Wind Tunnel Model and Field Studies to Investigate Stay Cable Vibration and Its Mitigation

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Stay Cable Vibration: Problem?

- Unsettling to bridge user and owner
- Possibility of fatigue in the stay cable attachments

Past Full Scale Observations

- **Vibration occurs when rain is moderate to heavy at wind speeds of 30 mph or less or with no rain at wind speeds beyond 50 mph**
- **Within a certain wind speed range (10-30 mph), two rivulets form**
  - One rivulet on lower, leeward side; one rivulet on upper, windward side
- **Vibration usually in first three modes**
- **Damping of 0.15% of critical for longest cables to 0.59% of critical for shortest cables**

Wianecki (1979); Hikami and Shiraishi (1988); Matsumoto (1992, 1995); WDP (1998); Poston (1998); Main and Jones (1999)

Mechanism

- **"Splitter Plate" action created by axial flow in near wake**
  - Strouhal number decreases (St = nD/U)
  - Upper rain water rivulet enhances flow separation
- **High speed vortex shedding**
- **Vortices are shed in a non-coherent manner along yawed cylinder**
- **Time dependent change in cross-sectional shape of stay-cable due to oscillation of upper and lower rain water rivulets**

Matsumoto et al. (1990, 1995); Yamaguchi (1990); Bosdogianni and Olivari (1996); Matsumoto (1998); Verwiebe (1998)

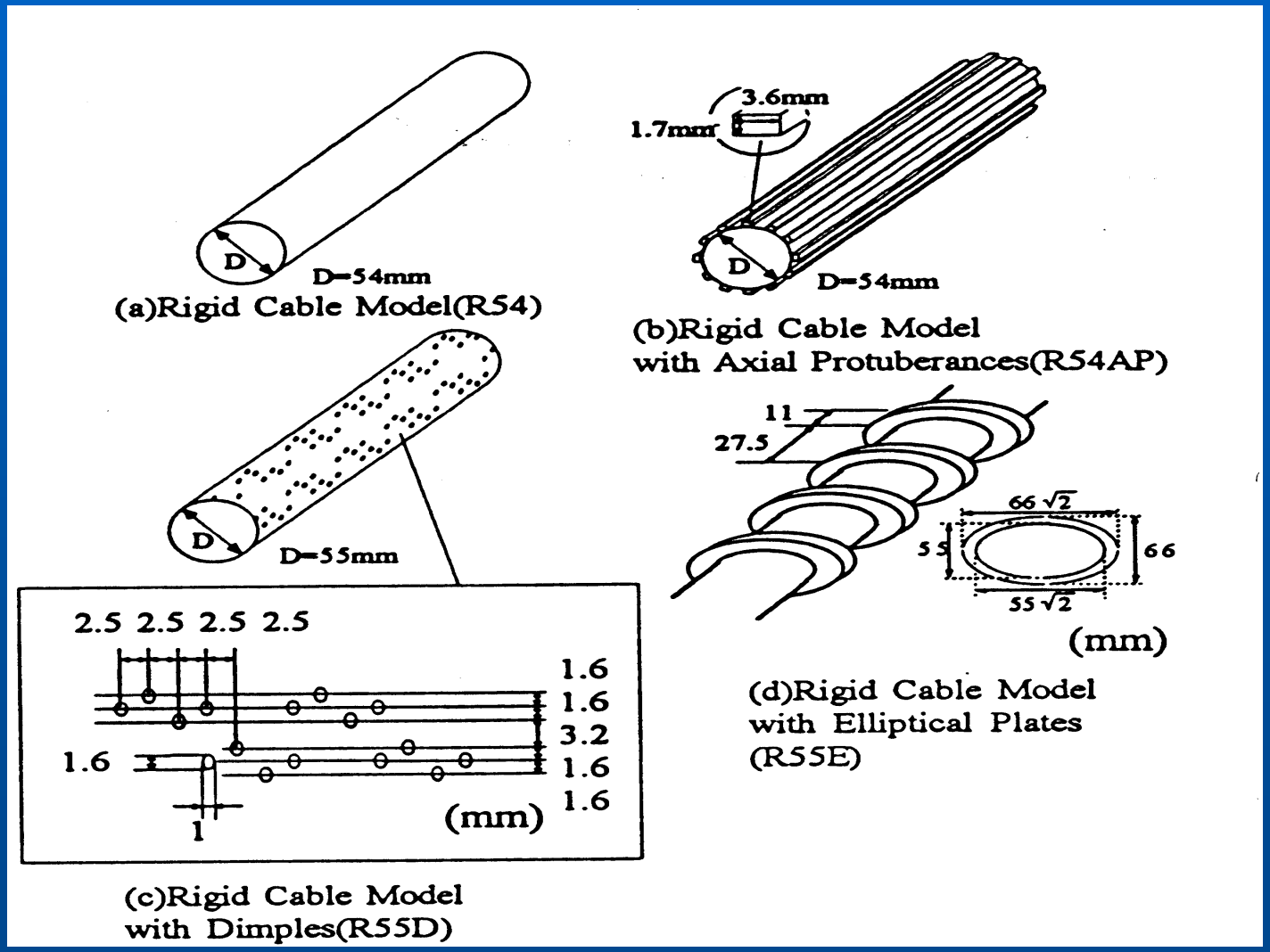
Vibration Mitigation Efforts

- **Wire ropes attached between adjacent stay cables**
- **Mechanical dampers**
- **Stay cable surface modifications**

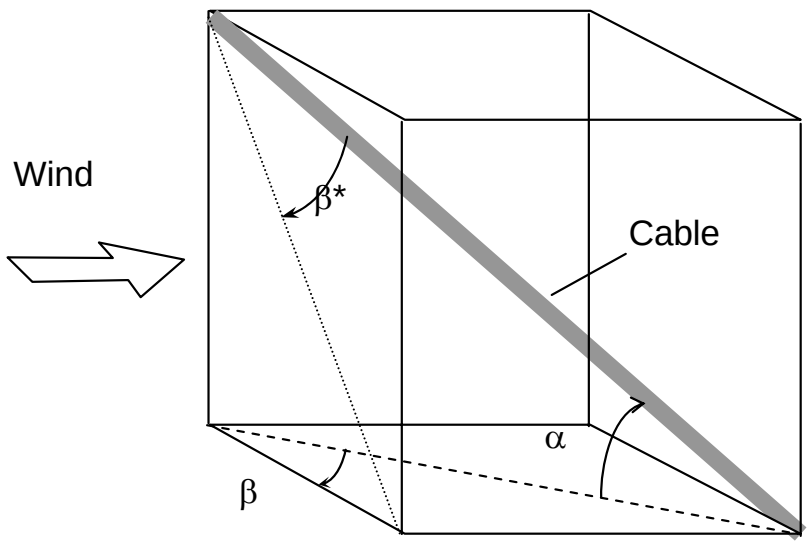
Matsumoto et al. (1997); Main & Jones (2001); WDP (2001)

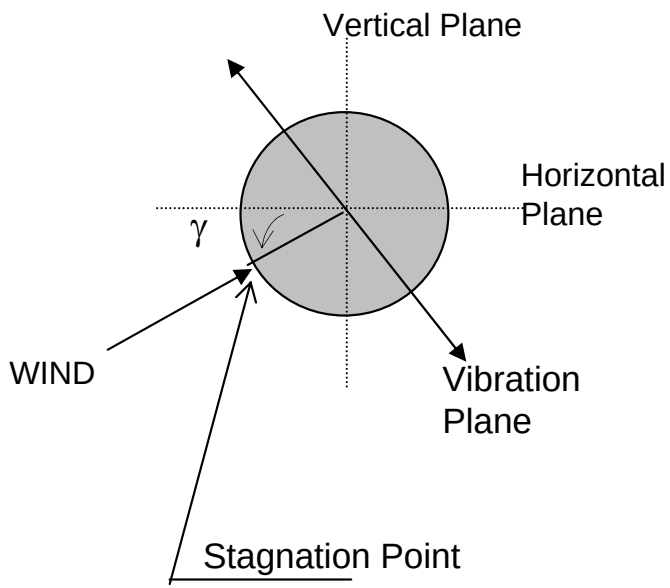
Stay Cable Surface Modifications

Matsumoto et al. (1997)

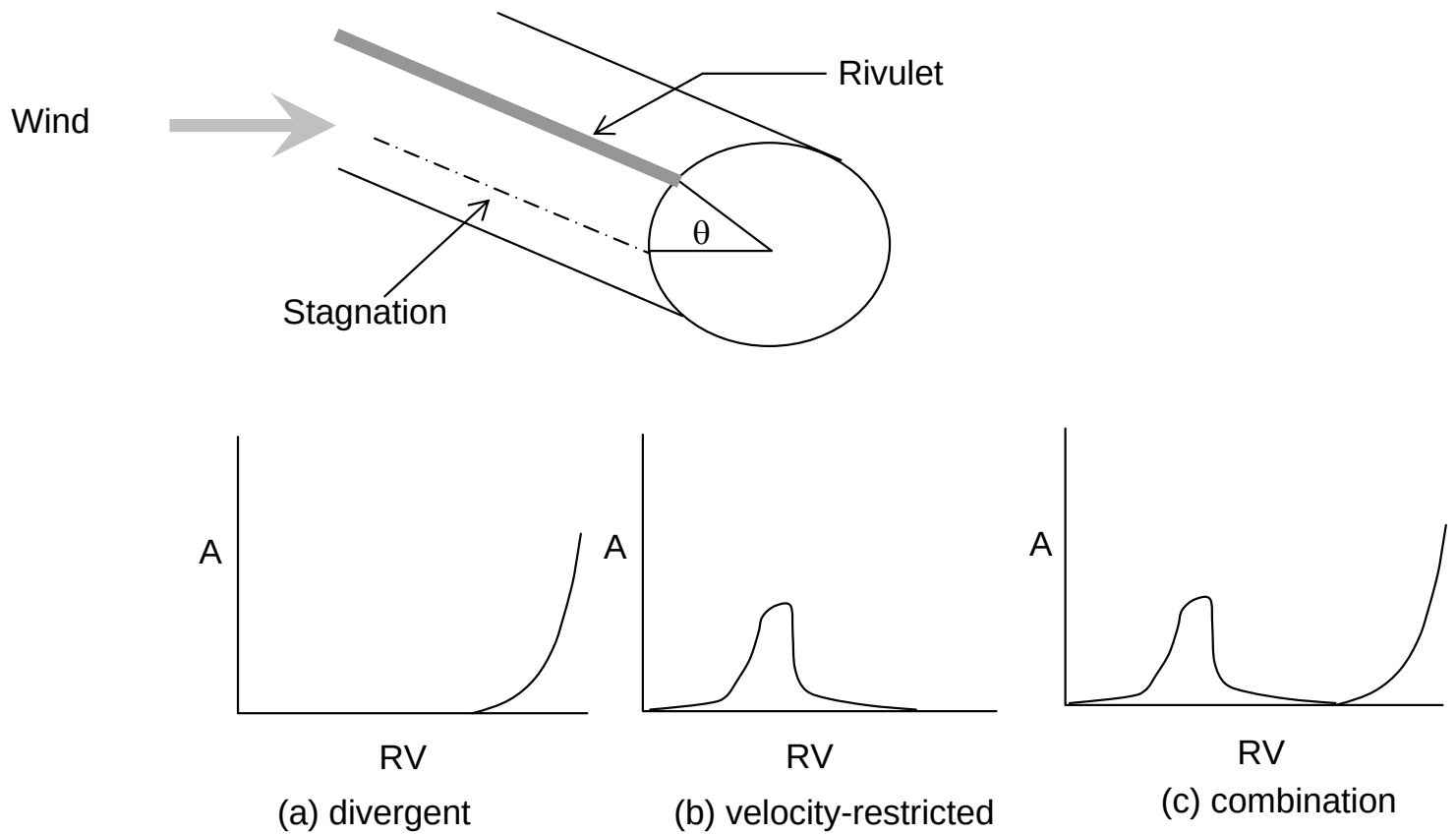


Definitions - Yaw (β), Inclination (α), Equivalent Yaw (β*) Angles; Wind Angle of Attack (γ), Stagnation Point and Plane of Cable Vibration





Definitions –
(a) Rivulet Location on Cable Surface
(b) Response Types



Research Approach

- **Wind Tunnel Tests by Sarkar et al.**
  - Texas Tech University (2-DOF Tests, 1998-1999)
  - Colorado State University (1-DOF Tests, 1998)

  Sarkar et al., 1998, 2000, 2004; Phelan et al. 2004
- **Field Data Collection**
  - Veterans Memorial Bridge (July 1999- June 2001)

  Phelan et al. 2004, 2006

References by Sarkar et al. (1998-2006)

- Sarkar, P.P., Mehta, K.C., Zhao, Z., Gardner, T.B. (1998). “Aerodynamic solutions to cable vibrations,” in: Proc., Texas Section ASCE FALL Meeting, Dallas, Texas, 1998.
- Sarkar, P. and Gardner, T. (2000). “Model tests to study rain/wind-induced vibration of stay cables,” in: Proc., ASCE Structures Congress, Philadelphia, Pennsylvania.
- Sarkar, P., Phelan, R. S. Mehta, K. C., Gardner, T.B. and Zhao, Z. (2002). “Cable Stay Aerodynamic Damper Band and Method of Use.” U.S. Patent No.: 6,386,526 B1, May 14, 2002. Other Patents: U.S. 6,435,323, August 2, 2002, U.S. 6,705,440, March 16, 2004
- Sarkar, P.P., Gan Chowdhury, A. and Gardner, T.B. (2004). “A novel elastic suspension system for wind tunnel section model studies,” Journal of Wind Engineering and Industrial Aerodynamics, Vol. 92, pp. 23-40.
- Phelan, R.S., Mehta, K.C., Sarkar, P.P. and Chen, L. (2004). “Investigation of Wind-Rain-Induced Cable-Stay Vibrations on Cable-Stayed Bridges,” Final report submitted to the Texas Department of Transportation (TxDOT), Austin, Texas, March 2004.
- Phelan, S., Sarkar, P.P. and Mehta, K.C. (2006). “Full-Scale Measurements to Investigate Rain-Wind Induced Cable-Stay Vibration and Its Mitigation,” ASCE Journal of Bridge Engineering, (in press, May 2006).

