Understanding the Mechanism of Rain-Wind-Induced Vibrations in the Context of Dry Cable Vibrations Observed in the Field and in the Wind Tunnel

Delong Zuo

and

Nicholas P. Jones

Johns Hopkins University

Motivation

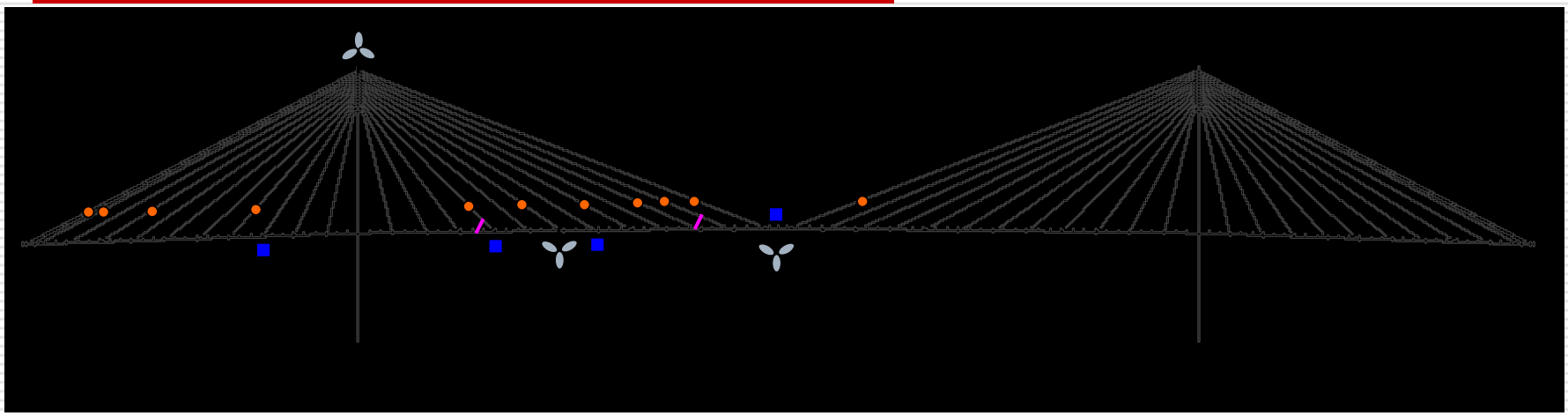
Outline

- Full-scale measurement
  - Full-scale measurement system
  - Characterization and categorization of observed stay cable vibrations
- Wind tunnel testing of sectional models

The Fred Hartman Bridge

- Over the Houston ship channel in Houston, Texas
- 384 m main span, 54 m clearance
- Twin-deck, each 24 m wide
- Double-diamond shaped towers
- 192 cables (59 m to 198 m long) in four inclined planes

Full-Scale Measurement System

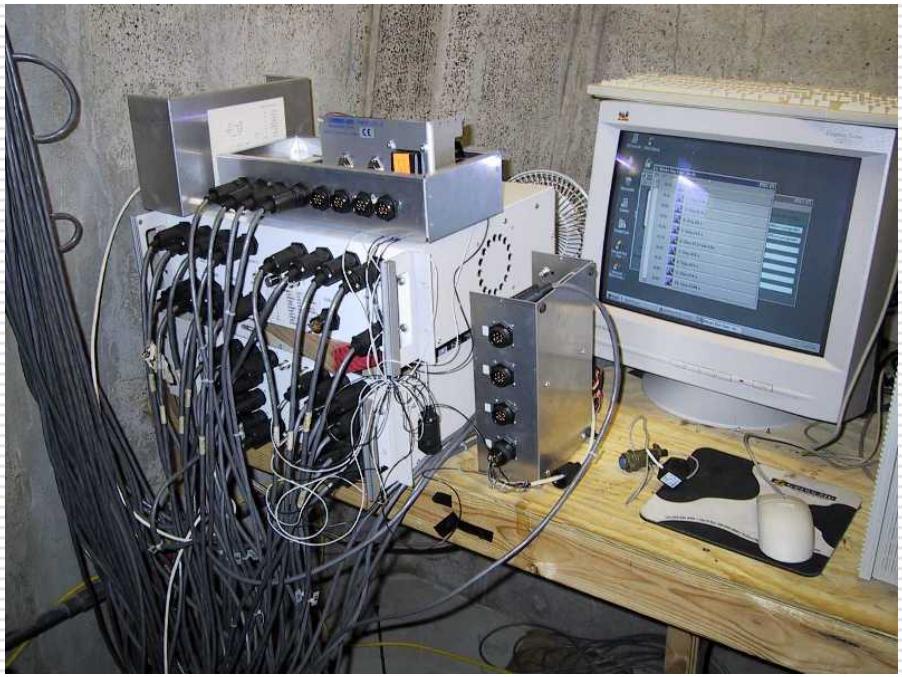


- Major measurement
  - Stays
    - Acceleration
    - Displacement
    - Damper force
  - Deck
    - Acceleration
  - Meteorological
    - Wind
    - Rainfall
    - Barometric Pressure

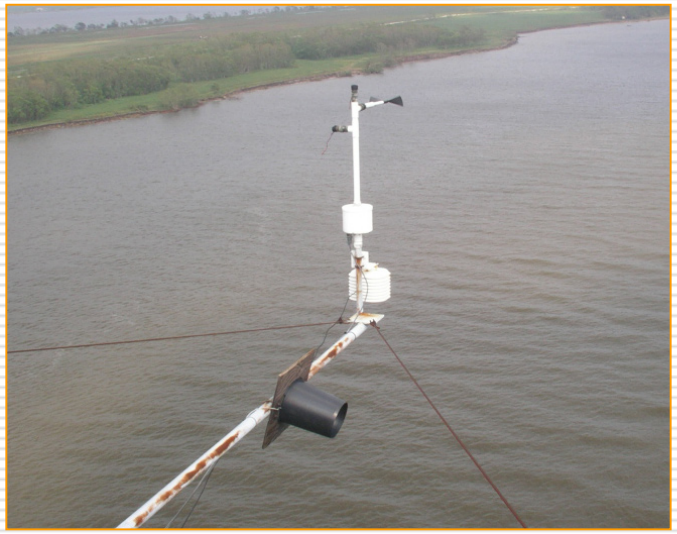
Anemometer
Bi-axial accelerometer
Uni-axial accelerometer

Data Acquisition Setup

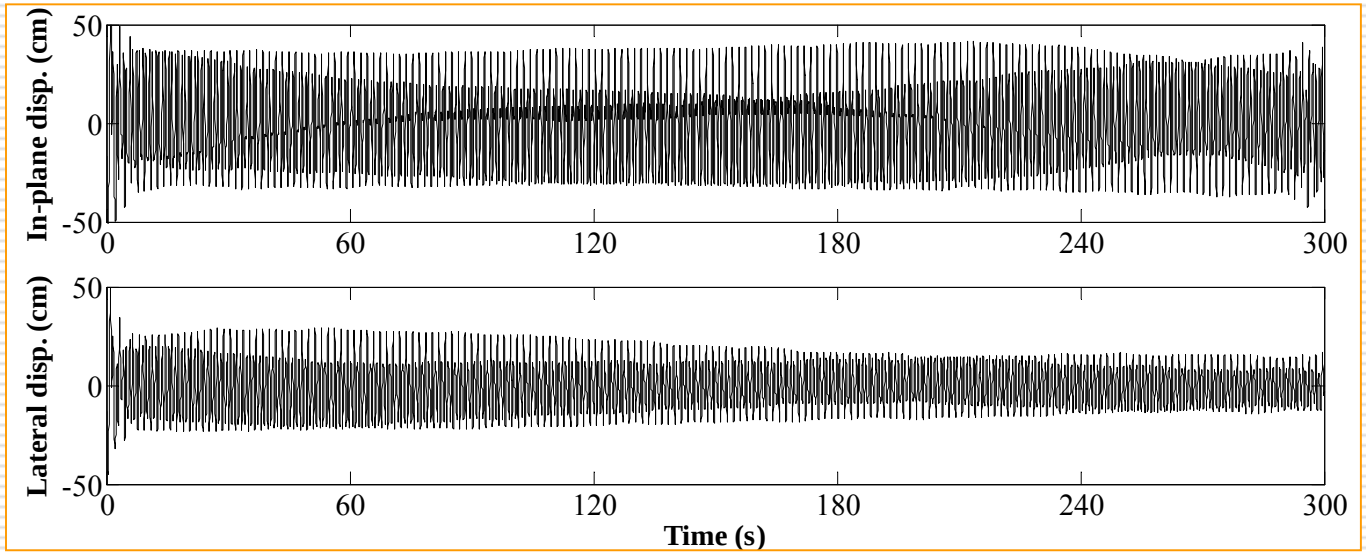
- Monitoring:
  - record summary statistics to disk every 10 minutes
  - Change to Triggered mode when thresholds are exceeded
- Triggered:
  - stream data for all channels to disk at 40 Hz for 5 minutes (More than 64000 records recorded.)

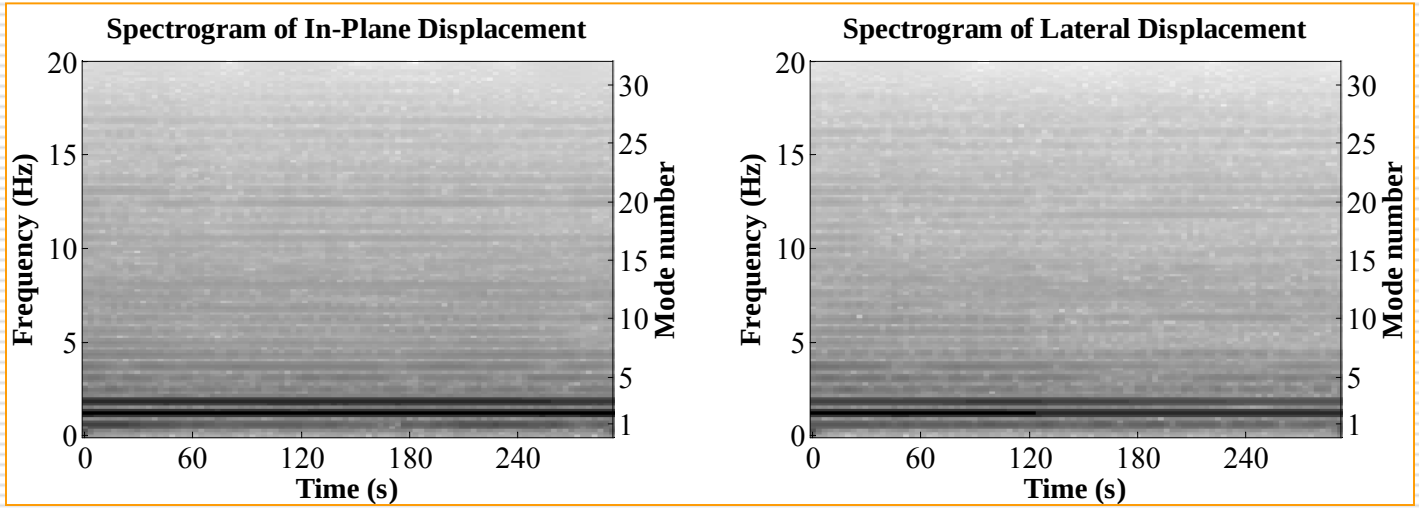


Oops…Or…Ouch!



