Wind Induced Vibration of Cable Stay Bridges Workshop, April 25-27, 2006

# Mechanism of Wind & Rain/Wind Induced Cable Vibrations

## The Generation Mechanism of Inclined Cable Aerodynamics-Rain-Wind Induced Vibration and Dry-State Galloping

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# Inclined Cable aerodynamics

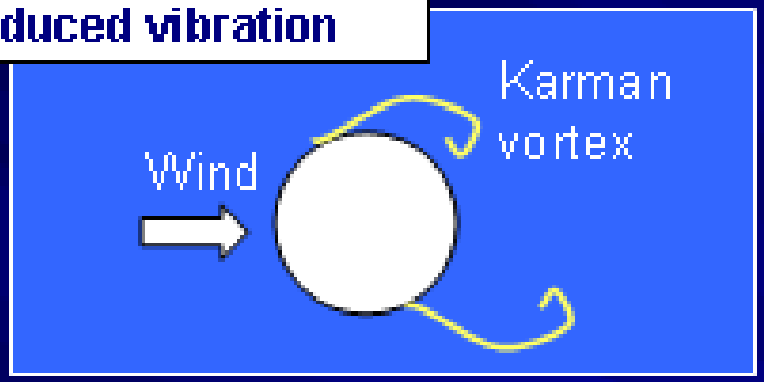
- **High Speed Vortex Induced Vibration**
  **Velocity-Restricted Response**
- **Galloping Instability**
  **Divergent Response**
  **Velocity Restricted Response**

?

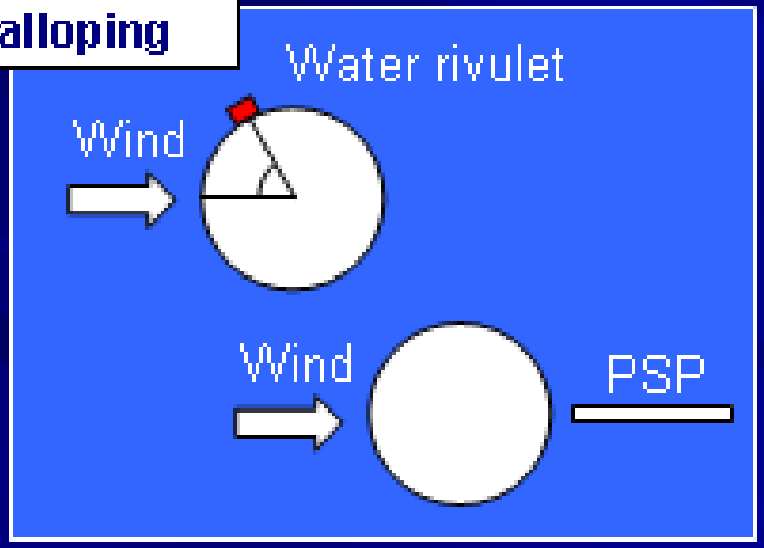
# Typical Response

## β=0°

**Karman vortex induced vibration**

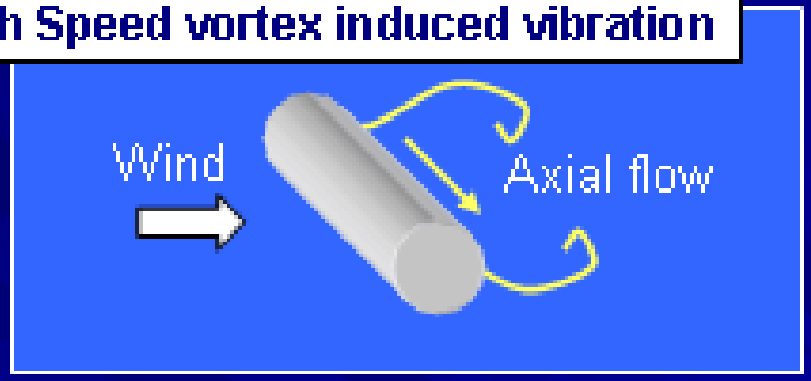



**Galloping**

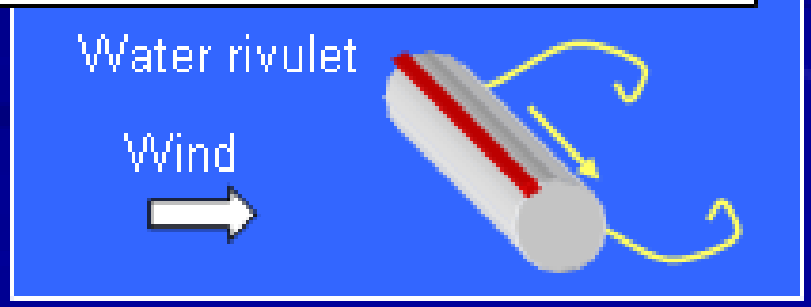



## β=45°

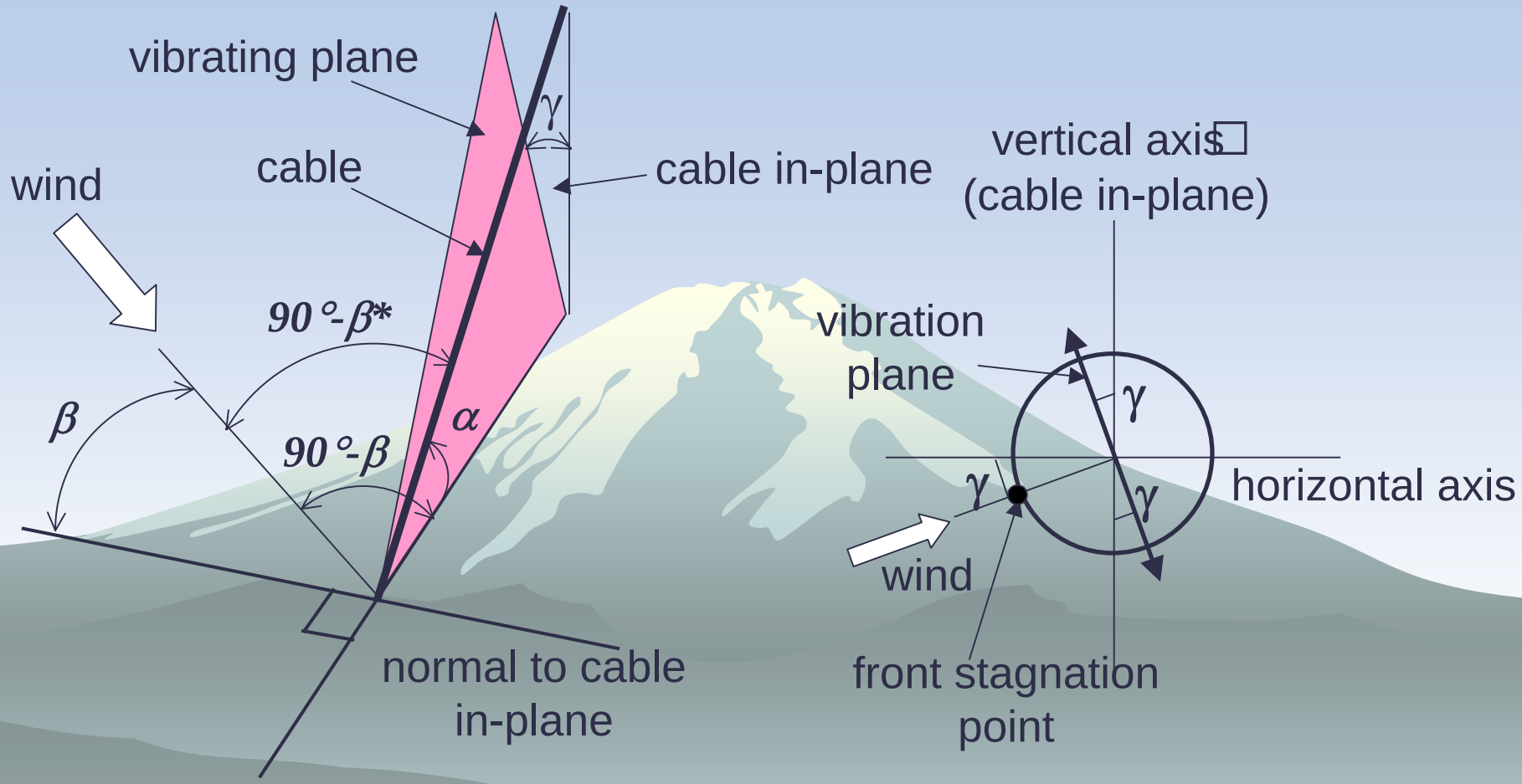
**Karman vortex induced vibration**
**Galloping**
**High Speed vortex induced vibration**




**Karman vortex induced vibration**
**Galloping**
**High Speed vortex induced vibration**



# Cable Attitude to Wind




$\alpha$ :vertical angle

$\beta$ :yaw angle

$\beta^*$ :effective yaw angle

$$\beta^* = \arcsin(\cos\alpha \cdot \sin\beta)$$

$$\gamma = 90° - \arccos(\sin\alpha \cdot \sin\beta / (\sin^2\alpha + \cos^2\alpha \cdot \cos^2\beta)^{1/2})$$

# Inclined Cable Aerodynamics

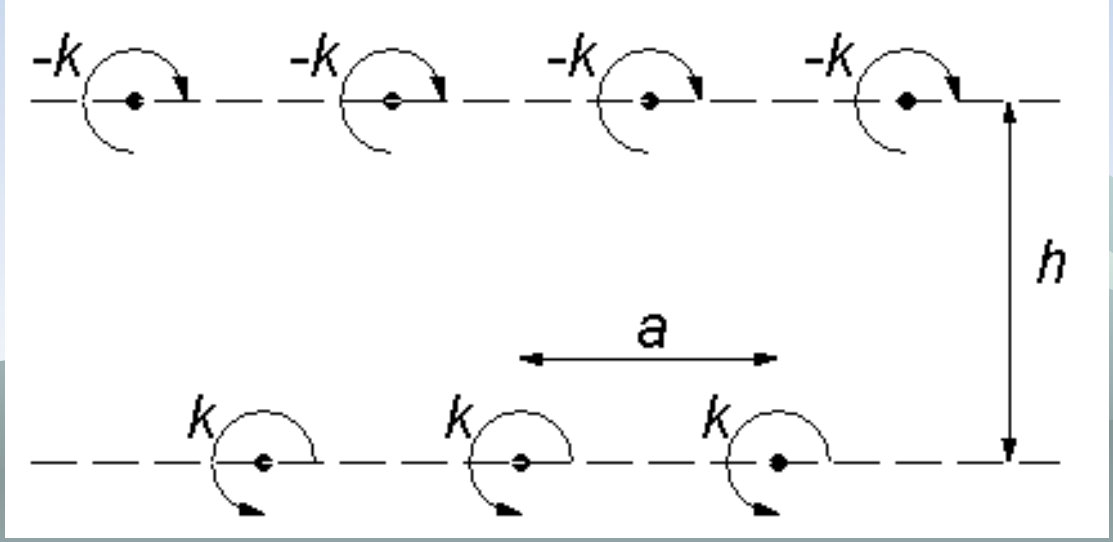
The substantial factors

- The upper water rivulet formation on a cable surface
- The axial flow in a near wake
- Critical Reynolds number

- **Cable Aerodynamics in related to Karman Vortex**

# Karman Vortex

# The Karman Vortex Street (KV)



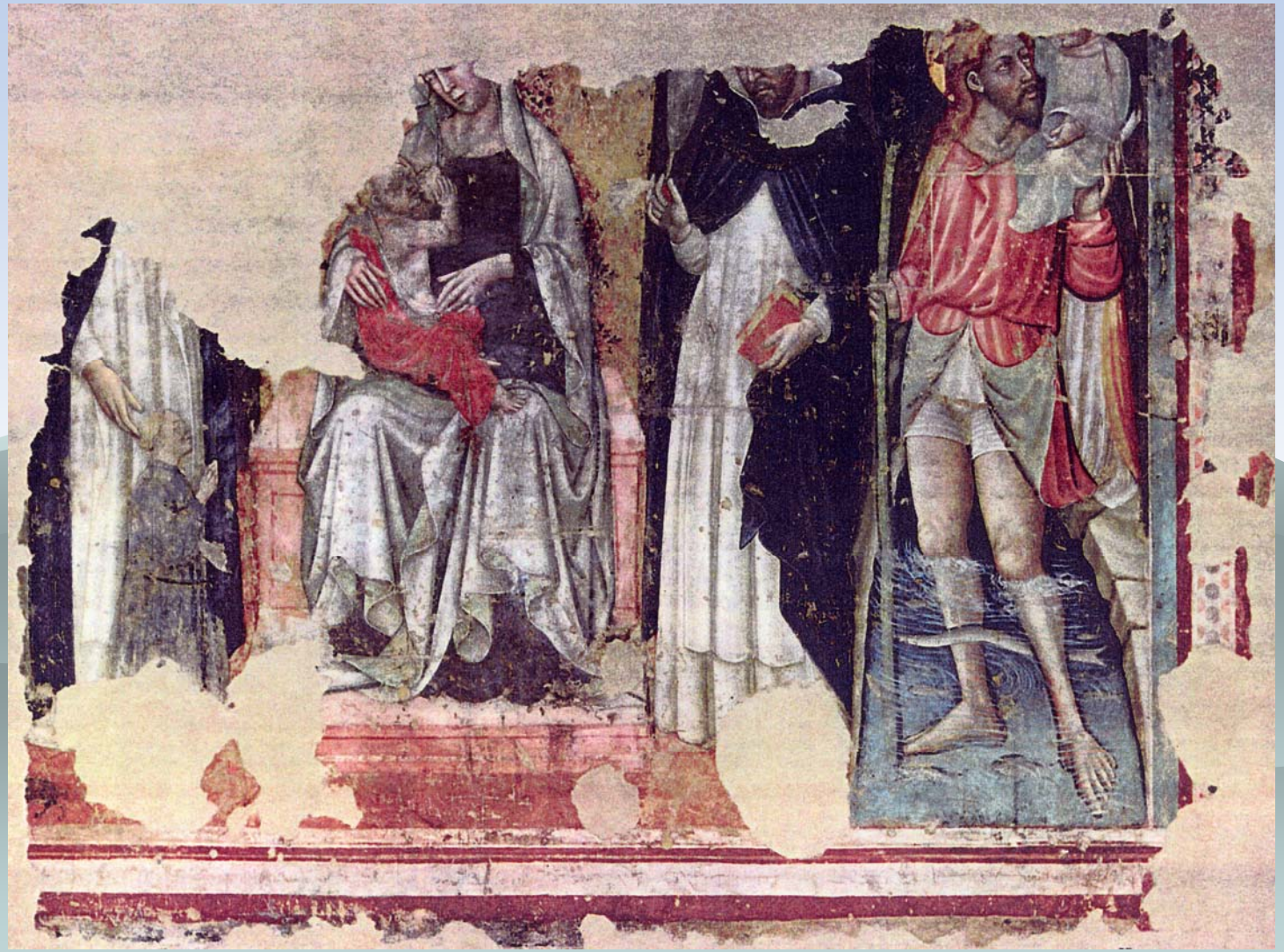

$$\sinh \pi (h/a) = 1$$

Theodore von Karman,

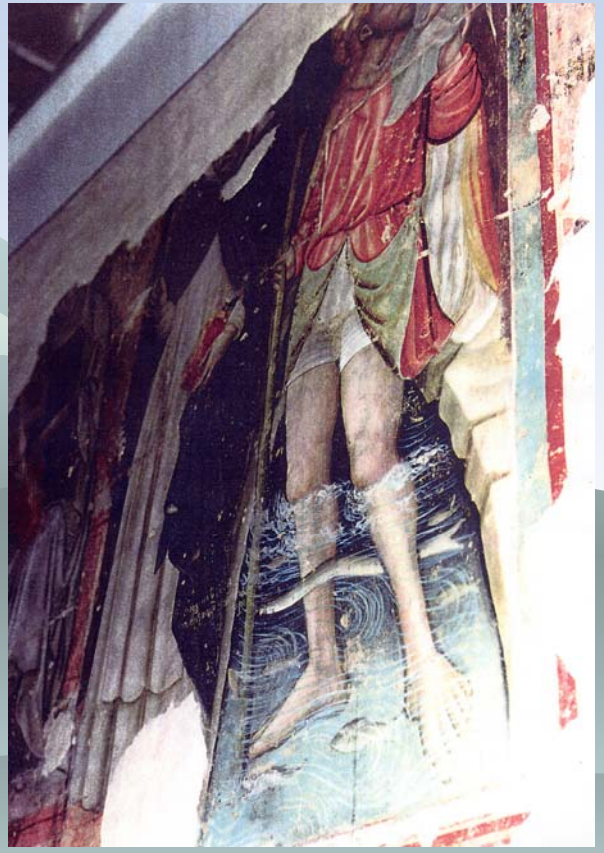
1881~1963

**Stable Condition of Vortex Street in Potential Flow,**
**[Theodore von Karman, 1911.]**

# Karman Vortex (KV)



# Karman Vortex (KV)



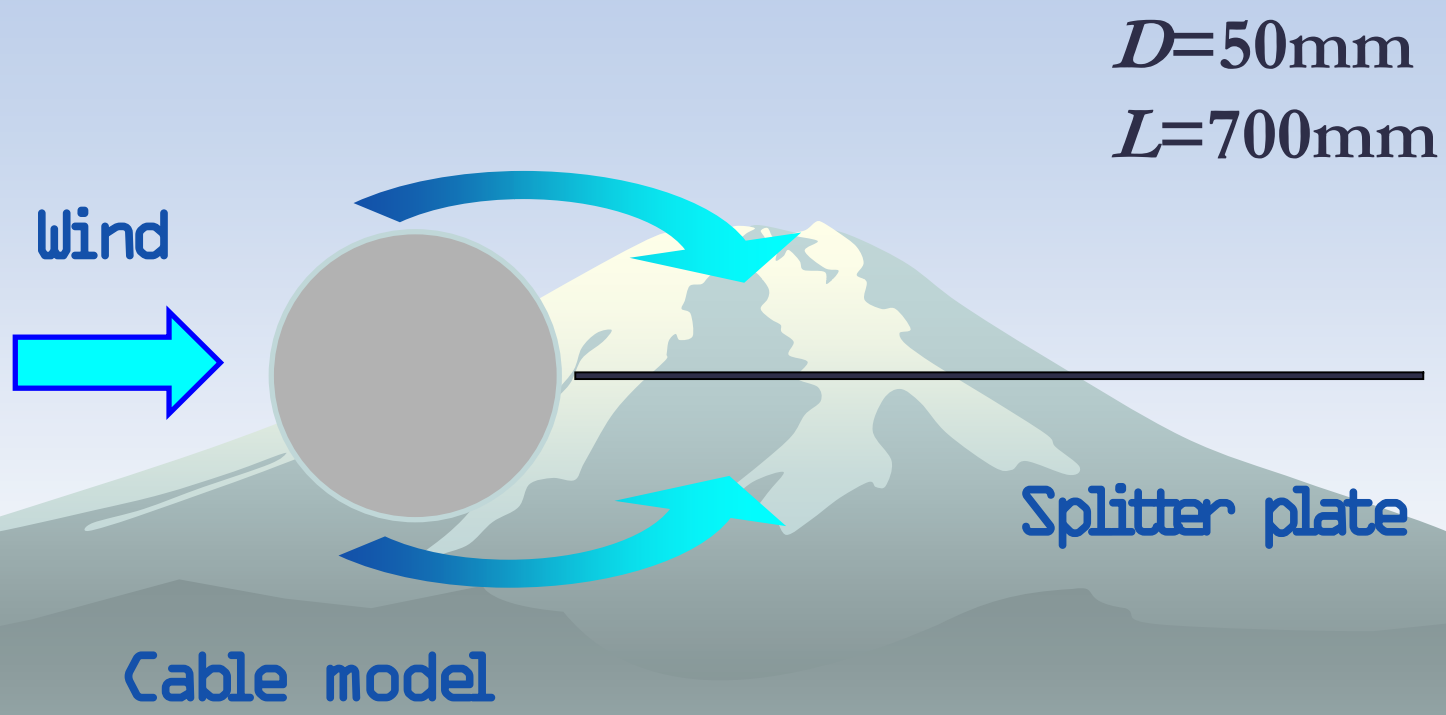
# Karman vortex (KV)

Karman vortex can be sensitively influenced by various factors.

# Lock-in Phenomena? (KV)

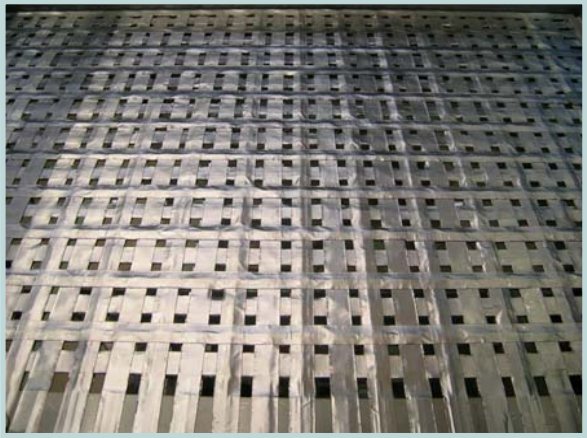
- At near resonance velocity to Karman vortex, the large amplitude response might be excited by motion-induced vortex, but not by Karman vortex. (Lanivier, Zaso etc.)

# Splitter Plate with suitable OR (KV)

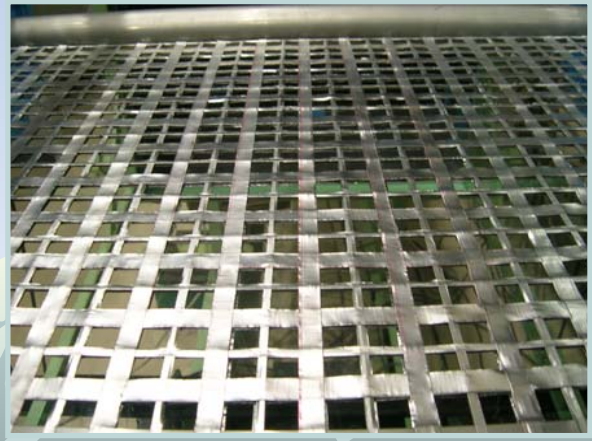



Opening ratio(OR) of Splitter plate was changed to suitably control the Karman vortex

