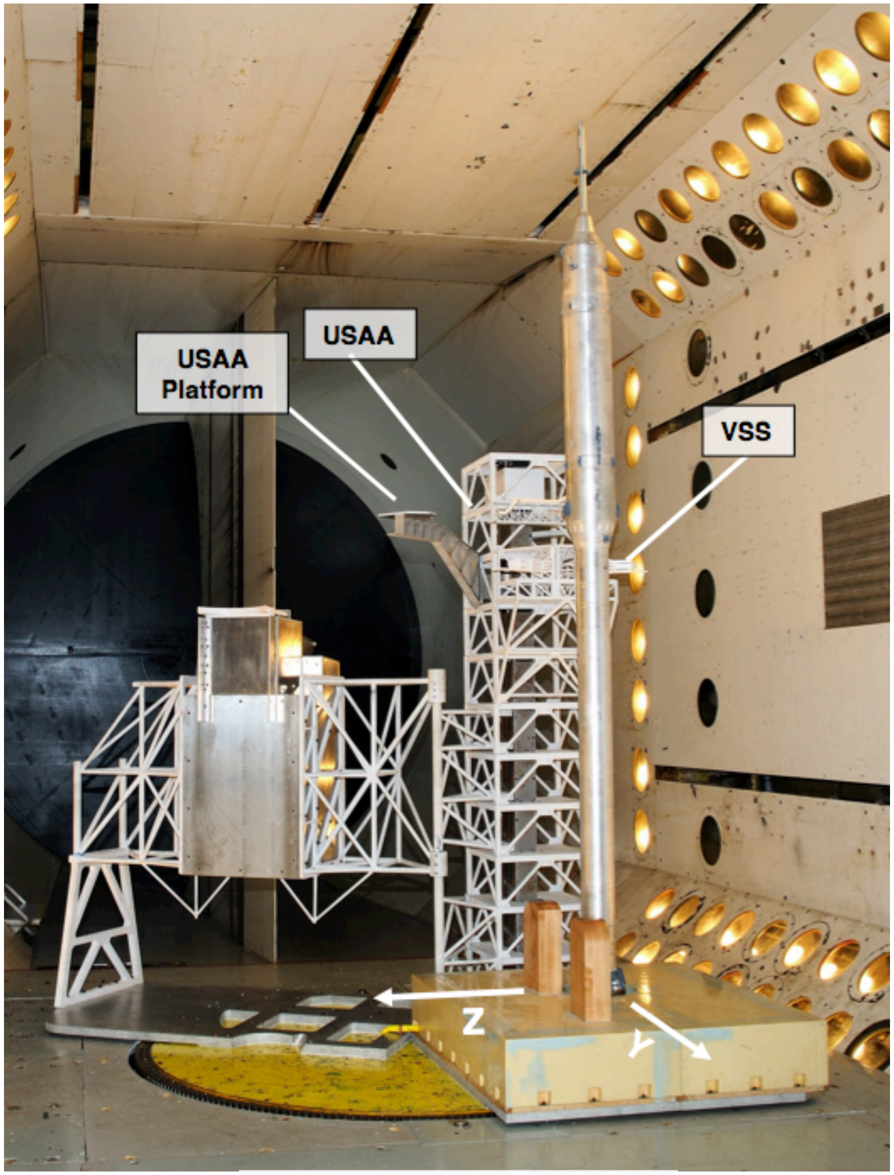
- **Instrumentation**
  - Balance to measure base bending moments
  - Unsteady press. transducers at two US stations (8/station)
  - Vertical rows of 9 accelerometers each along 0° and 90° model azimuth