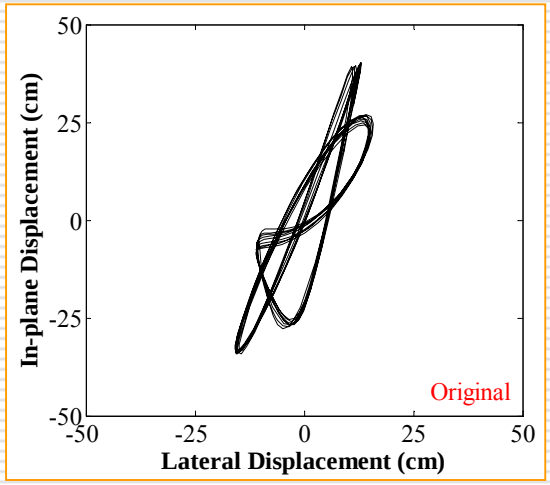
General Characteristics: Multi-Modal Participation

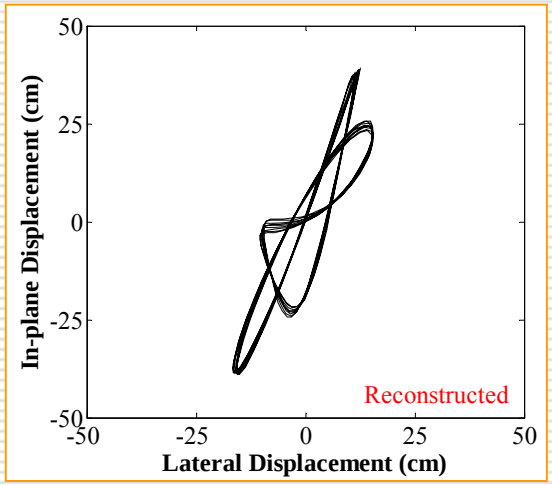




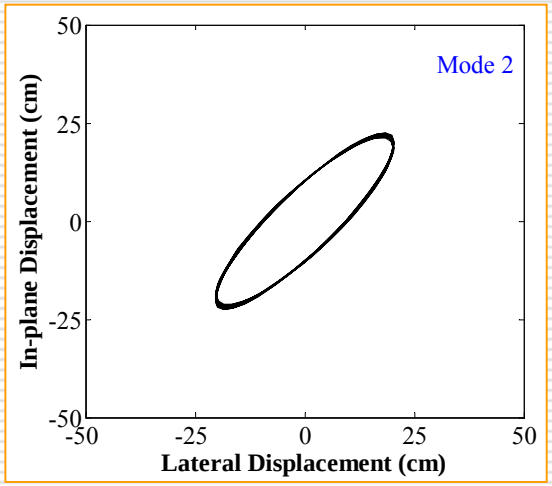
JOHNS HOPKINS UNIVERSITY

General Characteristics: Two-Dimensional Vibration

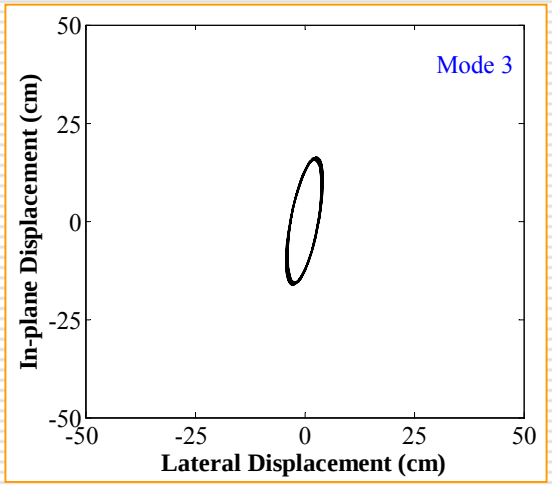




=

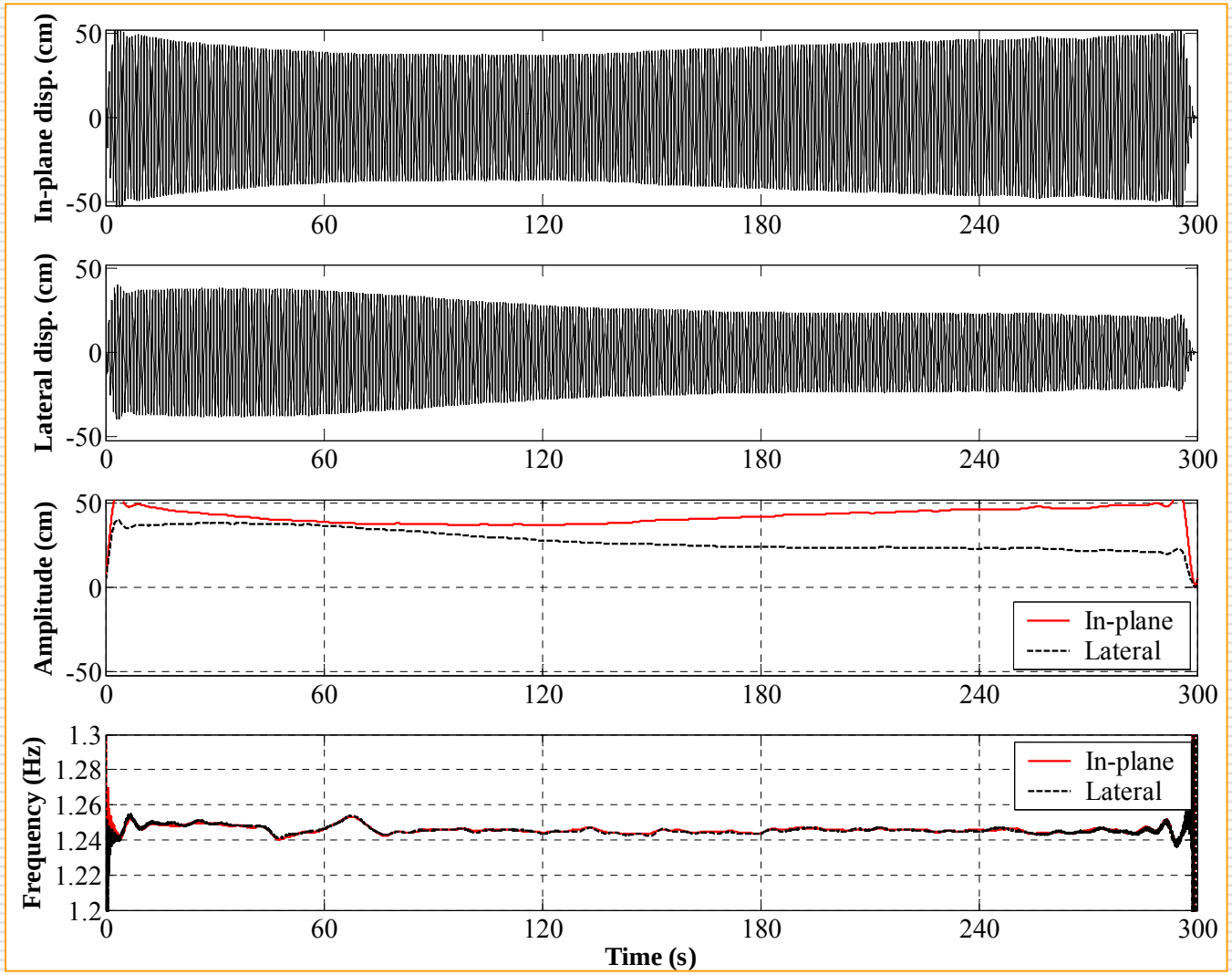


+



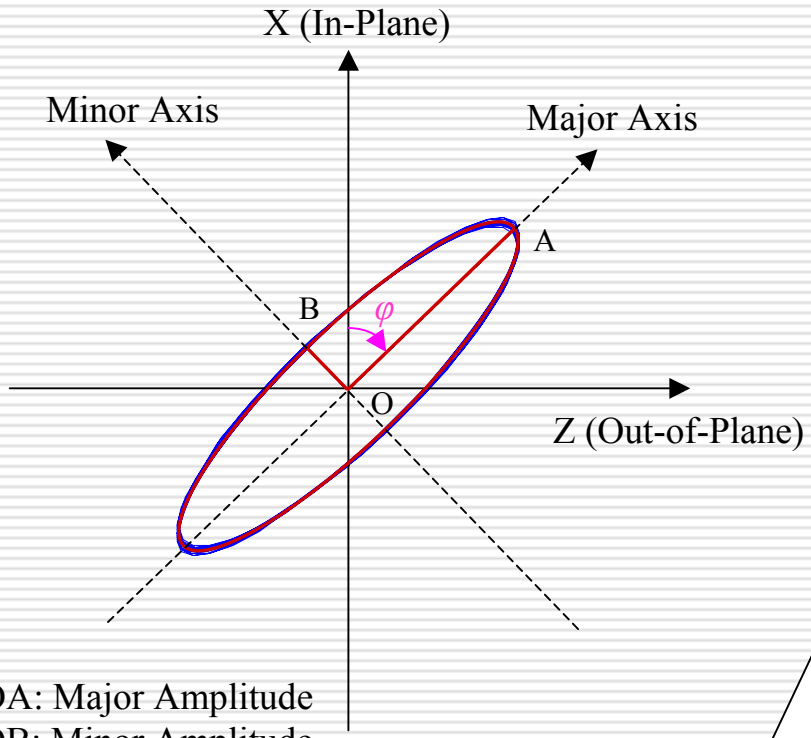
JOHNS HOPKINS UNIVERSITY

Frequency Estimation: The Hilbert Transform

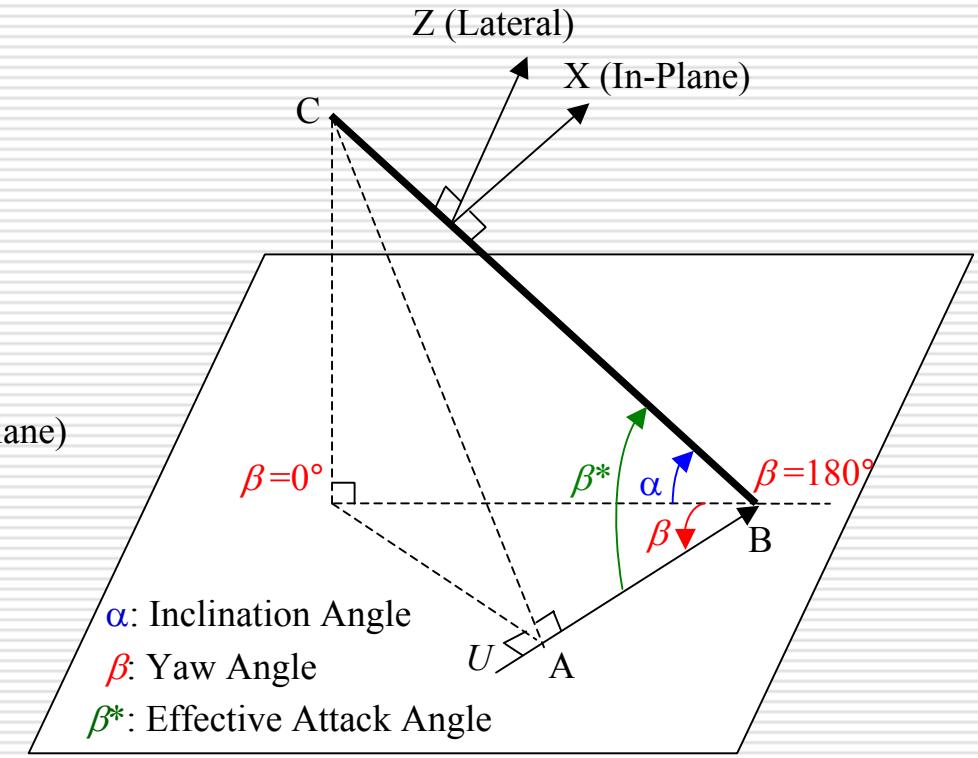


JOHNS HOPKINS UNIVERSITY

Spatial Coordinate System



OA: Major Amplitude
OB: Minor Amplitude