# Change of Opening Ratio(OR) of Splitter Plate (KV)



OR:10%



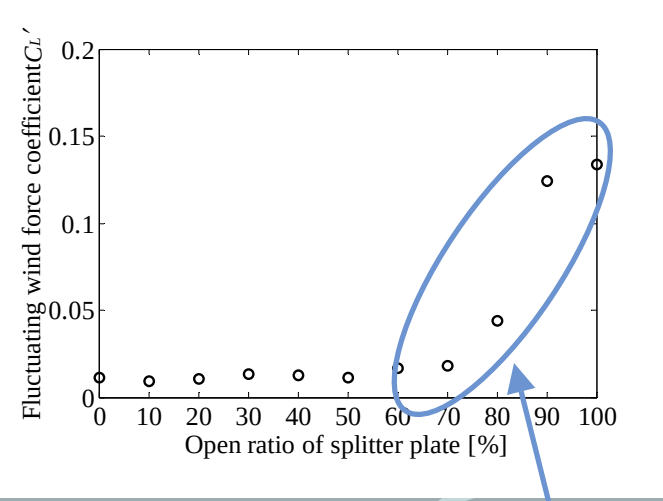
OR:40%

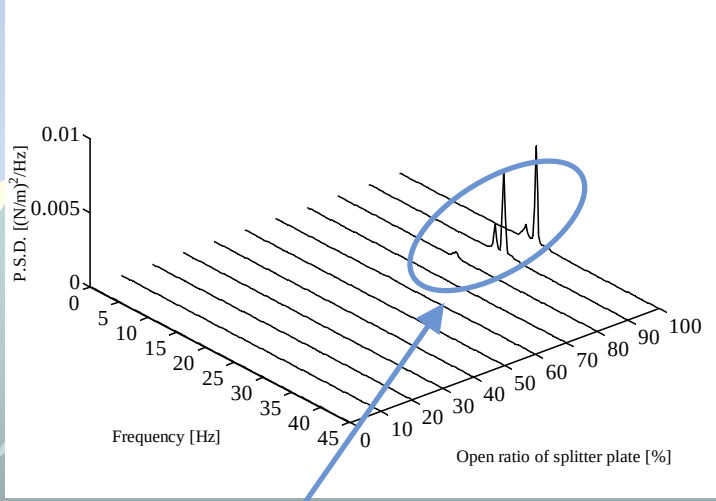
OR:90%

**OR is changed from 0% to 100%**

# Fluctuating Lift Force v.s. OR

# (KV)




$C_L'$

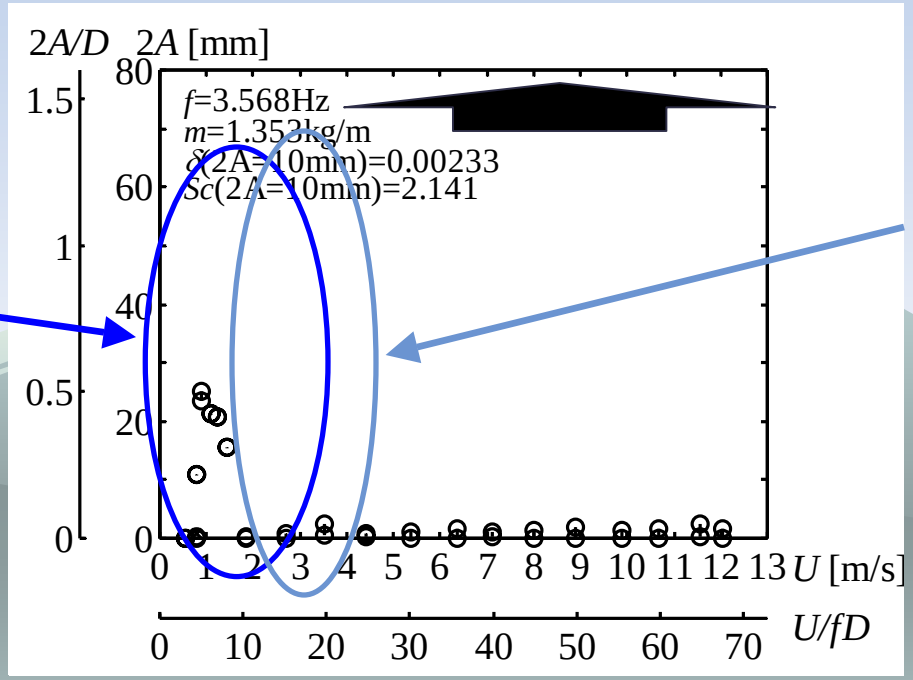
PSD of fluctuating lift force

**The intensity of Karman Vortex becomes significantly weak if OR decreases.**

$\beta$=0°, $U$=6.0m/s

# Free Vibration Test (KV)

**Enlarged maximum amplitude**



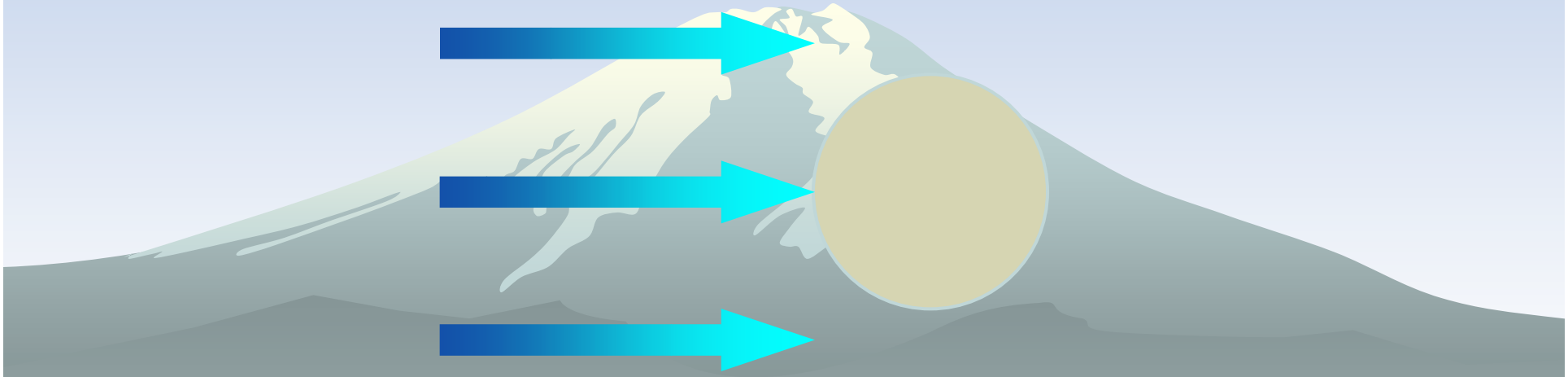

***Vortex induced vib. terminates at near U/fD=15 and another steady response appears***

OR

β=0°

# External Stimulation v.s. Karman Vortex (KV)

# Longitudinally Fluctuating Stimulation(LFS) (KV)

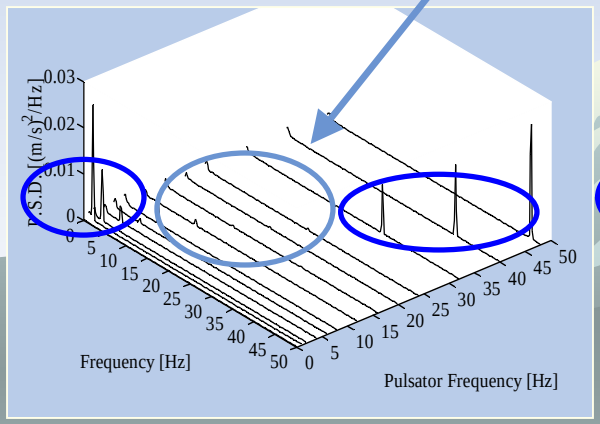


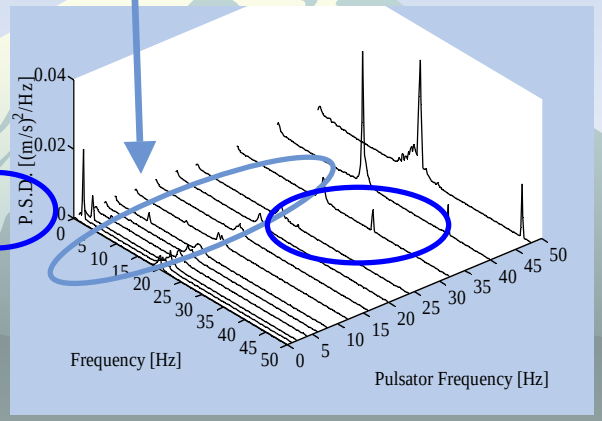
**In-phase stimulation at up and down sides separation points**

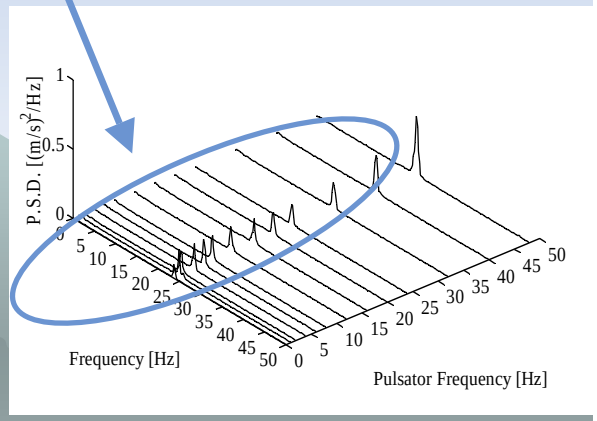
# PSD of Velocity in a Wake (by LFS) (KV)

**Due to Karman vortex**

**No appearance of stimulating frequency peak**



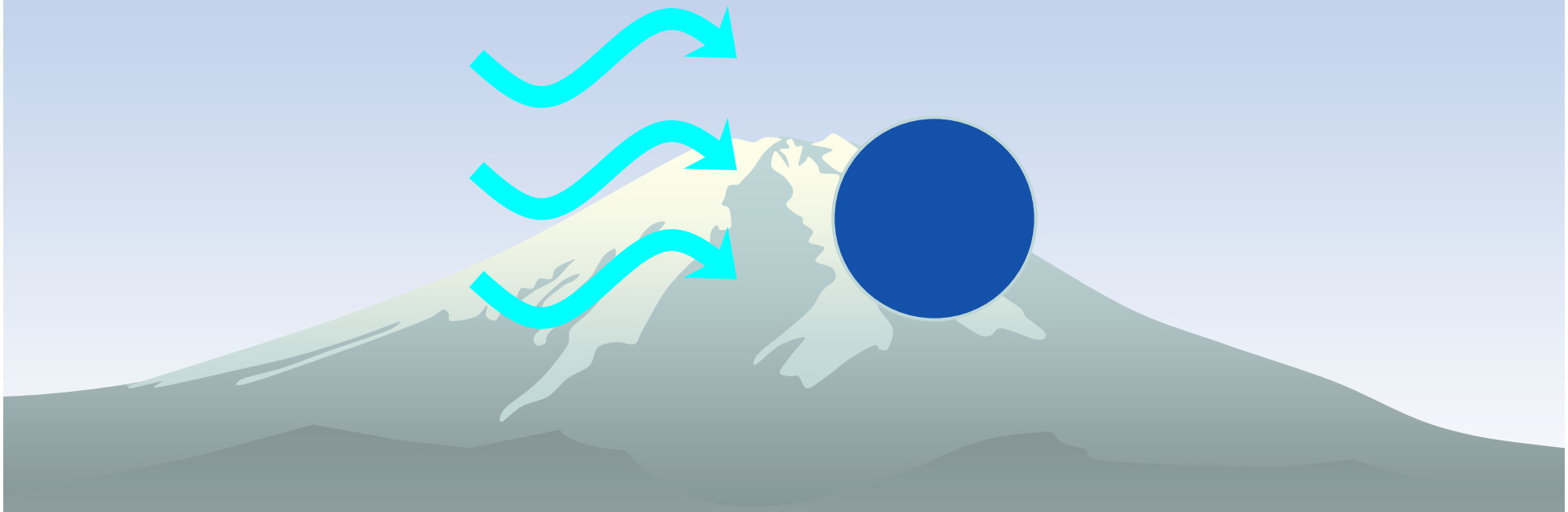

**OR10 %** **OR70 %** **OR100 %**

**weak** ⟷ **intensive**

**Intensity of Karman vortex**

$\beta$**=0°, *U*=6.0m/s,** measured point□1.5*D downr stream*, 1.0*D* beneath

# Vertically Sinusoidal Stimulation(VSS) (KV)

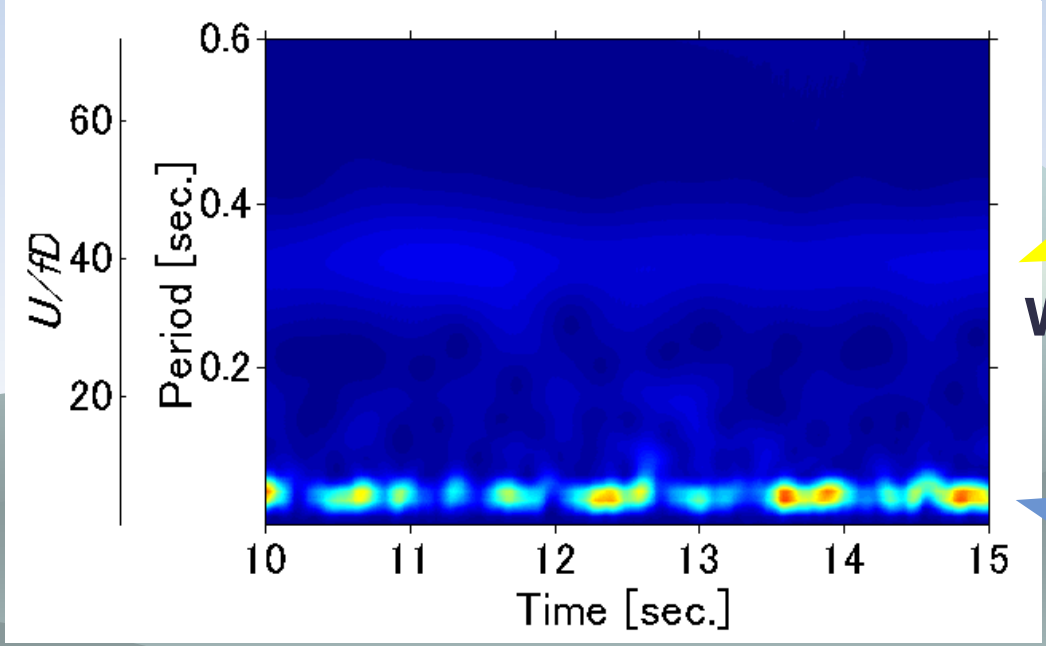


**Out-phase stimulation at up and down separation points**

# Wavelet Analysis of Fluctuating Lift Force(by VSS) (KV)

**Wing frequency□3Hz**

***U*=6.0m/s** ***β*=0°**

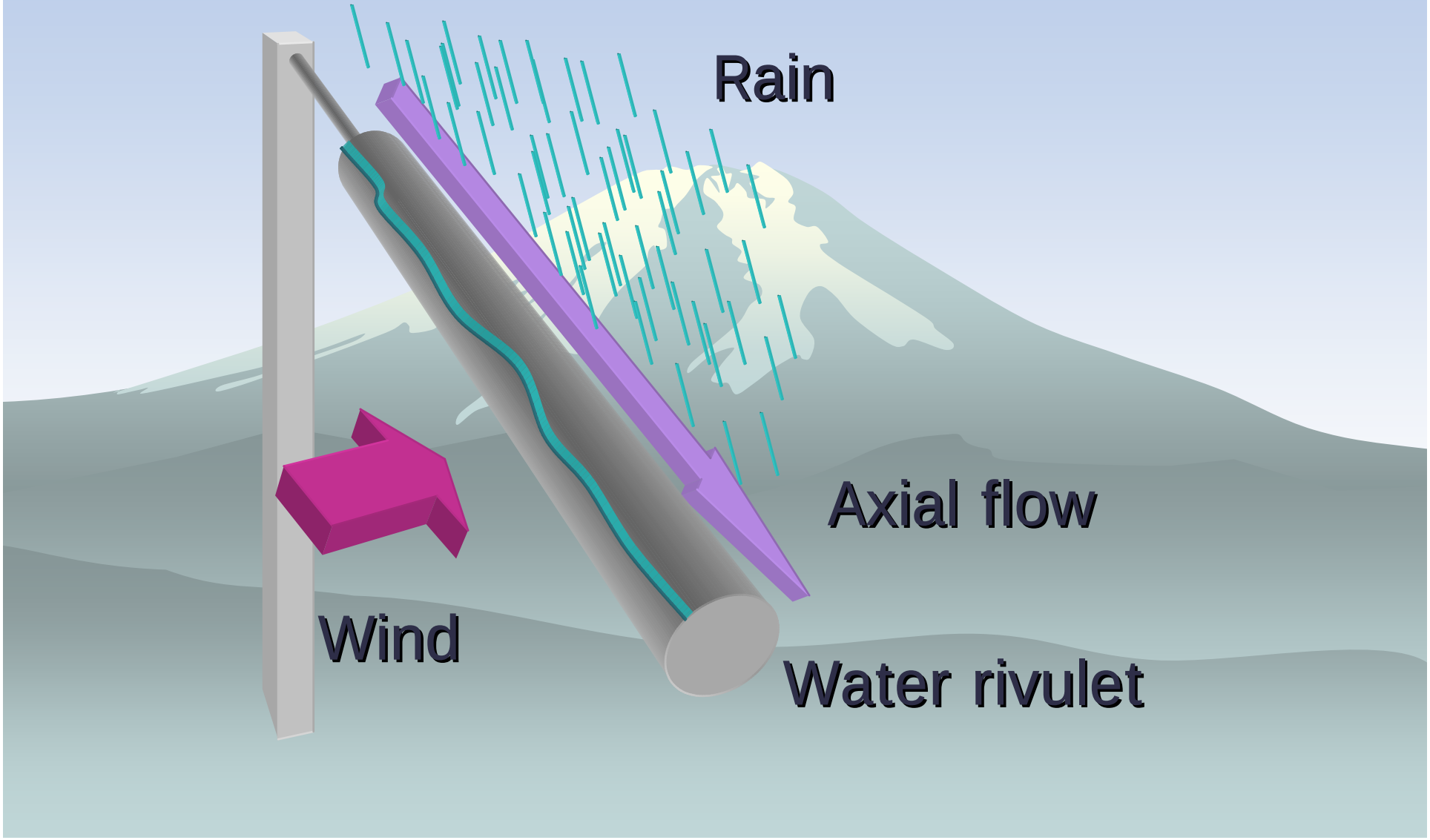



**Wing frequency**

**Karman vortex frequency**

**OR** 1[illegible]0%

# Water rivulet and axial flow



# Inclined Cable Aerodynamics

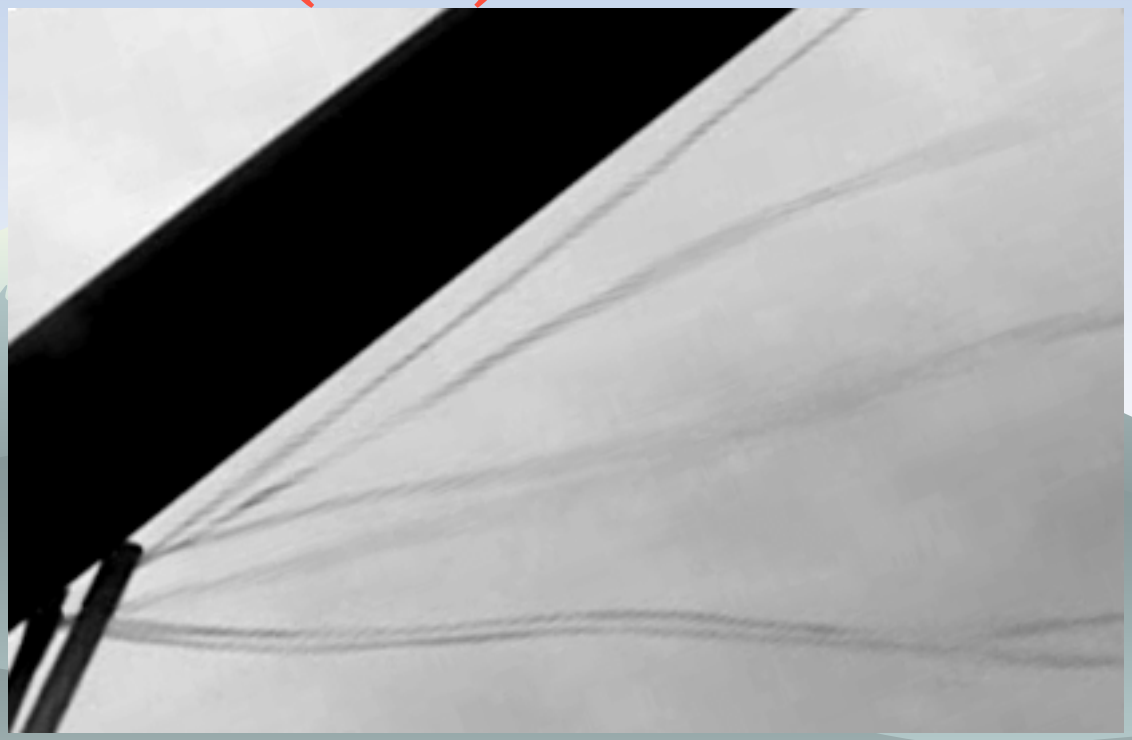
The substantial factors

- The upper water rivulet formation on a cable surface
- The axial flow in a near wake
- Critical Reynolds number

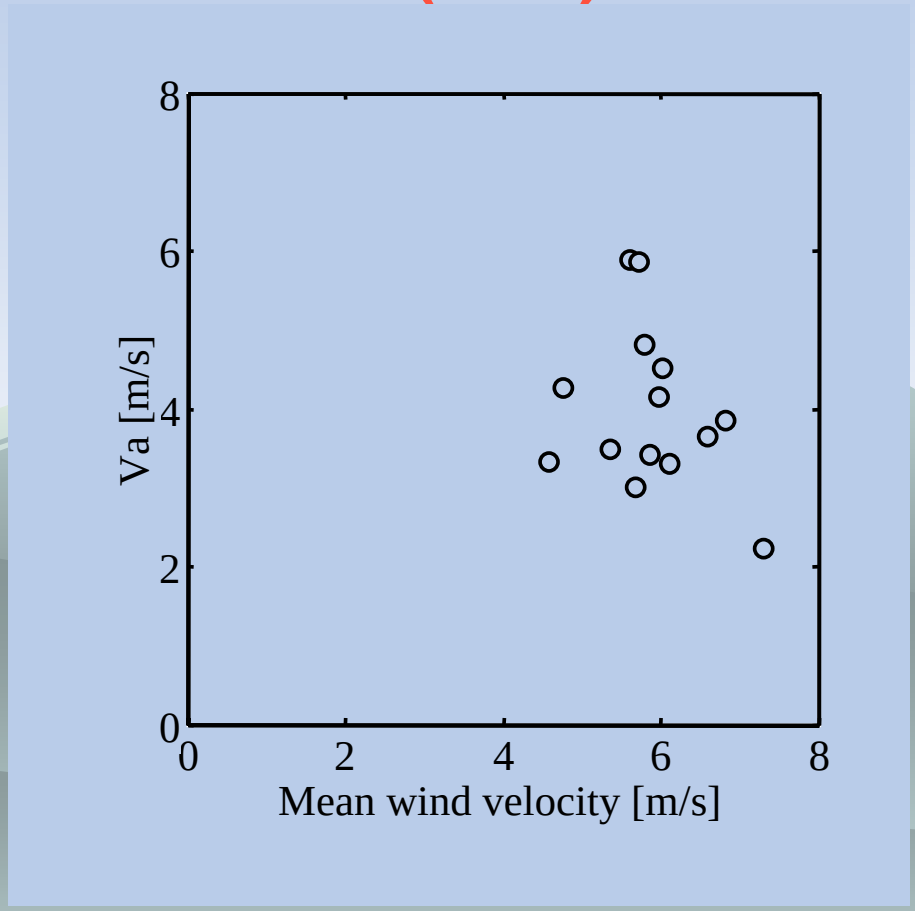
# Axial Flow

# Visualized axial flow by light strings for a proto-type cable (AX)

wind

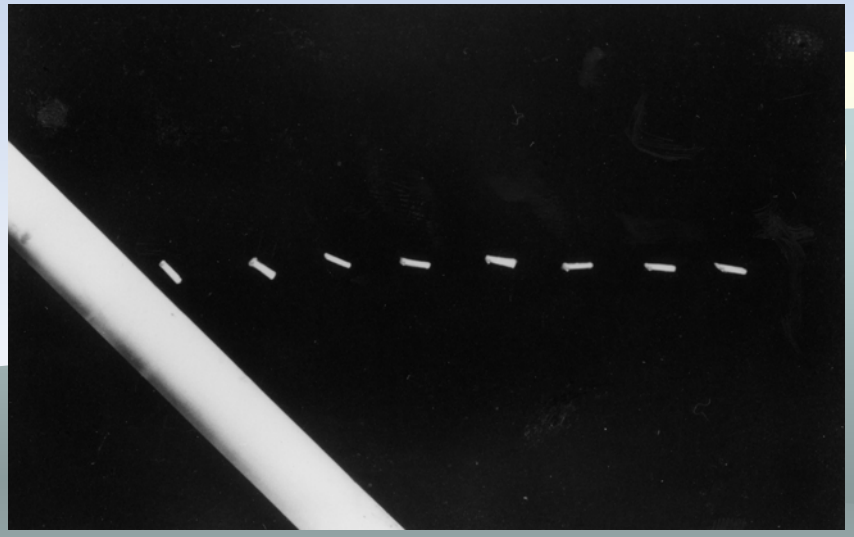


# Axial flow velocity -approaching wind velocity diagram of a proto-type stay-cable (AX)

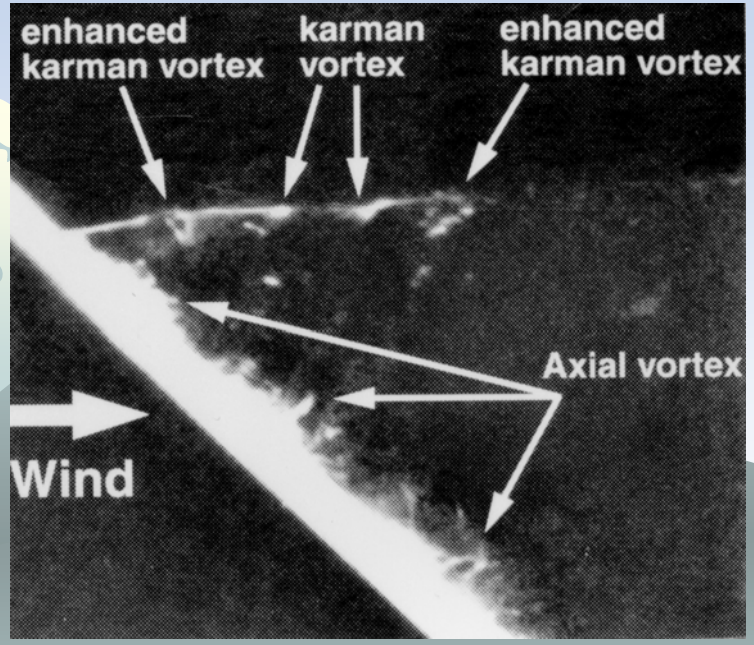



($\beta^*$ =40° -50°, where $\beta^*$: equivalent yawing angle)

# Visualized Flow Field around an Inclined Cable (AX)



Visualized axial flow by flags in a wake
of yawed cable ($\beta$=45°, $V$=1m/s)

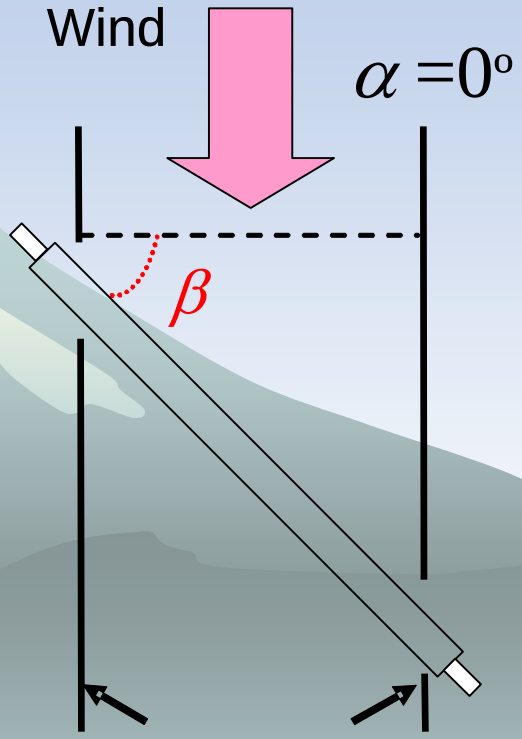



Visualized intermittently Karman vortices
and axial vortices by fluid paraffin
of yawed cable ($\beta$=45°, $V$=1m/s)