- **Test Conducted in TDT: August – October 2008**

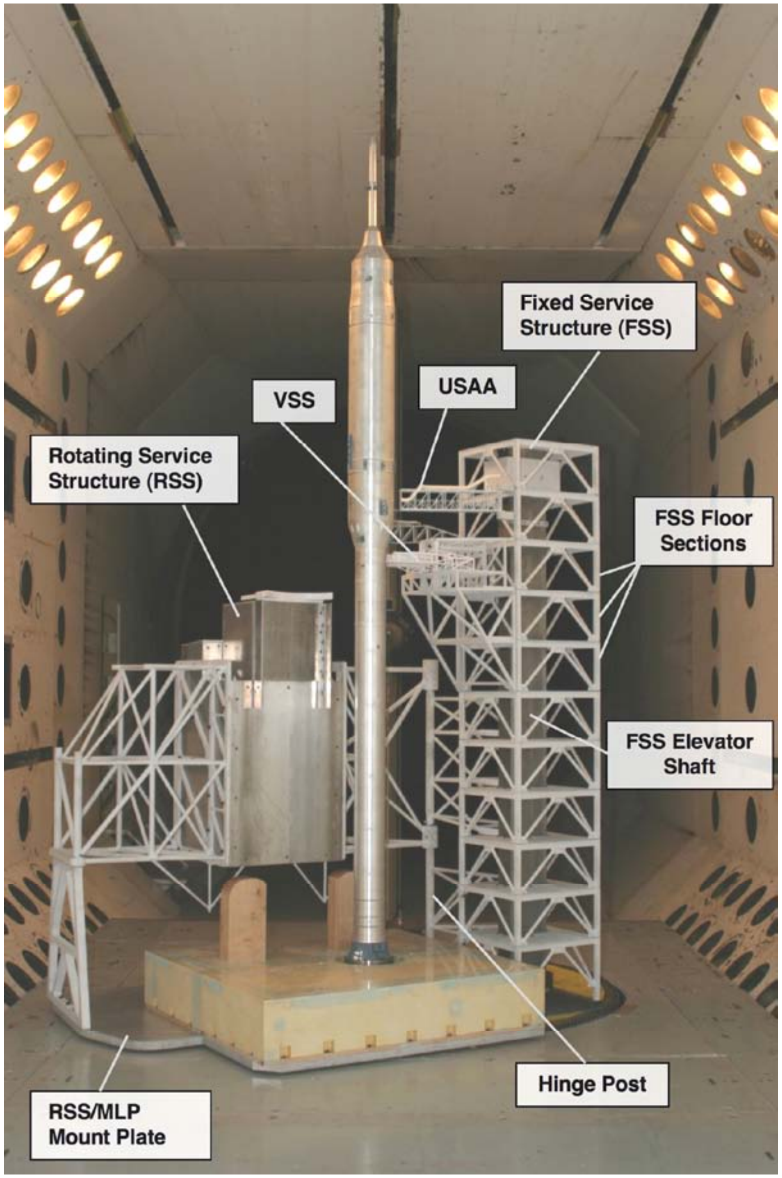


Ares I-X Rollout Configuration

Ares I-X GWL Model – Configurations



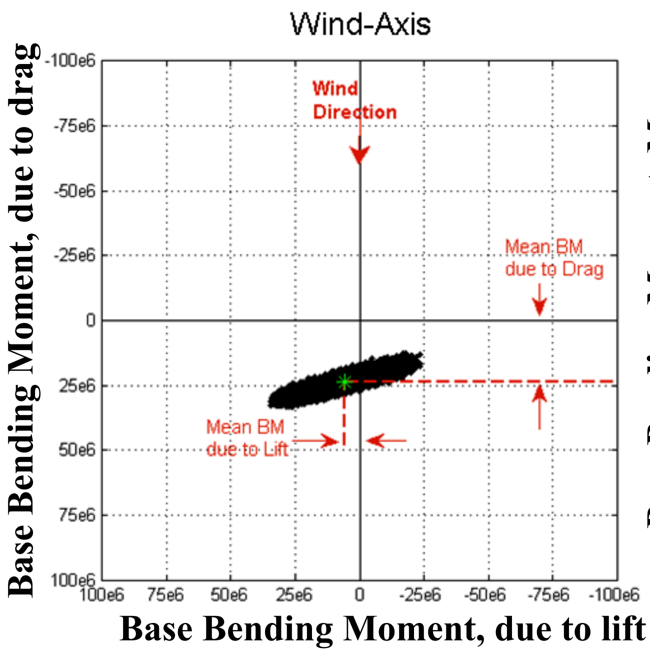
Ares I-X On-Pad Launch

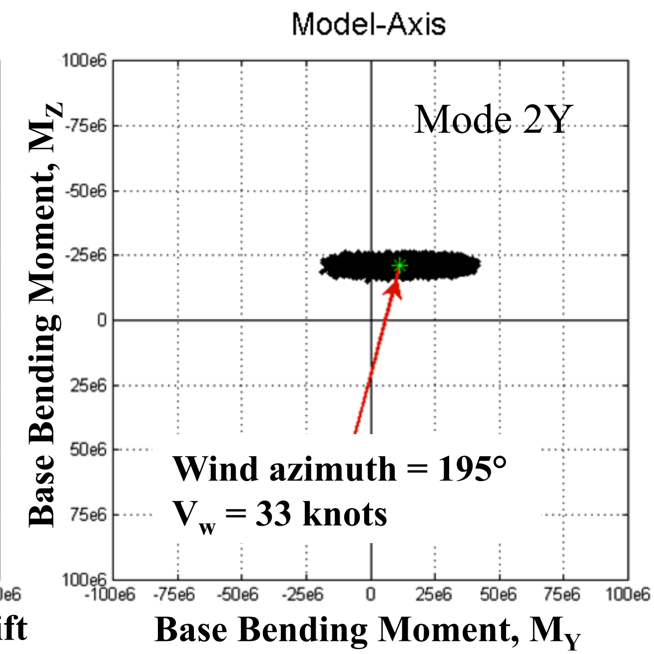


Ares I-X On-Pad Stay