Wind Tunnel Tests

- Development of a two-degree-of-freedom elastic suspension system for section model tests
- Determine response characteristics of yawed cylinder with and without artificial rivulet for yaw angles 0° to 55°
- Explore aerodynamic mitigation techniques

Wind Tunnel Tests

- **Development of a two-degree-of-freedom elastic suspension system (Sarkar et al., 2004)**
  - Compact
  - Two-degree-of-freedom
  - Low inherent damping (0.25%-0.33% of critical)
  - Low frequency to allow studies at high reduced velocities (~ 1 Hz)
  - Scruton number $[4\pi m\zeta_m/(\rho D^2)]$ comparable to prototype

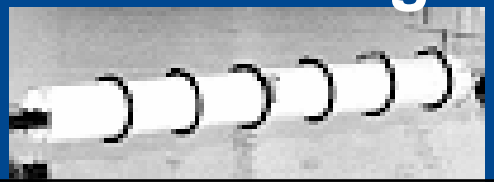
Wind Tunnel Tests by TTU (1-DOF)

CSU-MWT (6 ft x 6 ft)

Section Model $\alpha = 0^0$, $\beta = 37^0$, D=4 in.; Helical Strake

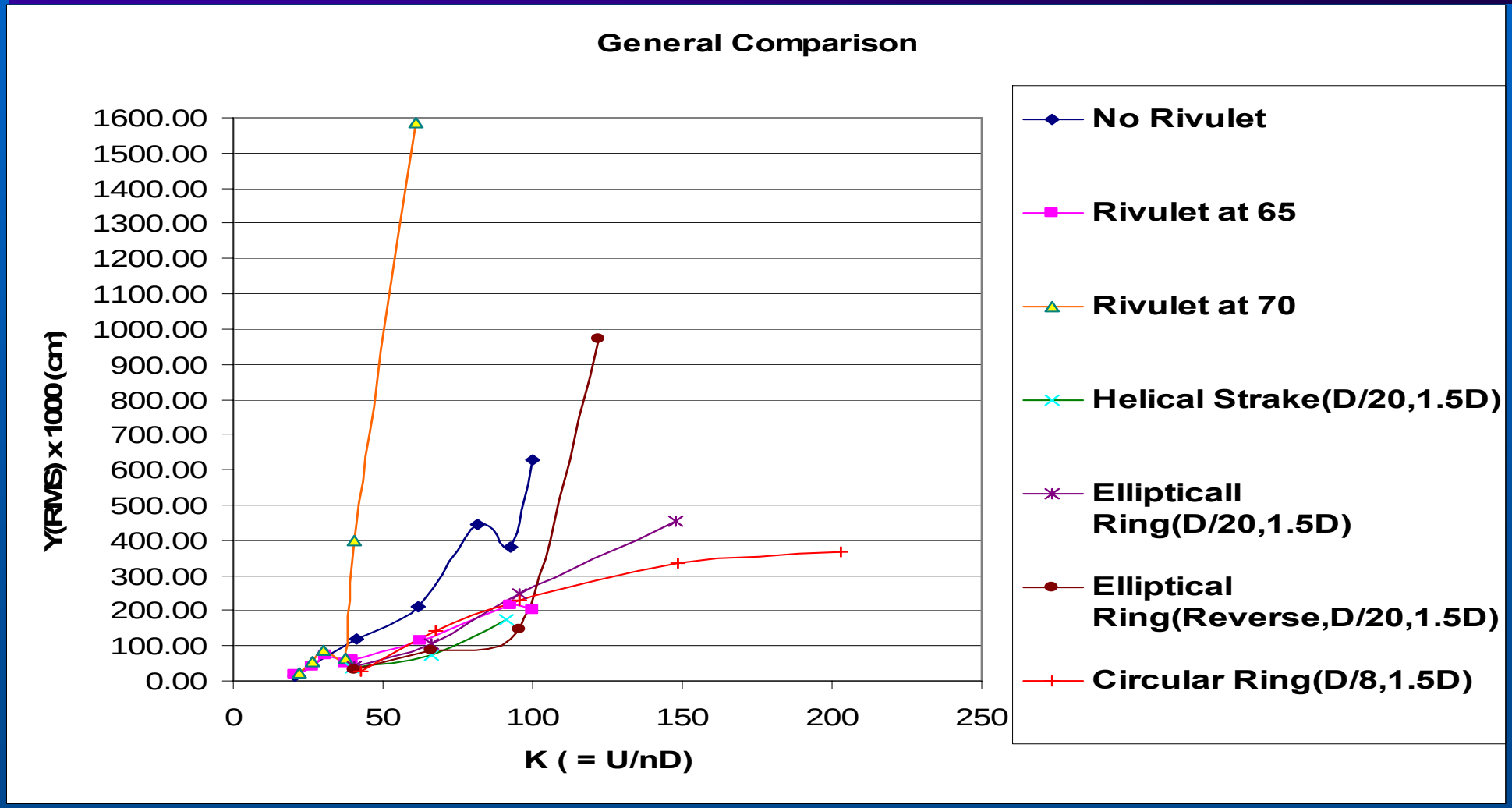
Elliptical rings

Circular rings



Wind Tunnel Tests (1-DOF)

Mitigation devices with artificial rivulet



Sc =7.6

Wind Tunnel Tests (1-DOF)

Generation of rivulet on an inclined and yawed cable inside the test section

Model $\alpha = 38^0$, $\beta = 38^0$

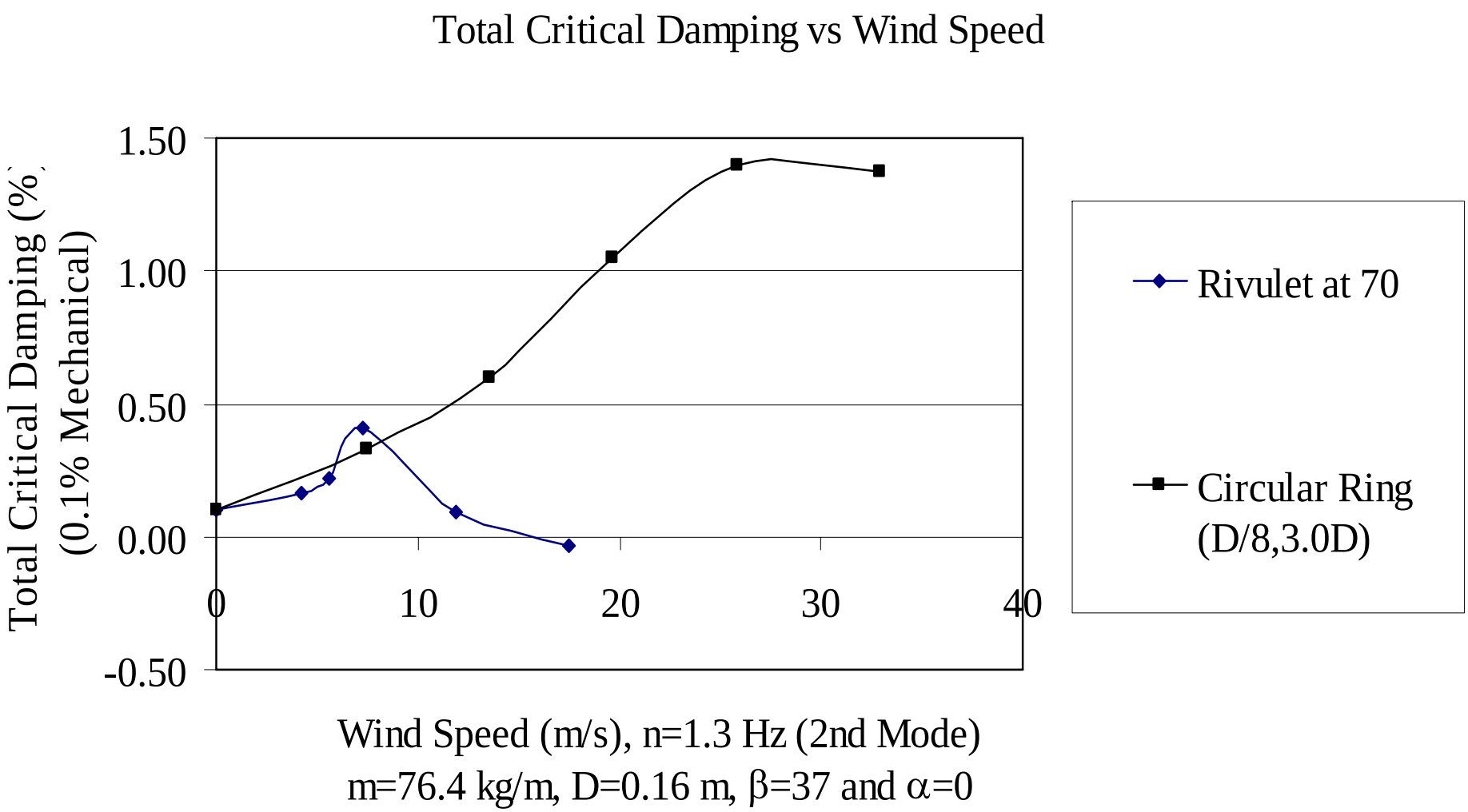
Wind Tunnel Tests (1-DOF)

Elimination of rivulet with circular rings

Model $\alpha = 38^0$, $\beta = 38^0$

Wind Tunnel Tests (1-DOF)

Calculation of total damping (including aerodynamic) for prototype cable



Wind Tunnel Tests (1-DOF)

Summary

- Model without any rivulet showed only divergent response at RV ≥ 80.

- Model with rivulet at 70^0 showed divergent response at RV ≥ 60 and weakly defined velocity-restricted response with crest at RV = 40.

- Circular rings of D/8 to D/20 diameter placed at a spacing of 1.5D to 3D along the cable were the most effective. Helical strakes and elliptical rings were not found to be effective for all wind directions.