# Wind tunnel tests

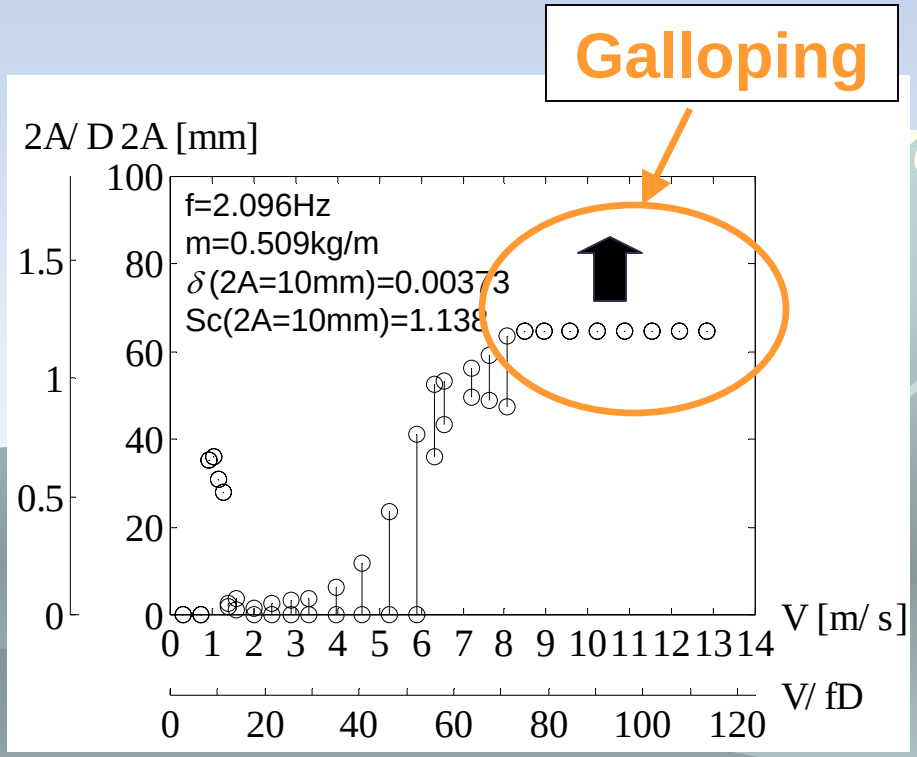
# (AX)

wind tunnel tests
($\alpha$=0°, $\beta$=45°)

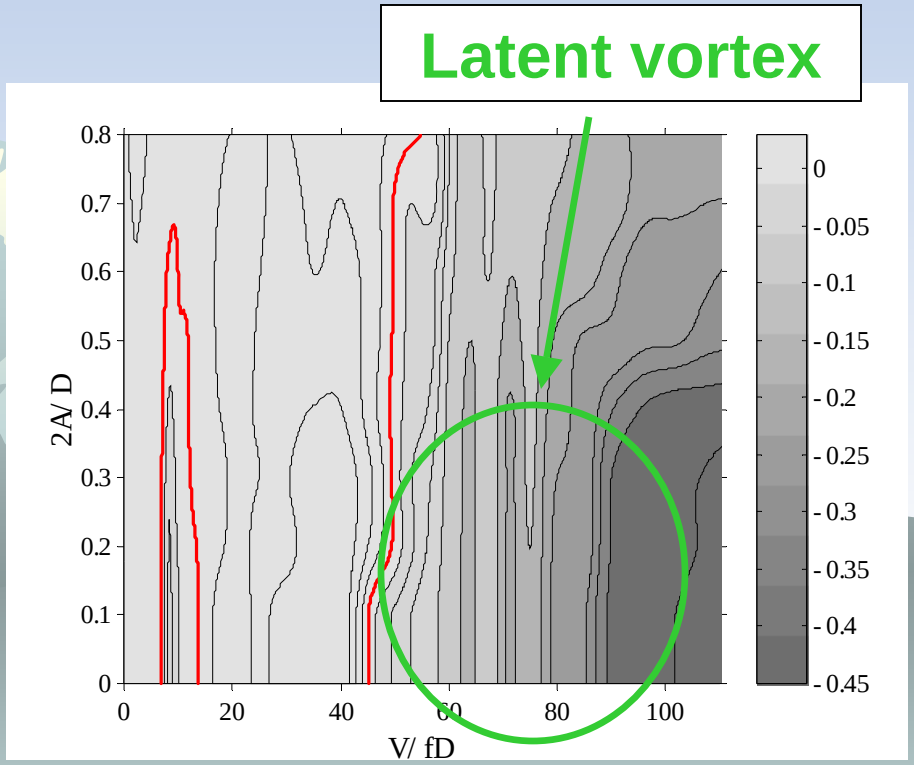



Top view of wind tunnel

# Typical Response (β=45°, in smooth flow, without water rivulet) (AX)



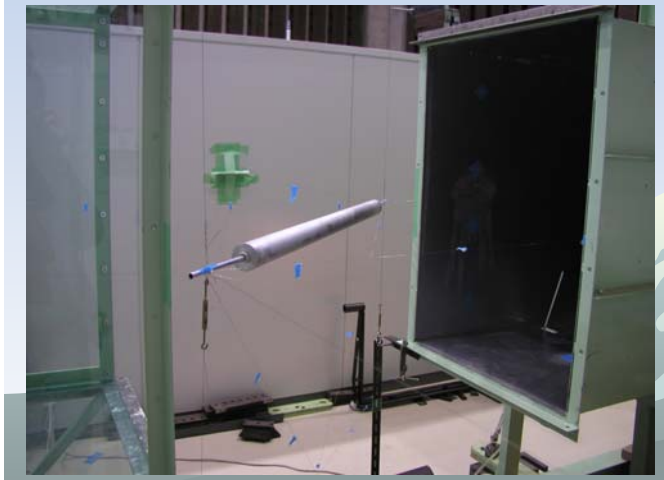

V-A diagram



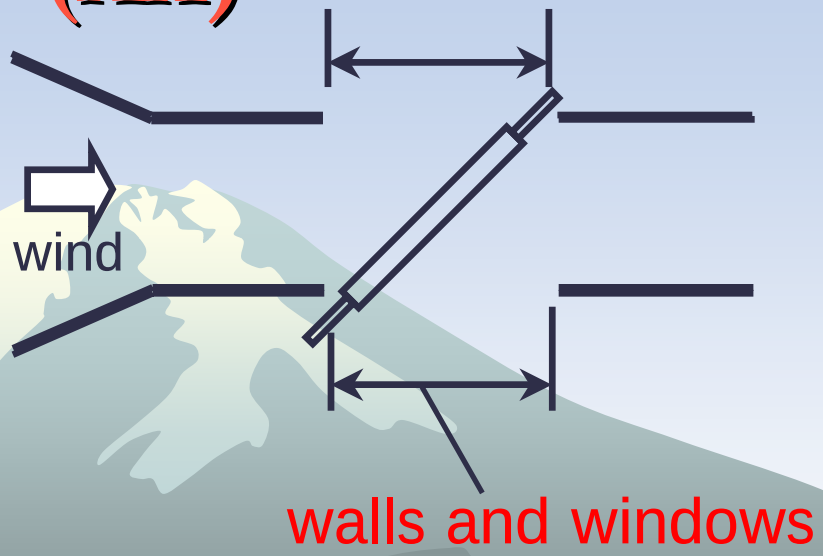

V-A-δ diagram

# Experimental set up (three end conditions) (without rivulet) (yawing angle=45deg)

(AX)



wind tunnel
(without wall)



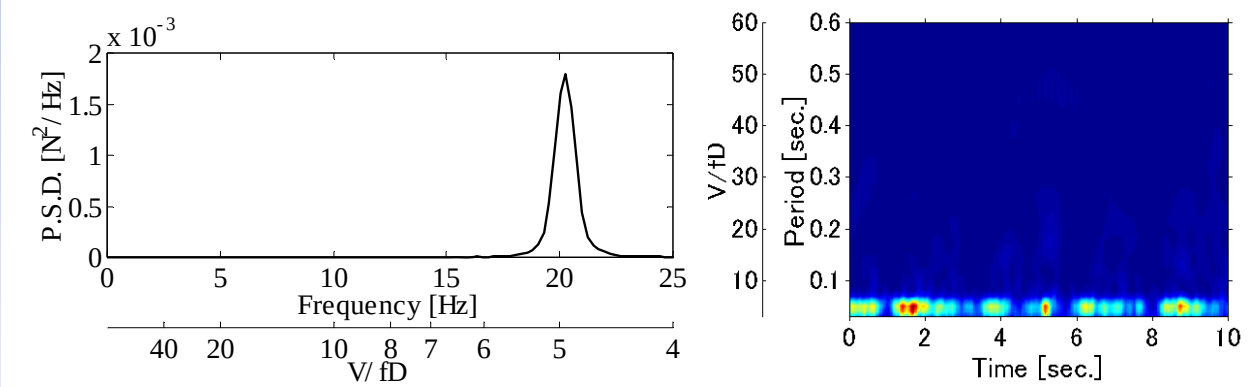

three end conditions

1. without wall
2. without wall and with end plates
3. with walls installed windows ($\phi$=170mm)

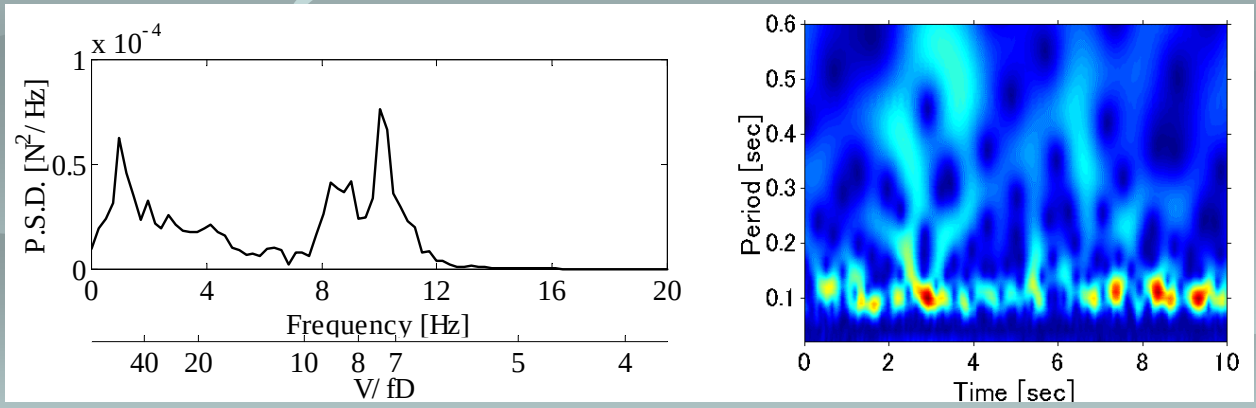
# Karman vortex v.s. low frequency component of lift and fluctuating velocity in wake (AX)

- If Karman vortex would be mitigated, low frequency lift/velocity appears.

# P.S.D. and wavelet analysis of the unsteady lift force on stationary cable model (without rivulet) (AX)

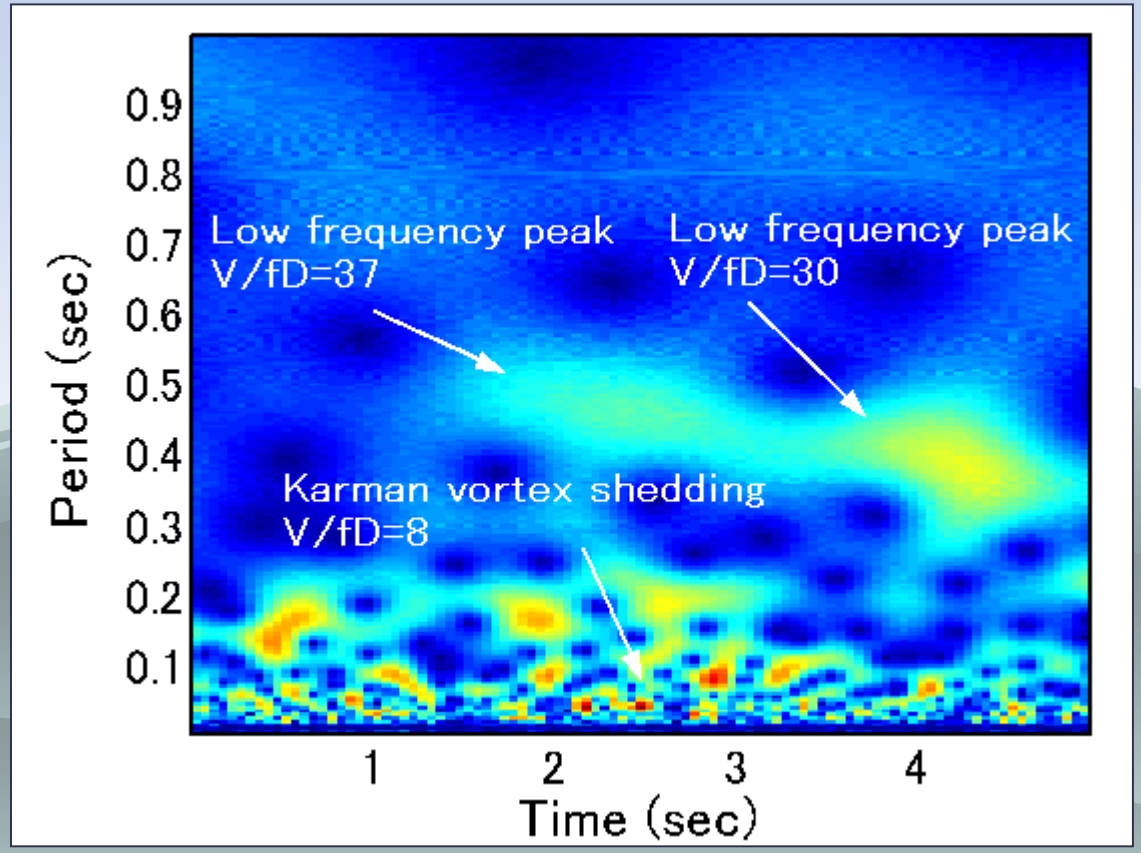



$\beta$=0°, in smooth flow, $V$=5.0m/s




$\beta$=45°, in smooth flow, $V$=4.0m/s

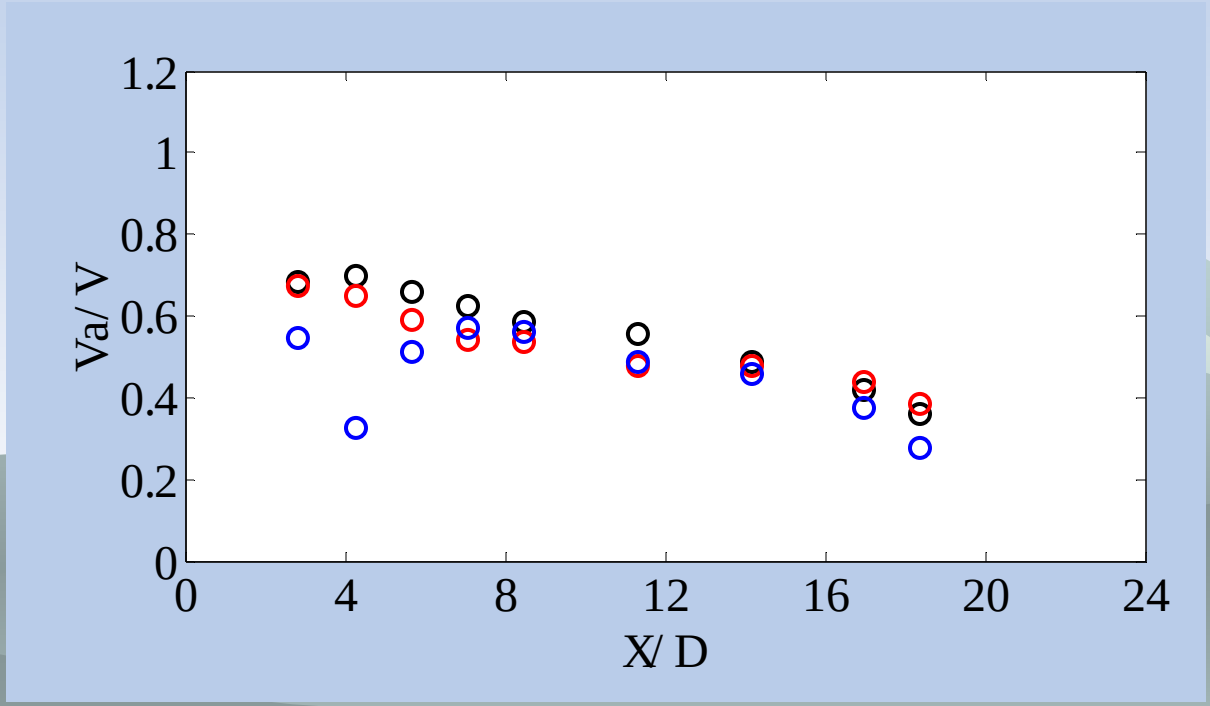
# Wavelet analysis of fluctuating wind velocity in the wake of stationary yawed cable model (AX)

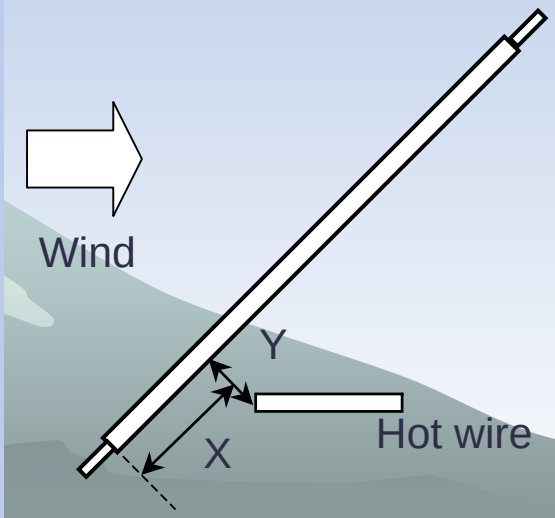



(without rivulet, $\beta$=45°, $V$=4m/s, in smooth flow)

- **Axial Flow v.s. Intensity of Karman Vortex**

# Axial flow velocity (Va) in a wake (AX)



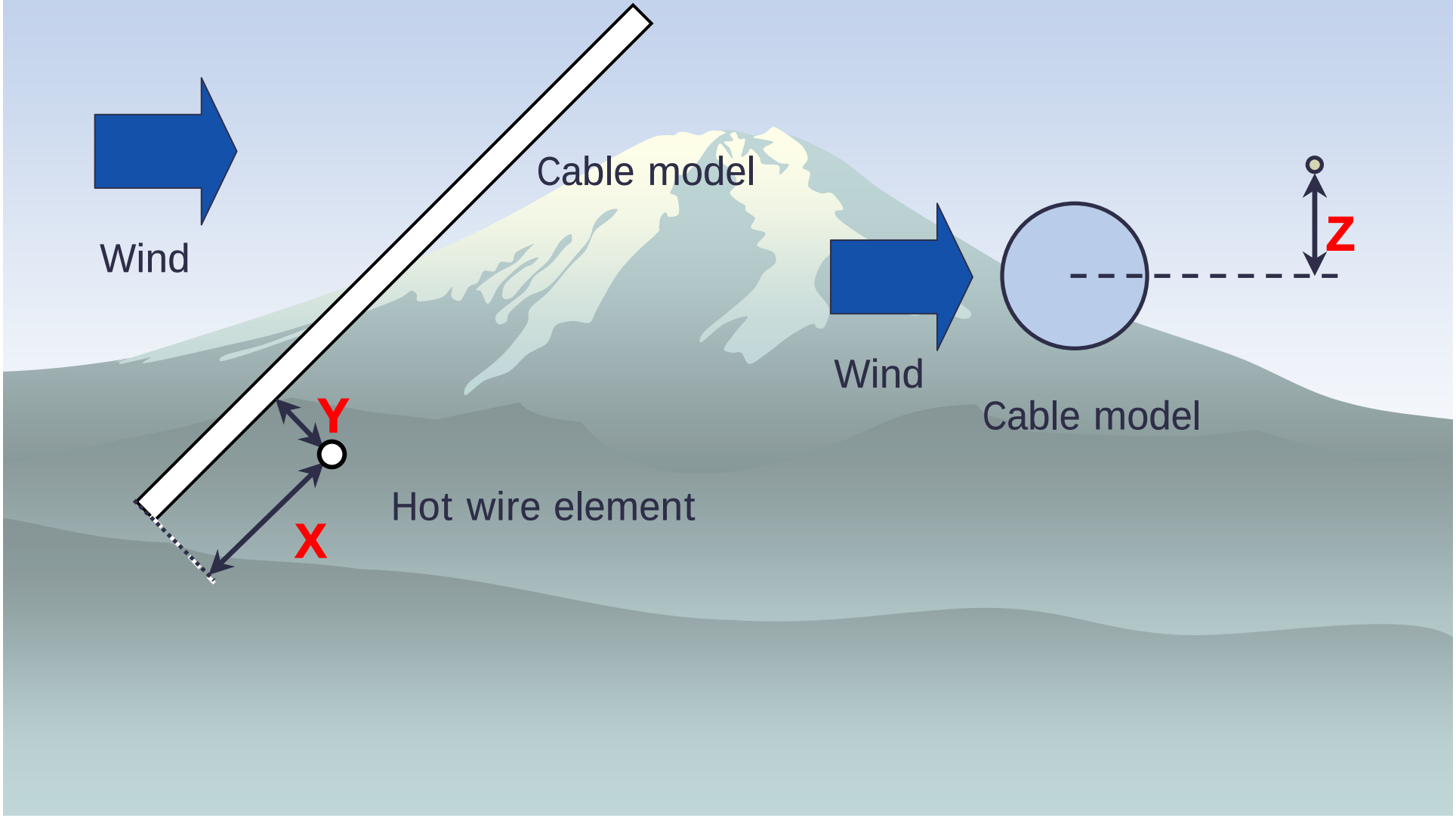

($V$=8m/s, $\beta$=45°)

(1) without wall

(2) without wall and with end plates

(3) with walls installed windows ($\phi$=170mm)

# Definition of coordinates, X, Y, Z (AX)

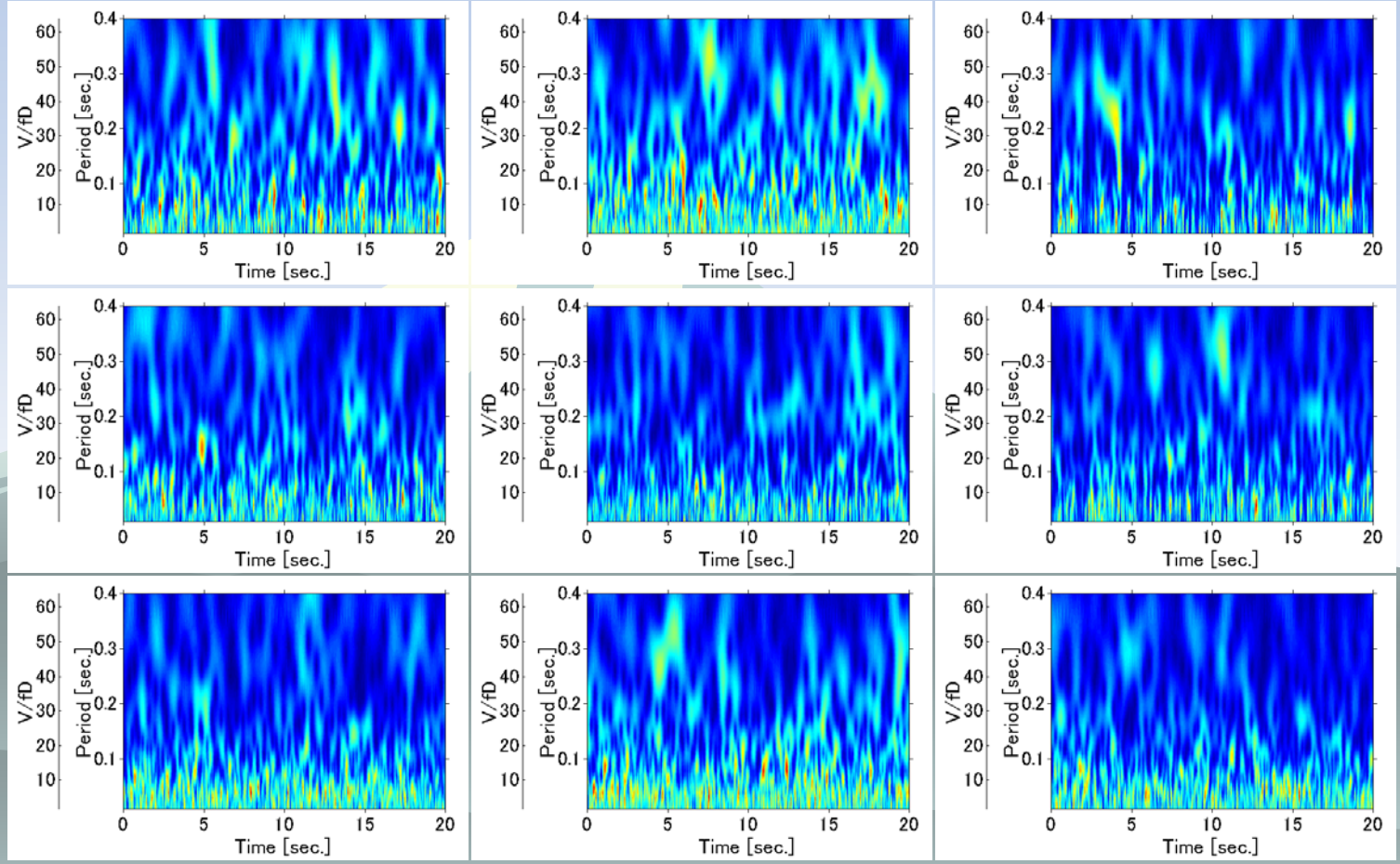


# Wavelet analysis of fluctuating wind velocity measured at various points in a wake (AX)

*X/D*=7.7

*X/D*=12.7

*X/D*=17.6



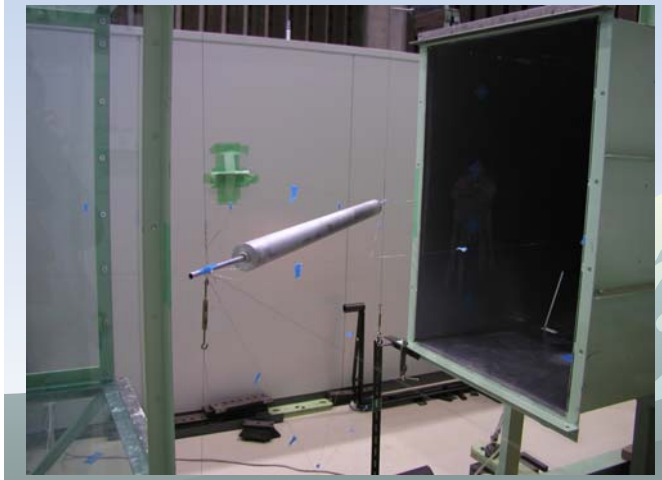

(1) without wall

(2) without wall and with end plates

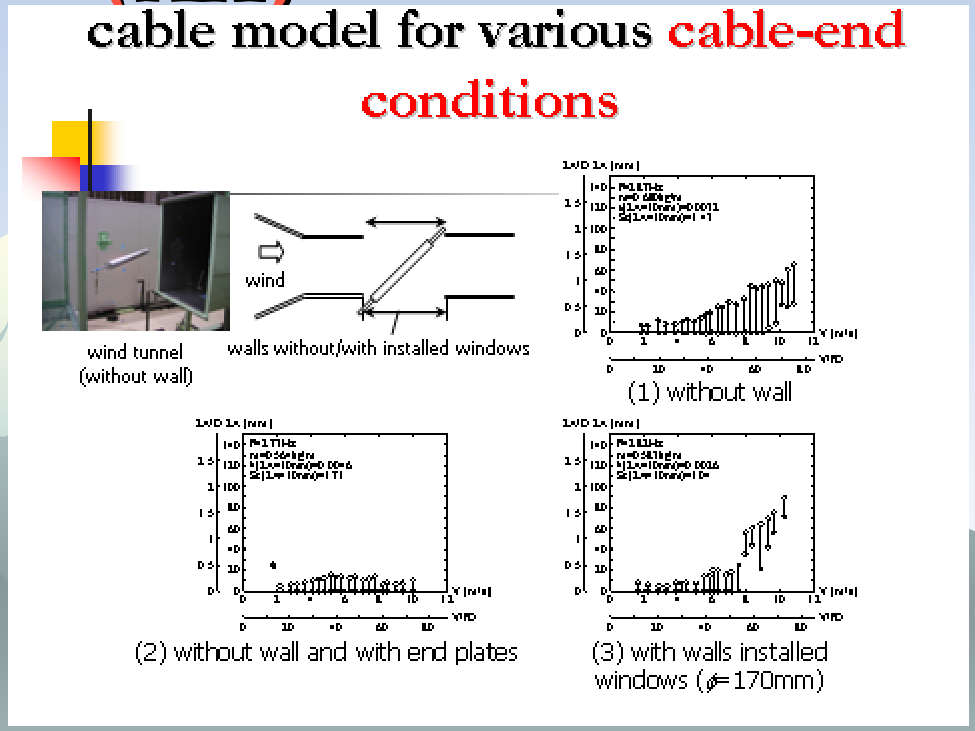
(3) with walls installed windows ($\phi$=170mm)