Ground Wind Loads

Ares I-X GWL Model – WIO





<u>Model (Full) Scale. Hz</u>

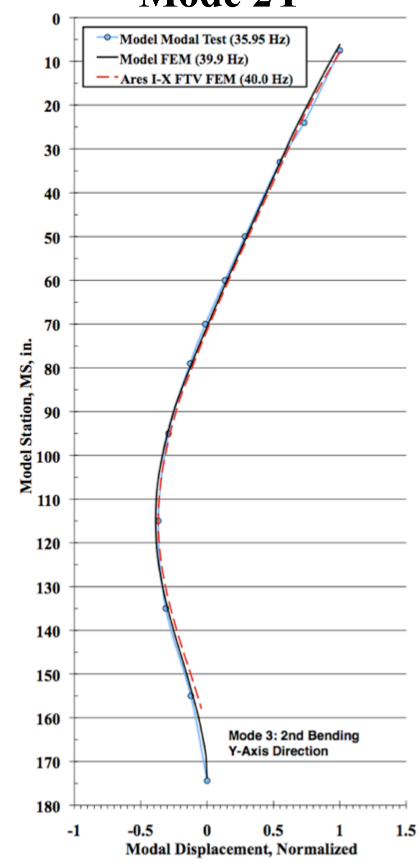
Mode 1Y = 6.7 (0.17)

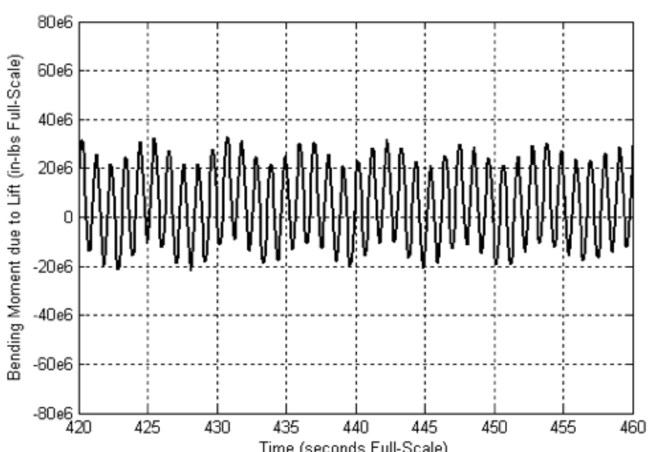
Mode 1Z = 8.3 (0.21)

Mode 2Y = 36.0 (0.92)

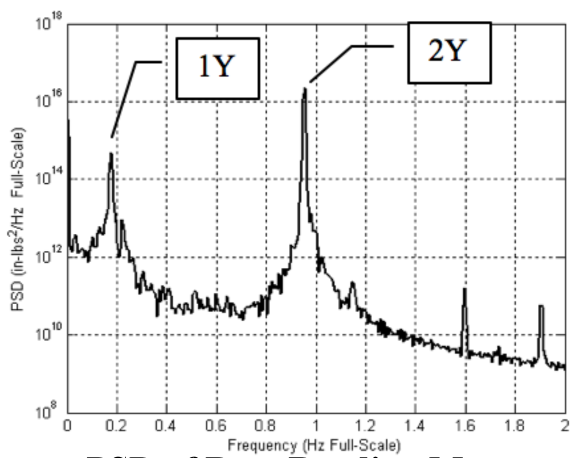
Mode 2Z = 43.0 (1.10)