φ: Major Axis Angle

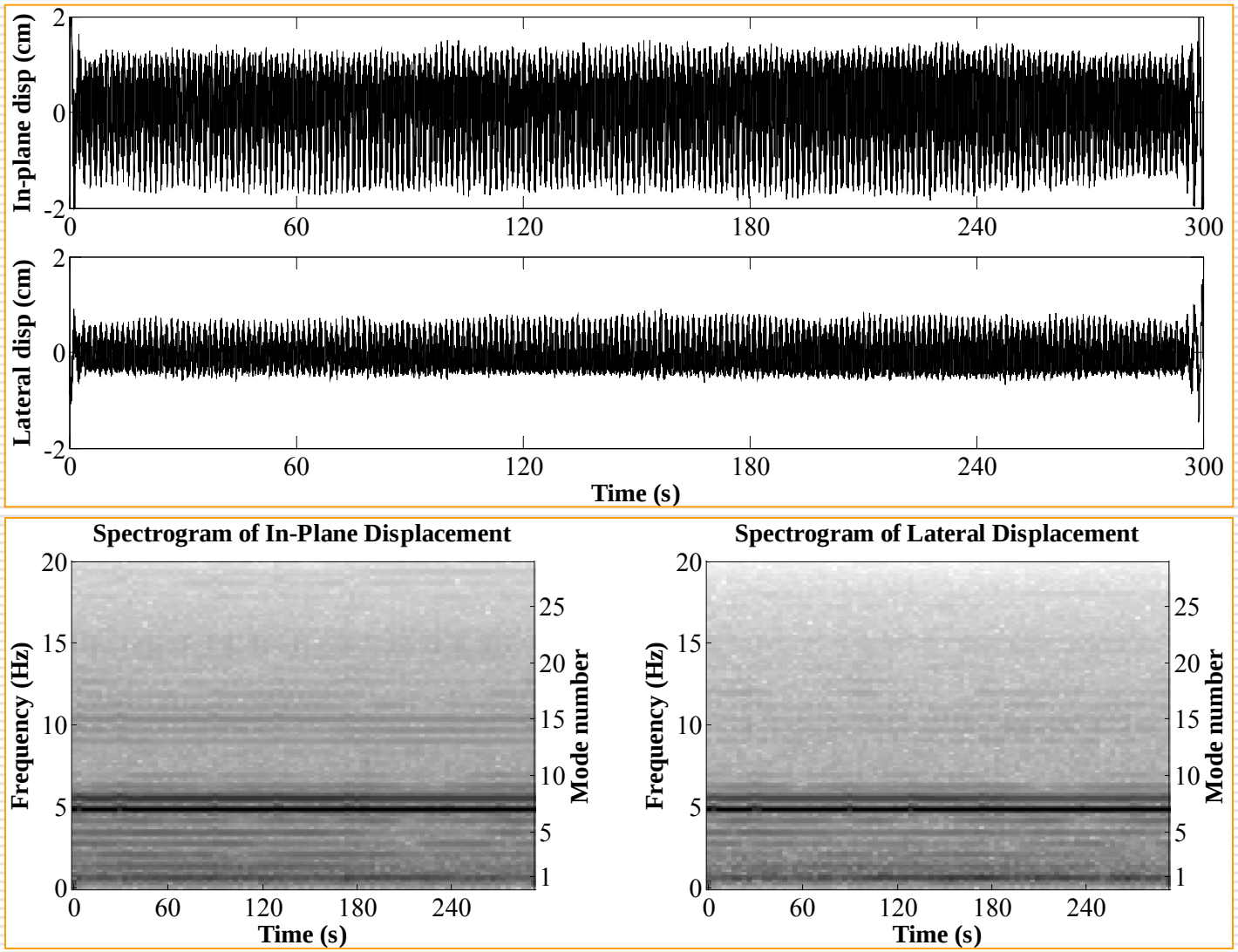


JOHNS HOPKINS UNIVERSITY

Observed Types of Vibrations

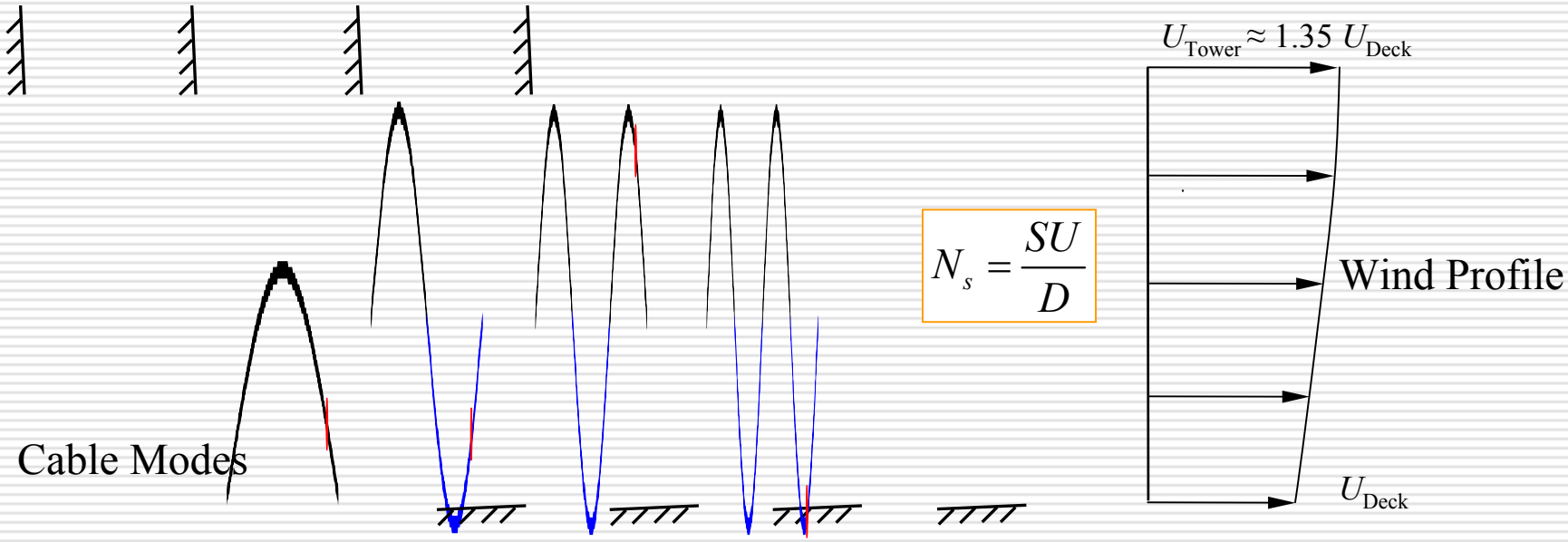
- (Kármán-) Vortex-induced vibration (VIV)
- Rain-wind induced vibration (RWIV)
- Large-amplitude dry cable vibration
- Deck-induced vibration
- Vibrations not categorized

Vortex-Induced Vibration: Example Record

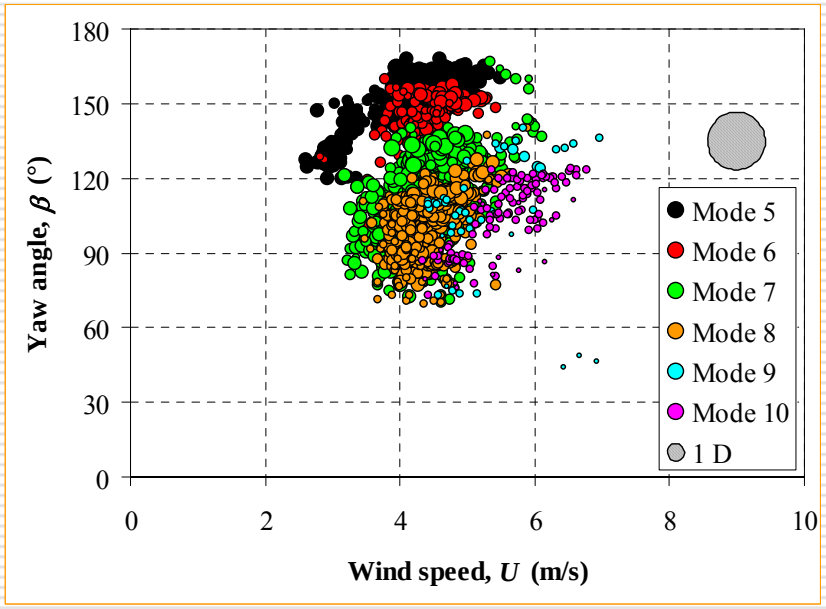


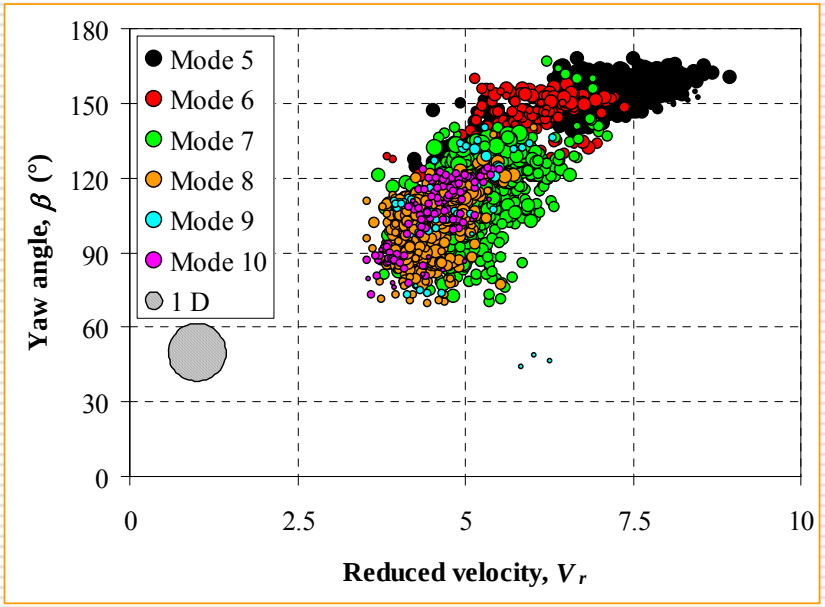
JOHNS HOPKINS UNIVERSITY

Significant Modes and Wind Profile

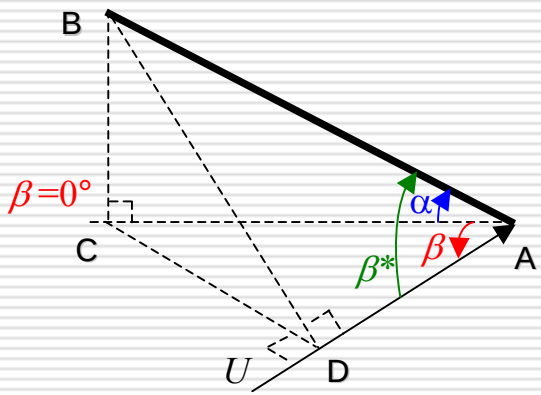


Vortex-Induced Vibration: Dependence on Wind (1)