**($\beta$=45°, *V*=8.0m/s, *Y/D*=1.8, *Z/D*=0.5)**

# Experimental set up (three end conditions) (without rivulet) (yawing angle=45deg) (AX)



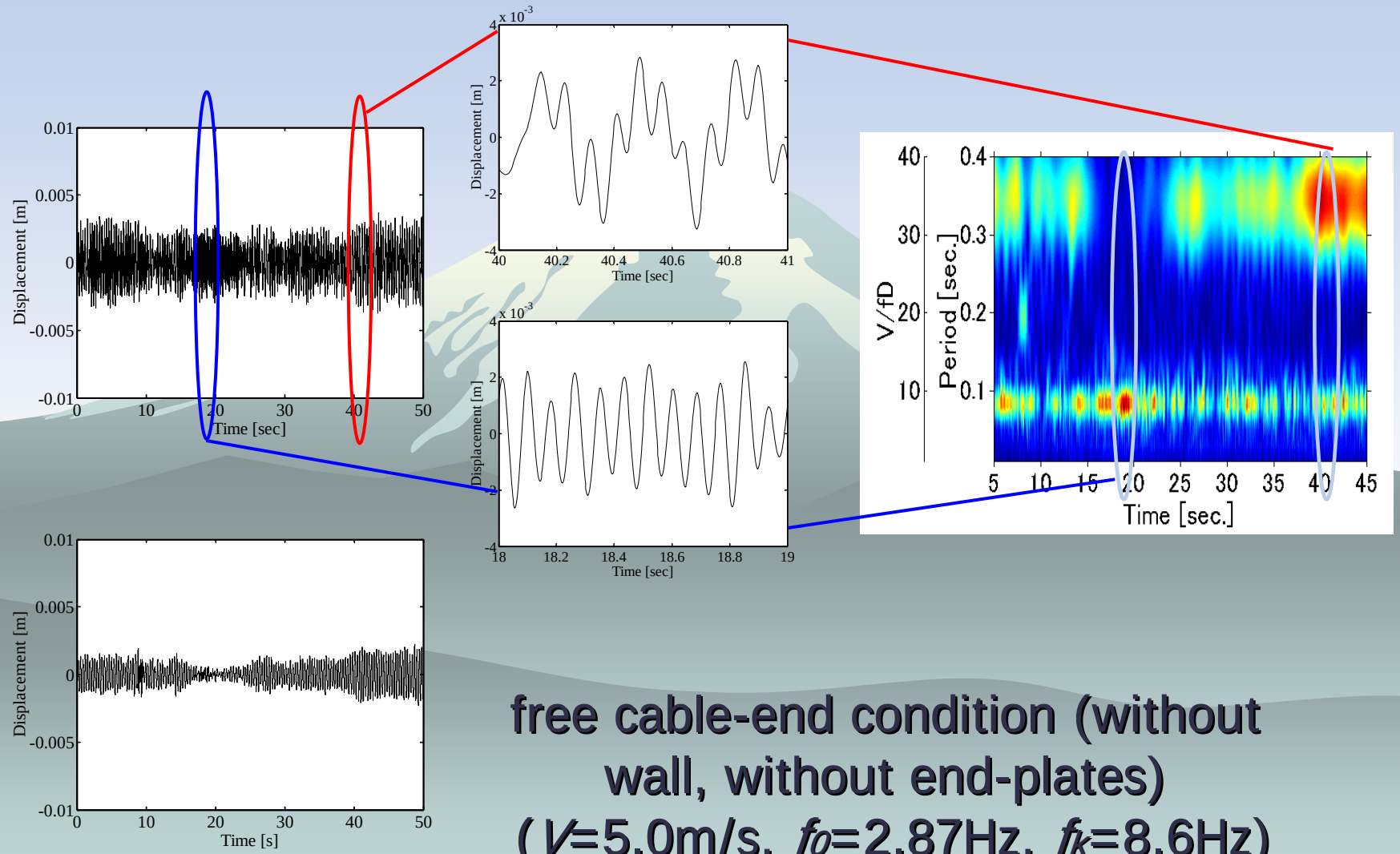
wind tunnel
(without wall)




three end conditions

1. without wall
2. without wall and with end plates
3. with walls installed windows ($\phi$=170mm)

# Time history and the wavelet analysis of the unsteady cross-flow displacement (unsteady galloping)




free cable-end condition (without wall, without end-plates)
($V$=5.0m/s, $f_o$=2.87Hz, $f_k$=8.6Hz)

# Intensity of Karman vortex shedding (AX)

- The most intensive: with end plates and without walls (no galloping appears)
- Weak: without end plates without walls (unstable galloping appears)
- The weakest : with walls installed windows (galloping appears)

# Upper water rivulet formation

# Rain Effect (WR)

## Water rivulet formation

### The effect of rivulet on response and stationary force (its location)

**The formation of the upper water rivulet and its location on an inclined surface can be determined by the following formula**

$$P_a+(\sigma/R)=P_0$$

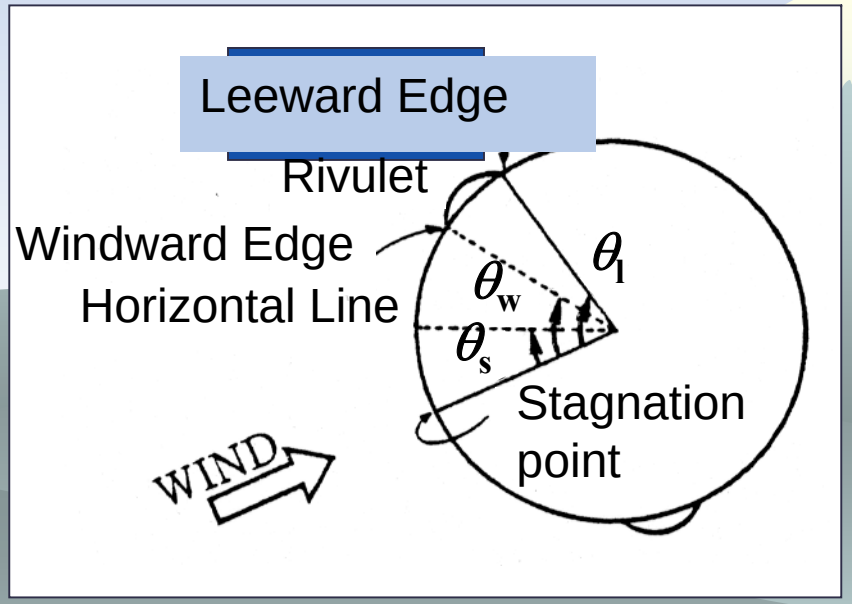
**$P_a$:the wind pressure on rivulet surface**

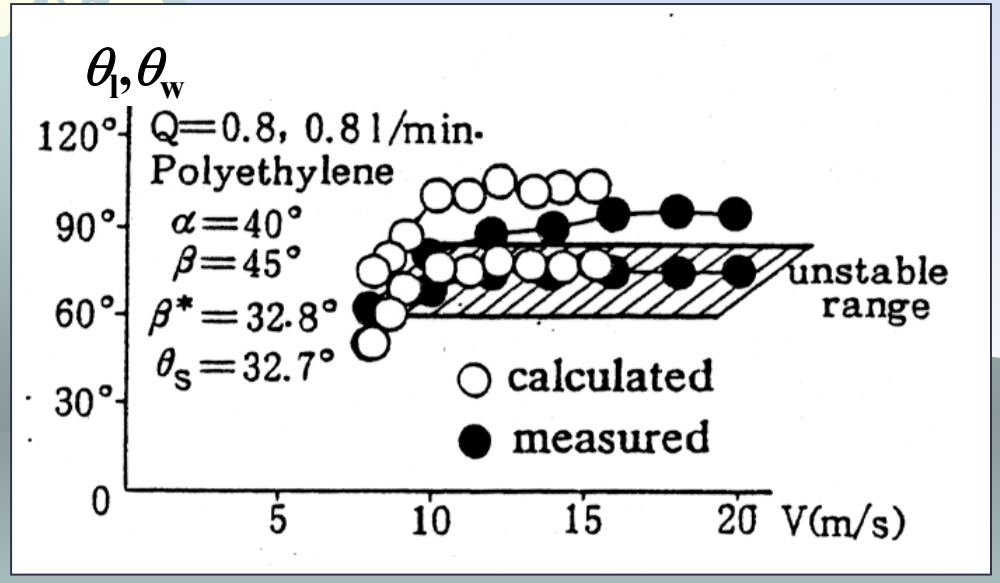
**$\sigma$ :the surface tensile force of water rivulet**

**R :the local curvature radius of water rivulet**

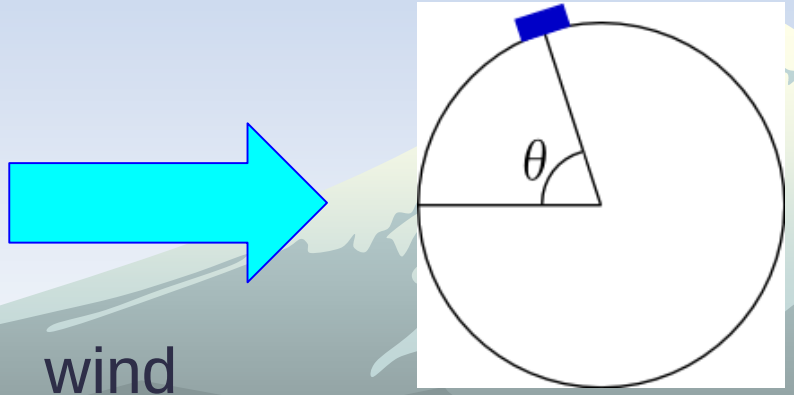
**$P_0$ :the hydro-pressure of water rivulet**

# The Relation of the Position of Upper Water Rivulet and its Response (WR)



# Artificial rivulet (WR)




wind

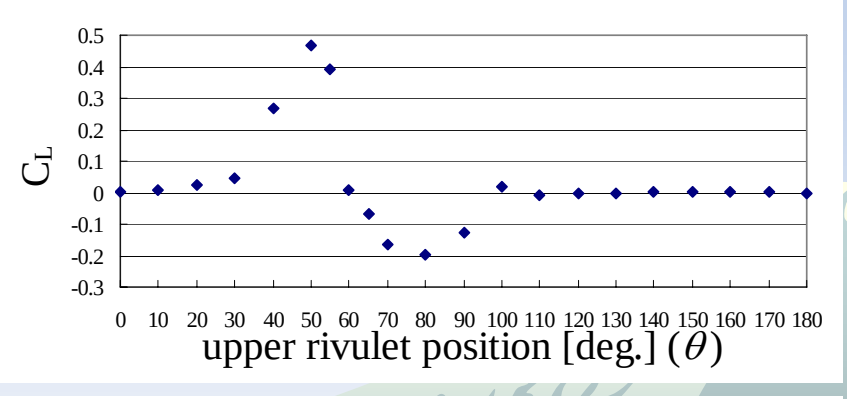
Artificial rivulet

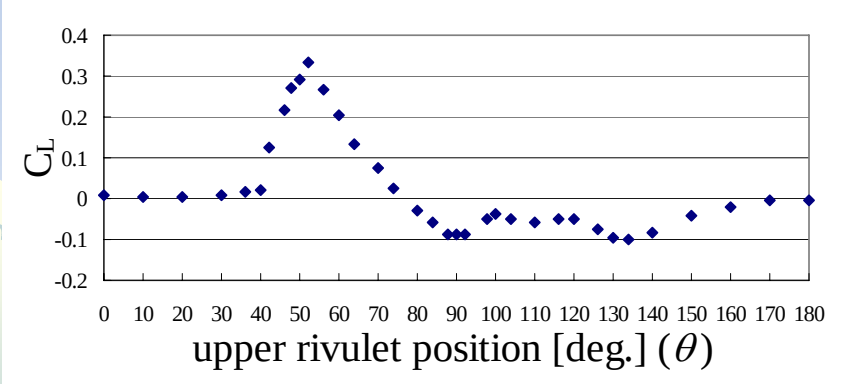
**Width:3.6mm**
**thickness:1.6mm**

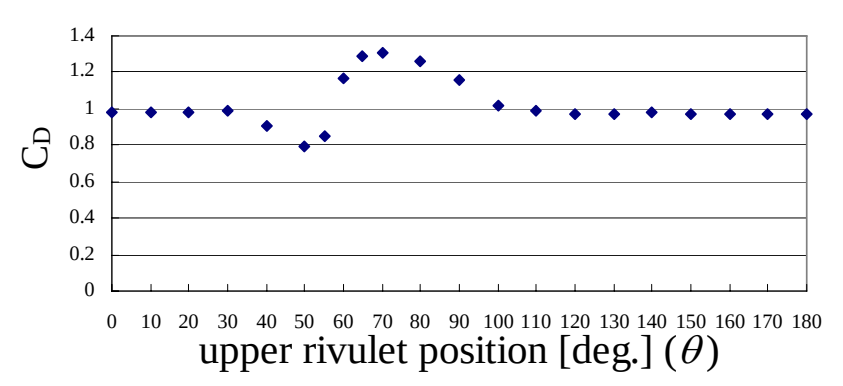
**Cable diam.:50mm**

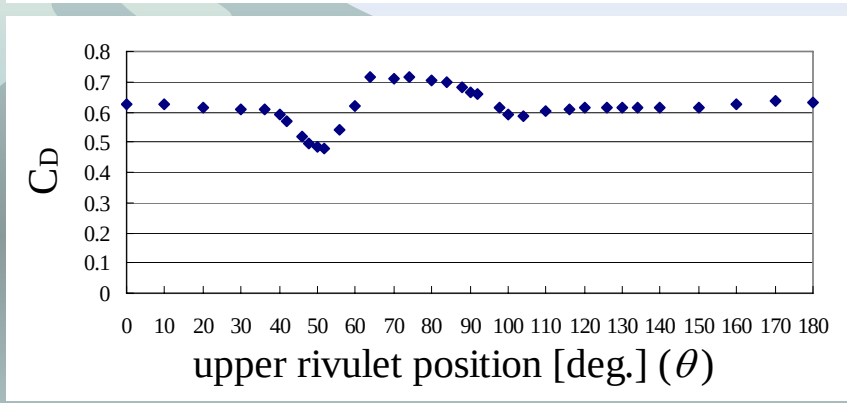
**cable length:1100mm**

# The detail stationary lift and drag force coefficient subject to rivulet position (WR)



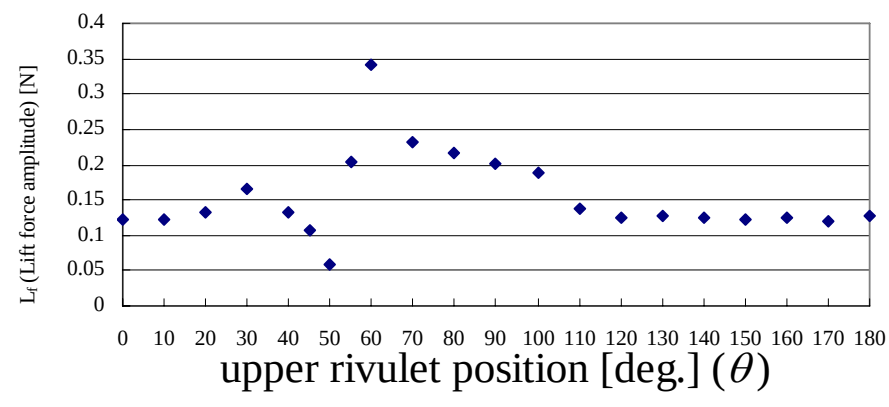



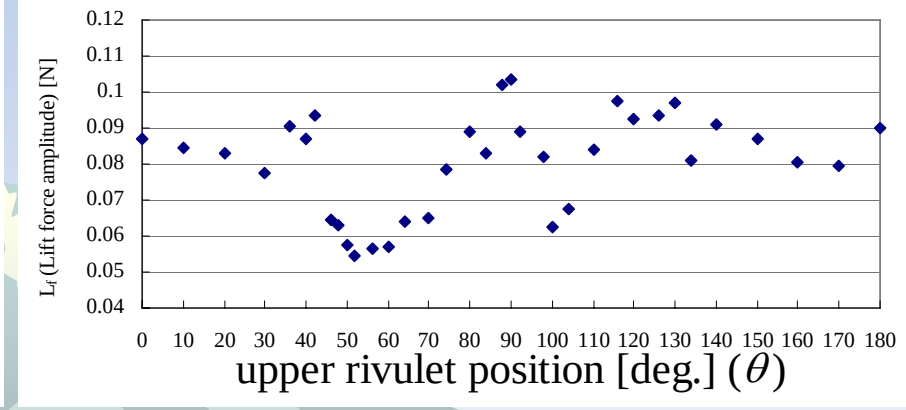



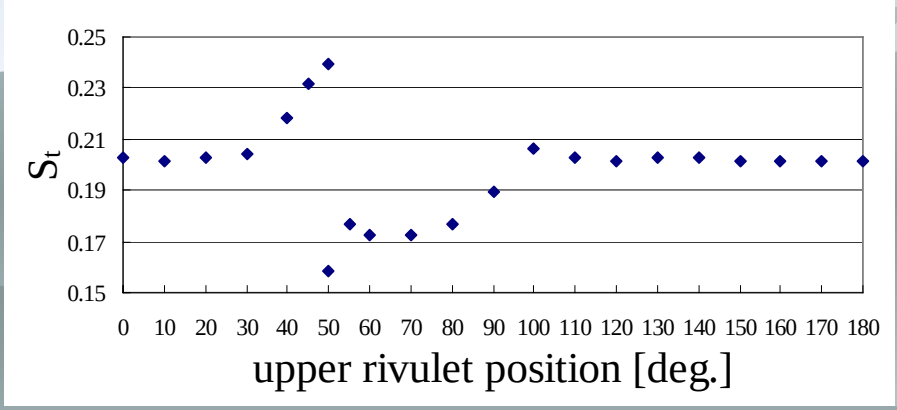

for non-yawed circular cylinder ($\beta$=0°)

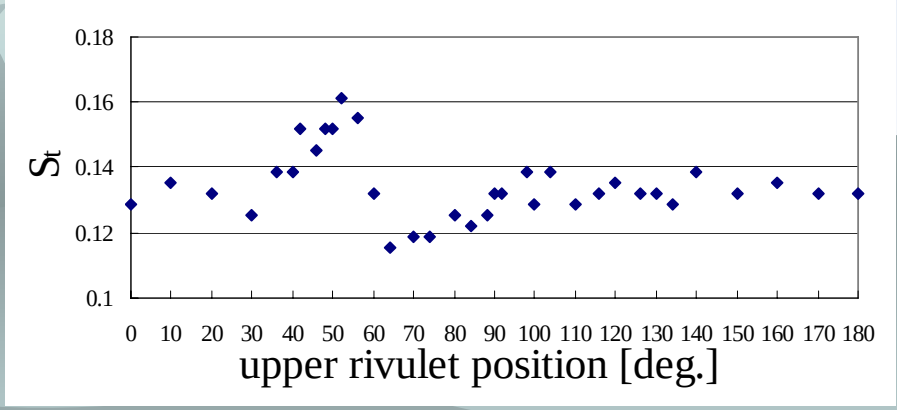
for yawed circular cylinder ($\beta$=45°)

# Rivulet position effect on unsteady lift force and Strouhal number induced by Karman vortex shedding (WR)



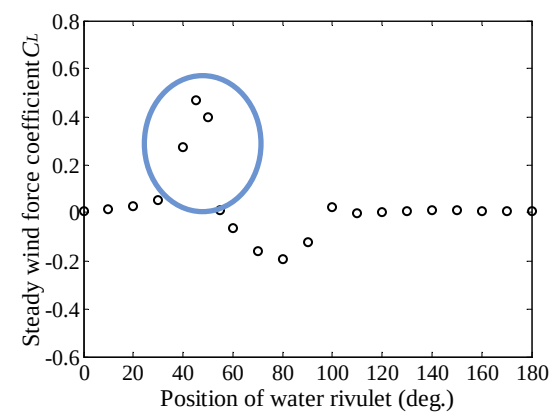



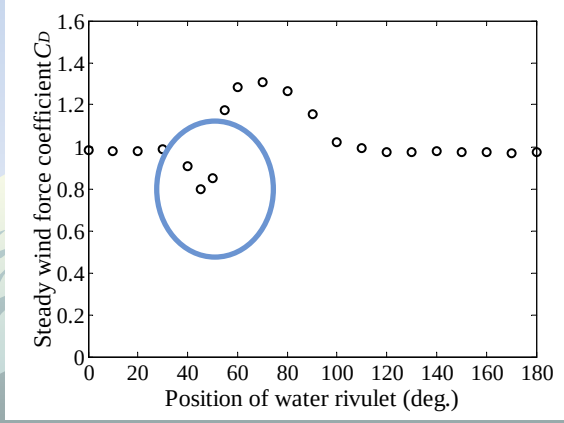

for non-yawed circular cylinder ($\beta$=0°)

for yawed circular cylinder ($\beta$=45°)

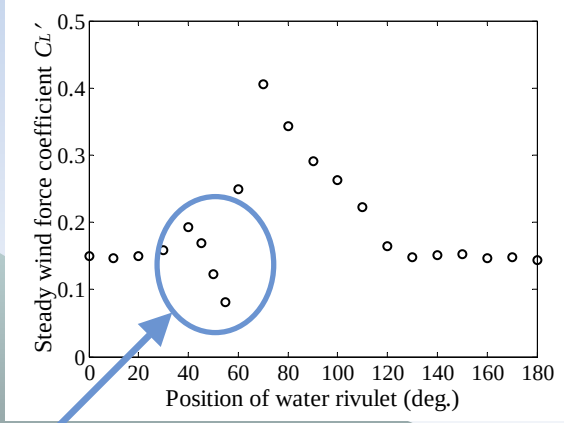
# Aerostatic/fluctuating force v.s. rivulet position□$\beta$=0°□(WR)




$C_L$




$C_D$




$C_L'$

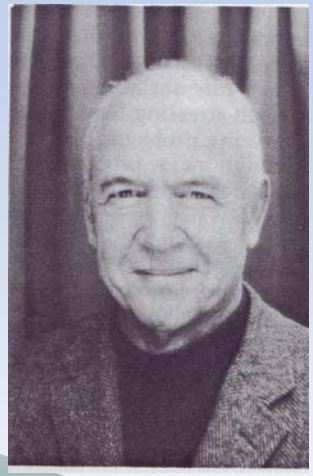
**At near 50deg., Karman vortex becomes weak, then drag decreases and stationary lift appears.**

# Scanlan's Flutter Derivatives (R. H. Scanlan, 1974)

- 2DOF

$$L=\frac{1}{2}\rho(2b)V^2\left\{kH_1^*\frac{\dot{\eta}}{V}+kH_2^*\frac{b\dot{\phi}}{V}+k^2H_3^*\phi+k^2H_4^*\frac{\eta}{b}\right\}$$

$$M=\frac{1}{2}\rho(2b^2)V^2\left\{kA_1^*\frac{\dot{\eta}}{V}+kA_2^*\frac{b\dot{\phi}}{V}+k^2A_3^*\phi+k^2A_4^*\frac{\eta}{b}\right\}$$