Mode 2Y





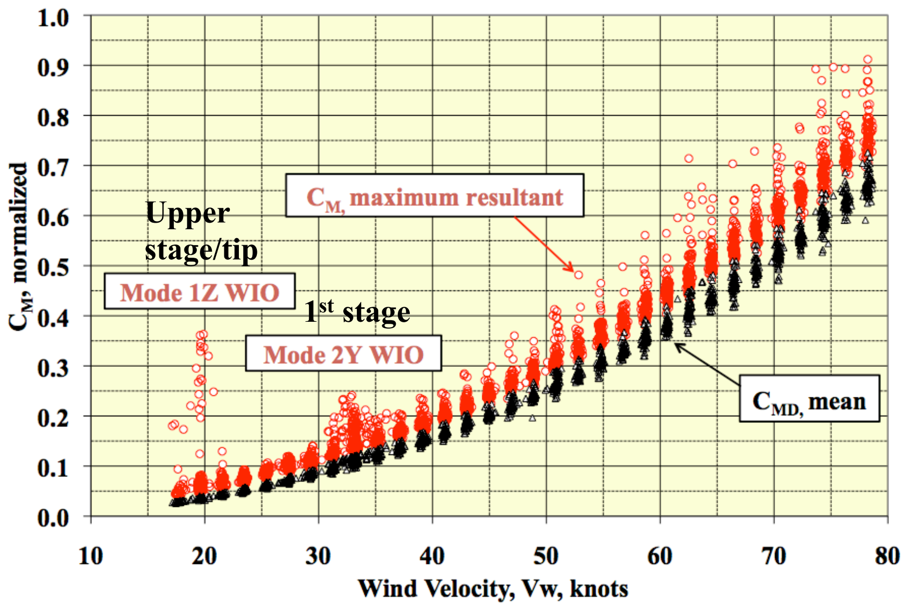
Time History

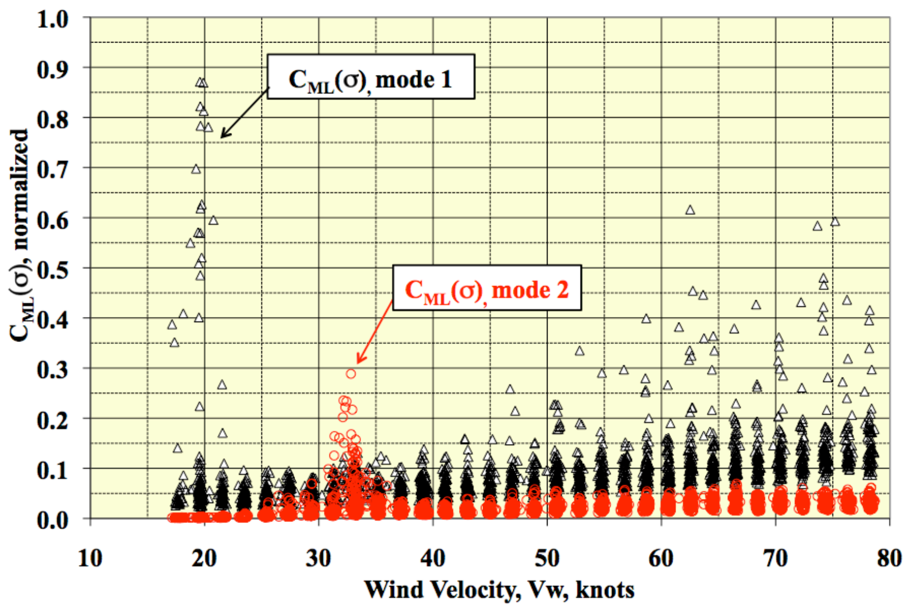


PSD of Base Bending Moment

Ares I-X GWL Model – WIO

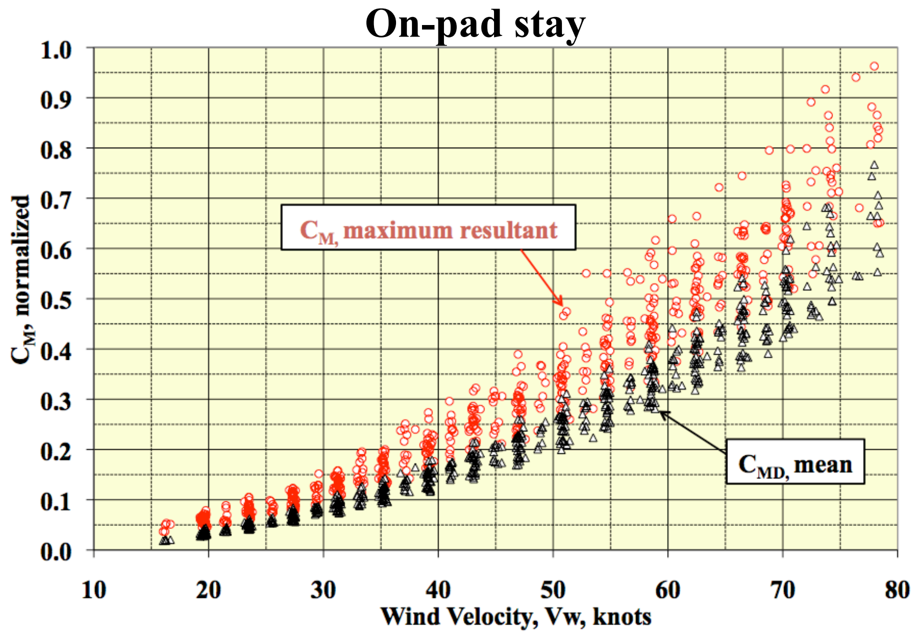
Rollout Configuration – No damper installed