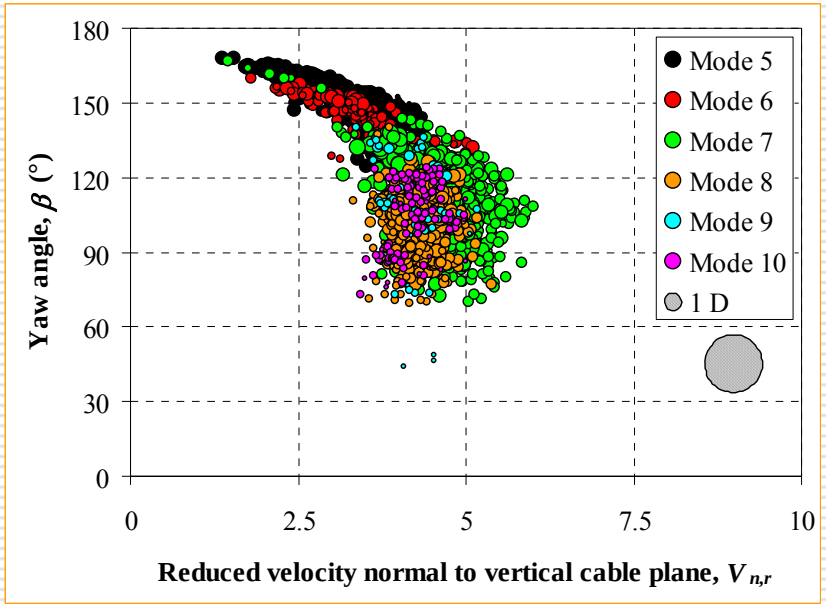


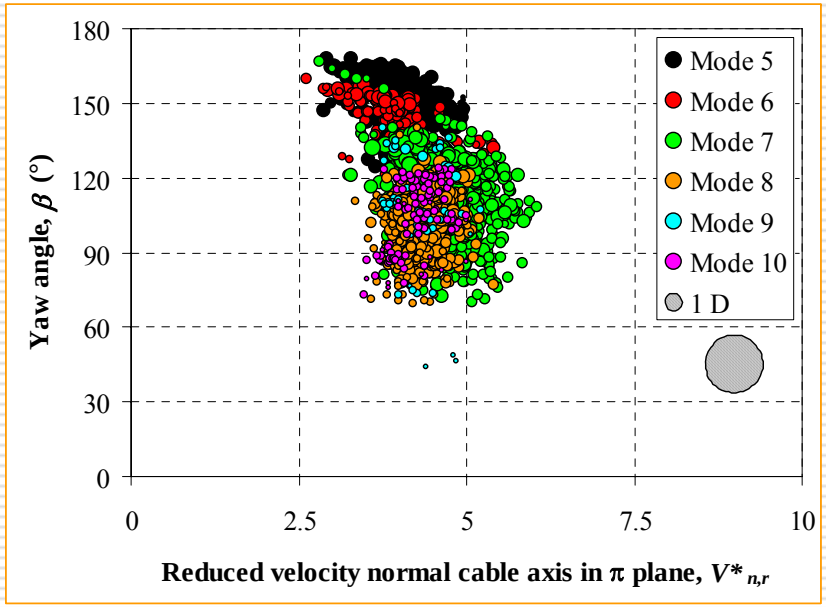
- Stay AS23: L=182.5 m; α=23.31°; D=0.194 m; f_1=0.64 Hz
- Reduced velocity: $V_r = \frac{U}{f_i \cdot D} = \frac{1}{S}$
- $V_r = 5$ for circular cylinder normal to flow
- Diameter of circles represents amplitude of vibration
- 1D=Diameter of cable



JOHNS HOPKINS UNIVERSITY

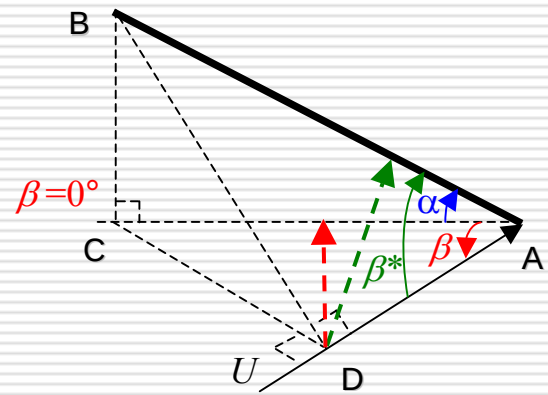
Vortex-Induced Vibration: Dependence on Wind (2)





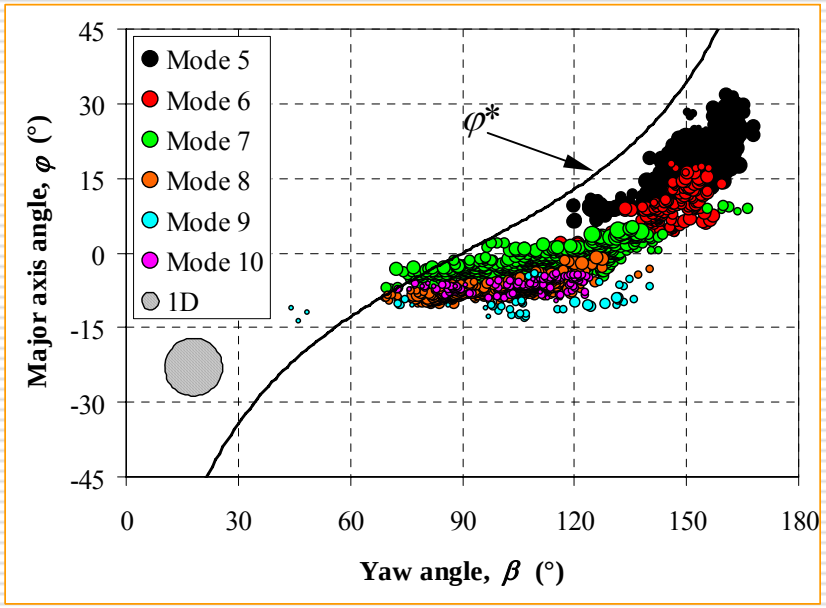
- Stay AS23: L=182.5 m; α=23.31°; D=0.194 m; f_1=0.64 Hz
- Reduced velocity normal to vertical cable plane: $V_{n,r} = \dfrac{U \cdot Sin\beta}{f_i \cdot D}$
- Reduced velocity normal to cable axis in the π plane:

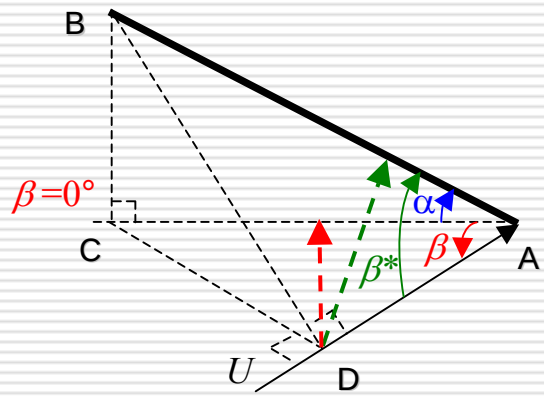
$$V^*_{n,r} = \frac{U \cdot Sin\beta^*}{f_i \cdot D}$$



JOHNS HOPKINS UNIVERSITY

Vortex-Induced Vibration: Dependence on Wind (3)



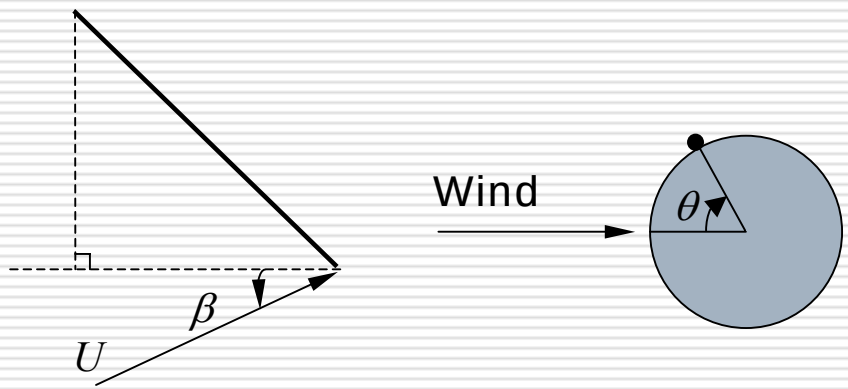


- Stay AS23: L=182.5 m; α=23.31°; D=0.194 m; f_1=0.64 Hz
- φ*: Angle between vertical cable plane and the plane perpendicular to the π plane

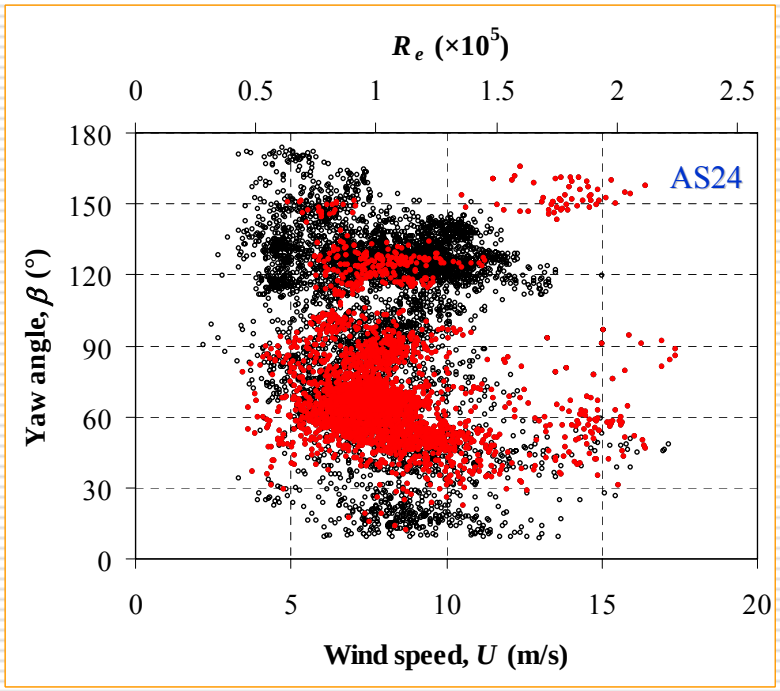
JOHNS HOPKINS UNIVERSITY

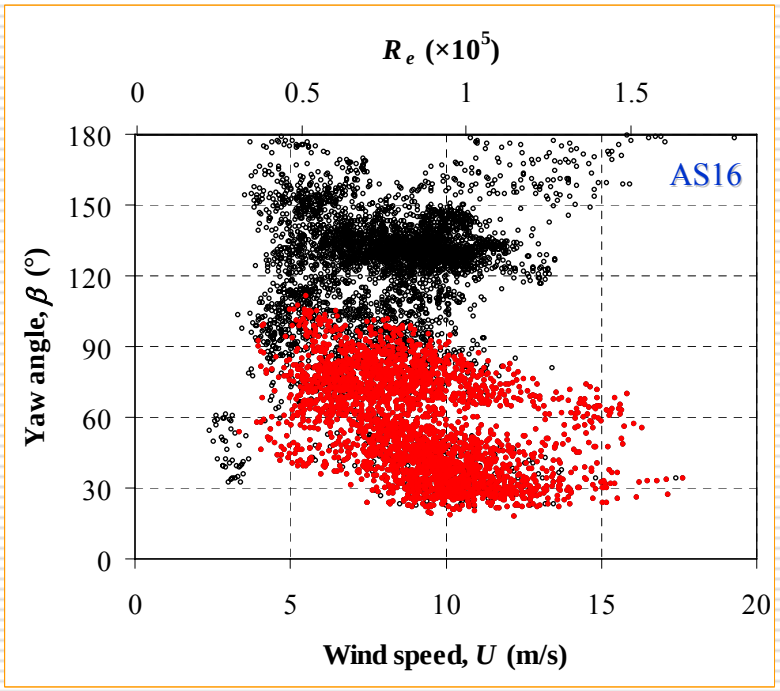
Rain-Wind-Induced Vibration: Previous Beliefs

- Occurs only with (light to moderate) rainfall
- Occurs in relatively smooth wind
- Preferred wind speed in the range of about 6-17 m/s
- Stays declining in the direction of wind are more susceptible (i.e., $0° < \beta < 90°$). (Being debated)
- Large amplitude, up to several diameters of stay
- Occurs in the lower modes (1-3 Hz)
- Movement/position of water rivulets critical for the onset of vibration