1914~2001
Scanlan

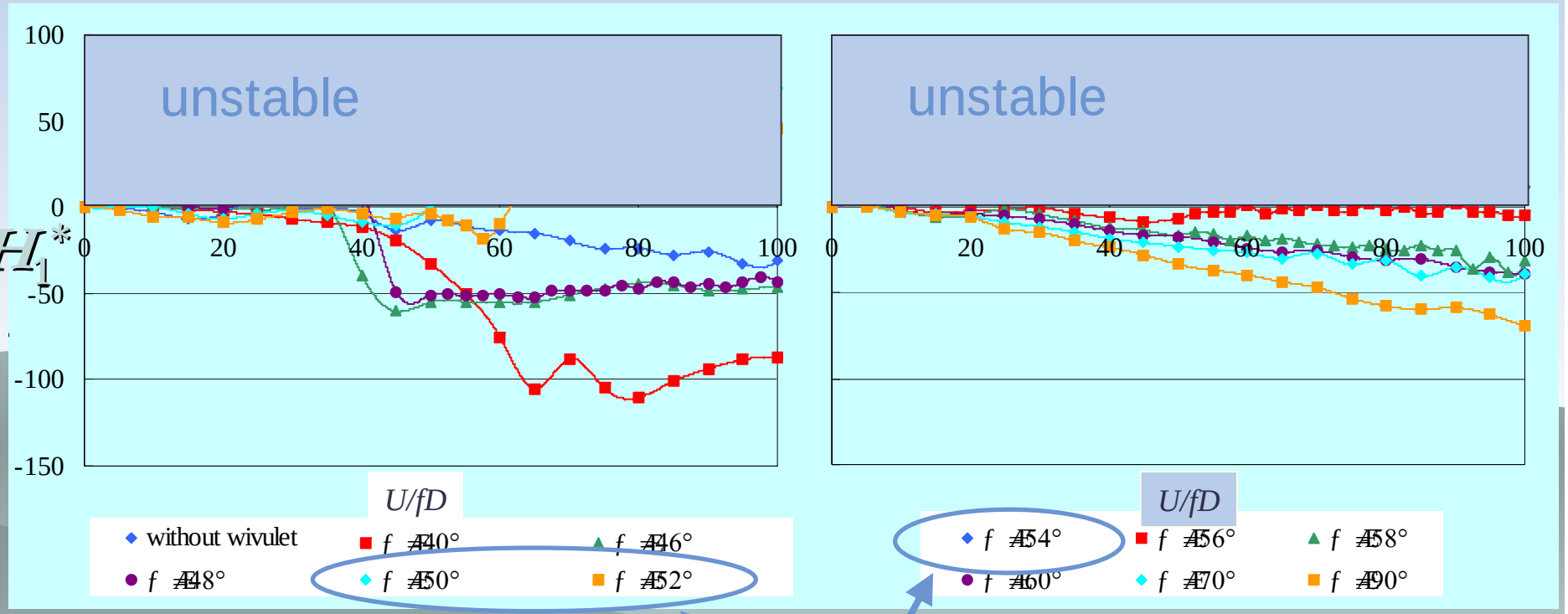
*L*/*M* : the unsteady lift force/pitching moment per unit span length
$\eta/\phi$ : the heaving/torsional displacements
$\rho$ : the air density
*b* : a half chord length
*Hi**, *Ai** (i=1-4) : the flutter derivatives
*k* : the reduced frequency ($k=b\omega/V$)
$\omega$ : flutter circular frequency

1DOF $\eta$, $\phi$ motion

⇩ superposition

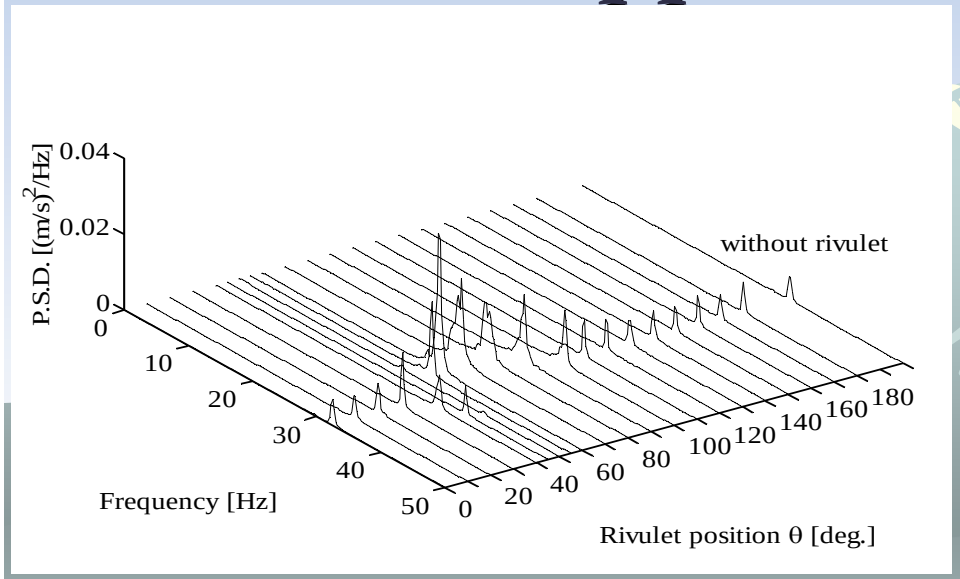
2DOF $\eta$, $\phi$ coupled motion

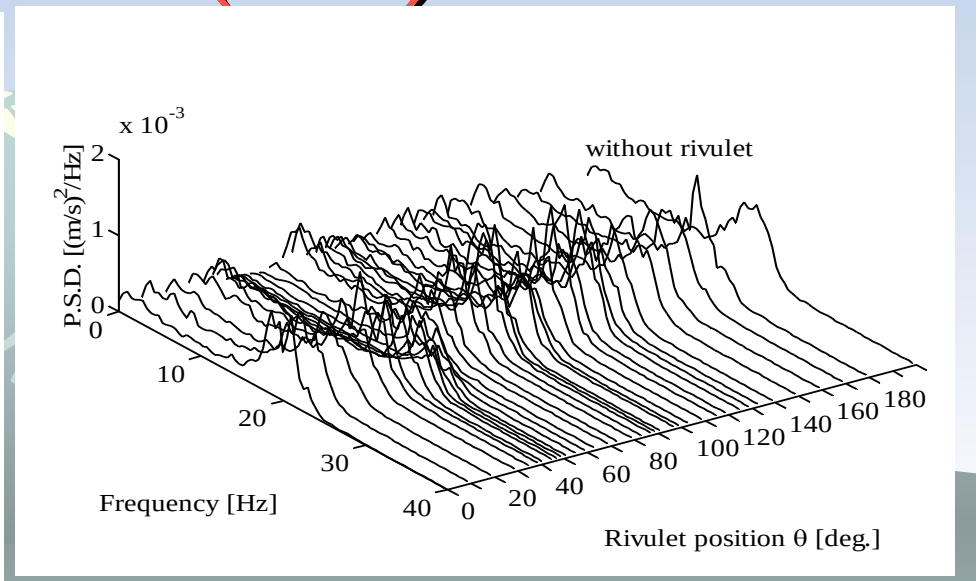
# *Aerodynamic derivative* $H_1^*$ □ $\beta=0°$ □ at sub-cr. Re number (WR)




Aerody. unstable rivulet position

# P.S.D. of the fluctuating lift force on stationary cable model with artificial upper rivulet (WR)

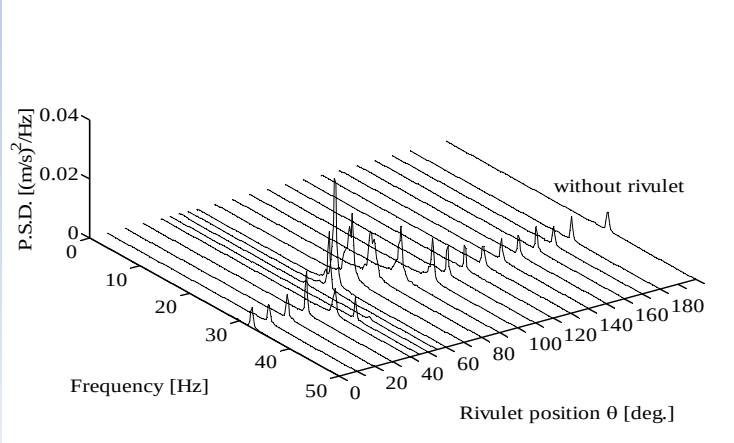


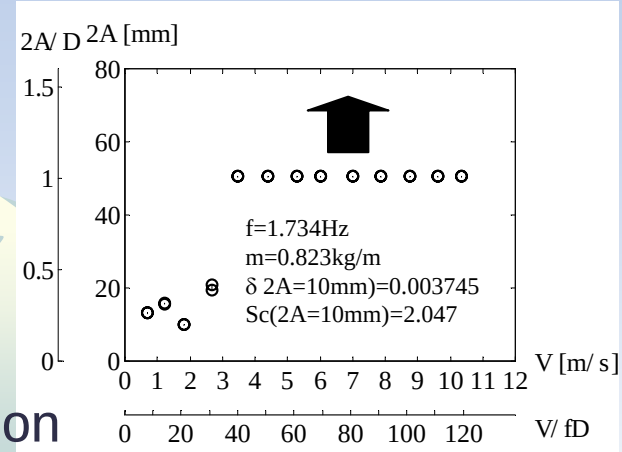

for non-yawed circular cylinder ($\beta$=0°)

for yawed circular cylinder ($\beta$=45°)

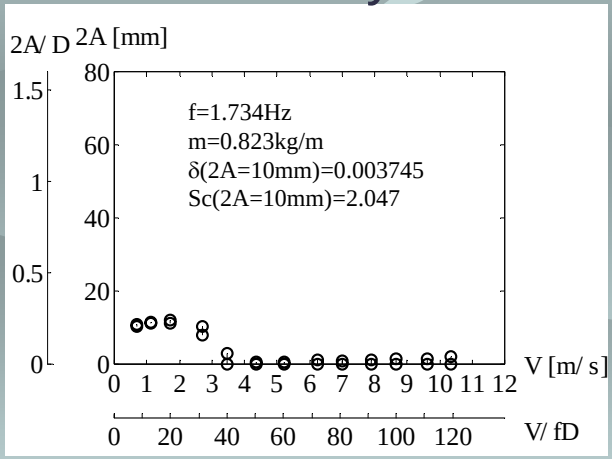
# Rivulet position effect on velocity-amplitude diagrams of non-yawed cable model ($\beta$=0°) (WR)



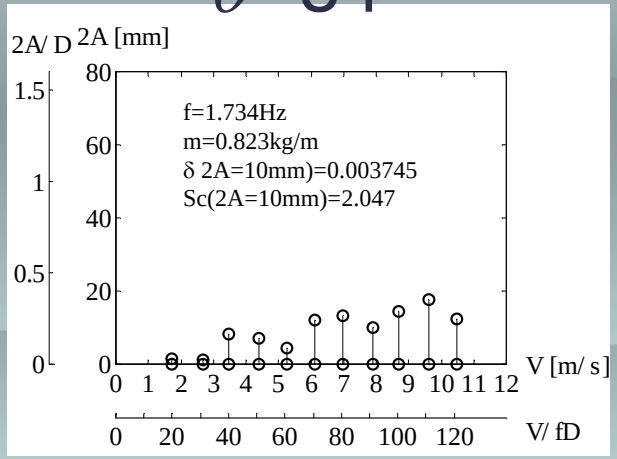

P.S.D. of the fluctuating lift force on stationary cable model




$\theta$=54°

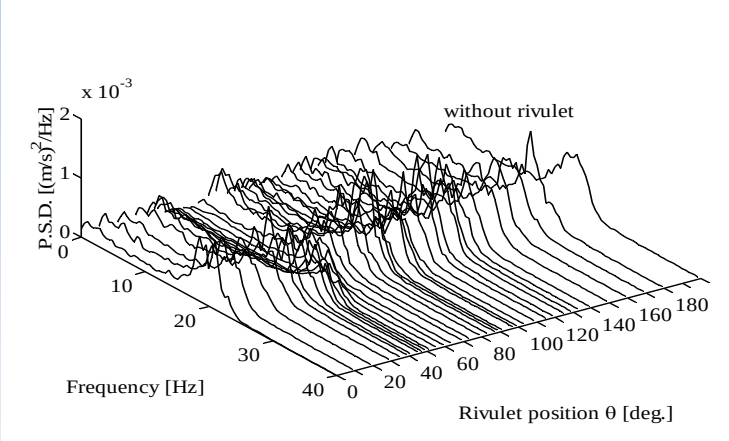



$\theta$=47°

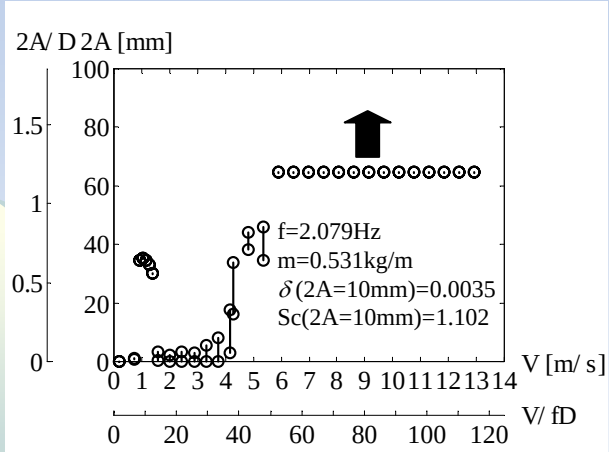



$\theta$=58°

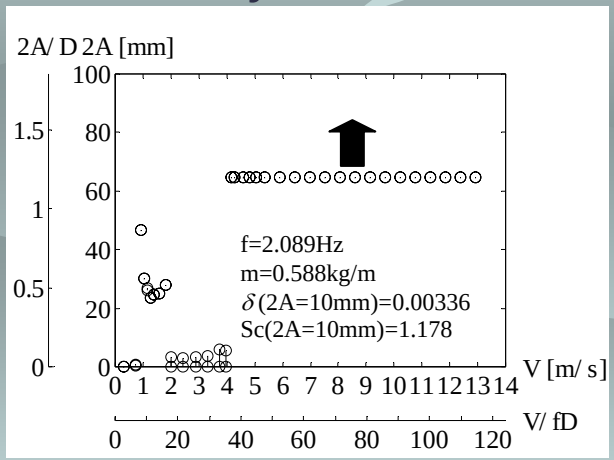
# Rivulet position effect on velocity-amplitude diagrams of non-yawed cable model ($\beta$=45°) (WR)



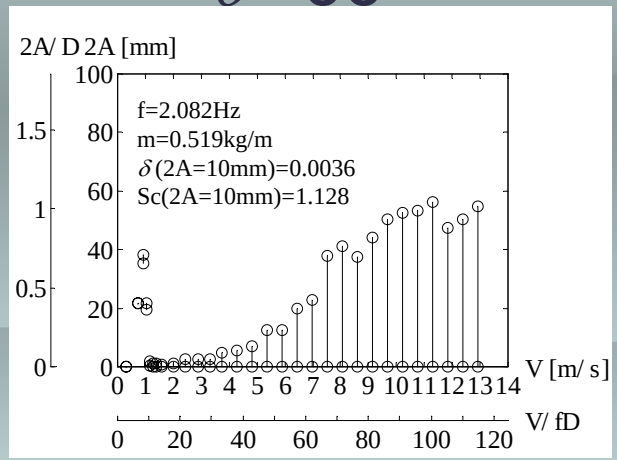

P.S.D. of the fluctuating lift force on stationary cable model




$\theta$=66°




$\theta$=56°



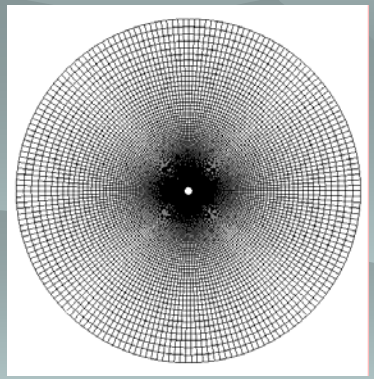

$\theta$=94°

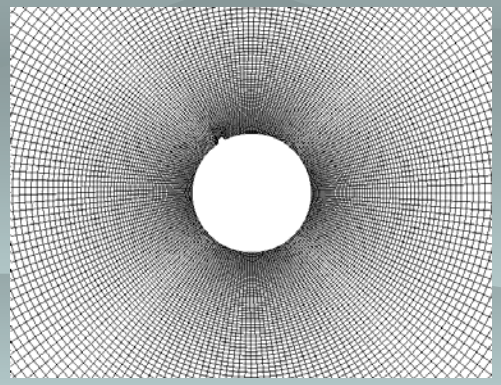
# CFD analysis (3D LES) (WR)

- Flow field and stationary and unsteady forces of non-yawed cable with upper rivulet

| Rivulet position | Grid | Domain | *Re* | Time step | Total time |
|---|---|---|---|---|---|
| no rivulet | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 40° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 46° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 50° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 52° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 56° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 60° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 66° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 70° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 80° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 90° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 110° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |
| 140° | 189×131×3 | 20D×20D×0.2D | 10000 | 0.002 | 200 |

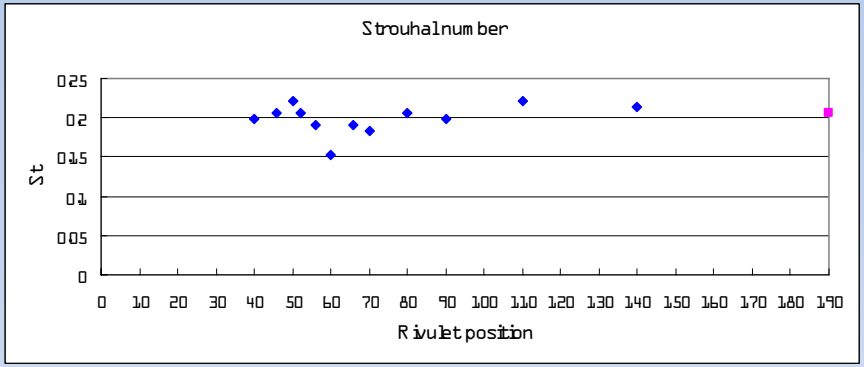
**Computational cases of large eddy simulation of flow around a cable model (WR)**

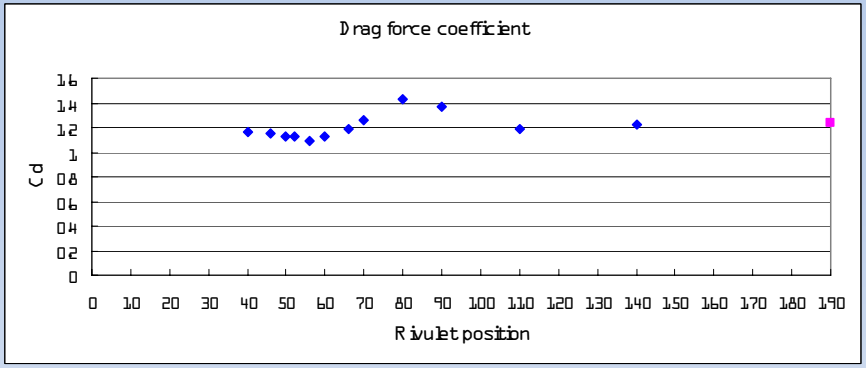




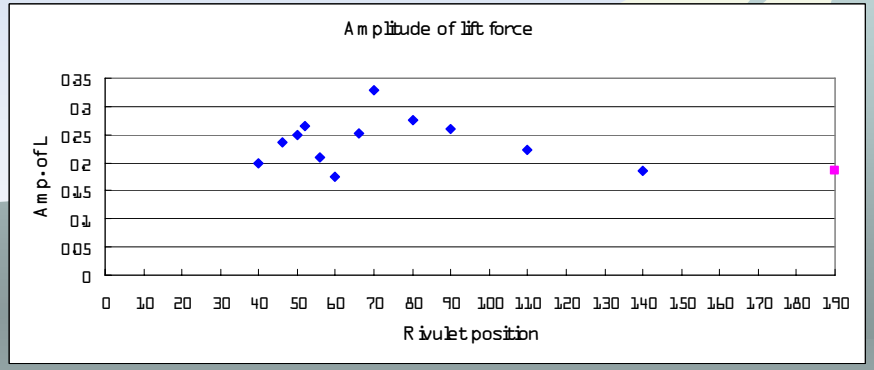
**Entire domain□□□□□□□□□□□□□□Grid around cable model**

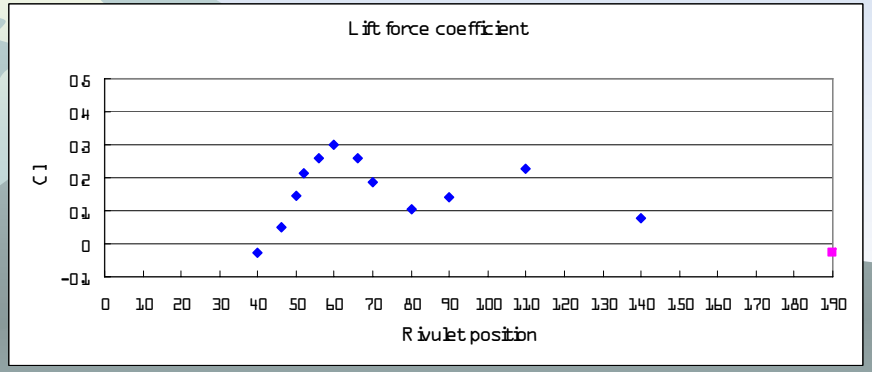
**Computational grid (WR)**



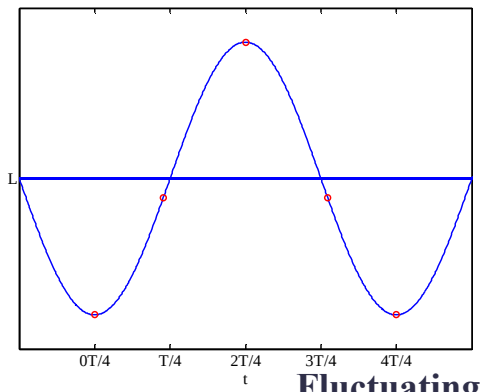

**Strouhal number (by fluctuating lift force, ■: no rivulet) (WR)**



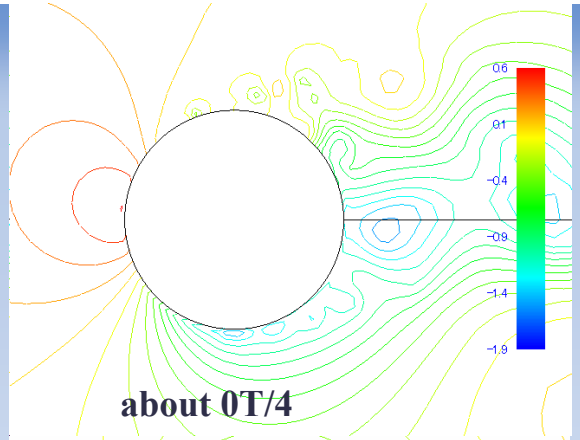




**Amplitude of fluctuating lift force (■: no rivulet) (WR)**

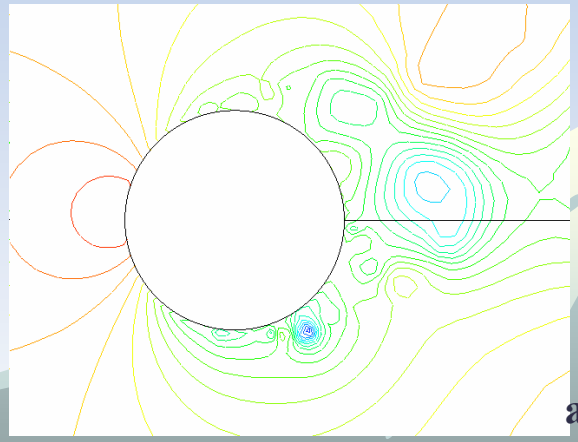
**Drag force and lift force coefficient (■: no rivulet) (WR)**