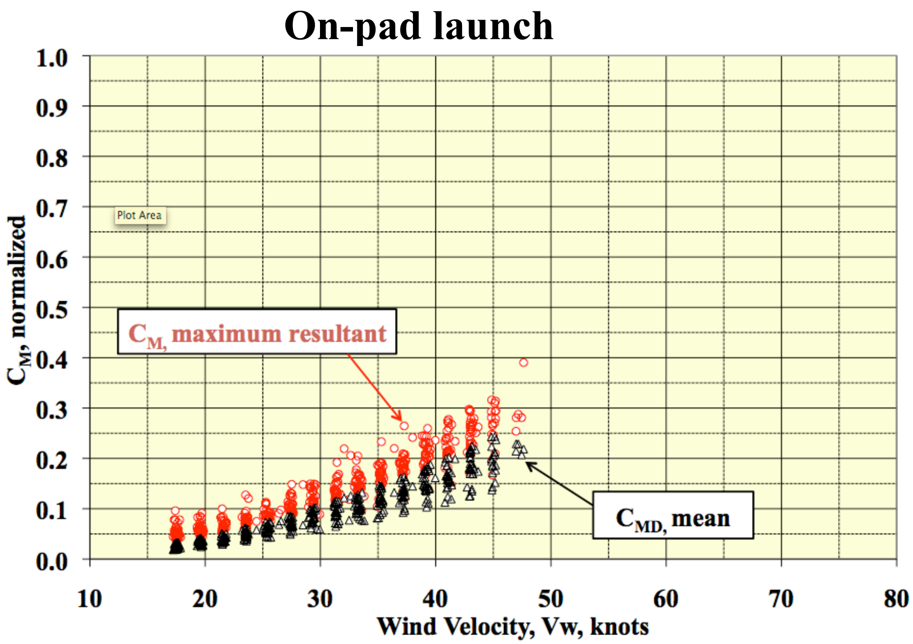




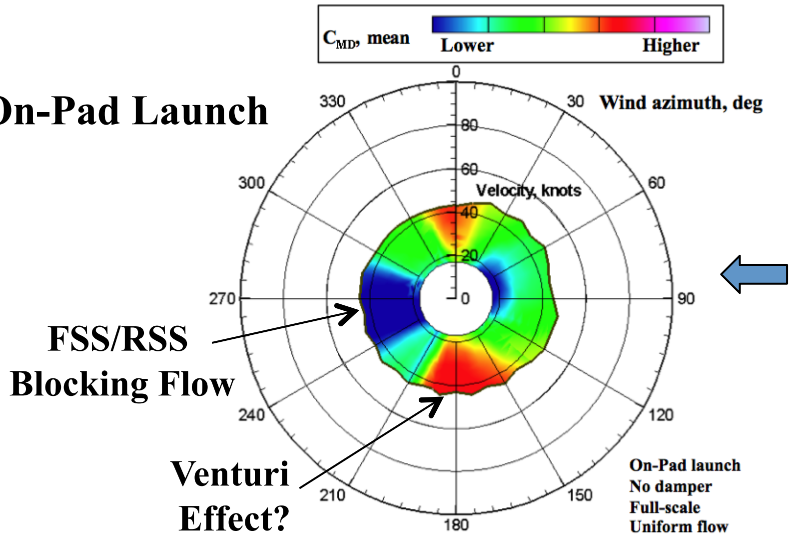
- **Strong WIO encountered for Rollout configuration for 2 wind velocities**
  - 1st bending mode (1Z) WIO at 19 knots (FS)
    - ~ Very narrow wind azimuth (≈ 270°)
    - ~ Upper stage/tip vortex shedding?
    - ~ Dynamic load several factors great than mean loads due to drag
  - 2nd bending mode (2Y) WIO at 33 knots (FS)
    - ~ 1st stage vortex shedding, St ≈ 0.21
    - ~ Dynamic loads approx 2 times mean loads due to drag
    - ~ Azimuth = 195° and 311°
  - Strong sinusoidal response for both WIO
  - Amplitude fell off less sharply with velocity than wind (flow) azimuth
  - WIO seemed to be related to orientation of protuberances and bending mode axes
- **Band-pass filtered data showed contribution of modes to dynamic base bending moments**
  - Confirmed WIO dominant modes although some 1st bending mode response in 2nd bending mode WIO