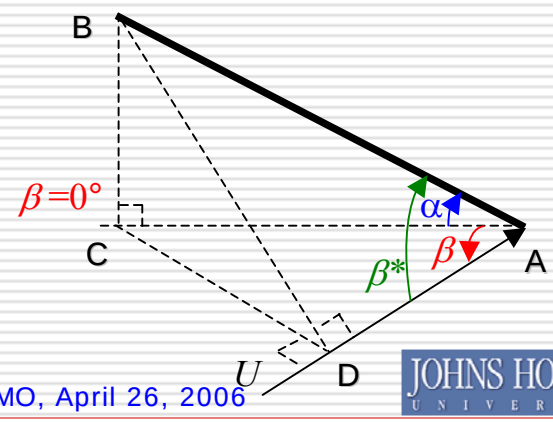


RWIV: Preferred Wind Speed and Direction



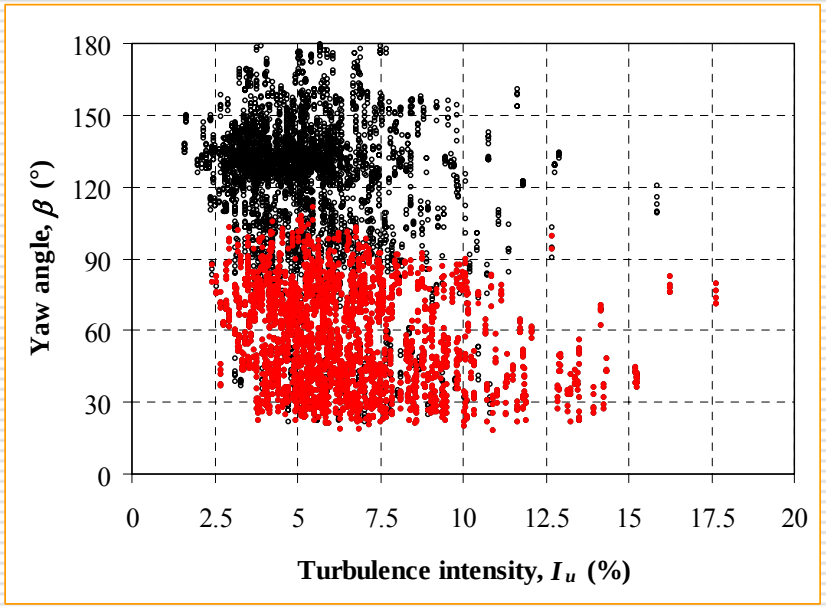


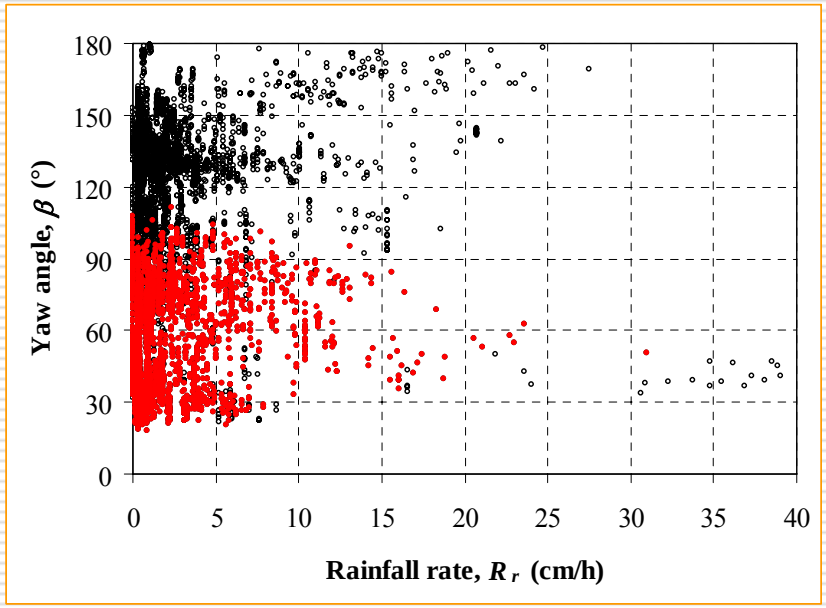
- Stay AS24: L=197.8 m; α=21.11°; D=0.194 m; f_1=0.57 Hz
- Stay AS16: L=87.3 m; α=45.92°; D=0.141 m; f_1=1.24 Hz
- Open circles=simultaneous occurrence of wind and rain
- Solid red circles=Large amplitude vibrations with simultaneous occurrence of wind and rain



JOHNS HOPKINS UNIVERSITY

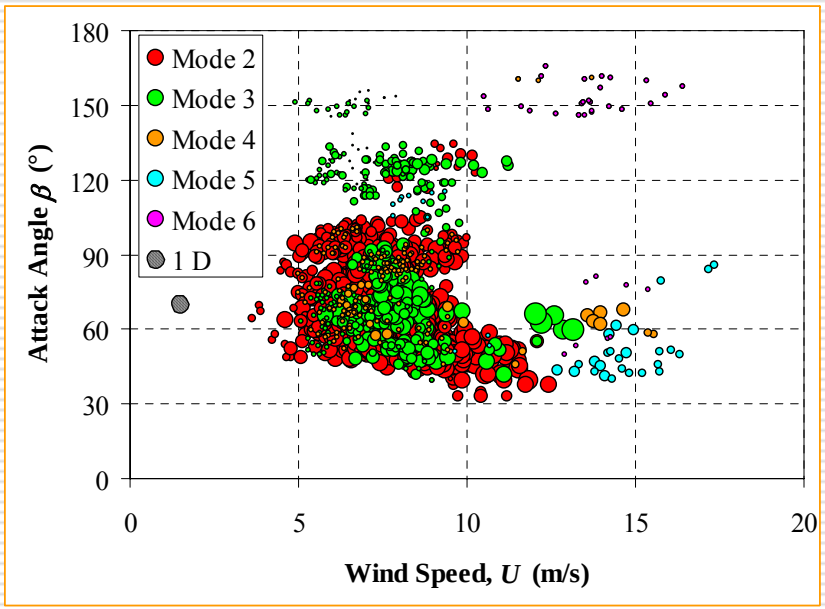
RWIV: Effects of Turbulence and Rate of Rainfall

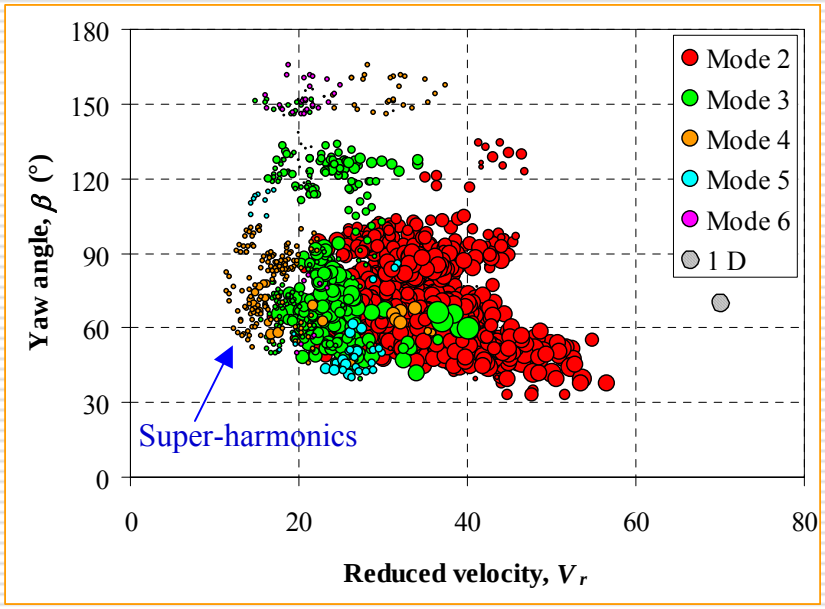




- Stay AS16: L=87.3 m; α=45.92°; D=0.141 m; f_1=1.24 Hz
- Turbulence intensity is based on one-minute values
- Open circles=simultaneous occurrence of wind and rain
- Solid red circles=Large amplitude vibrations with simultaneous occurrence of wind and rain

RWIV: Dependence on Wind (1)

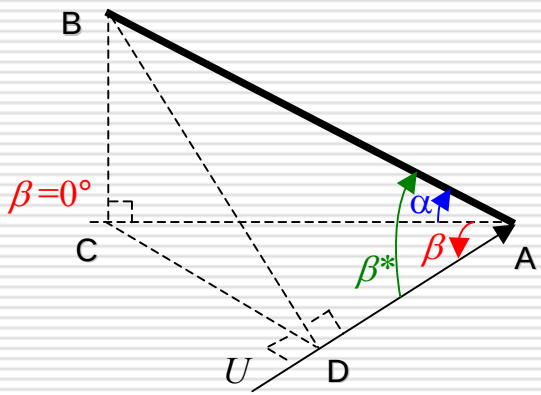




$$F(t) = F(t+T) = b_0 + \sum_{j=1}^{\infty}(b_j \cos\omega_j t + a_j \sin\omega_j t)$$

$$\omega_j = \frac{2j\pi}{T} = j\omega$$

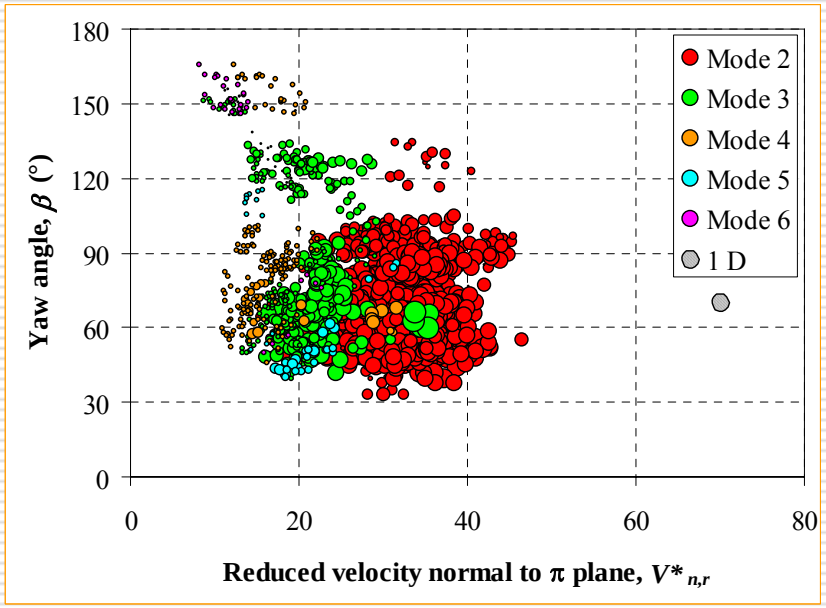
$$a_j = \frac{\omega}{\pi}\int_0^{2\pi/\omega} F(t)\sin\omega_j t dt;\ b_j = \frac{\omega}{\pi}\int_0^{2\pi/\omega} F(t)\cos\omega_j t dt$$