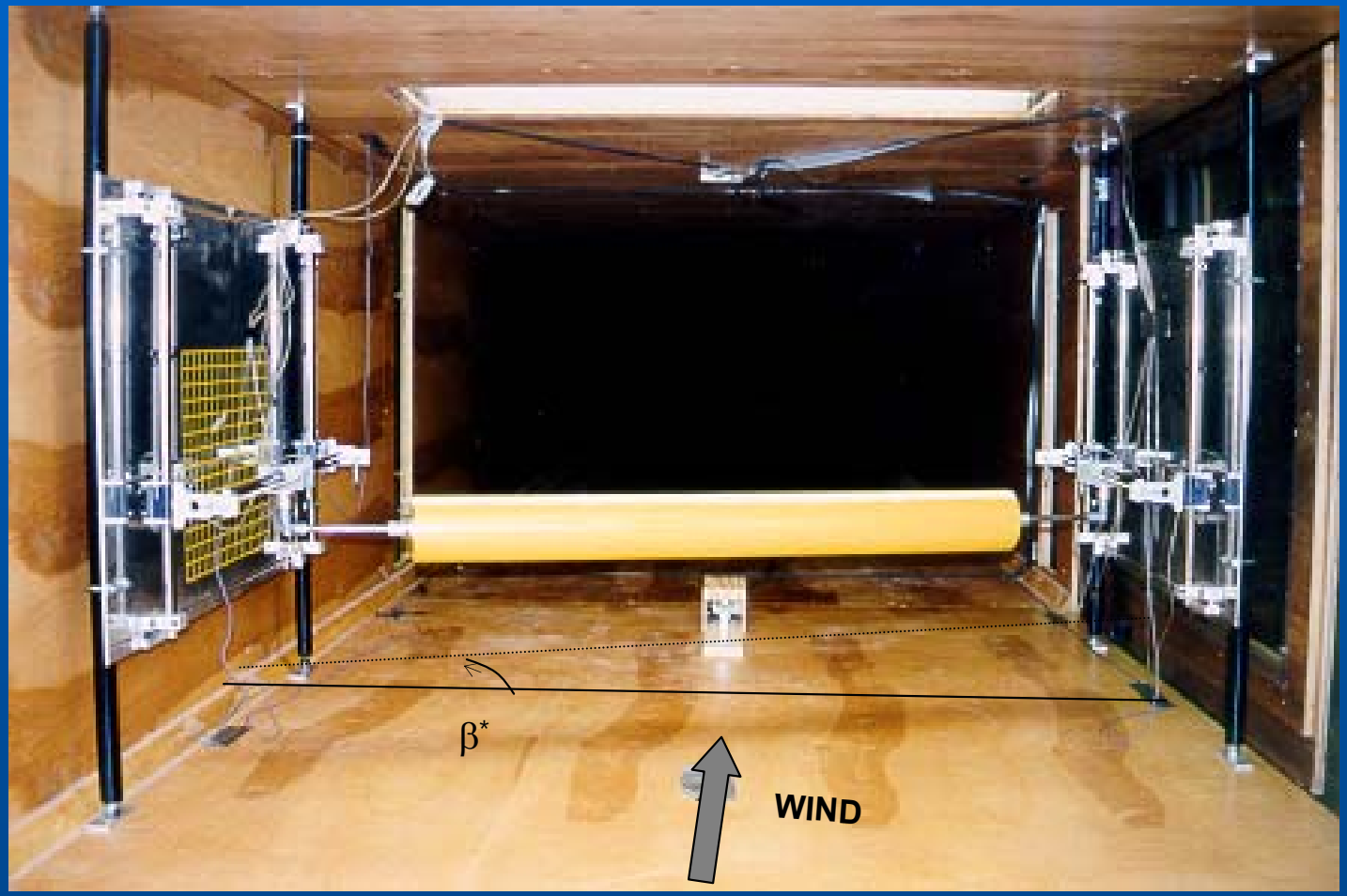
- The circular rings eliminate rivulet, and thereby eliminate the cause of rain-wind vibration at low speeds. Further, it can add some aerodynamic damping, say 0.25% at U=6.7 m/s (15 mph).

- At high wind speeds, it adds higher damping, say 1.4% at U = 27 m/s (60 mph); both 0.25% and 1.4% calculated for a long cable vibrating in 2nd mode (1.3 Hz).

Wind Tunnel Tests (2-DOF Tests)
(Texas Tech CE/ME Wind Tunnel, 6 ft x 4 ft)

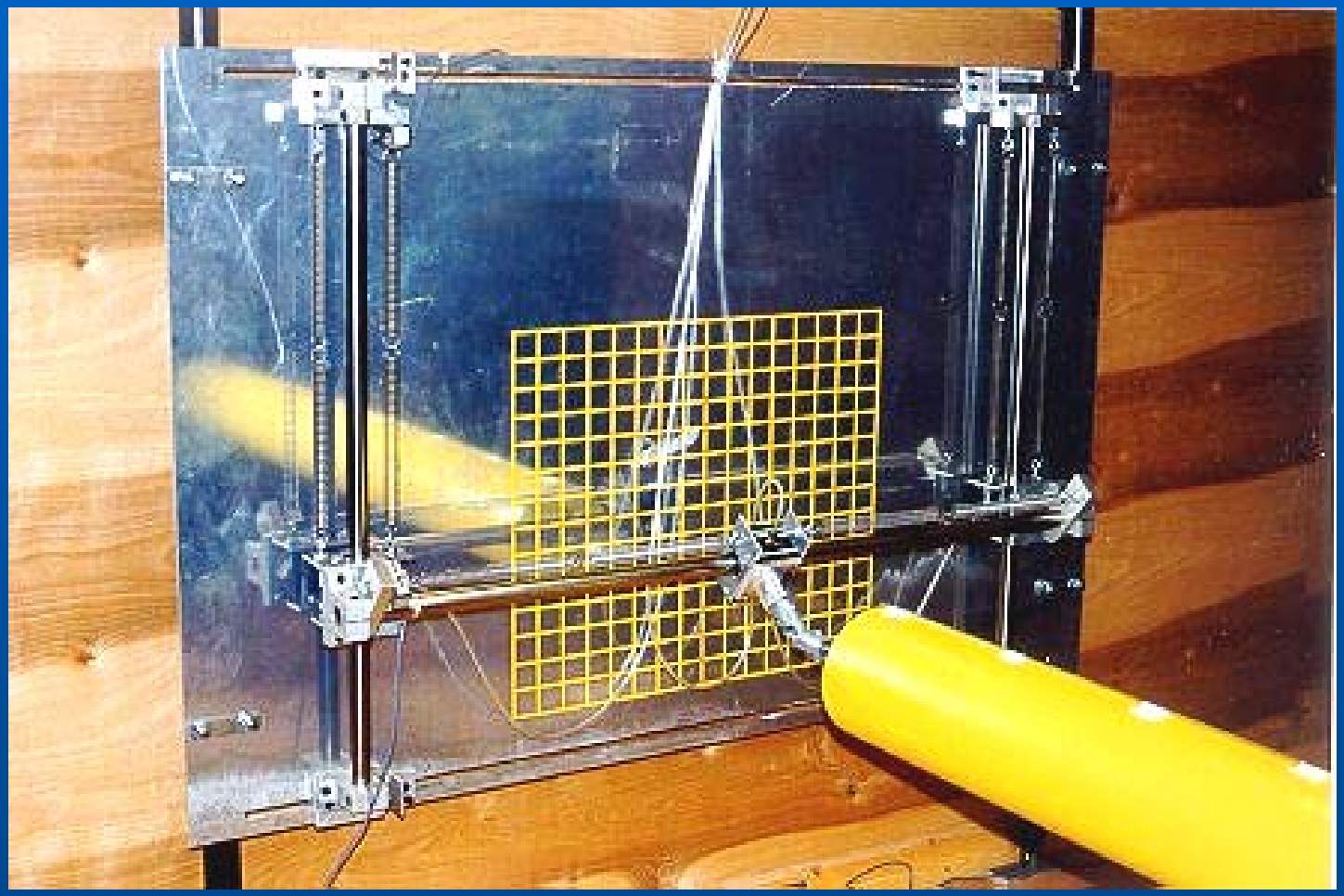
Wind Tunnel Tests (2-DOF)

Elastic Suspension System, Sc = 31.7, D =3.5 in.



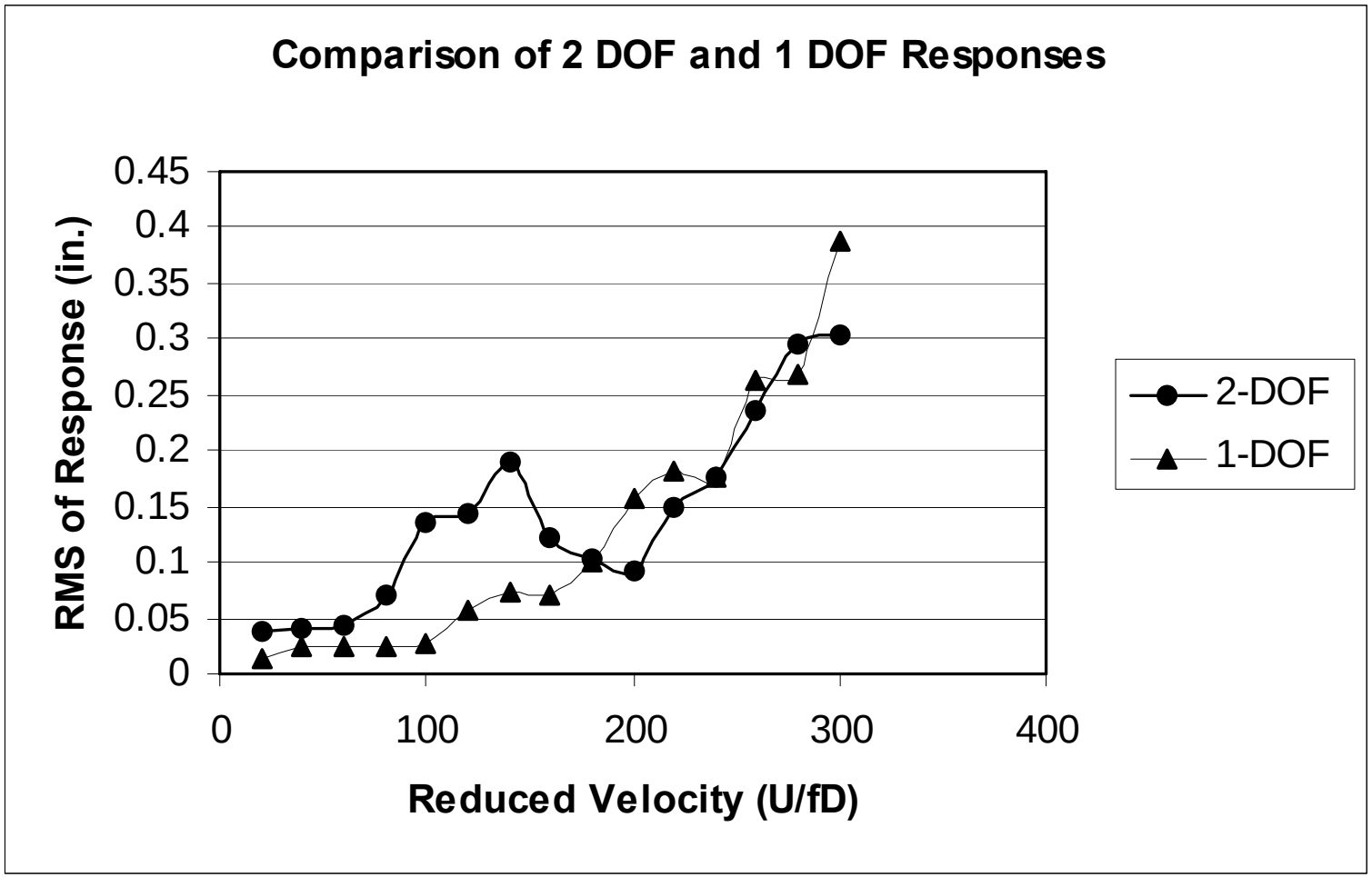
Wind Tunnel Tests (2-DOF)

Elastic Suspension System, Sc = 31.7, D =3.5 in.