  - Response at higher velocities due primarily to 1st mode

Ares I-X GWL Model – Test Results





On-Pad Launch



Base Bending Moment due to drag (mean)

Ares I-X FTV – Full-Scale GWLs

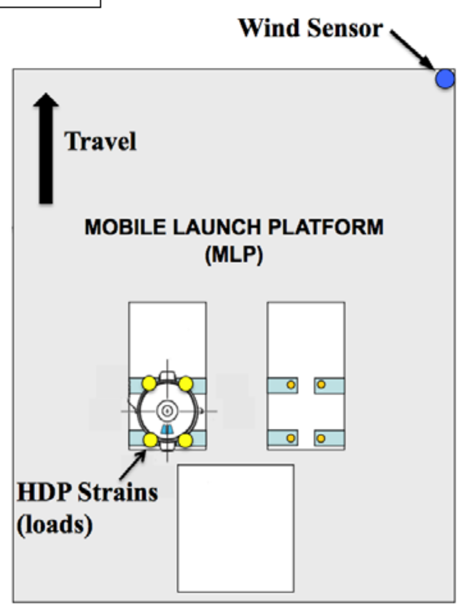
- **Potential unique opportunity to acquire model and full-scale modal and GWL data**

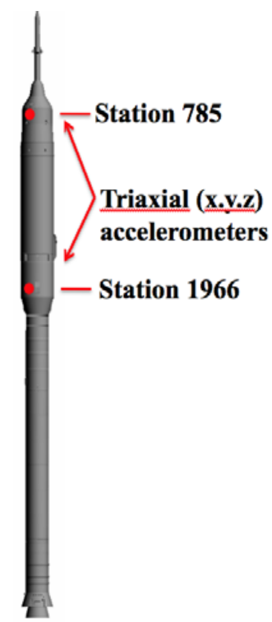
- **Ares I-X FTV Modal Test in VAB**
  - Reasonably good agreement between model (scaled to full-scale) and full-scale frequencies
  - Full-scale damping values less than 1% for critical modes and closer to model values than thought likely

Mode	Full-scale, Hz	Model, Hz.	Full-scale Damping, %Cr	Model Damping, %Cr
1 (1Y)	0.18	0.17	0.85	0.46
2 (1Z)	0.21	0.21	0.43	0.38
3 (2Y)	1.06	0.92	0.29*	0.40
4 (2Z)	1.19	1.10	0.37*	0.74

*Insufficient excitation for accurate determination of representative damping values.