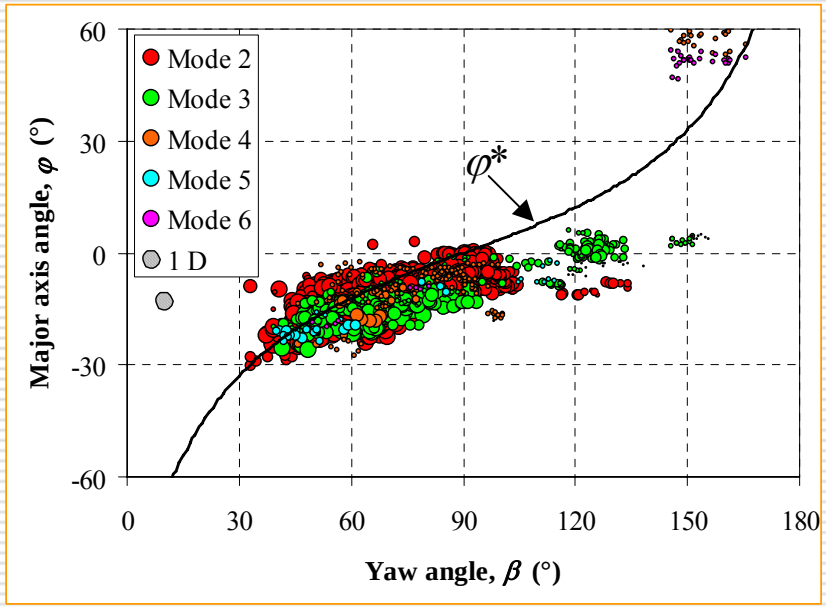


- Stay AS24: L=197.8 m; α=21.11°; D=0.194 m; f_1=0.57 Hz
- Reduced velocity: $V_r = \dfrac{U}{f_i \cdot D}$

JOHNS HOPKINS UNIVERSITY

RWIV: Dependence on Wind (2)

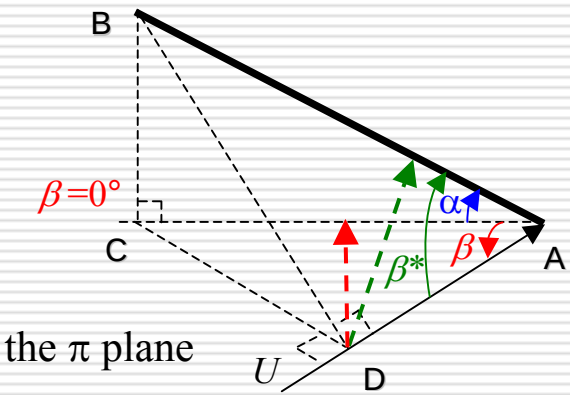




- Stay AS24: L=197.8 m; α=21.11°; D=0.194 m; f_1=0.57 Hz
- Reduced velocity normal to cable axis in the π plane:

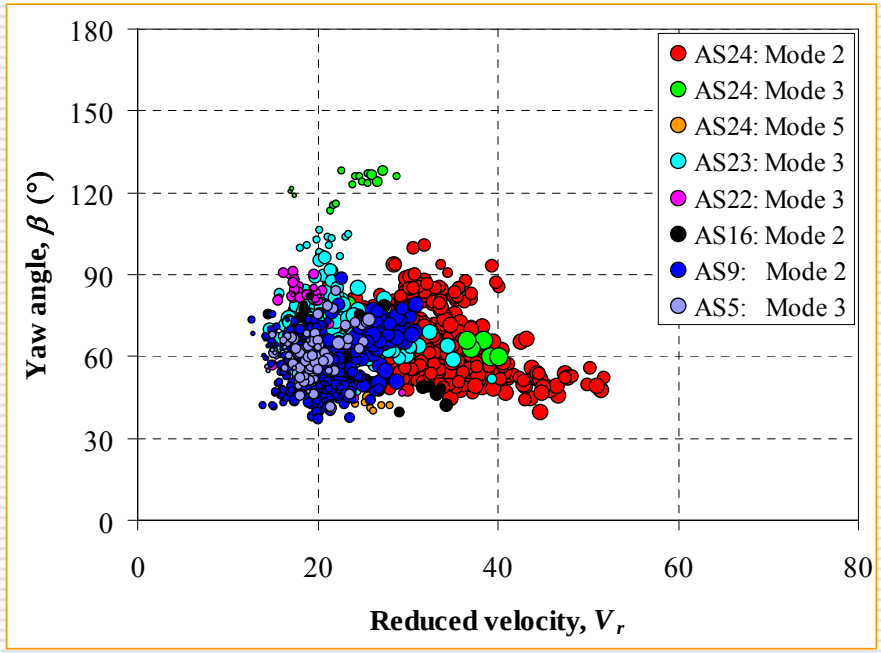
$$V^*_{n,r} = \frac{U \cdot Sin\beta^*}{f_i \cdot D}$$

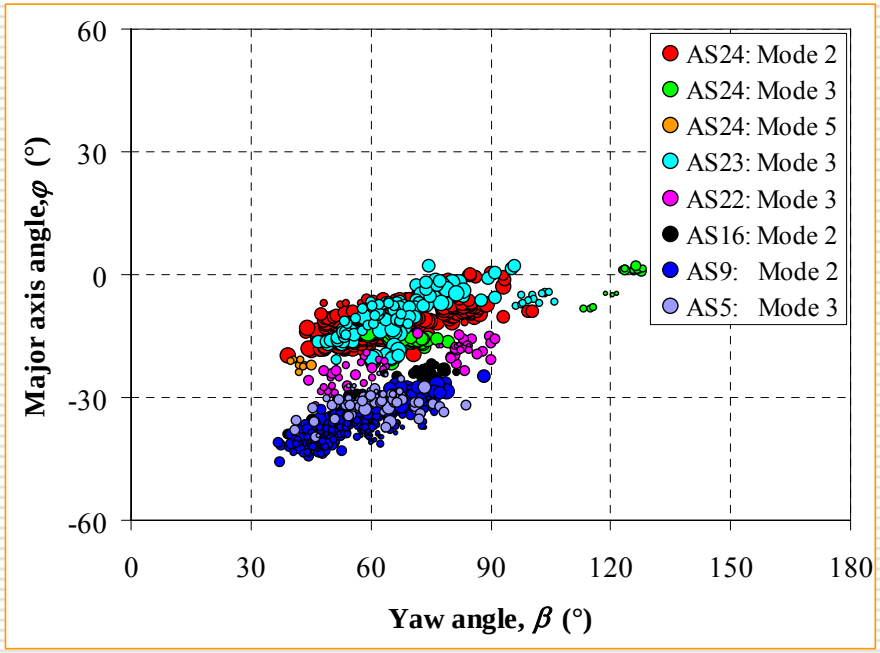
- φ^*: Angle between vertical cable plane and the plane normal to the π plane



JOHNS HOPKINS UNIVERSITY

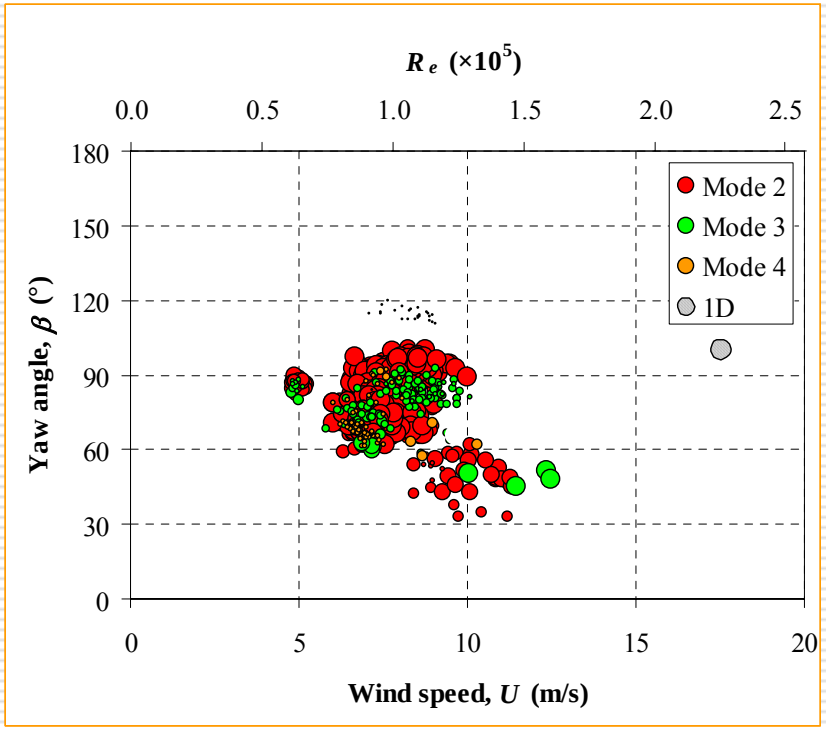
RWIV: Dependence on Wind (3)

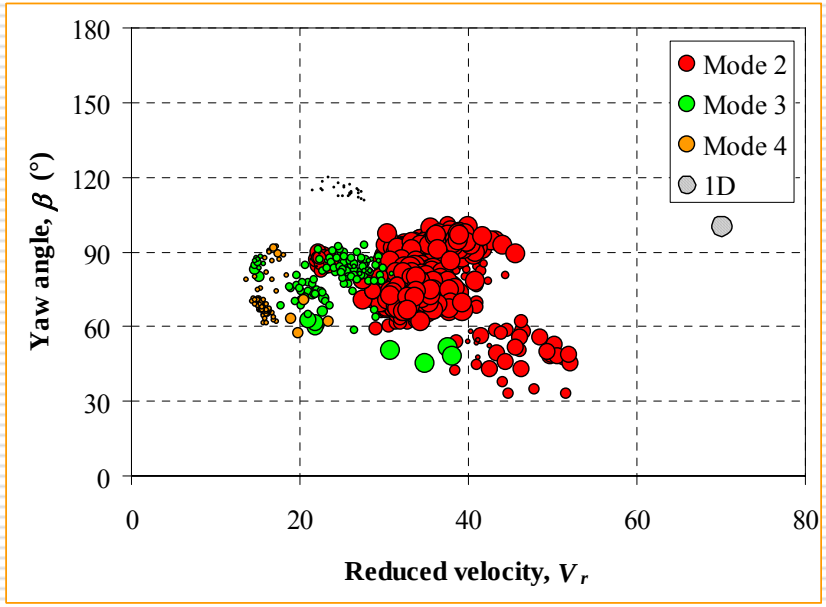




- Stay AS24: L=197.8 m; α=21.11°; D=0.194 m; f_1=0.57 Hz
- Stay AS23: L=182.5 m; α=23.31°; D=0.194 m; f_1=0.64 Hz
- Stay AS22: L=168.4 m; α=24.13°; D=0.168 m; f_1=0.69 Hz
- Stay AS5 : L=137.0 m; α=32.21°; D=0.168 m; f_1=0.80 Hz
- Stay AS16: L=87.3 m; α=45.92°; D=0.141 m; f_1=1.24 Hz
- Stay AS9 : L=87.0 m; α=48.95°; D=0.141 m; f_1=1.24 Hz

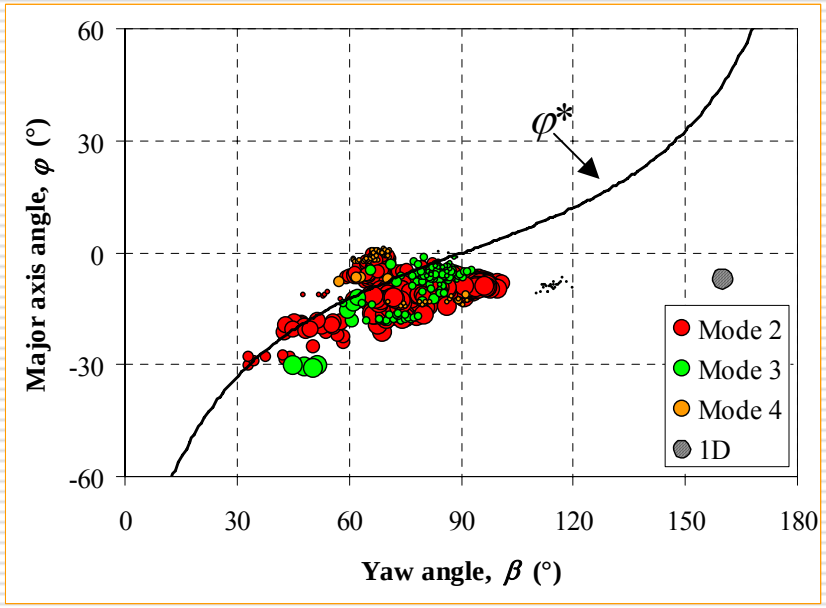
Dry-Cable Vibration: Dependence on Wind (1)