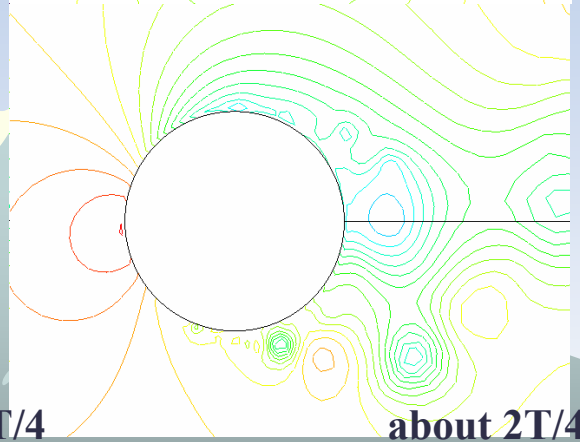

Fluctuating lift force



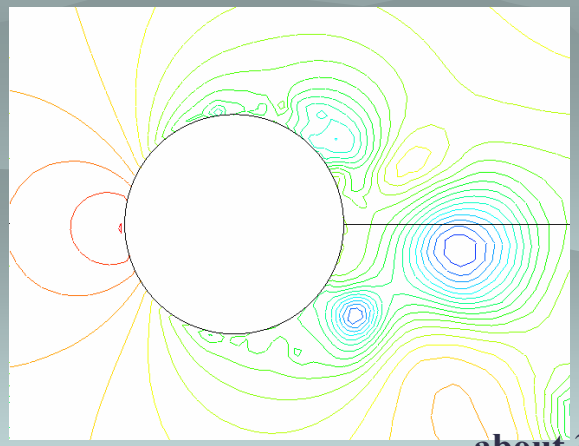

about 0T/4



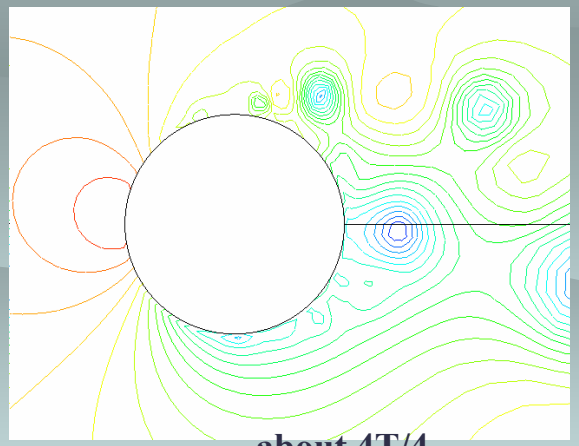
about T/4



about 2T/4

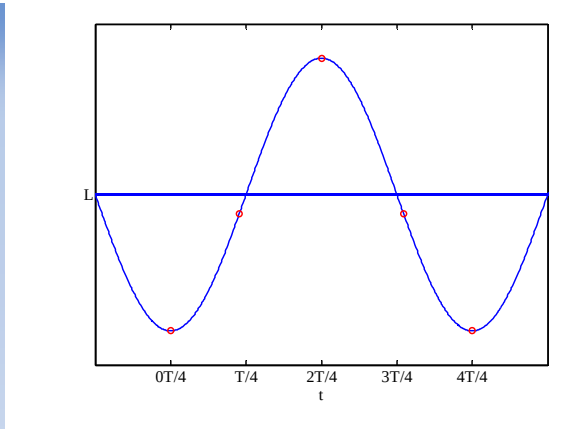


about 3T/4

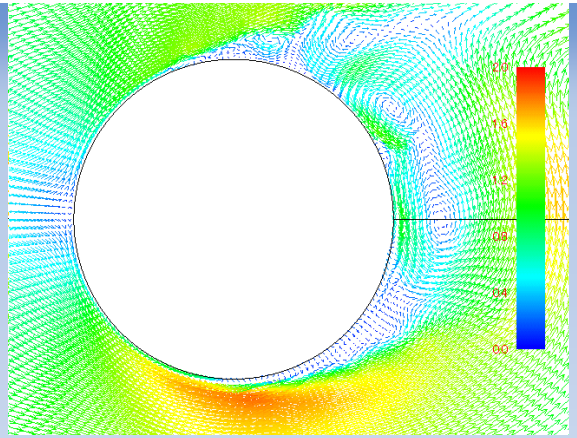


about 4T/4

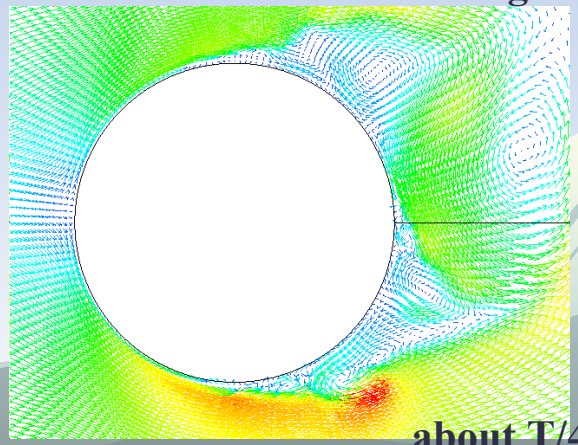
Pressure contour around cable during one period of fluctuating lift force (no rivulet) (WR)



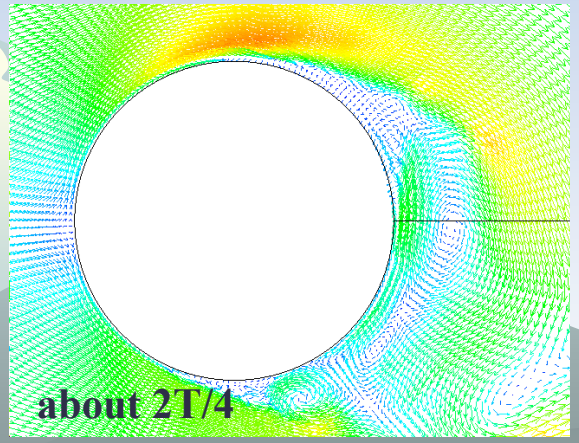

Fluctuating lift force



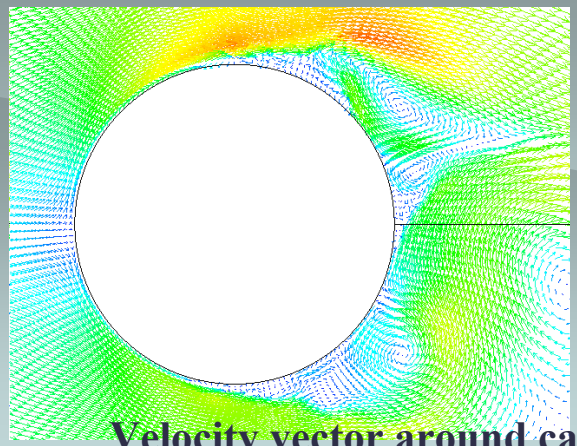
about 0T/4



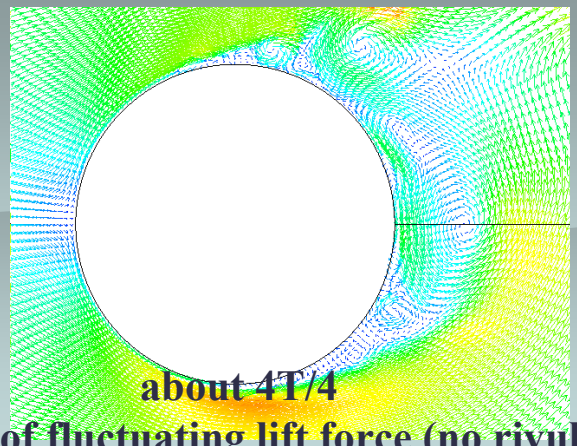
about T/4



about 2T/4



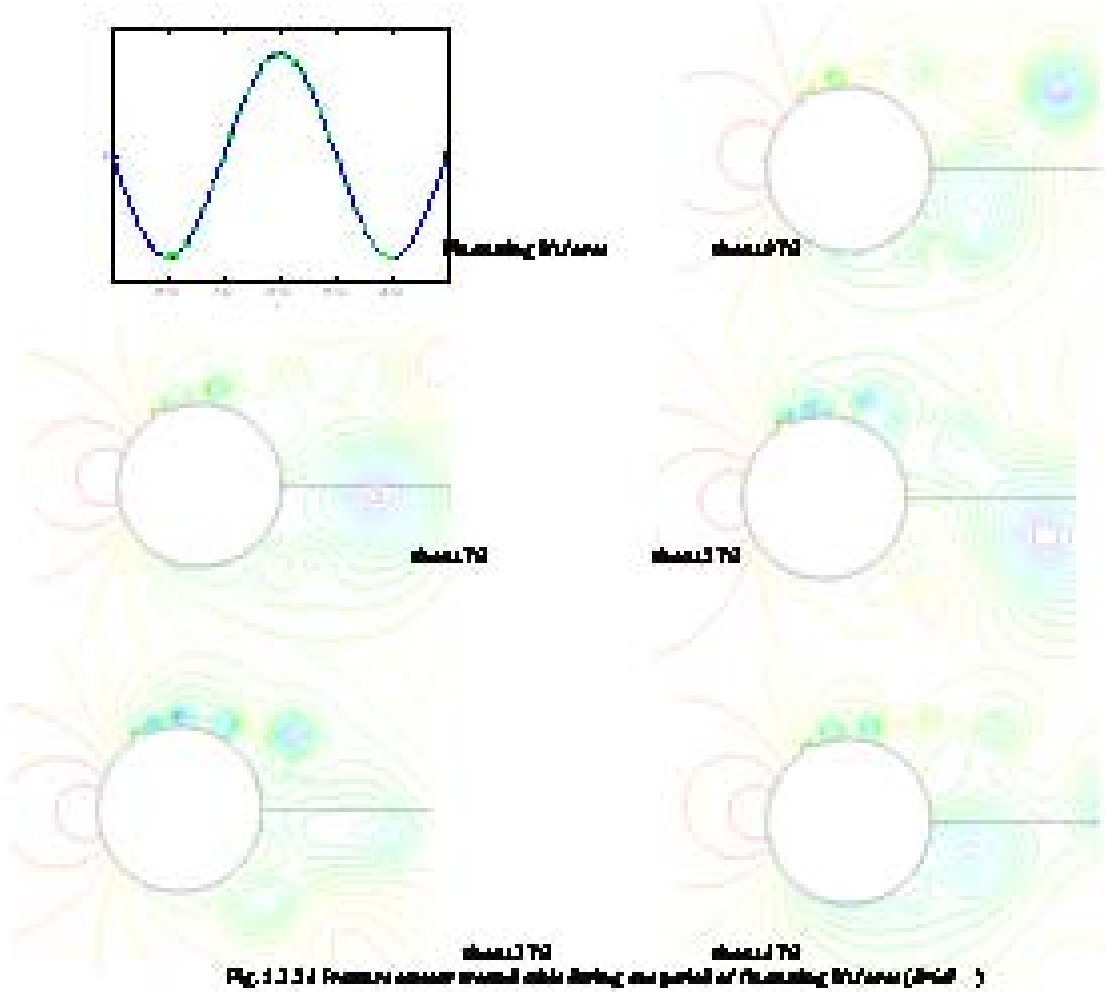
about 3T/4

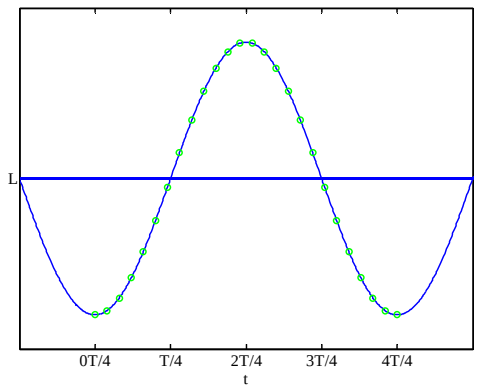


about 4T/4

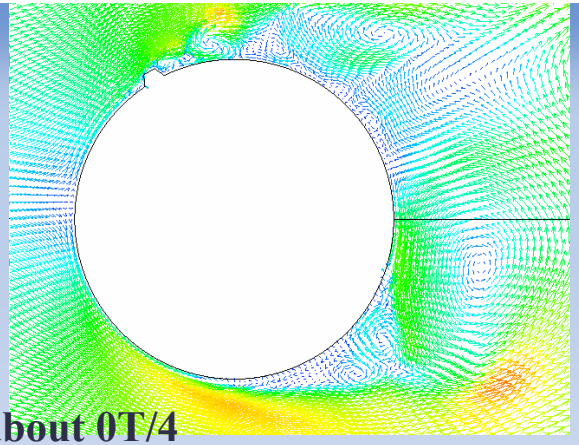
Velocity vector around cable during one period of fluctuating lift force (no rivulet) (WR)

# Rivulet position 60 degree

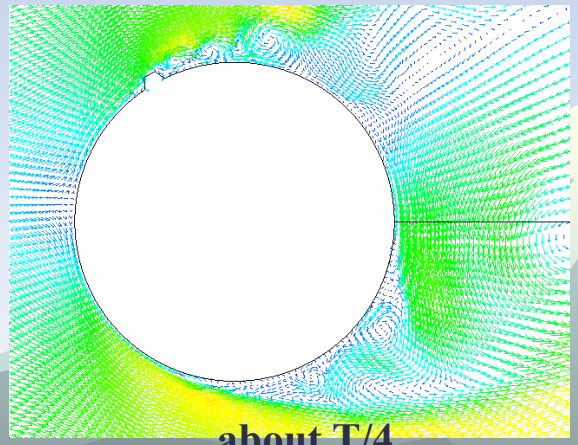




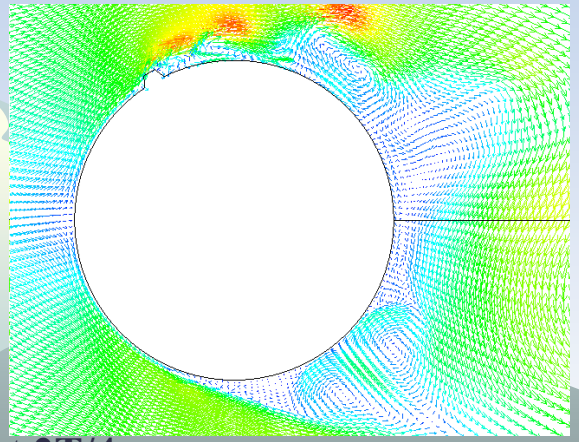

Fluctuating lift force



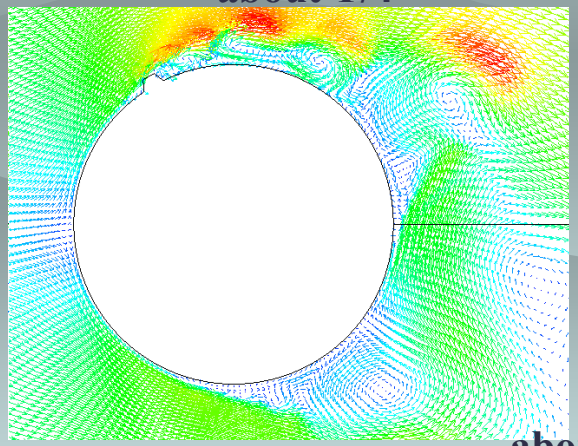
about 0T/4



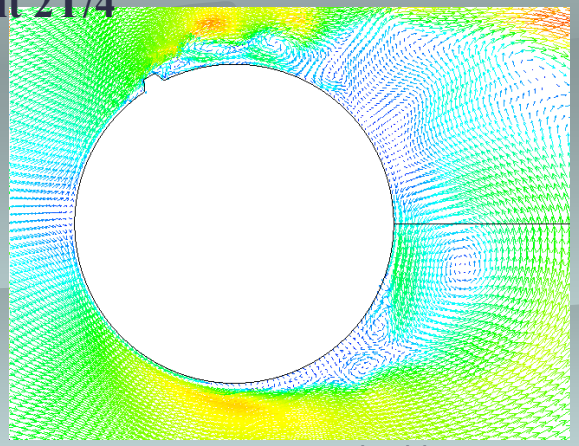
about T/4



about 2T/4

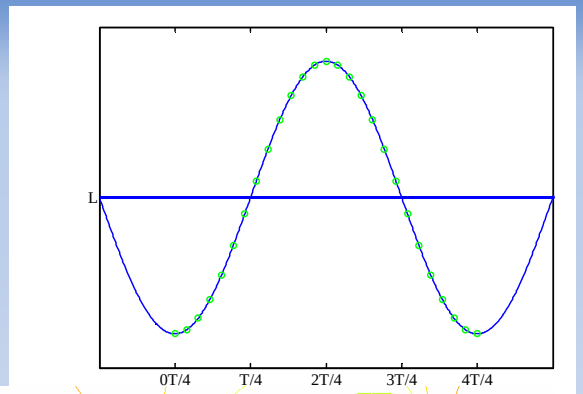


about 3T/4

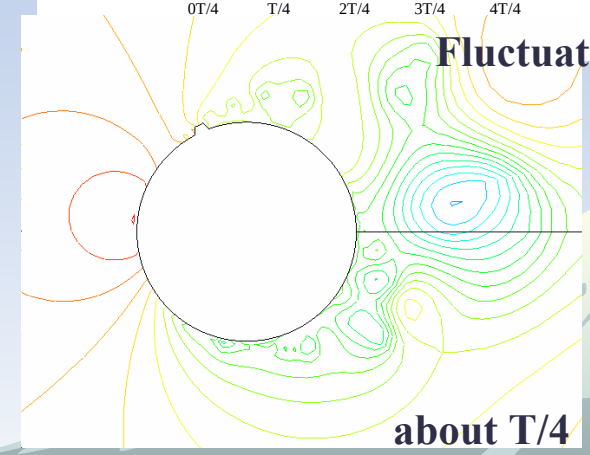


about 4T/4

Velocity vector around cable during one period of fluctuating lift force ($\theta$=60°) (WR)



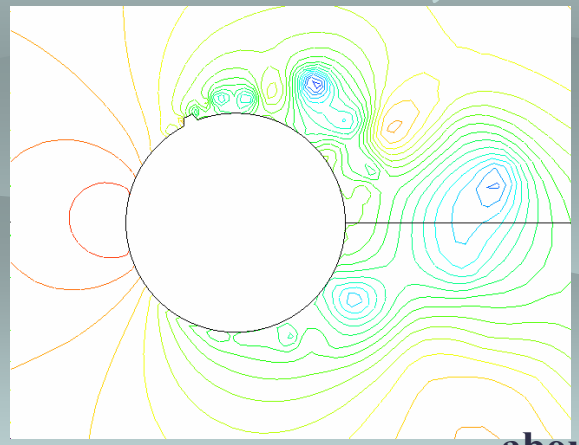

Fluctuating lift force

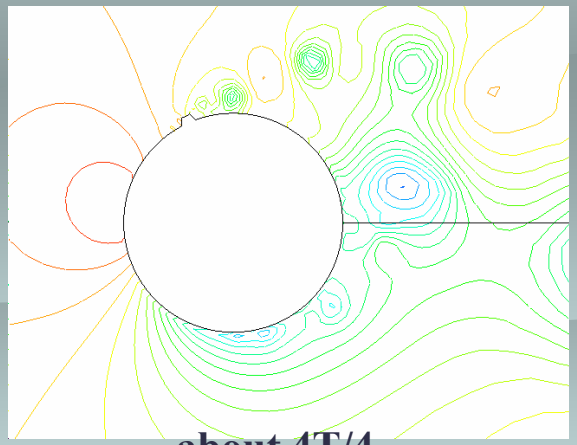


about T/4

about 0T/4

about 2T/4

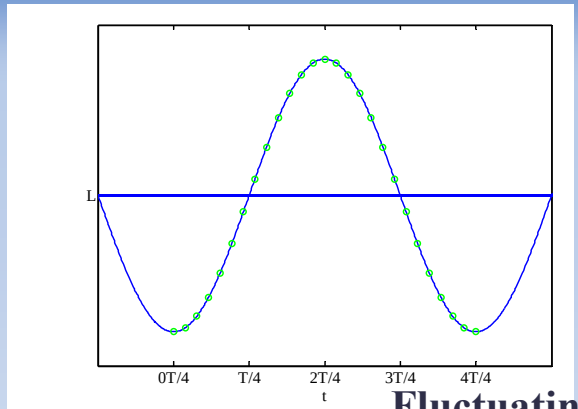




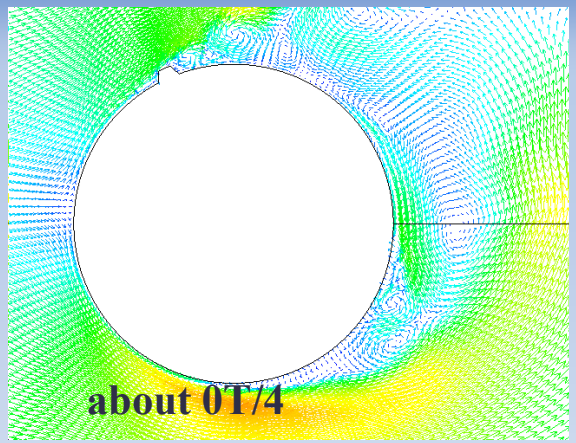
about 3T/4

about 4T/4

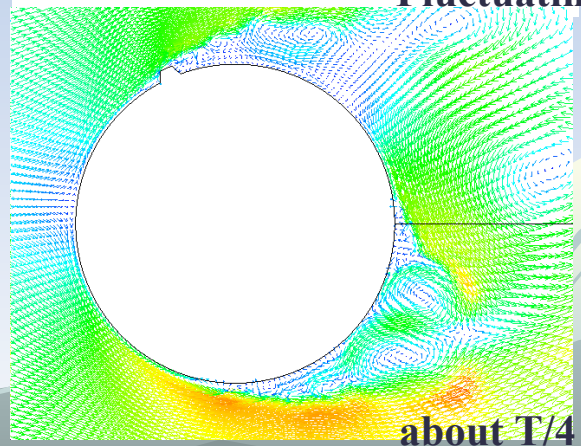
Pressure contour around cable during one period of fluctuating lift force ($\theta$=66°) (WR)



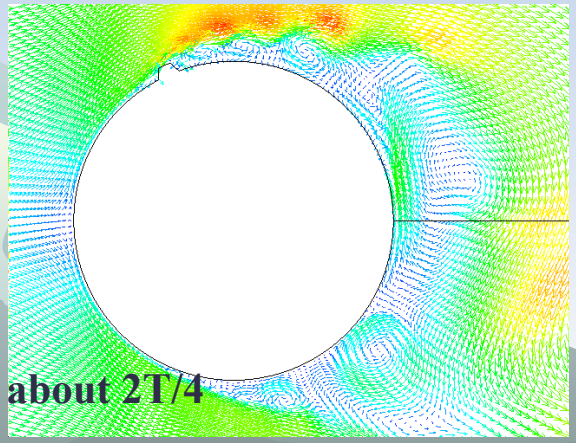

Fluctuating lift force



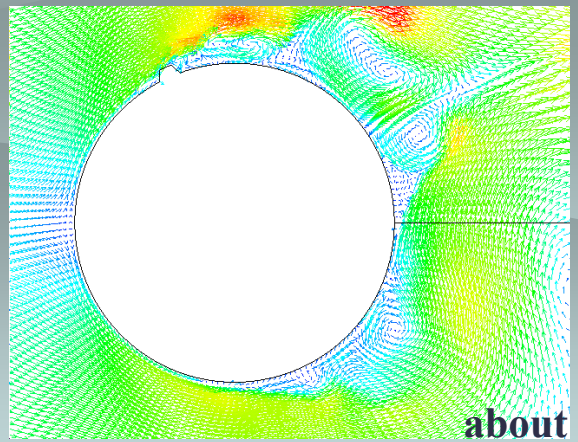
about 0T/4



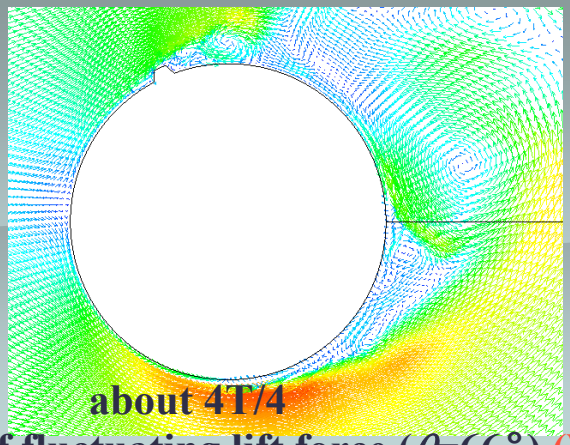
about T/4



about 2T/4



about 3T/4



about 4T/4

Velocity vector around cable during one period of fluctuating lift force ($\theta$=66°) (WR)

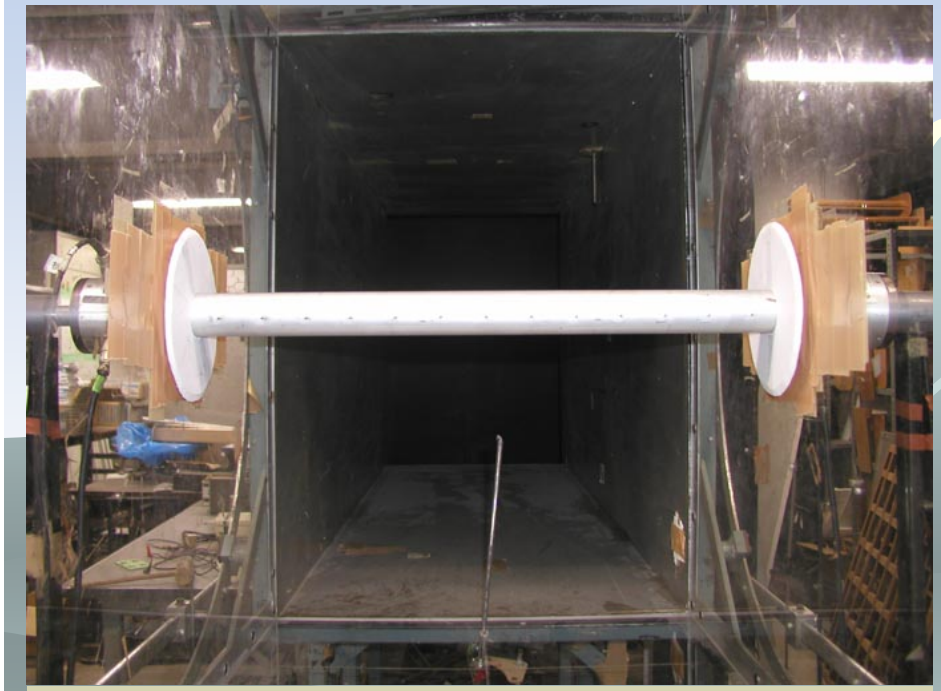
# High Speed Vortex Excitation

- 3D Karman Vortex Shedding along Cable Axis (WR)