- **GWL data from rollout and on-pad**
  - Wind sensors, vehicle mounted accelerometers, and HDP strain gauges
  - Inadequate and questionable wind data for accurate wind profile
  - CT induced frequency response during rollout
  - Limited on-pad data since VSS attached while on-pad except for arrival and pre-launch
  - Critical winds ID'd during test not encountered
  - Some limited wind induced response observed but small





Steady GWL's – Recommendations

- Estimate Loads using existing data for similar configurations and/or textbook values
  - Rollout
  - On-Pad
  - Launch
- Apply reasonable margin to account for error in loads estimate and/or vehicle load capability
- Estimates for effects of tower and major vehicle protuberances
- Conduct loads analysis – Does vehicle look good for maximum target winds (supported/ unsupported) for launch and on-pad stay when exposed to winds? Margins?
- Decision on whether support (stay) is needed for prelauch loads if one is not already planned
- Wind-tunnel test may be warranted if margins are too small for max winds, etc. or unusual configuration with low confidence in load predictions or potential for large error in load predictions.
- Each vehicle has its own set of specific characteristics and ground ops that will determine how steady GWL's are determined and loads analysis performed.

Dynamic GWL's – Recommendations

- Stay/Damper already planned for launch vehicle?
  - If yes, then wind-tunnel test likely unnecessary if vehicle damping will be above 2% – 3% for critical mode(s) with damper attached – assumes launch vehicle structural model available
  - T-0 damper required? Worth cost and complexity and need for 100% reliability at launch?
  - Rollout? Stay/damper at rollout or only on-pad? Exposure time? Ground ops and risk tolerance?
- If no damper planned
  - Use NASA SP-8008 as starting point for estimate of potential wind-induced dynamic loads – early in design program: GWL's = 1.5 x steady loads (max wind speed)
  - Conduct WIO analysis to attempt to bound potential dynamic loads and determine potential critical wind speeds and flow angles (probably modal based only), assume worst case damping => vehicle should be at final design stage
  - Determine requirement for stay/damper for dynamic loads
  - Wind-tunnel test may be warranted if loads and WIO analysis indicate potential for excessive wind-induced dynamic loads AND/OR
  - Plan on having stay/damper system attached to launch vehicle for critical conditions
  - Level of acceptable risk? Temptation to combine risks or margins of safety.
  - Gust loads? Critical load station on vehicle may not be at base. (i.e. 2nd mode WIO)
- Modal test of vehicle in roll-out and launch configuration to determine damping and accuracy of FEM

Publications

Some good places to start: (as well as literature search on topic)

- "Prelaunch Ground Wind Loads." NASA Space Vehicle Design Criteria, NASA SP-8008, 1965.
- "A Full-Scale Ground Wind Load Program", Foughner and Duncan, NASA N66-32230, 1966.
- "A Wind-Tunnel Study of Ground Wind Loads on Launch Vehicles Including the Effects of Conduits and Adjacent Structures", McCullough and Steinmetz, NASA TN D-2889, 1965.
- ARES Program reports by Ivanco and Keller (as available)
    - ARES-AE-TA-001: Test Summary for GWL Checkout Model, August 2007
    - ARES-AE-TA-003: Database Release for GWL Checkout Model, April 2008
    - ARES-AE-TA-006: Test Summary for Ares I-X GWL Model in TDT, July 2009 (ITAR)
    - ARES-AE-TA-007: Ares I-X GWL Database and Data Analysis Report, April 2009 (ITAR)
- "Wind Tunnel Investigation of Ground Wind Loads for Ares Launch Vehicle", Keller and Ivanco, AIAA-2010-4371, 2010.
- "Investigation of Ground Wind Loads for Ares Launch Vehicles", Ivanco and Keller, AIAA Journal of Spacecraft and Rocketry, Late 2011/Early 2012.
- Various IHS (Information Handling Services) Engineering Data Sciences Unit publications including:
    - ESDU 77032 – Fluctuating Loads and Dynamic Response of Bodies and Structures in Fluid Flows: background information.
    - ESDU 81017 – Mean Forces, Pressures and Moments for Circular Cylindrical Structures: finite length cylinders in uniform and shear flow.
    - ESDU 96030 – Response of Structures to Vortex Shedding.