- Stay AS24: L=197.8 m; α=21.11°; D=0.194 m; f_1=0.57 Hz

Dry-Cable Vibration: Dependence on Wind (2)

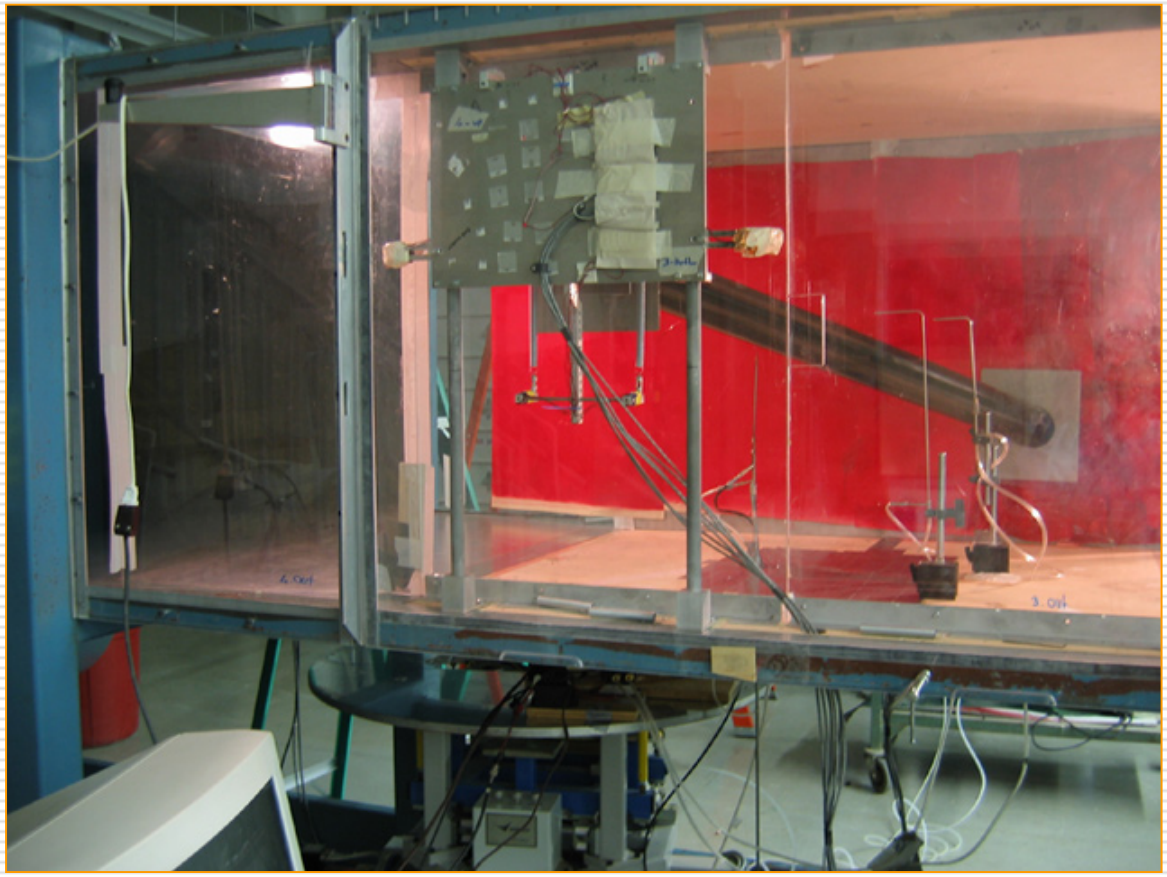


- Stay AS24: L=197.8 m; α=21.11°; D=0.194 m; f_1=0.57 Hz
- φ^*: Angle between vertical cable plane and the plane normal to the π plane

Summary of Field Observations

- The so-called rain-wind-induced vibration can occur without rainfall
- Frequent large-amplitude vibration, regardless of rainfall, occurs at a high reduced velocity range over a broad range of wind direction
- Large-amplitude vibration at high reduced velocity is likely a vortex-induced type, but not Kármán vortex-induced

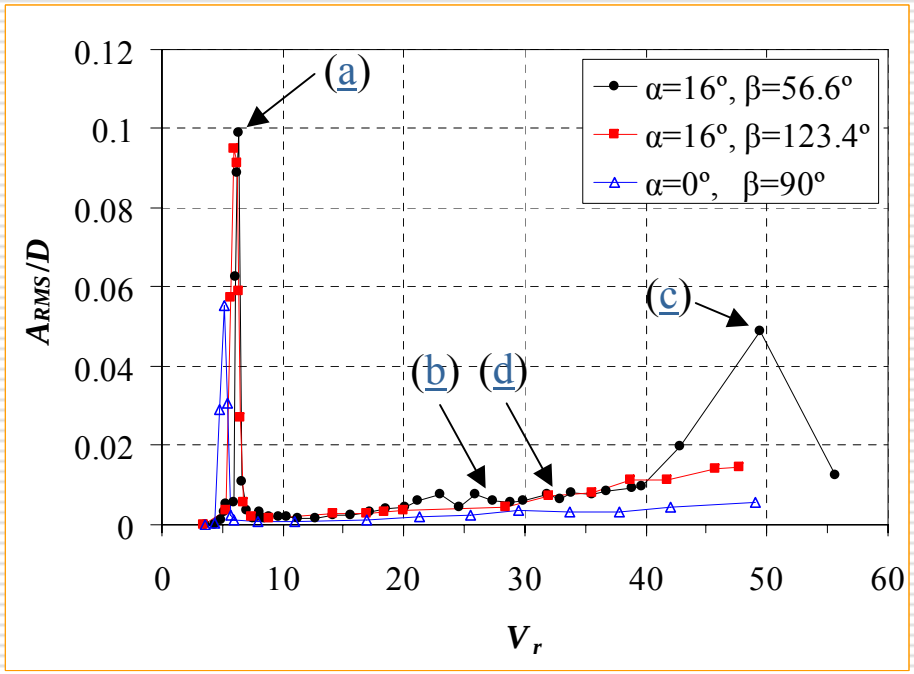
Wind Tunnel Tests: Example Setup



- Length: 1.12 m
- Diameter: 0.091m
- Mass:2.32 kg
- Incl. Angle: 16°
- Yaw Angle: 56.6°
- Damping Ratio: 0.35%

Wind Tunnel Tests: Configurations and Results

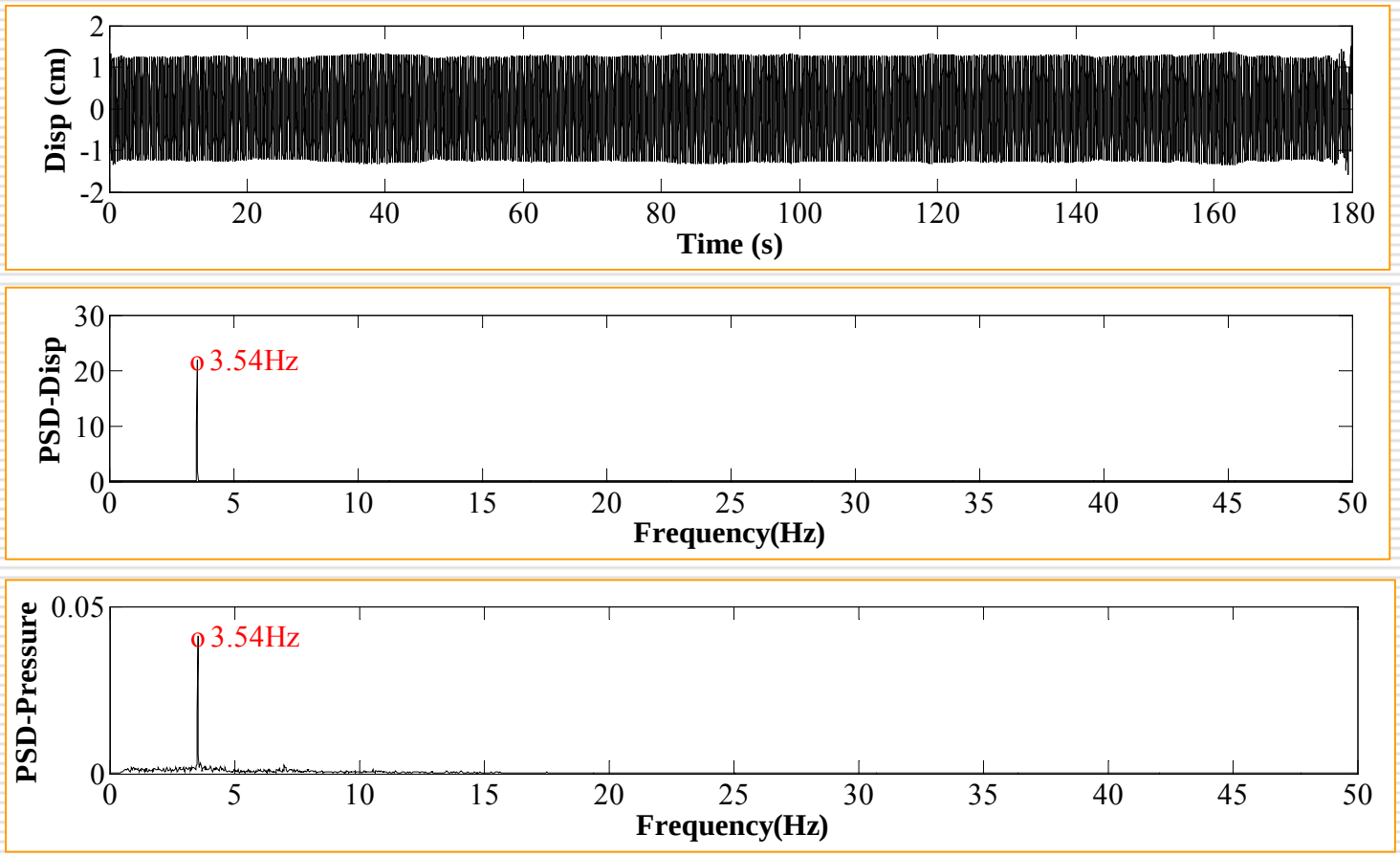
Config. #	α (°)	β (°)	f (Hz)	ζ (%)
1	16	56.6	3.52-3.76	0.35
2	16	123.4	3.52-3.91	0.35
3	0	90	3.61-3.80	0.35