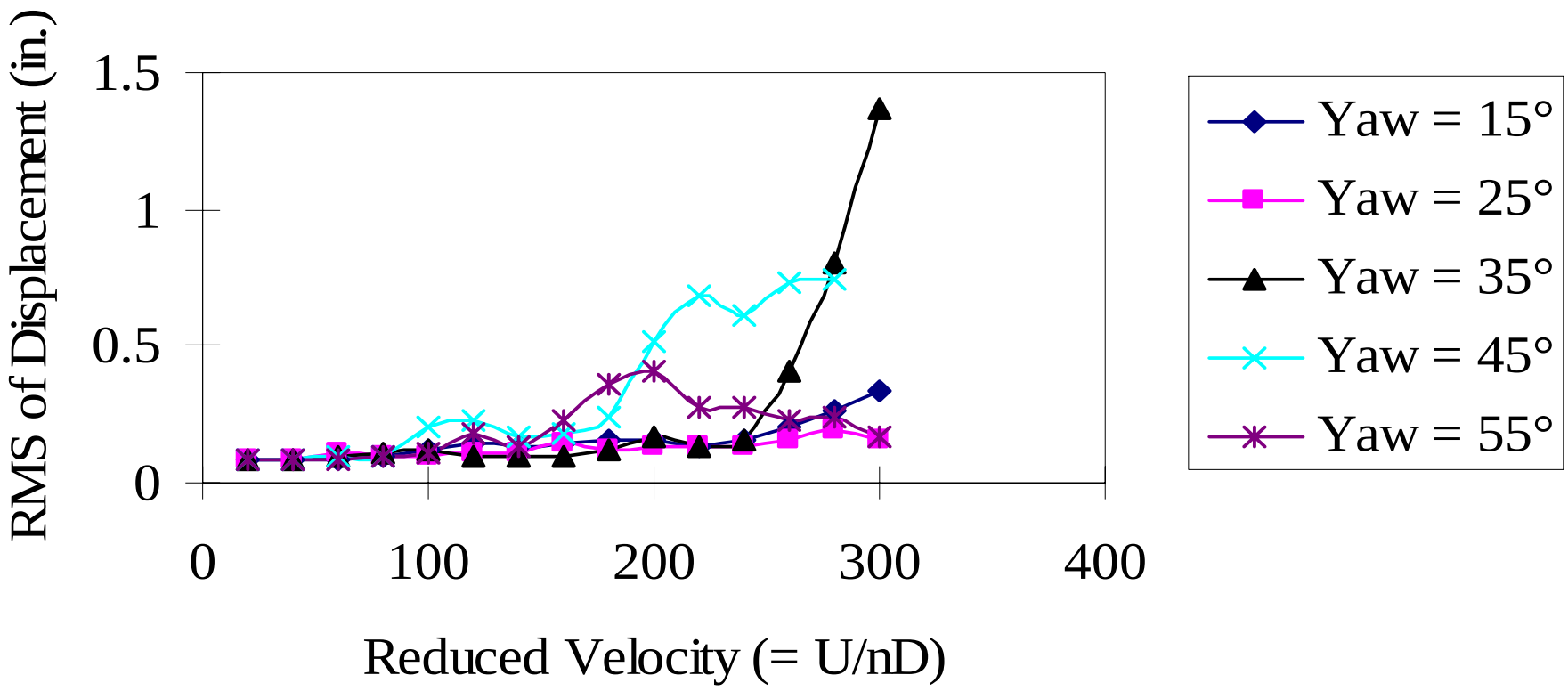


Video

2-DOF versus 1-DOF Responses

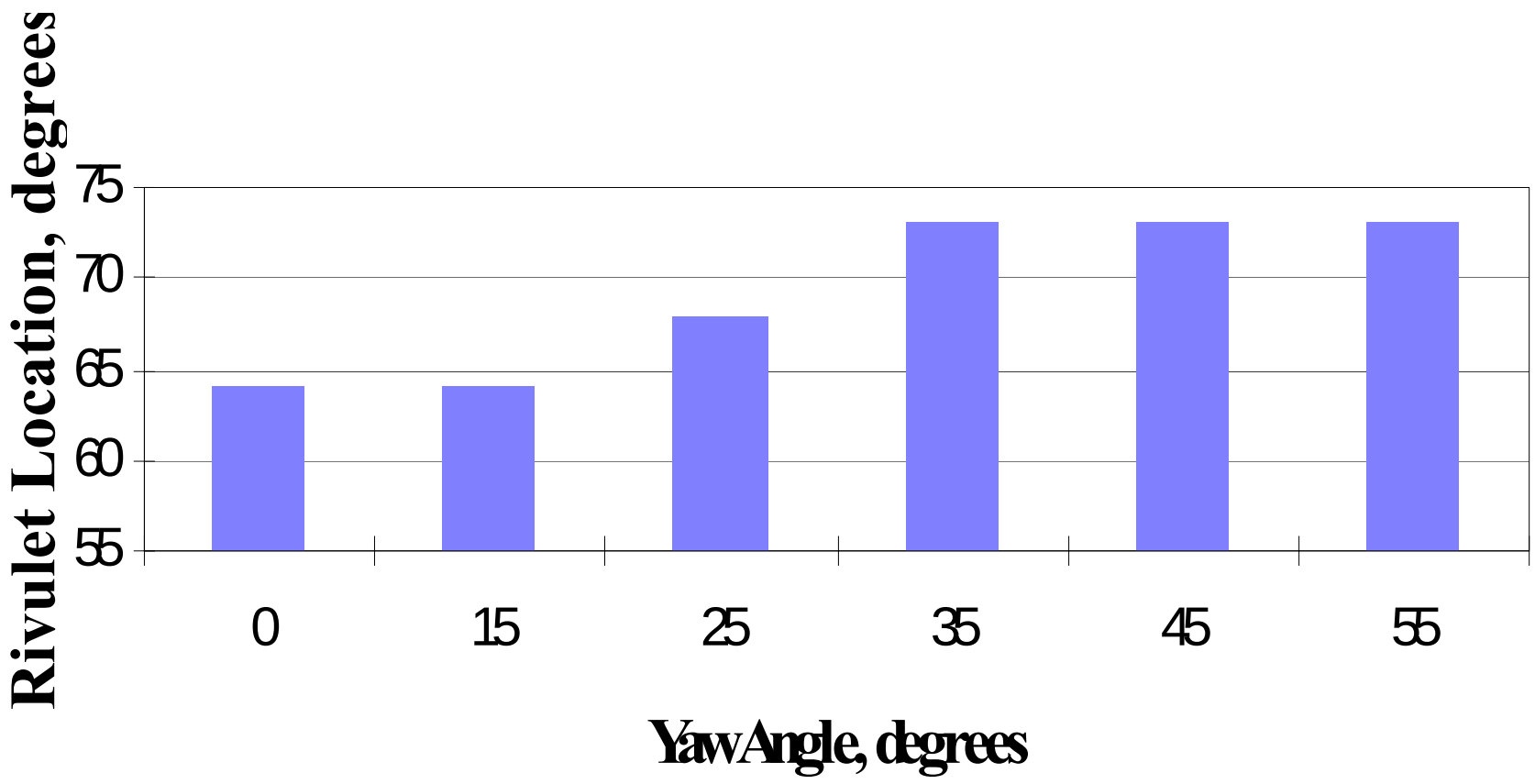


1-DOF Vertical Response of Bare Yawed Cylinder without Rivulet, $\beta^* = 15°, 25° 35° 45° 55°$