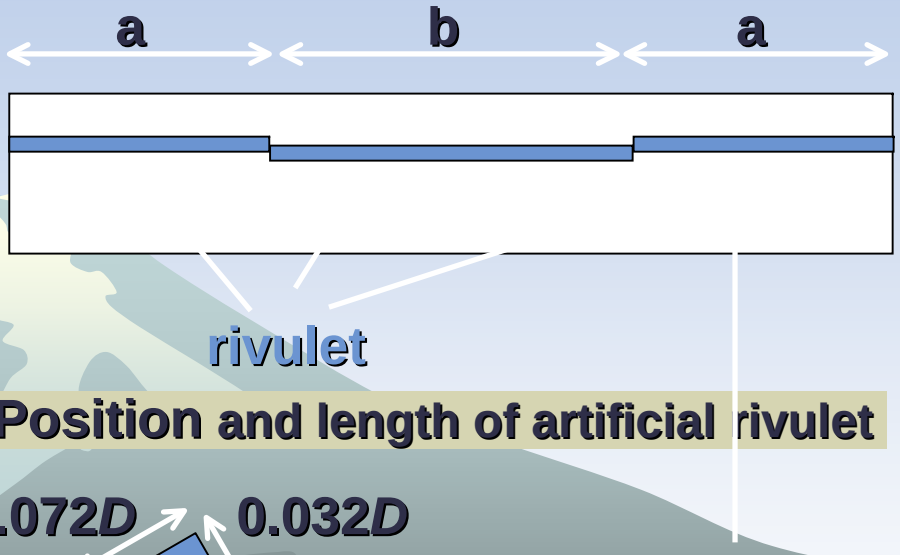
# Instantaneous water rivulet distribution (WR)

$V$=10m/s

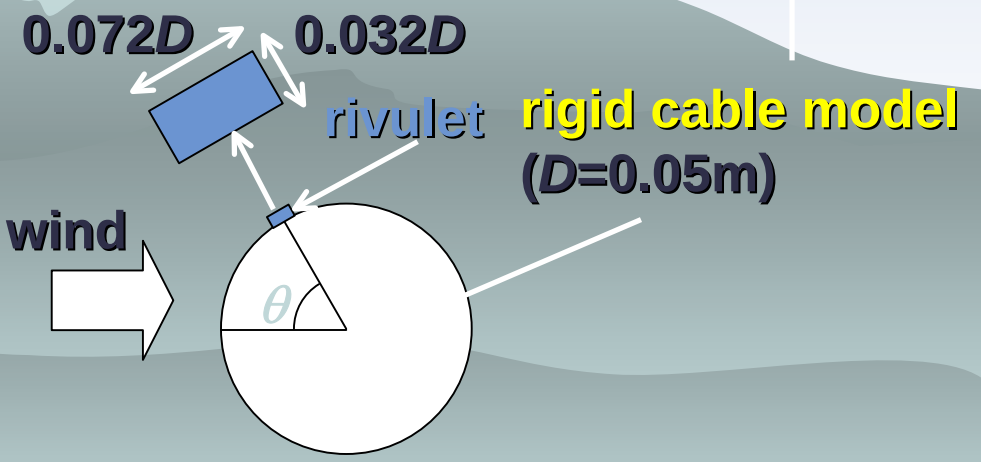
# Wind Tunnel Tests (WR)



Wind tunnel

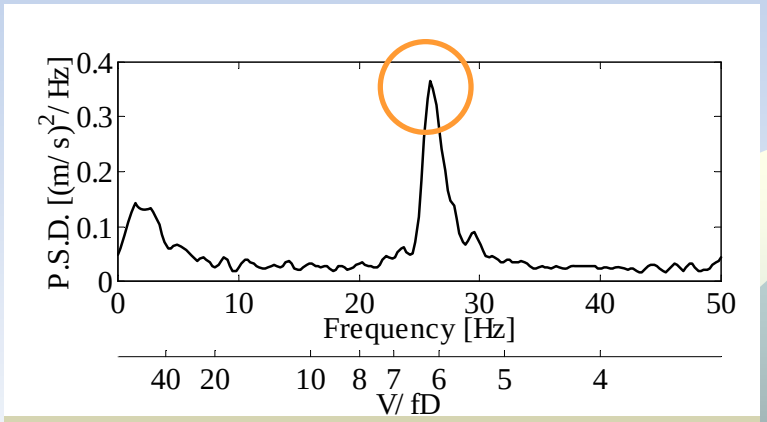



Position and length of artificial rivulet

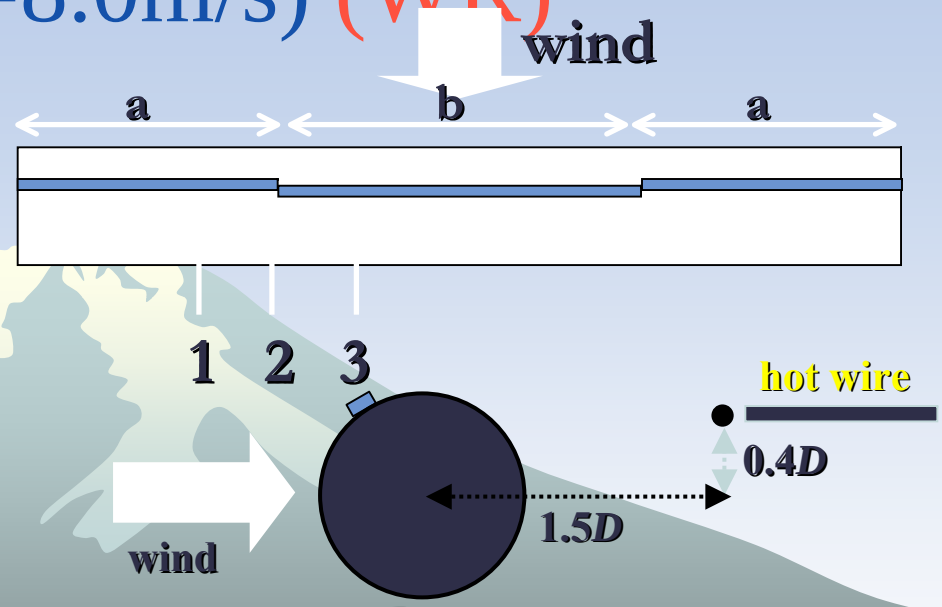


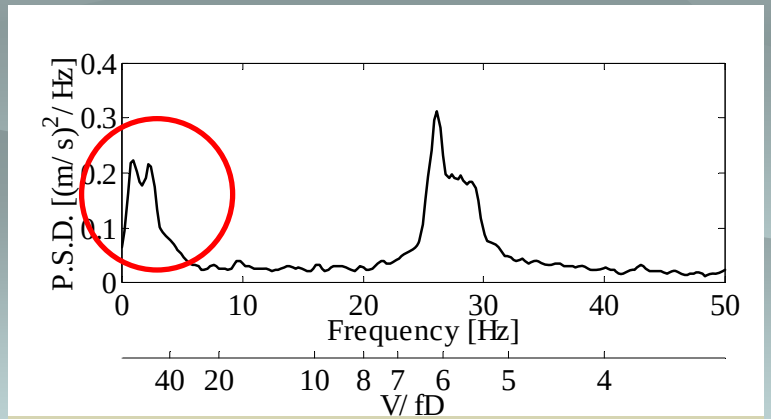

Position of artificial rivulet

# P.S.D. of fluctuating velocity in a wake (a: $\theta$=65°(a/l=0.35), b: $\theta$=55°(b/l=0.24), in smooth flow, $V$=8.0m/s) (WR)

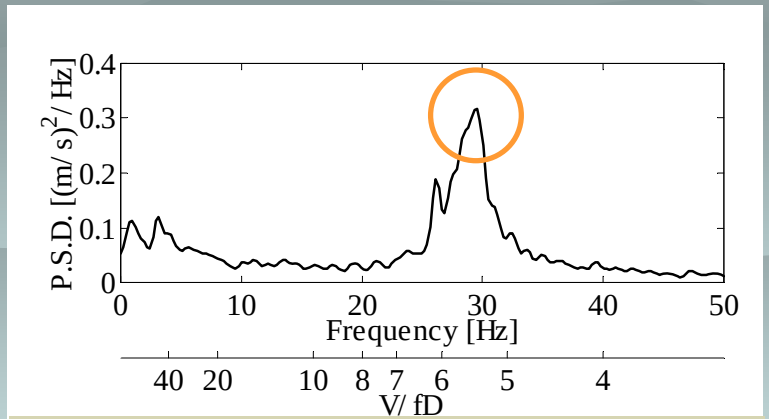



1) $\theta$=65° (St:0.167)




2) $\theta$=55°/65°

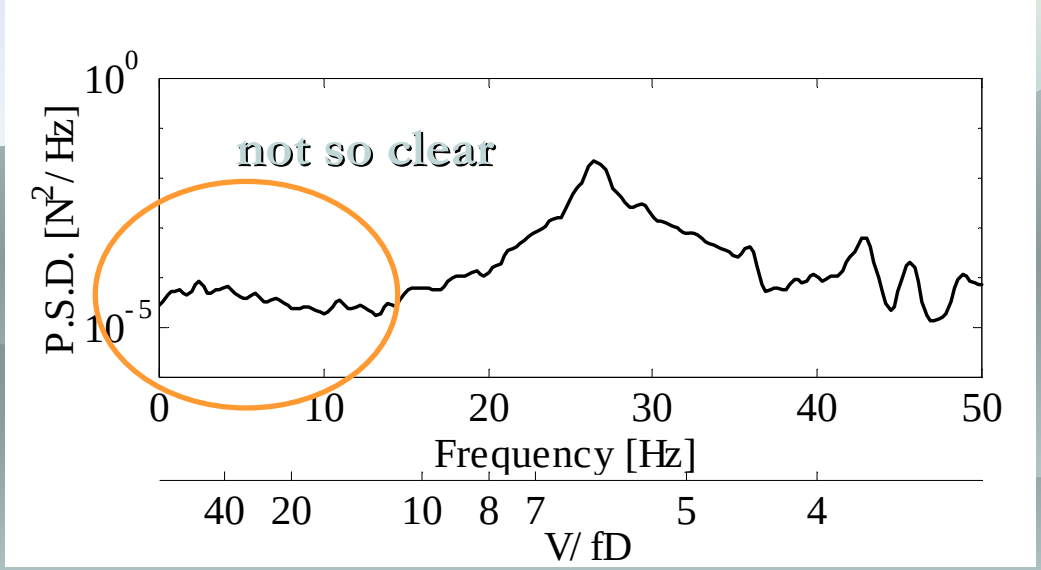



3) $\theta$=55° (St:0.189)

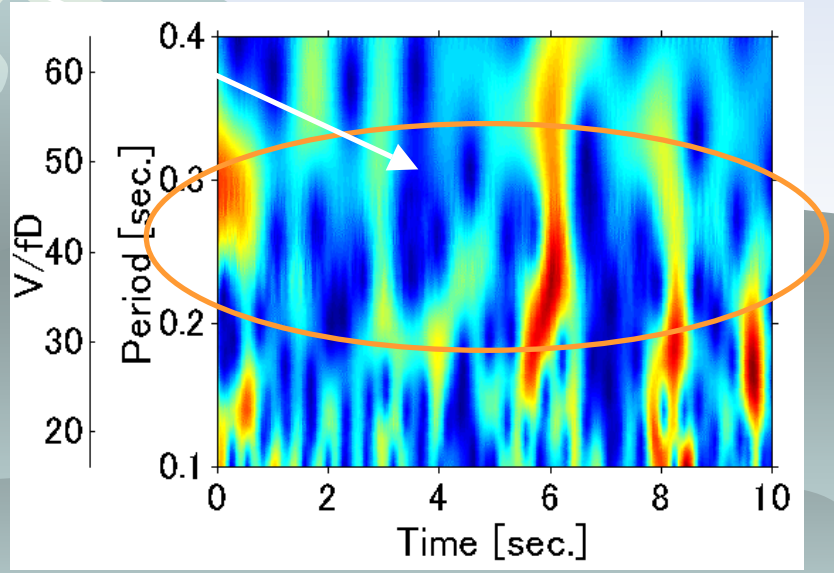
# P.S.D. & Wavelet analysis of fluctuating lift force

**(a: $\theta$=65°(a/l=0.35), b: $\theta$=55°(b/l=0.24), in smooth flow, $V$=8.0m/s) (WR)**

intensive unsteady power appears at high reduced velocity range




**P.S.D.**

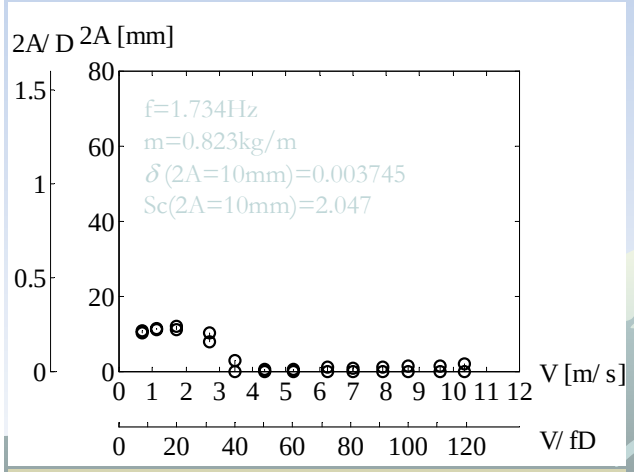



**Wavelet analysis**

# V-A diagrams

## (uniform rivulet $\theta$=47°, 54°, 58°, in smooth flow)

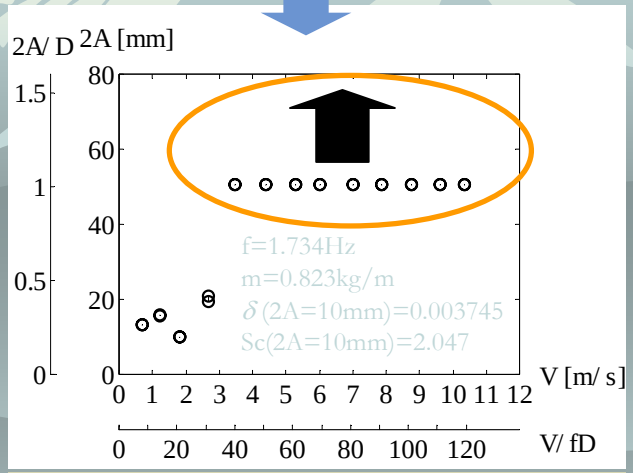
## (WR)



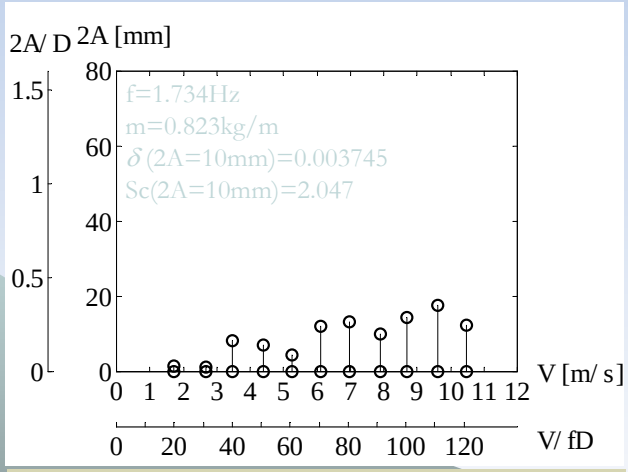

$\theta$=47°

Non - Galloping (NG)

Galloping (G)



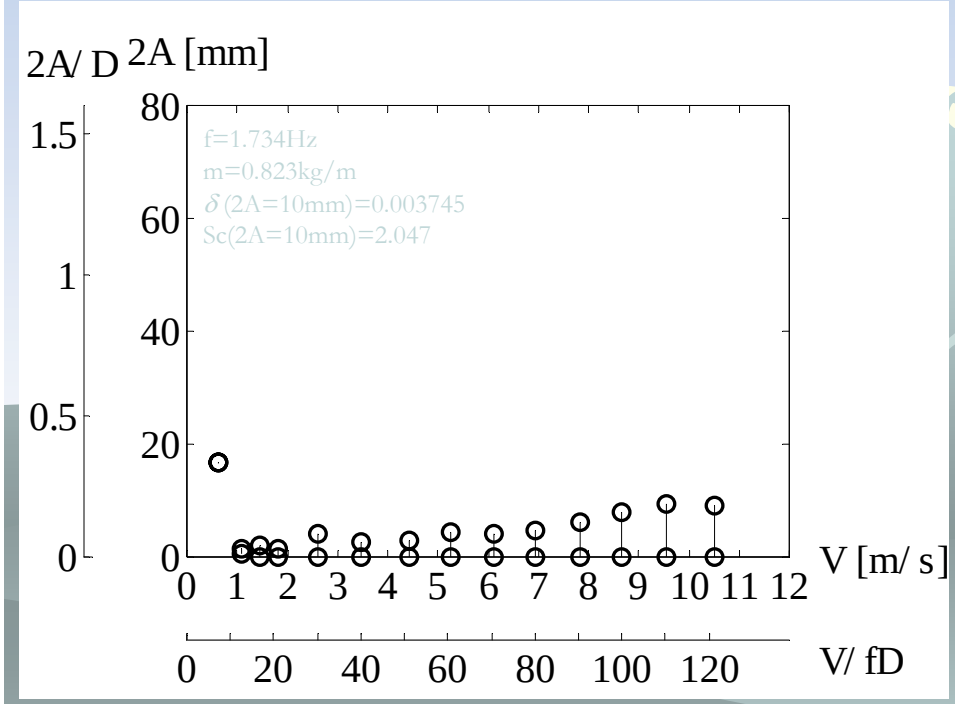

$\theta$=54°

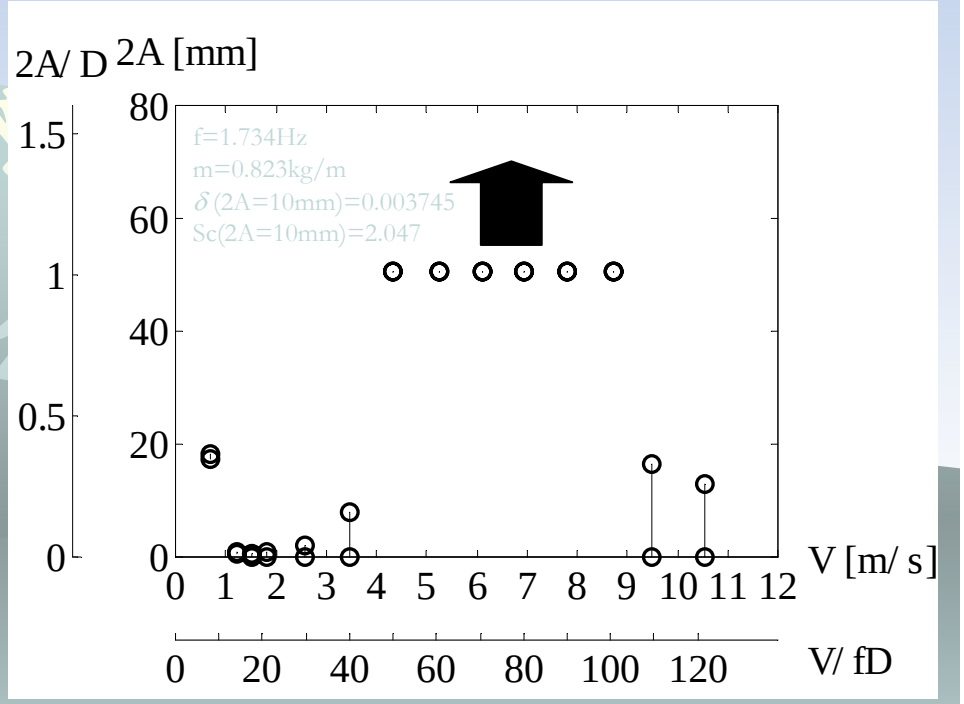



$\theta$=58°

Non - Galloping (NG)

# V-A diagrams (in smooth flow) (WR)



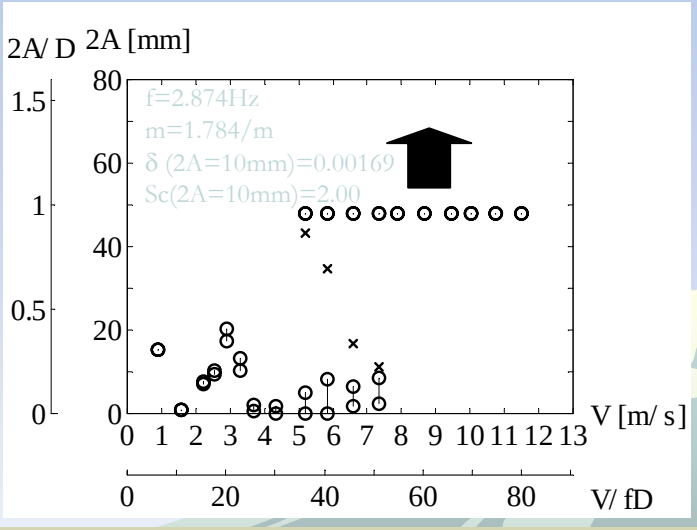

a: $\theta$=58°(a/l=0.31), b: $\theta$=47°(b/l=0.33)

(NG) (NG)

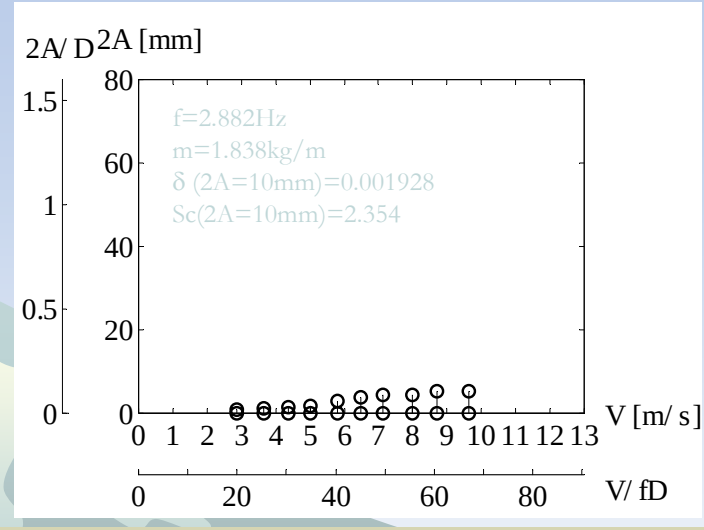
a: $\theta$=58°(a/l=0.31), b: $\theta$=54°(b/l=0.33)

(NG) (G)

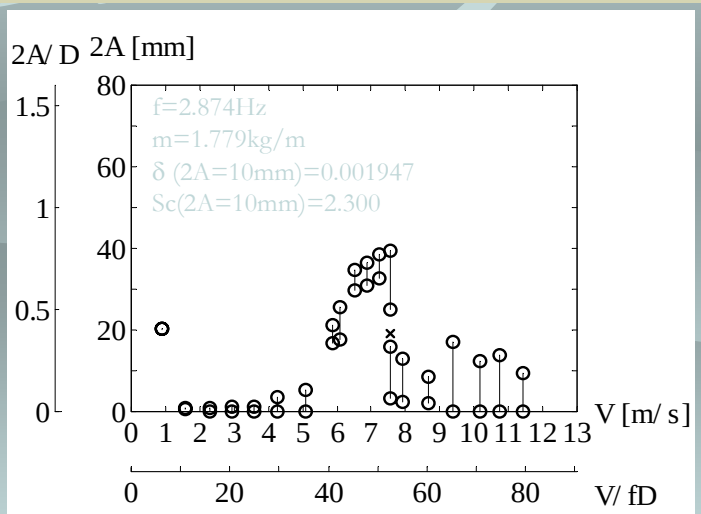
# V-A diagrams (in smooth flow) (WR)



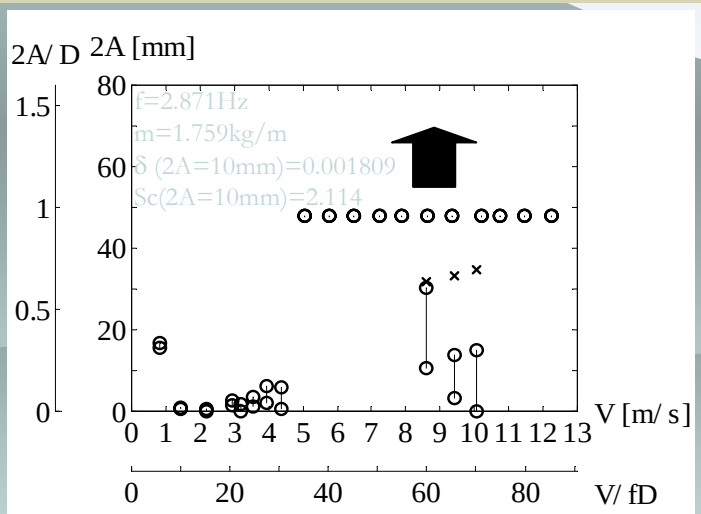

a:$\theta$=50°(a/l=0.31), b:$\theta$=55°(b/l=0.33)




a:$\theta$=65°(a/l=0.41), b:$\theta$=55°(a/l=0.12)



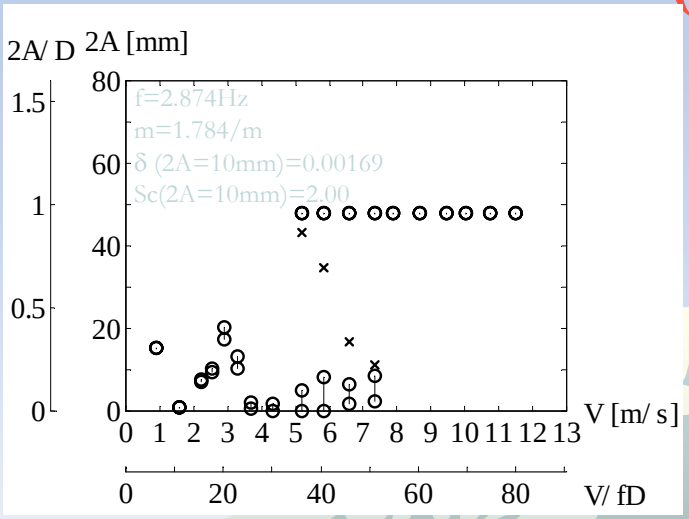

a:$\theta$=65°(a/l=0.36), b:$\theta$=55°(b/l=0. 24)