- (a): V_r=6.2
- (b): V_r=27.3
- (c): V_r=49.5

JOHNS HOPKINS UNIVERSITY

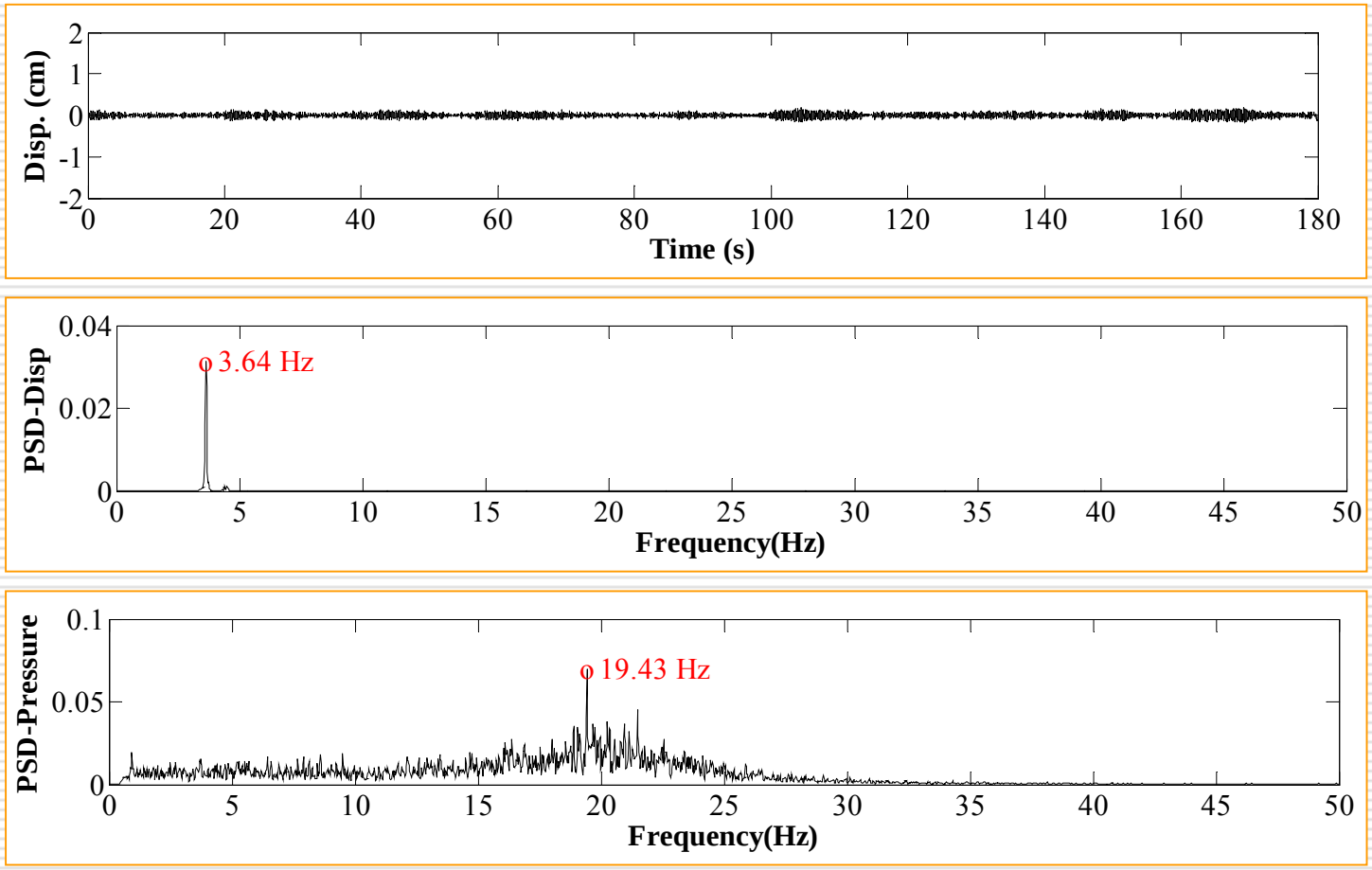
Record (a): Locked-in Kármán Vortex Shedding



Configure # 1: α=16°; β=56.6°; U=2.1 m/s; V_r=6.2

Record Index

Record (b): Vortex shedding not locked-in

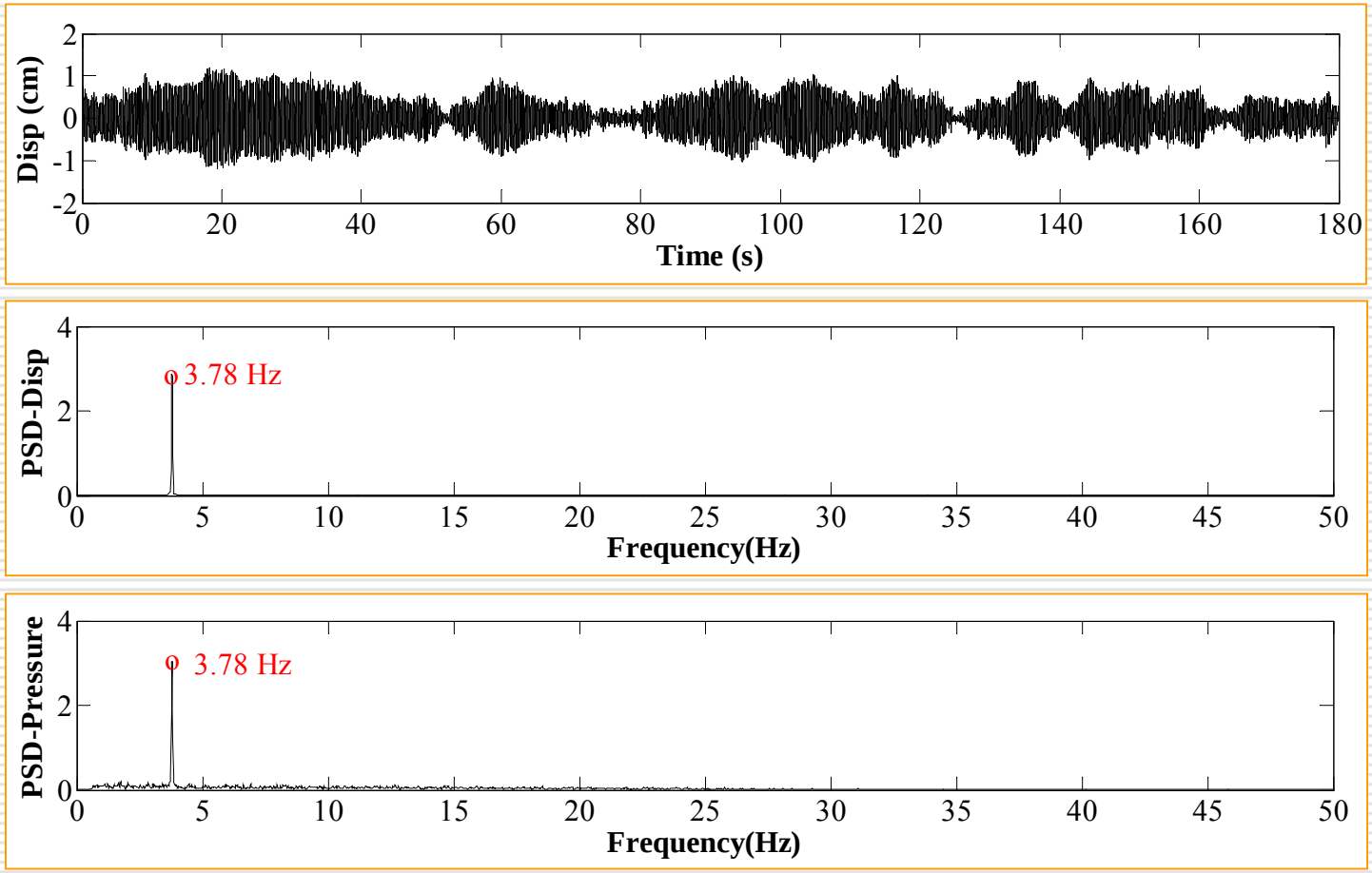


Configure # 1: α=16°; β=56.6°; U=9.1 m/s; V_r=27.3

Record Index

JOHNS HOPKINS UNIVERSITY

Record (c): Large Amplitude at High Reduced Velocity

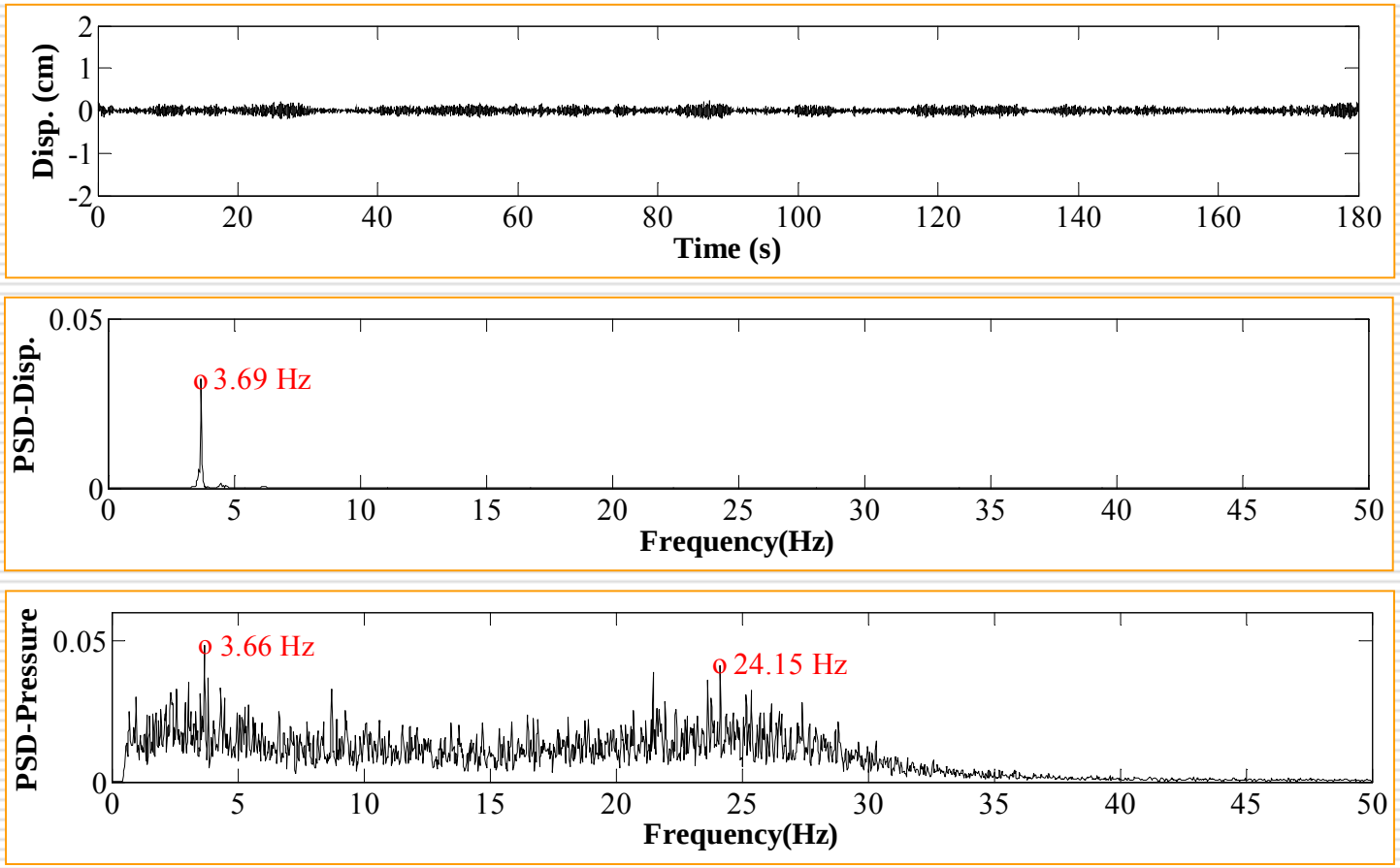


Record Index

Configure # 1: α=16°; β=56.6°; U=16.9 m/s; V_r=49.5; $R_e = 1.03\times10^5$

JOHNS HOPKINS UNIVERSITY

Record (d): Transition between Two Mechanisms



Configure # 1: α=16°; β=56.6°; U=11.0 m/s; V_r=32.9

Record Index

JOHNS HOPKINS UNIVERSITY

Summary of Wind Tunnel Test Results

- Yawed and inclined circular cylinders are susceptible to wind excitation over a range of high reduced velocity
- The wind excitation mechanism at high reduced velocity is likely related a type of three-dimensional vortex shedding
- Spatial orientation of stay cables is important for aeroelastic stability

Acknowledgement

- TXDOT
- FHWA
- NSF
- Jack Spangler, senior mechanical technician, JHU
- Former students in Professor Nick Jones's research group at JHU