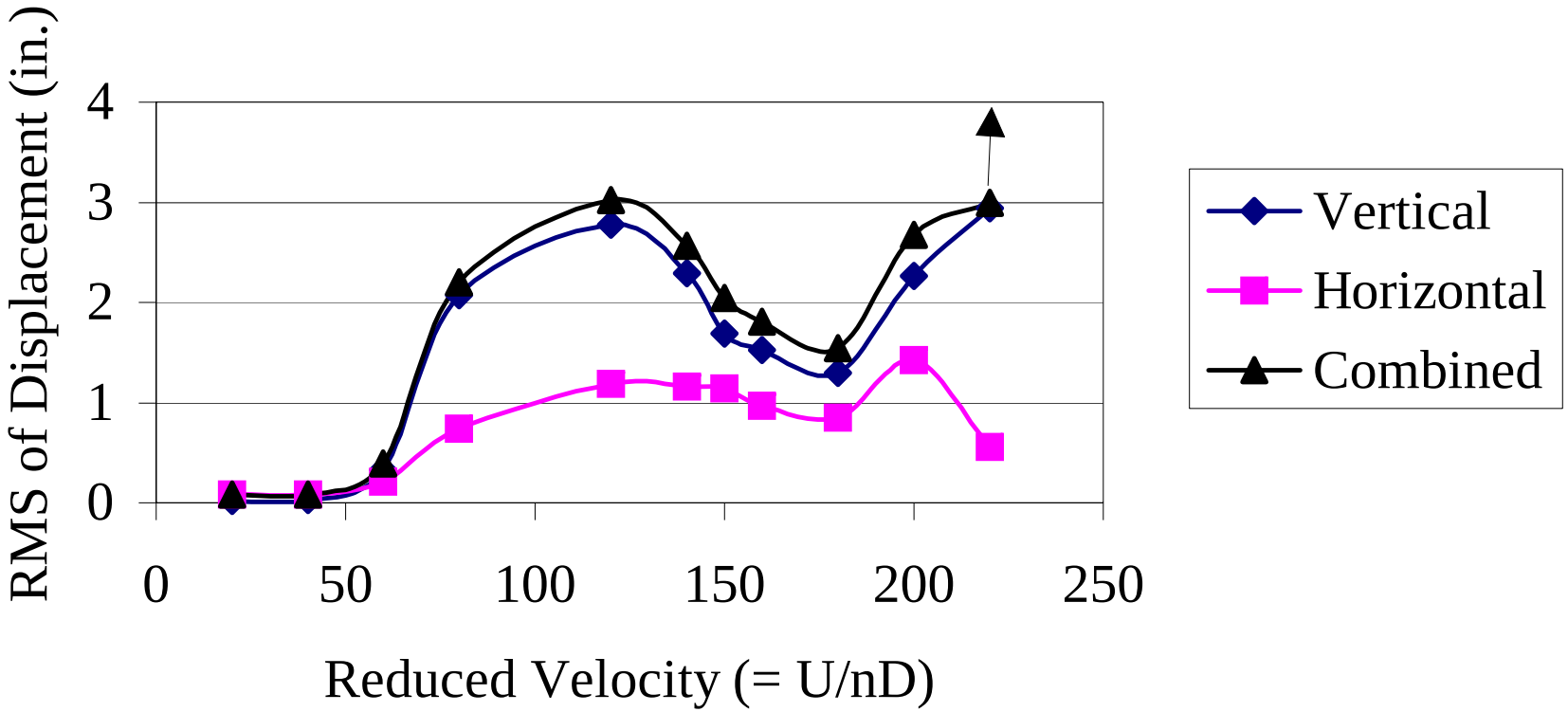


Sc =31.7

Critical Rivulet Locations for Maximum 2-DOF Response

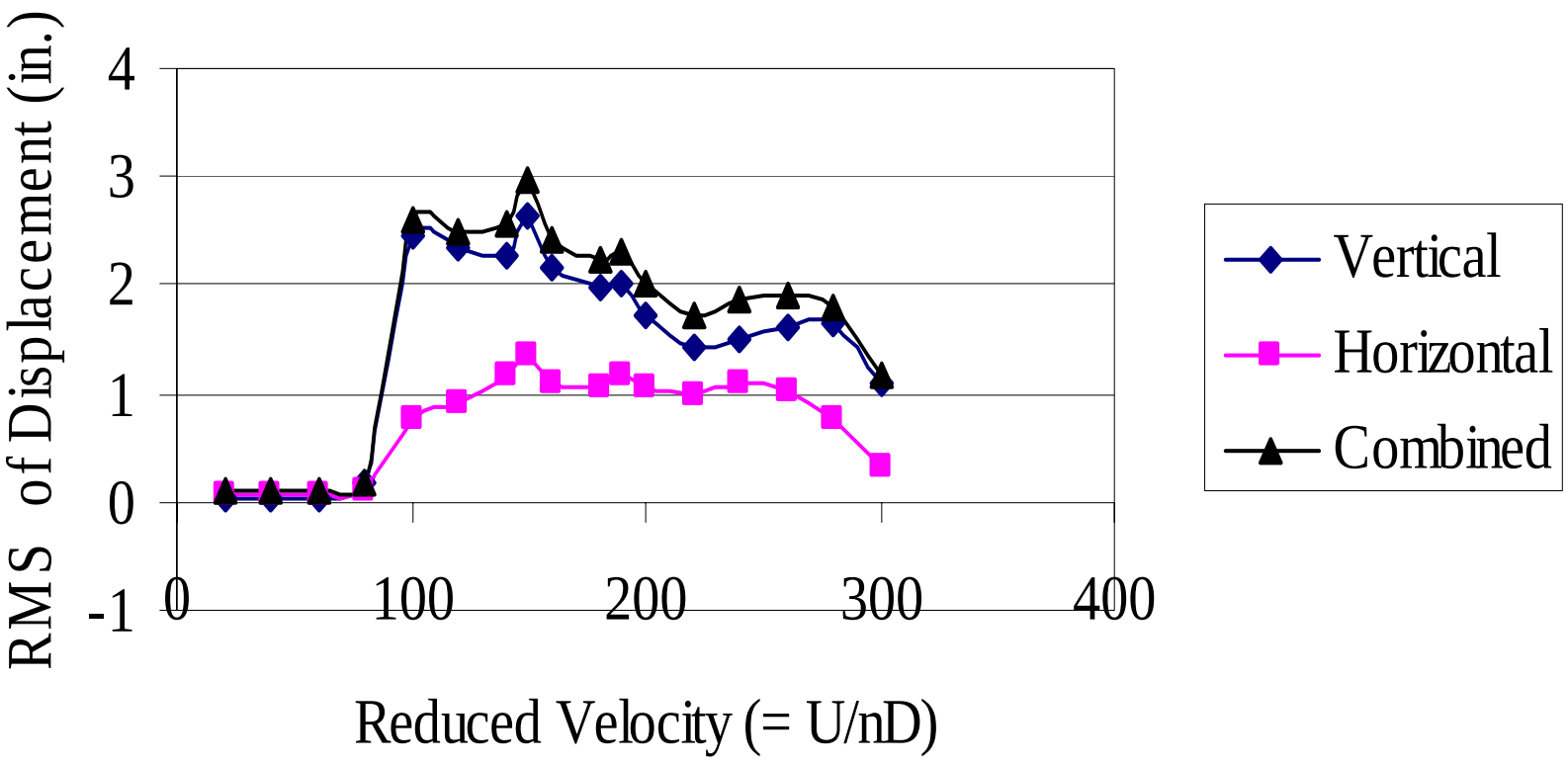


Response of Yawed Cylinder at $\beta^* = 15°$ with Artificial Rivulet



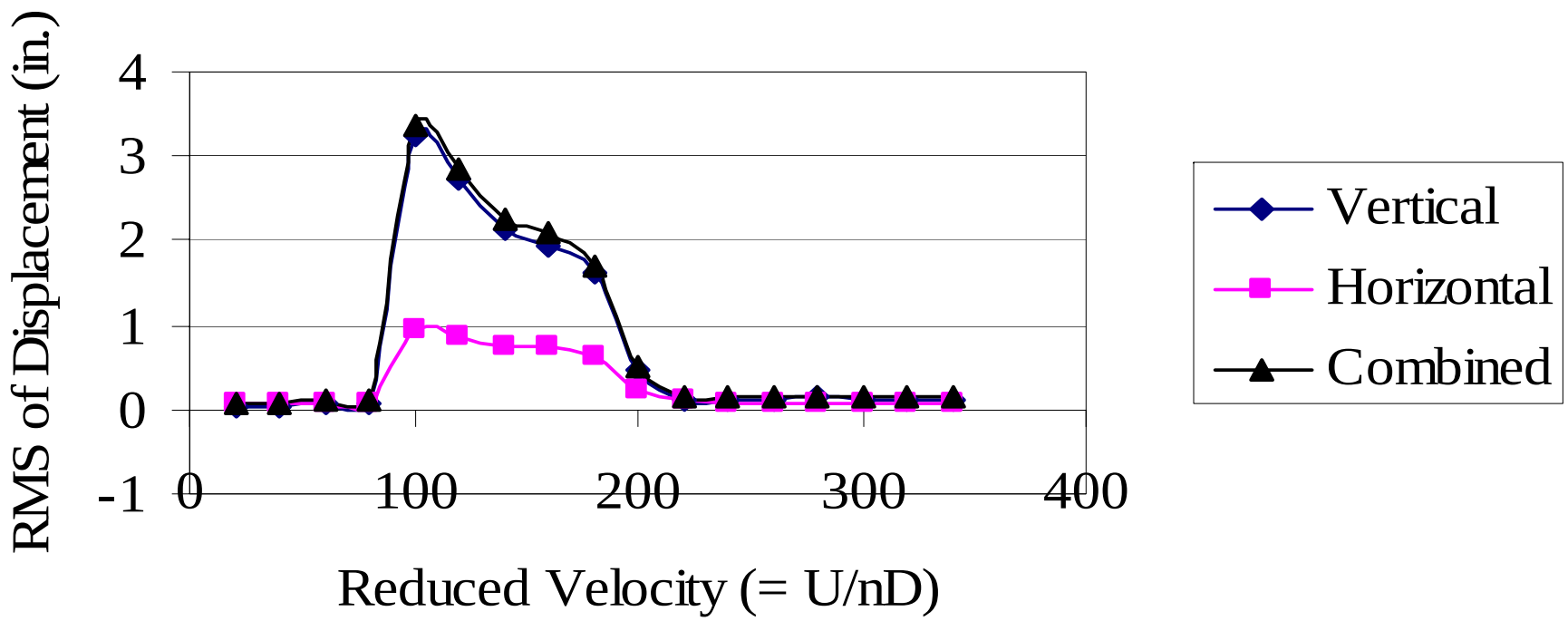
Sc =31.7

Response of Yawed Cylinder at $\beta^* = 25°$ with Artificial Rivulet



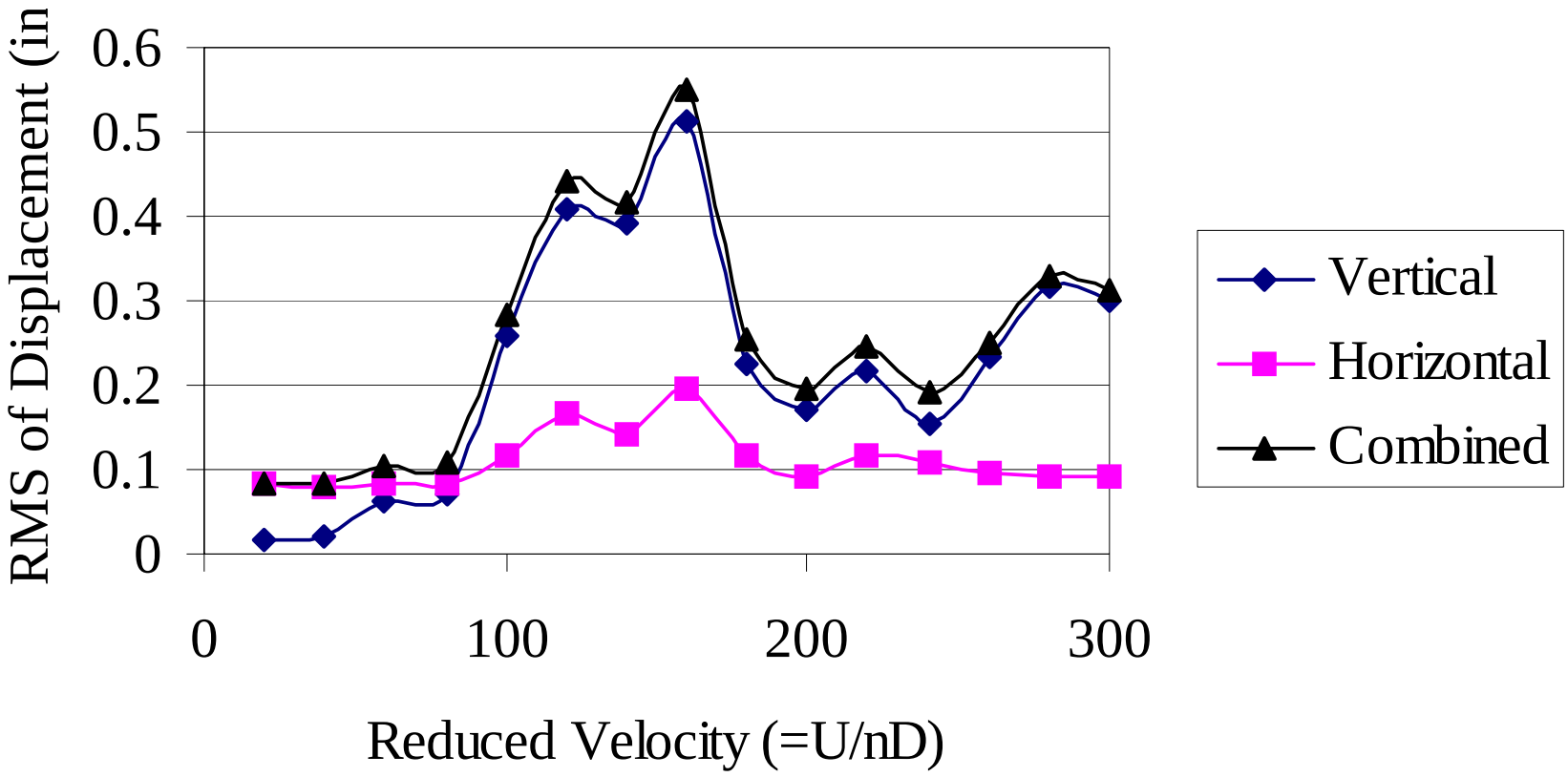
Sc =31.7

Response of Yawed Cylinder at $\beta^* = 35°$ with Artificial Rivulet



Sc =31.7

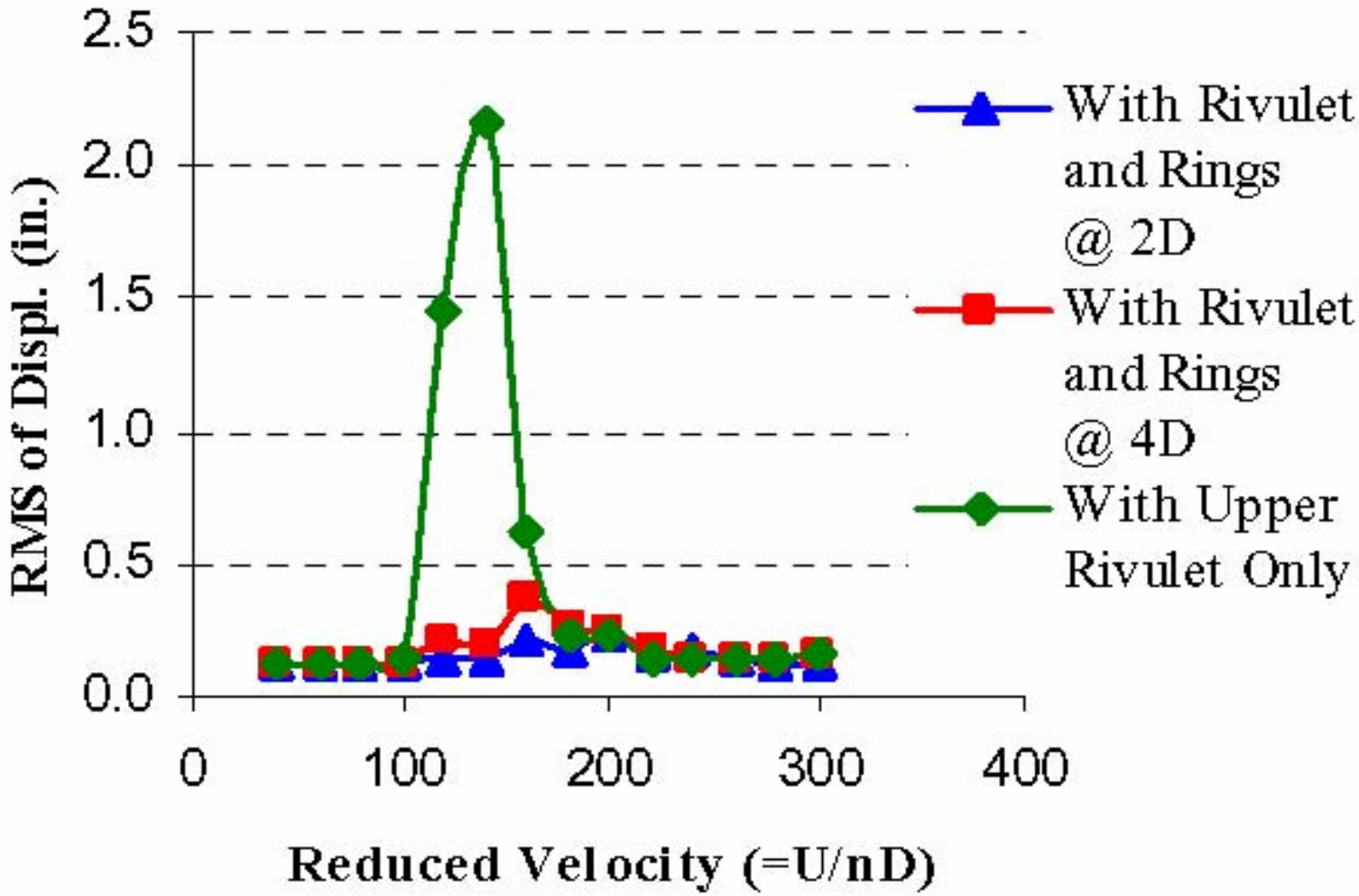
Response of Yawed Cylinder at $\beta^* = 45°$ with Artificial Rivulet



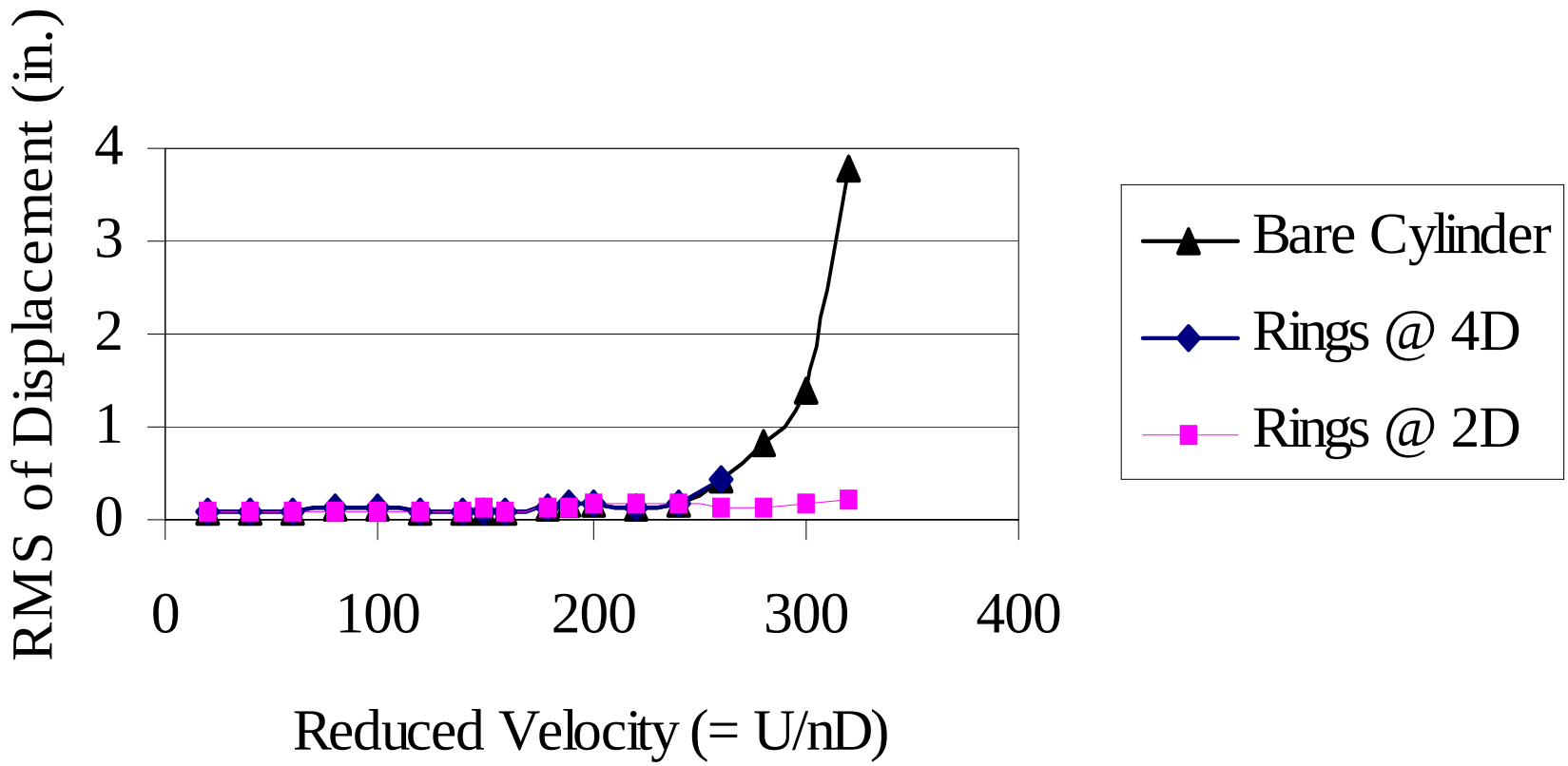
Sc =31.7

2-DOF Section Model with Rings

Comparison of Responses of Yawed Cylinder with and without Circular Rings and Rivulet, $\beta^* = 35°$



Comparison of Response of Bare Yawed Cylinder with and without Circular Rings, $\beta^* = 35°$

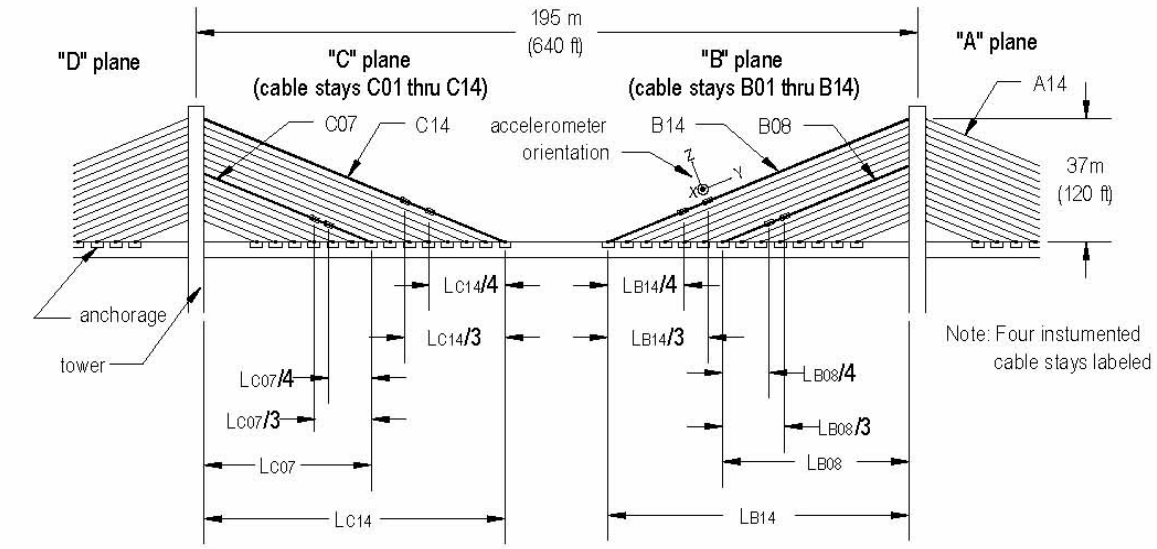


Wind Tunnel Tests (2-DOF)
Summary

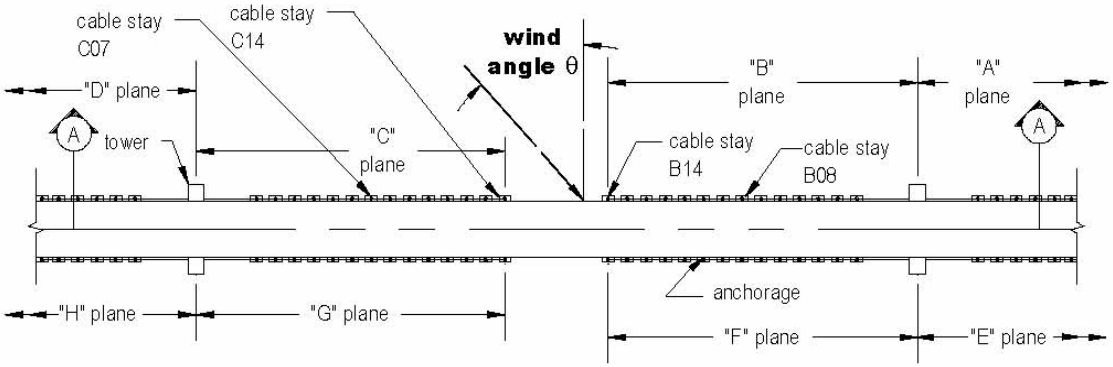
- Model ($\beta^* = 15$ to $40°$) without any rivulet showed only divergent response at RV > 300; Worst case was $\beta^* = 35°$.
- Model ($\beta^* = 0$ to $55°$) with rivulet at 63 to 73^0 angles showed velocity-restricted response between RV = 100 to 200 with crest at RV = 120-160; Worst case was $\beta^* = 35°$ with crest at RV = 120; For $\beta^* = 0^0$ and $15°$, divergent response was also observed around RV > 220.
- Response along the horizontal direction was always lower than that along the vertical direction for all tests by a factor of 2 to 3.5.
- Circular rings of dimension D/14 placed at a spacing of 2D to 4D along the cable reduced the response by as much as 90% compared to the no-ring and worst yaw angle case, both for velocity-restricted and divergent type responses.

Field Data Collection
Veterans' Memorial Bridge, Port Arthur, Texas, July 1999-June 2001

Veterans' Memorial Instrumentation Scheme and Wind Angle



SECTION A–A



PLAN VIEW

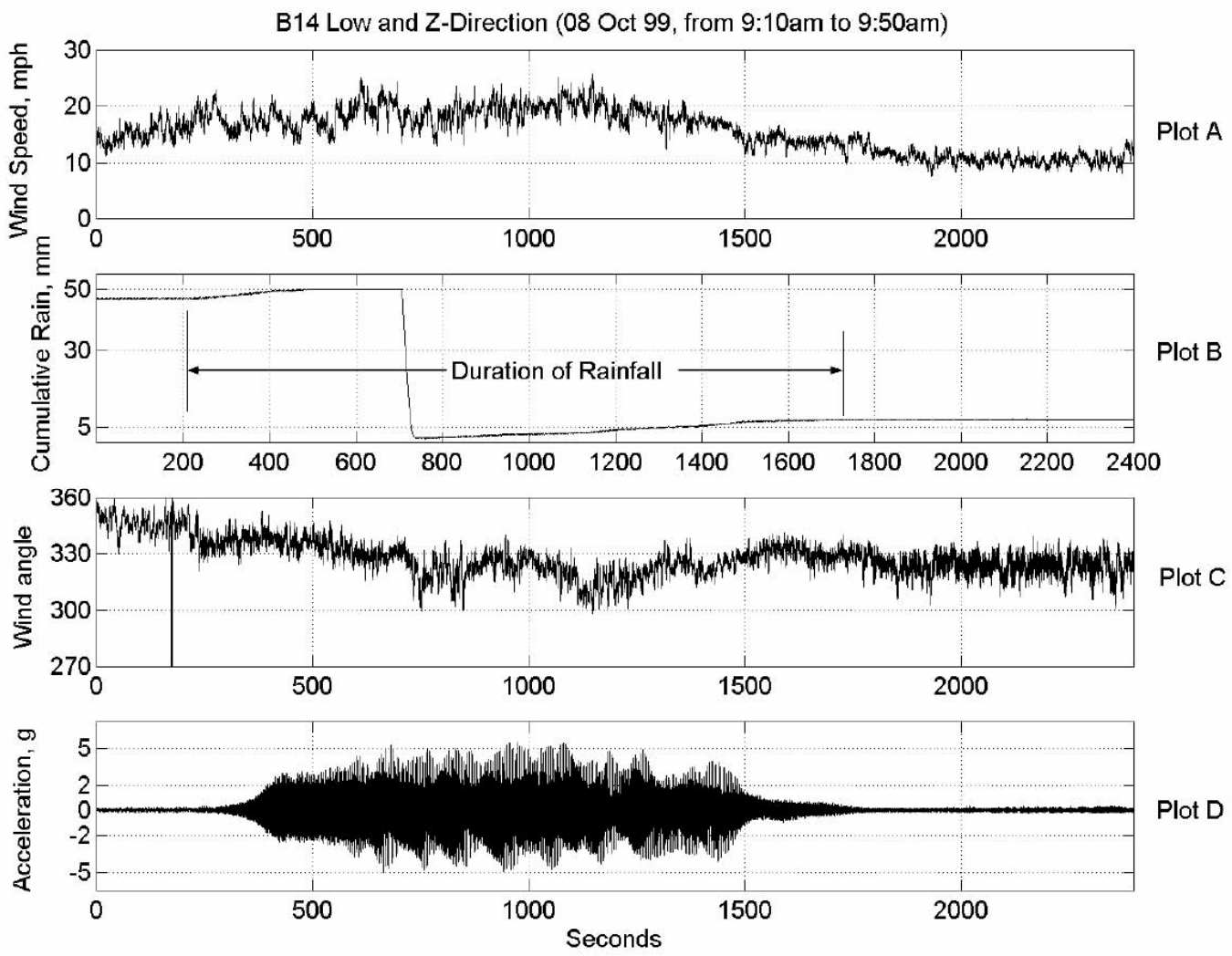
Field Instrumentation by TTU

- **Anemometer (UVW)**
- **Temperature gauge and two rain gauges**
- **Accelerometers**

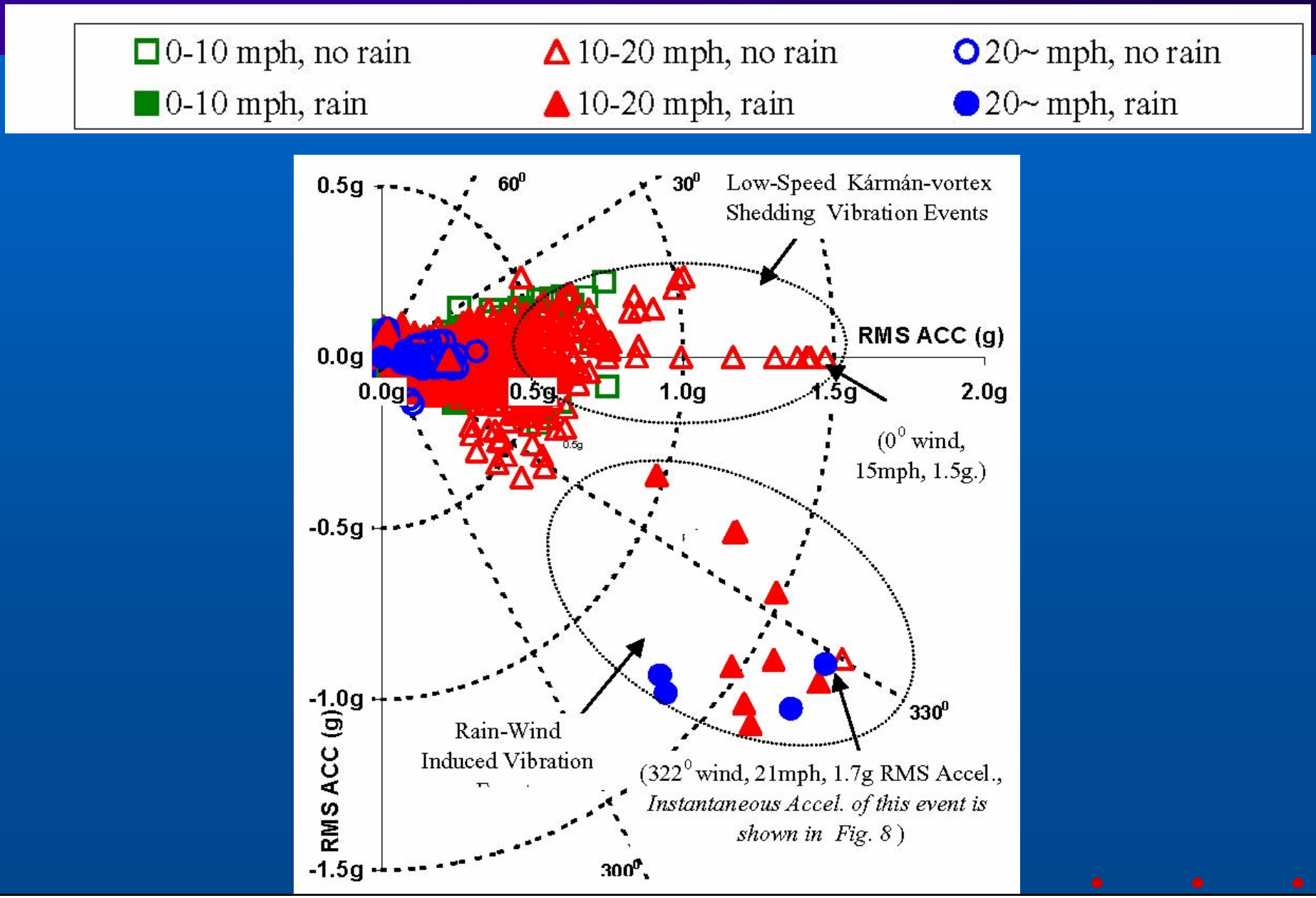
  two tri-axis on each of cables B08, B14, C07 and C14
- **Remote-controlled DAQ**

Field-Installed Prototype Rings

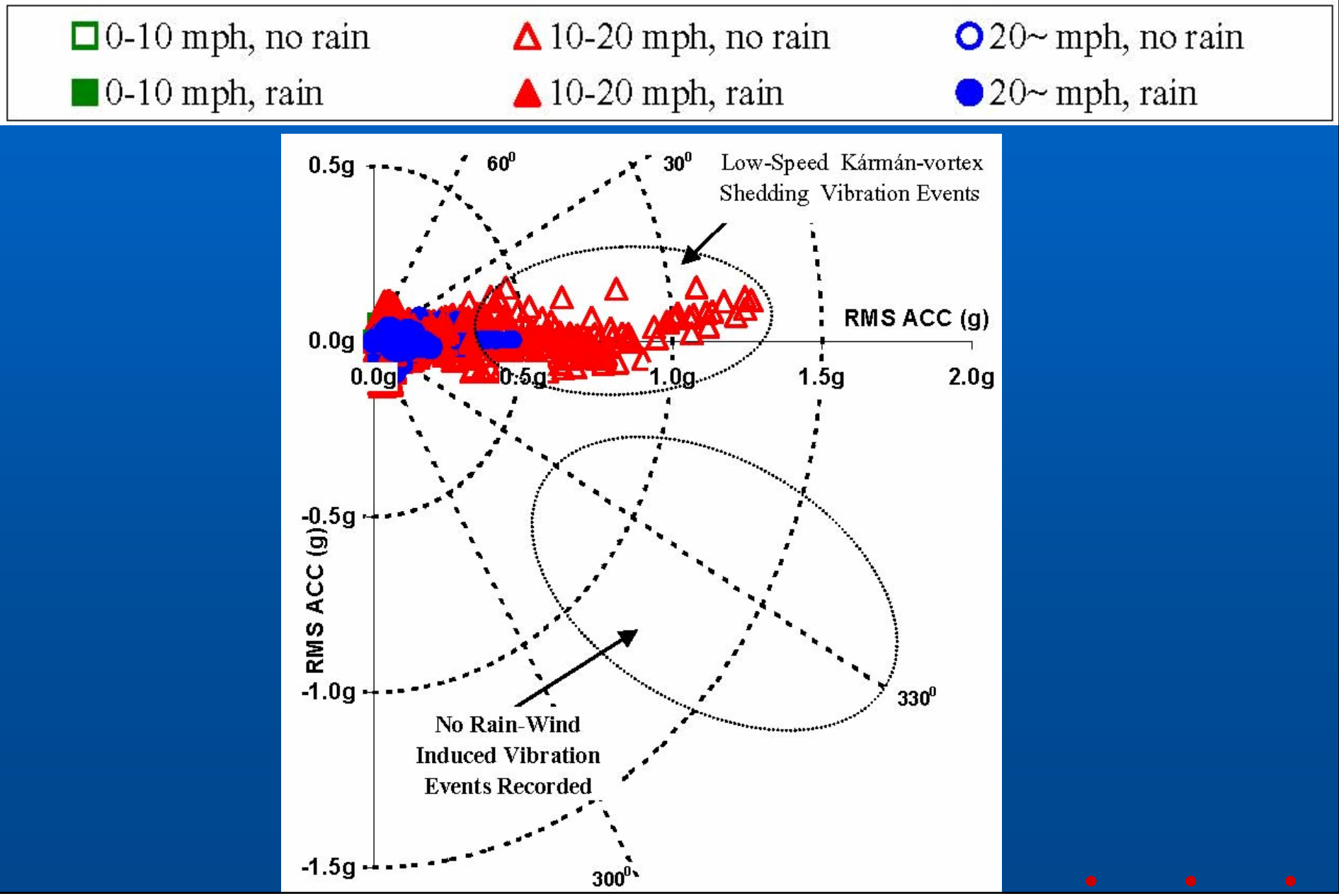
Veterans' Memorial 5g cable-stay Vibration Event



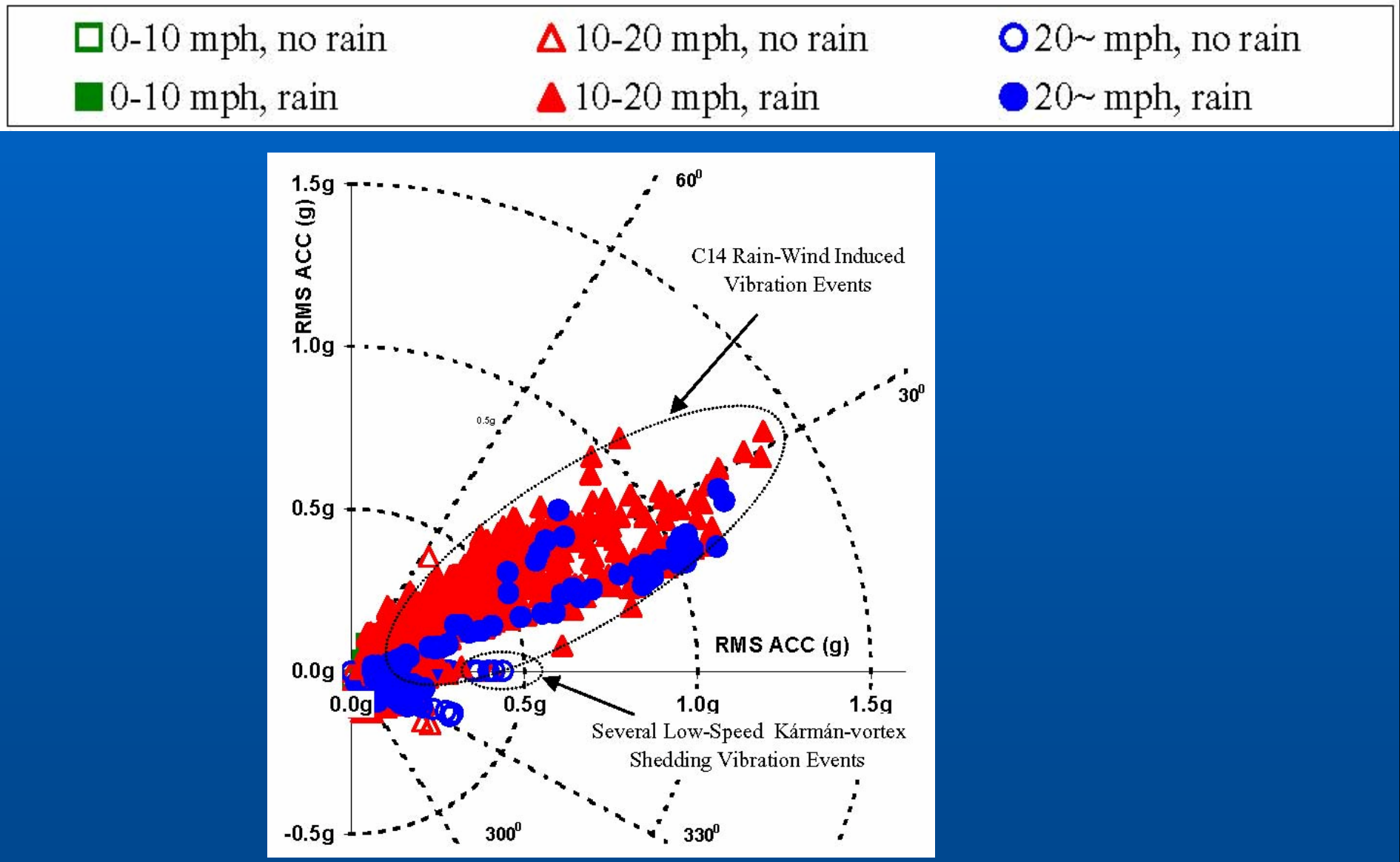
B14HZ One-Minute RMS Acceleration (before ring installation)



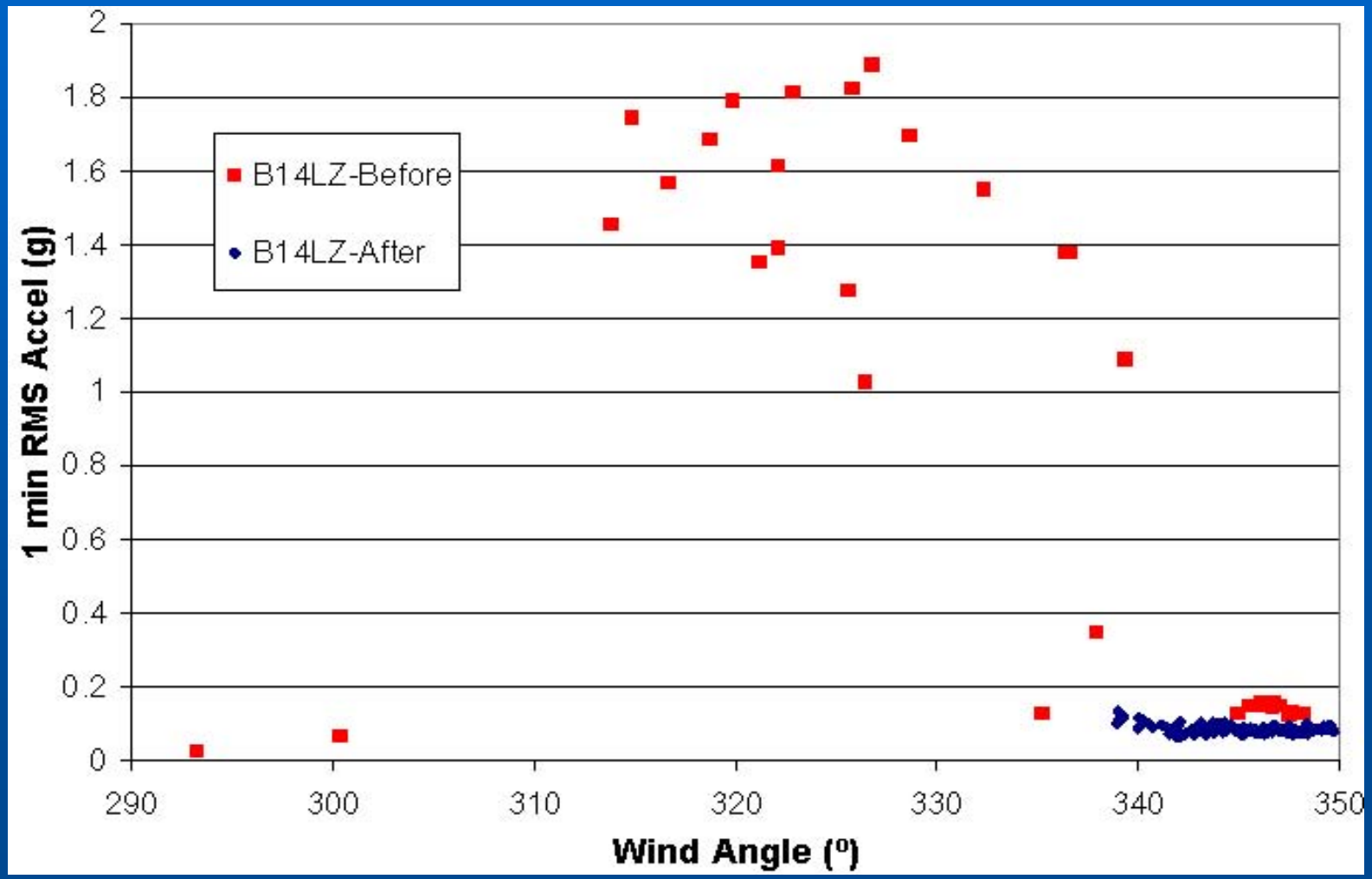
B14HZ One-Minute RMS Acceleration (after ring installation)



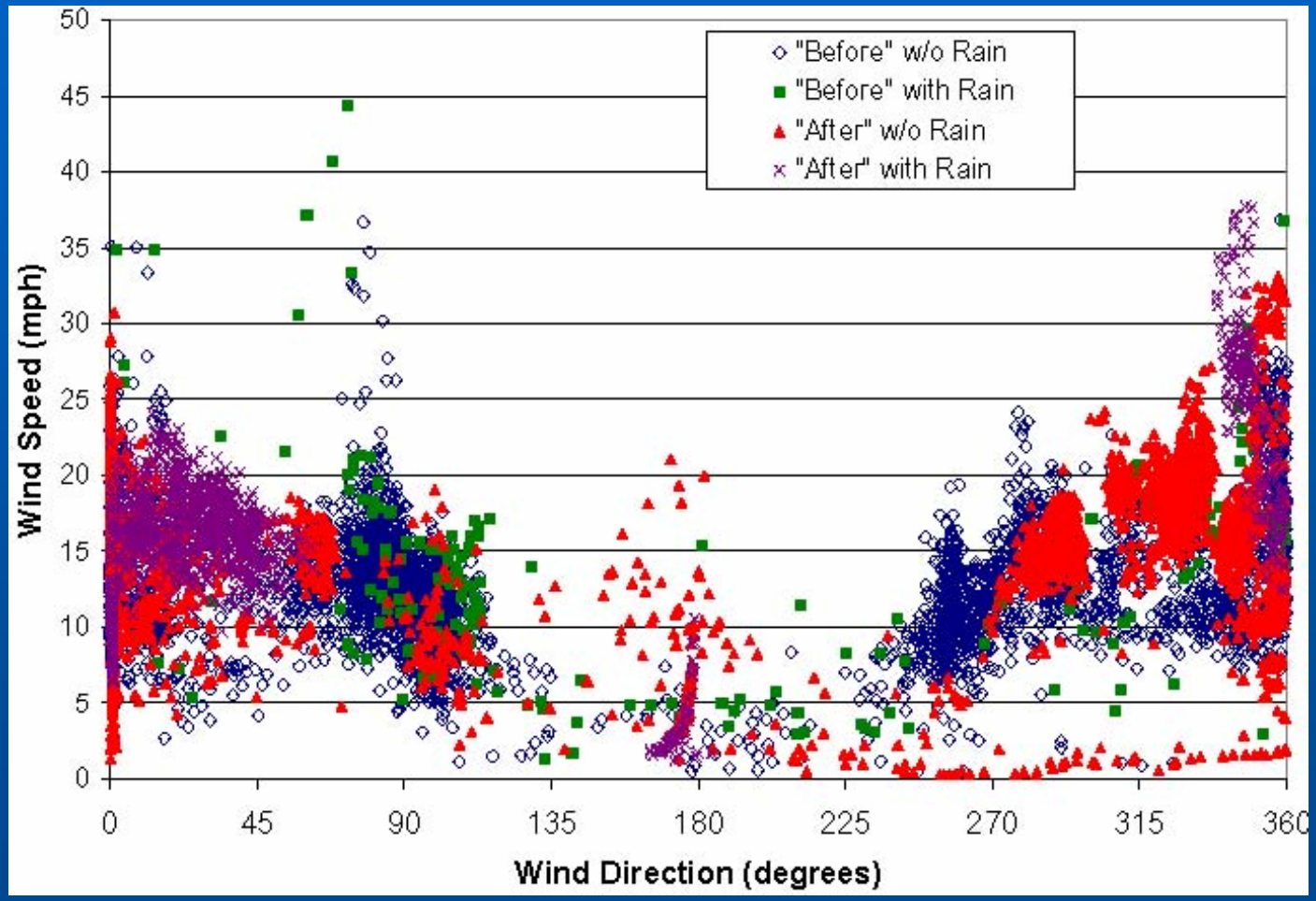
C14HZ One-Minute RMS Acceleration (after ring installation on B14 -- no rings on C14)



Cable B14 One-Minute RMS Acceleration in the Z-Direction vs. Wind Angle



One-Minute Mean Wind Speeds vs. Wind Direction



Field Result Findings Summary

- Under favorable conditions, cable stay will vibrate until one or more of the parameters causing the vibration ceases. Rain-wind vibrations appeared when (a) wind speeds were between 6.3-14 m/s (14-31 mph), (b) wind direction was 19 to 44^0 for Cable C14 and 314 to 339^0 for Cable B14.

- The critical yaw angle (β^*) is 10 to 52^0 for moderate to large vibrations (>0.5g RMS at L/3 location) with largest vibrations at $\beta^* = 30$ to 35^0. This matches well with the wind tunnel results.

- Velocity-restricted type response was often triggered when there was no rain and wind speeds were between 7-11 m/s (16-25 mph) and at ~0^0 wind direction. The most dominant mode of vibration was 13th mode for B14 (no rings) and C14 during these events. The natural frequency of 13th mode and wind speeds show possible excitation from Kármán vortex shedding. Although accelerations during these events were comparable to rain-wind case, maximum amplitudes were low.

Field Result Findings Summary

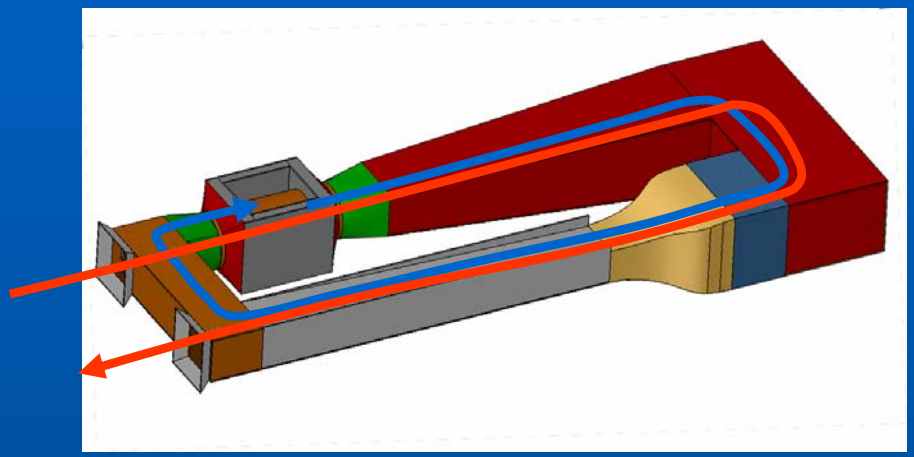
- Based on wind events at angles close to 0^0 without rain, rings seem to be adding aerodynamic damping to the cable B14 and reducing its amplitude of vibration.

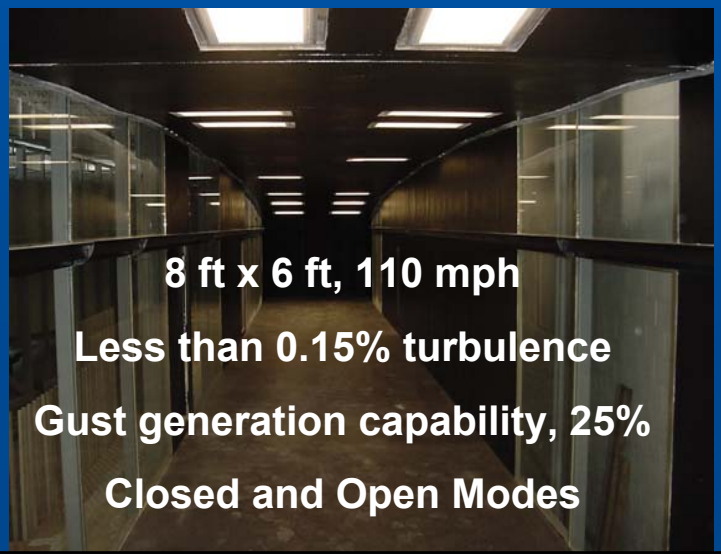
- Based on limited number of events with wind within the critical range of wind speed and direction ($314\text{-}339^0$) that is accompanied by rain for B14 to vibrate, it seems rings did reduce the rain-wind induced cable-stay vibrations significantly (RMS acceleration reduced from 1.14g to 0.11g for wind angle 338^0, i.e. by 90% as found in wind tunnel tests).

Future Plans

Wind Simulation and Testing (WiST) Laboratory
Iowa State University

AABL Wind and Gust Tunnel





Bill James Wind Tunnel

3 ft x 2.5 ft, 150 mph

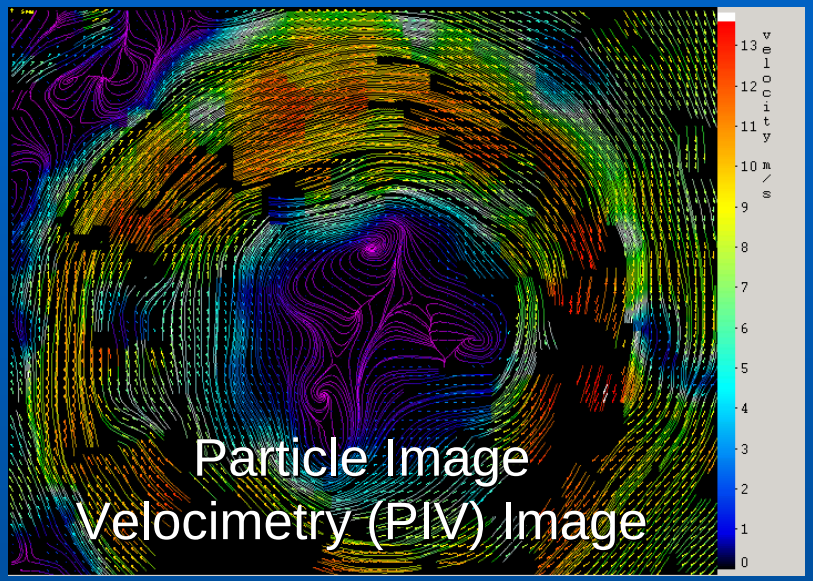
5 ft circular, 50 mph

- Free and forced vibration studies of 3DOF section models
- Full aeroelastic model studies with rain

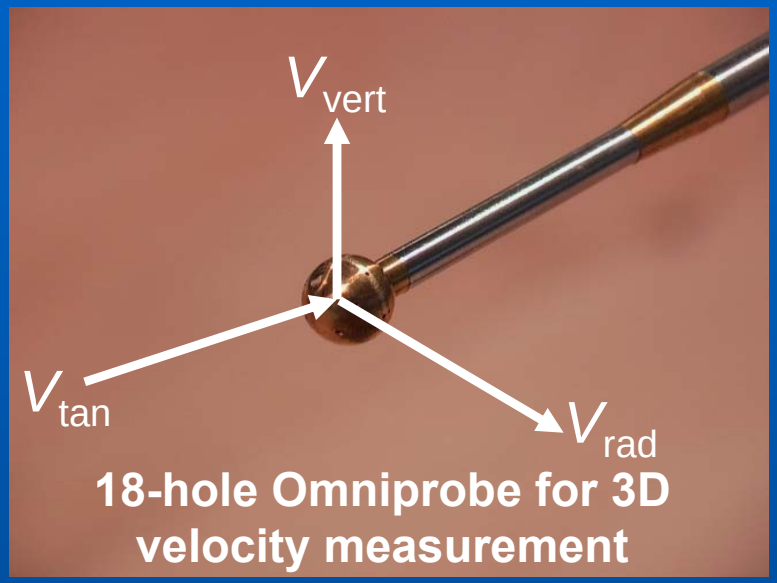
Future Plans

Wind Simulation and Testing (WiST) Laboratory

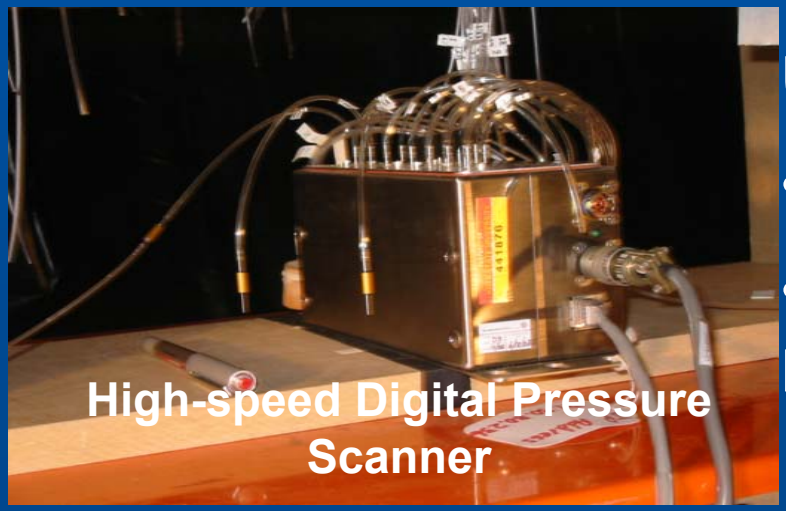
Iowa State University



Particle Image Velocimetry (PIV) Image



18-hole Omniprobe for 3D velocity measurement



High-speed Digital Pressure Scanner

Use modern instrumentation (Examples)

- **High-speed stereoscopic PIV system**
- **High-speed (500 Hz/ch) multi-channel pressure scanners**

Acknowledgment

Funding

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- Dr. Randy Poston, WDP & Associates

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- Drs. Z. Zhao, L. Chen