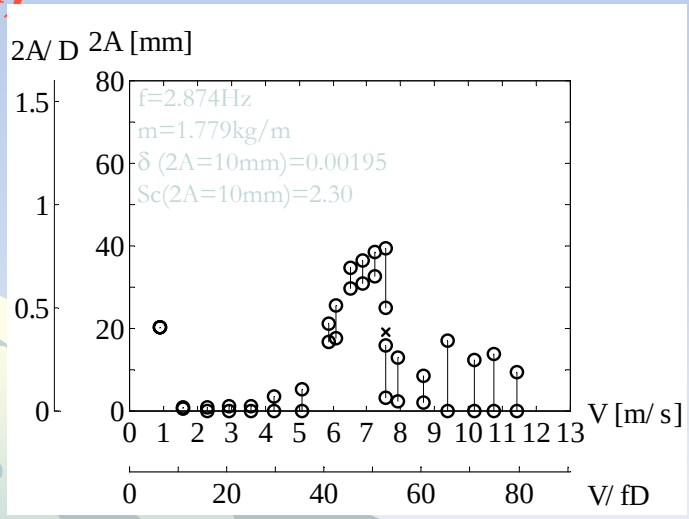


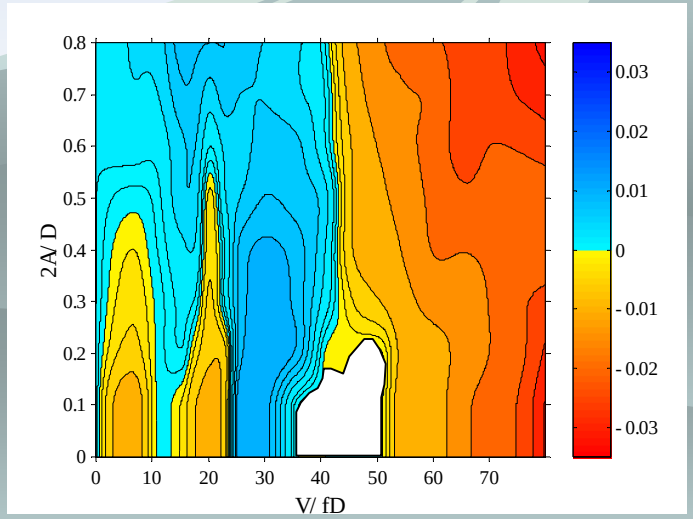

a:$\theta$=65°(a/l=0.31), b:$\theta$=55°(b/l=0.33)

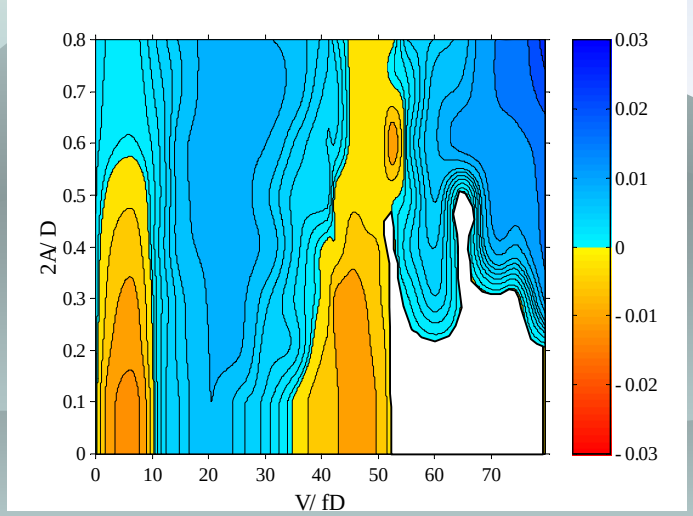
# V-A & V-A-δ diagrams (in smooth flow)

## (WR)



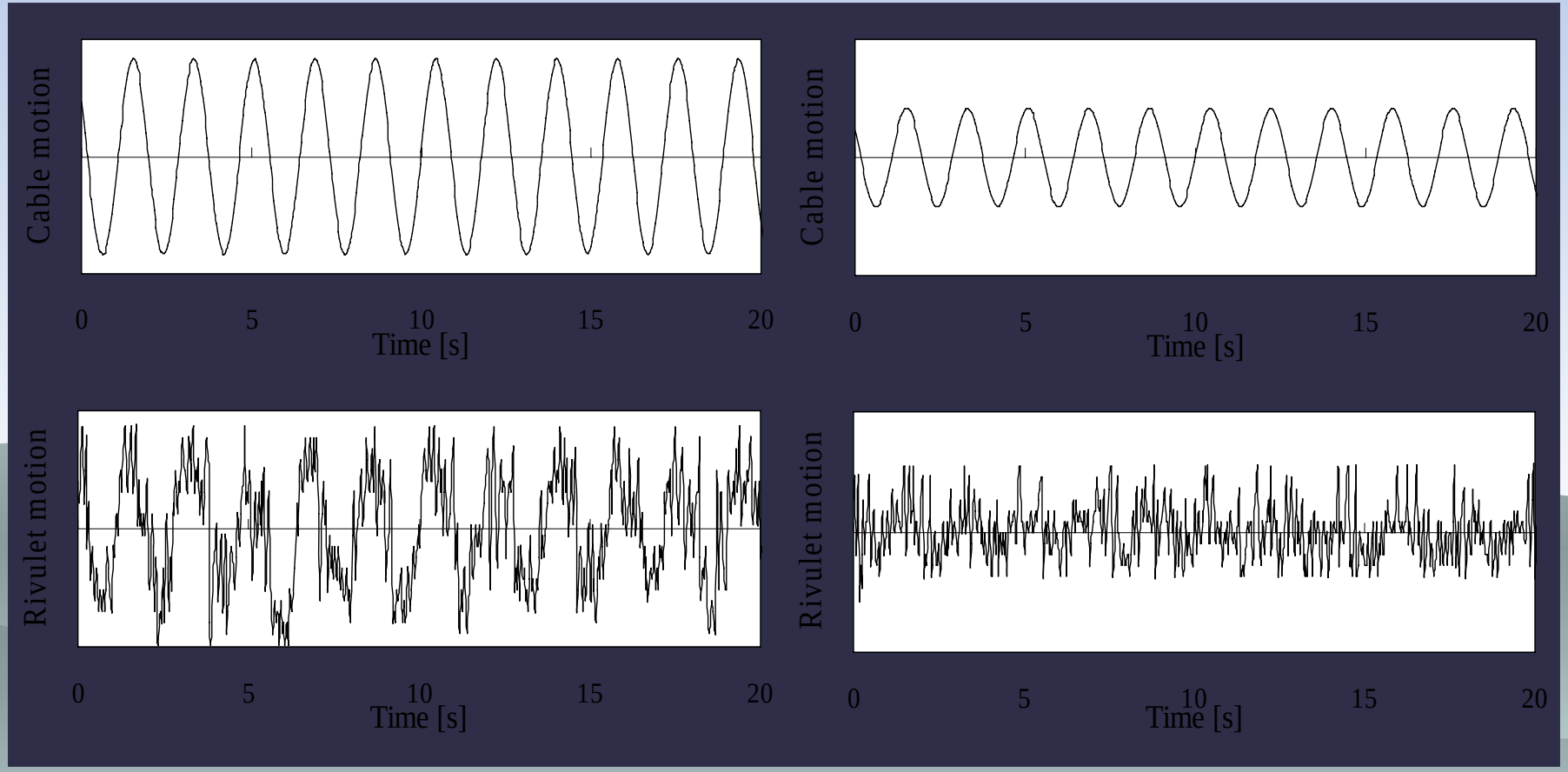

a: $\theta$=50°(a/l=0.31), b: $\theta$=55°(b/l=0.33)

a: $\theta$=65°(a/l=0.36), b: $\theta$=55°(b/l=0.24)

# Movement Effect of Upper Water Rivulet

# Observed water rivulet movement on prototype scale cable model during rain-wind induced vibration (MR)

# The time history of cable vibration and rivulet movement (MR)




**(large cable amplitude)** **(small cable amplitude)**

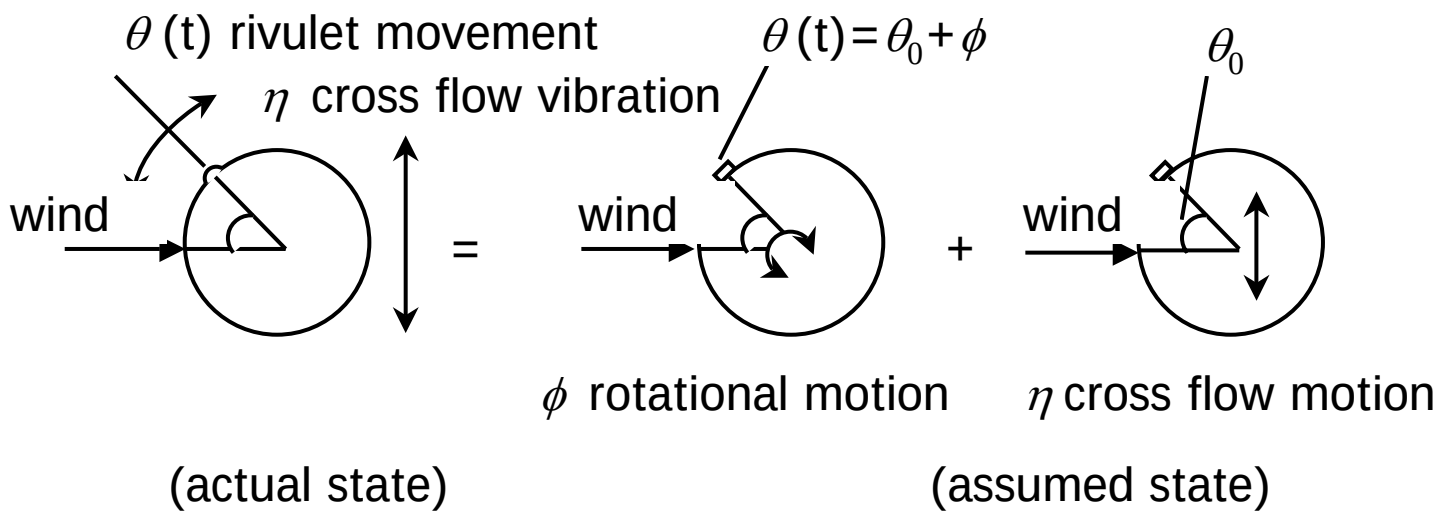
# Rivulet movement (MR)

**Rivulet movement behaves non-uniformly and non-stationary along cable axis even stationary cross-flow vibration.**

# Rivulet movement and cable vibration (MR)

- When Karman vortex intensively sheds, cable vibration is mitigated.
- Rivulet tends to move in synchronization to cable motion, when Karman vortex shedding becomes weak.
- Rivulet movement is controlled by Karman vortex shedding when it becomes intensive.

# Simulation of rivulet movement during cross flow vibration (MR)



# The unsteady lift forces can be expressed by use of aerodynamic derivatives (MR)

$$\ddot{\eta}+\left[-\frac{\rho D^2\omega}{4m}\left\{H_1^*+\frac{D}{2}\frac{\phi_0}{\eta_0}\left\{(\cos\lambda)H_2^*+(\sin\lambda)H_3^*\right\}\right\}\right]\dot{\eta}+$$

$$\left[\omega_0^2-\frac{\rho D^2\omega^2}{4m}\left\{\frac{D}{2}\frac{\phi_0}{\eta_0}\left\{(-\sin\lambda)H_2^*+(\cos\lambda)H_3^*\right\}+H_4^*\right\}\right]\eta=0$$

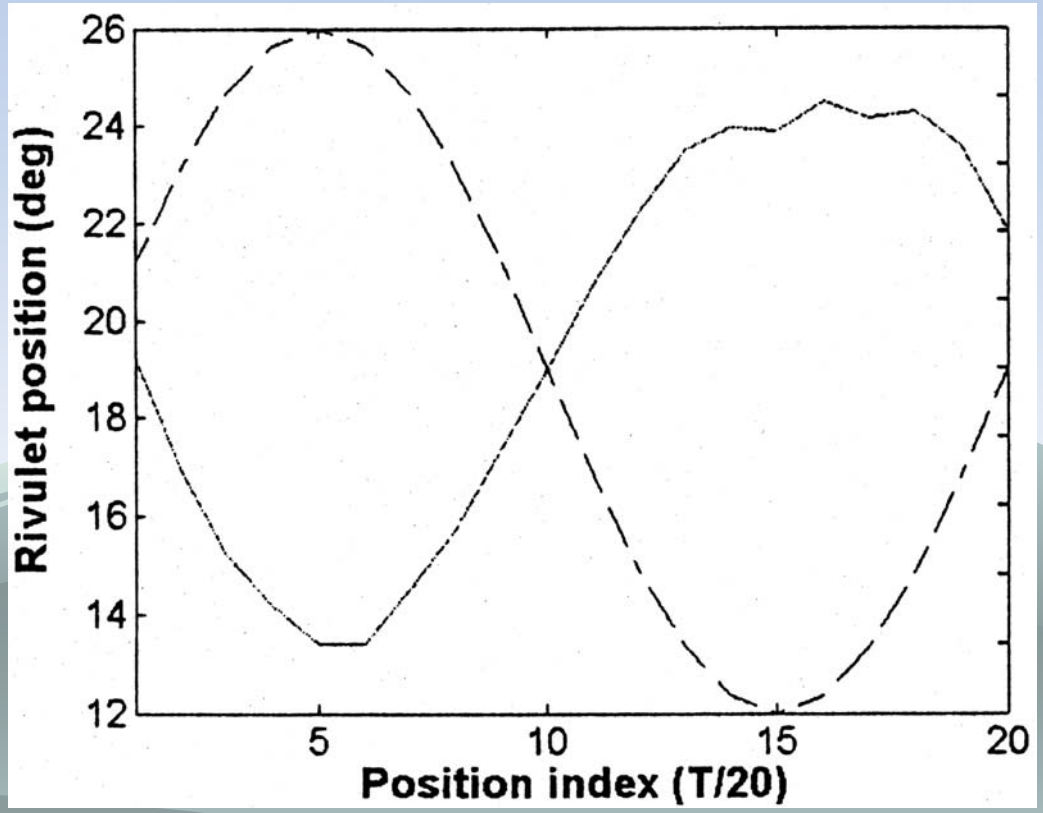
where

$\eta=\eta_0\sin\omega t$

$\phi=\phi_0\sin(\omega t+\lambda)=(\phi_0\sin\lambda/(\eta_0\omega))\,d\eta/dt+(\phi_0\cos\lambda/\eta_0)\,\eta$

$R=(D/2)(\phi_0/\eta_0)$

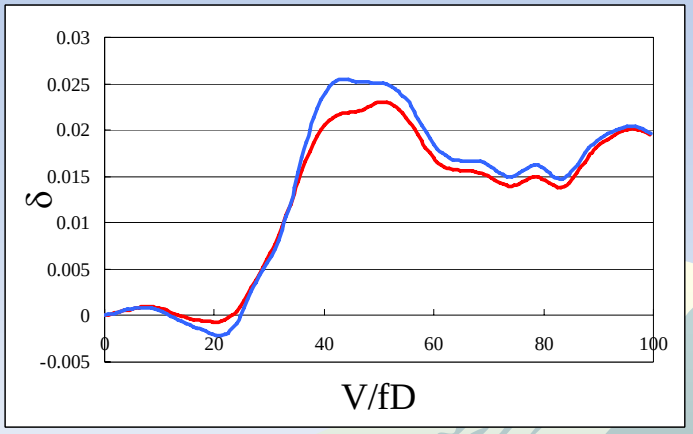
# Characteristics of vibration and rivulet motion (Cosenteno et al) (MR)



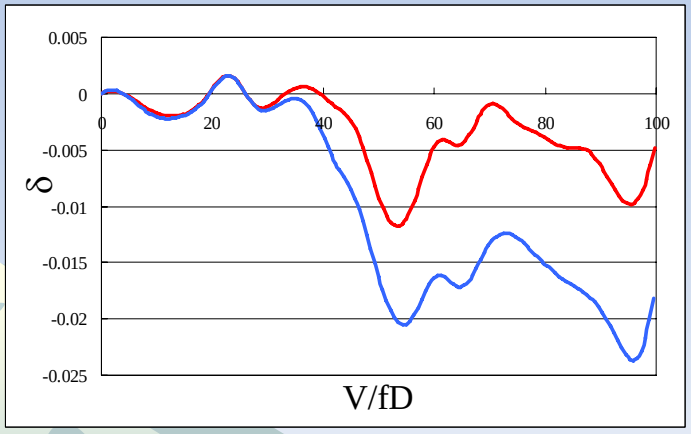

Time history of rivulet position and cable motion

——— rivulet position
– – – – – cable motion

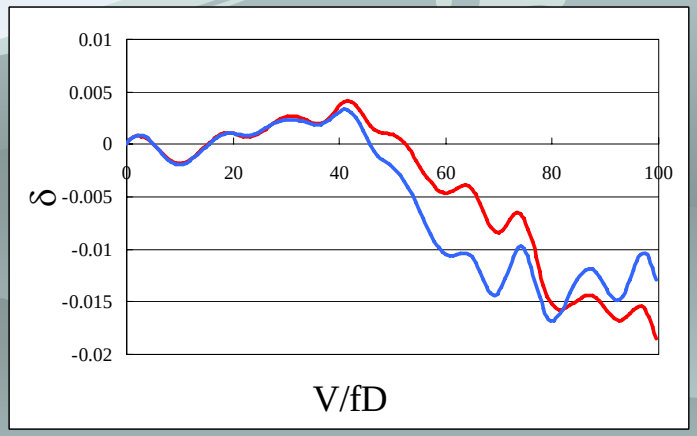
# Rivulet position effect on velocity – damping diagrams of yawed cable (MR)



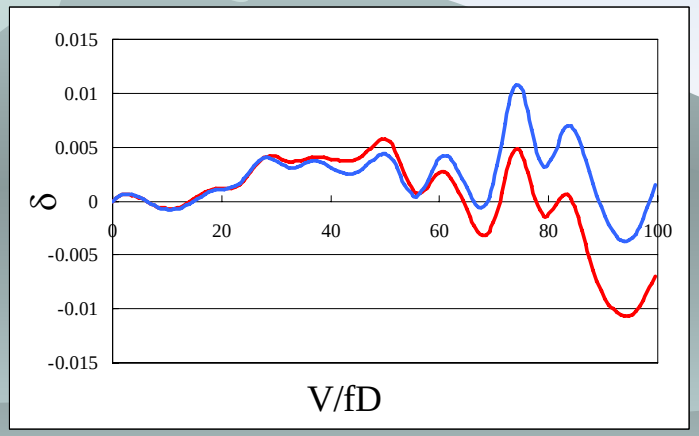

a) $\theta$=50°




b) $\theta$=56°




c) $\theta$=66°




d) $\theta$=72°

($\beta$=45°, $\lambda$=180°, $R$=0.0698)

—— :fixed water rivulet

—— :moving water rivulet

# Rivulet Movement Effect (MR)

**Wind tunnel test results suggest that the rivulet movement synchronized to cable motion affects the cable vibration more or less, however, the fundamental response characteristics of cable vibration can be framed by the neutral rivulet position.**

# Reynolds Number Effect

# Critical Reynolds Number

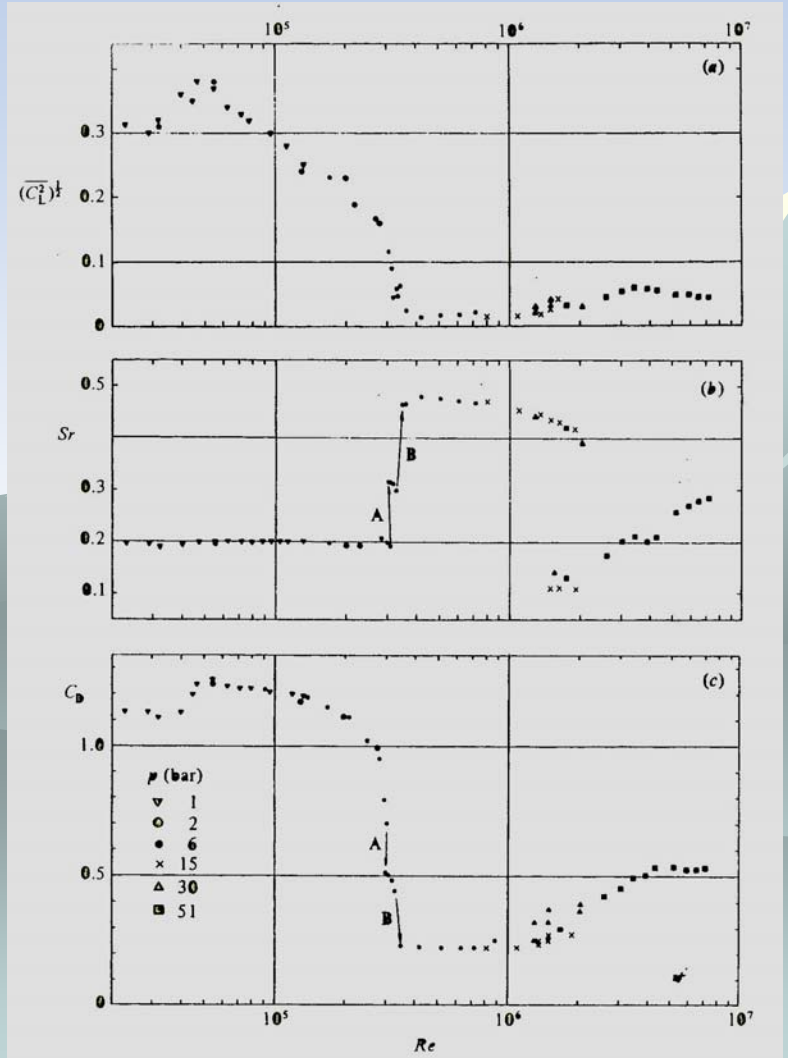
$Re=UD/\nu$

$\nu$ □ $1.5\times10^{-5}$

$D=0.15m$

if $Recr=(3\text{-}5)\times10^{5}$, then $U=30m/s\text{-}50m/s$.

# Reynolds number effects on circular cylinder aerodynamics (Schewe) (RE)

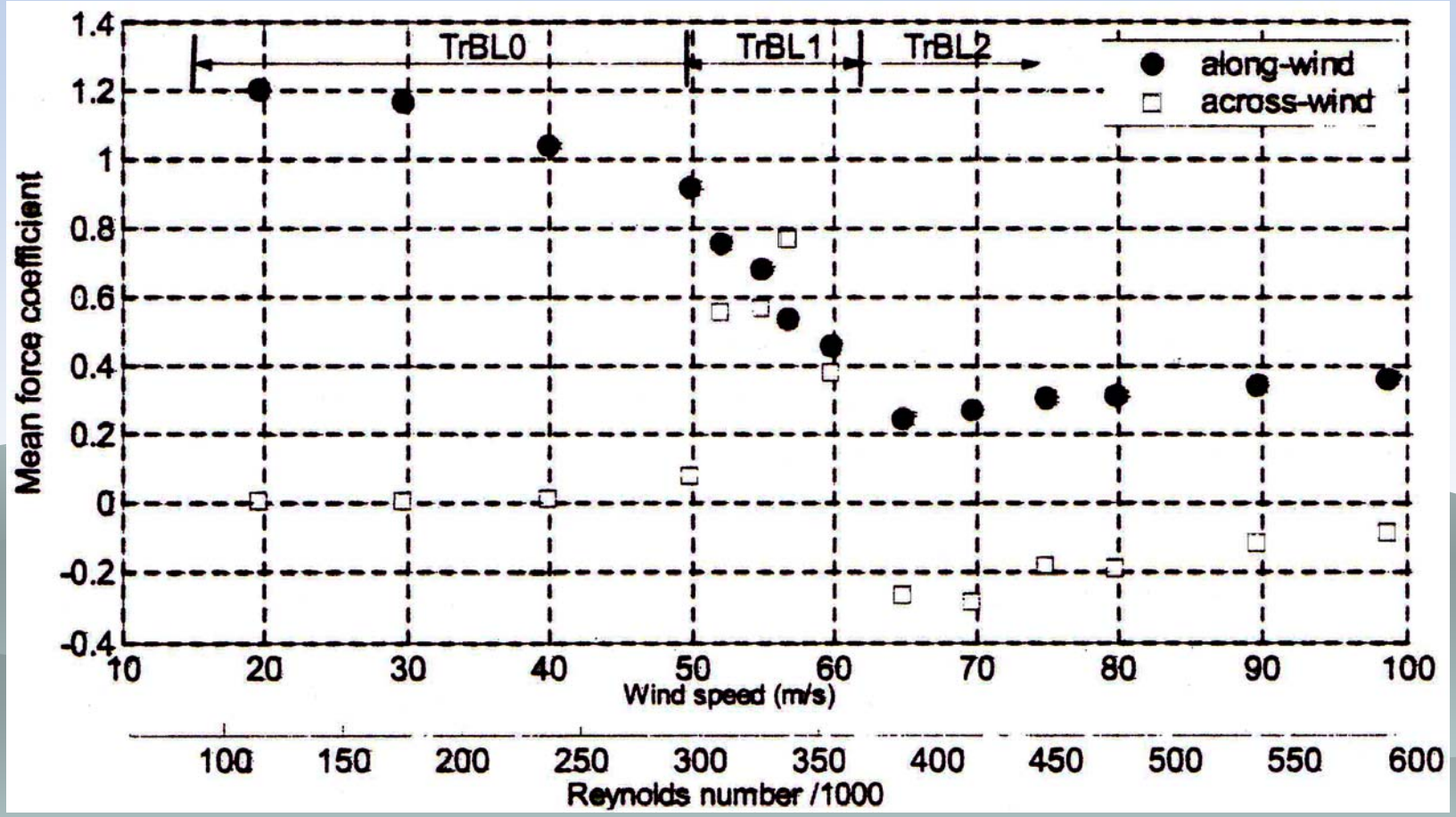



(a) r.m.s. of the lift fluctuations

(b) Strouhal number of the lift fluctuatio
Sr = *fD/ u*∞

(c) drag coefficient

# Reynolds number effects on inclined cable aerodynamics (NRCC) (RE)




● drag force coefficient □ lift force coefficient

# Reynolds number effects (RE)

**Surface roughness**
Styrene foam

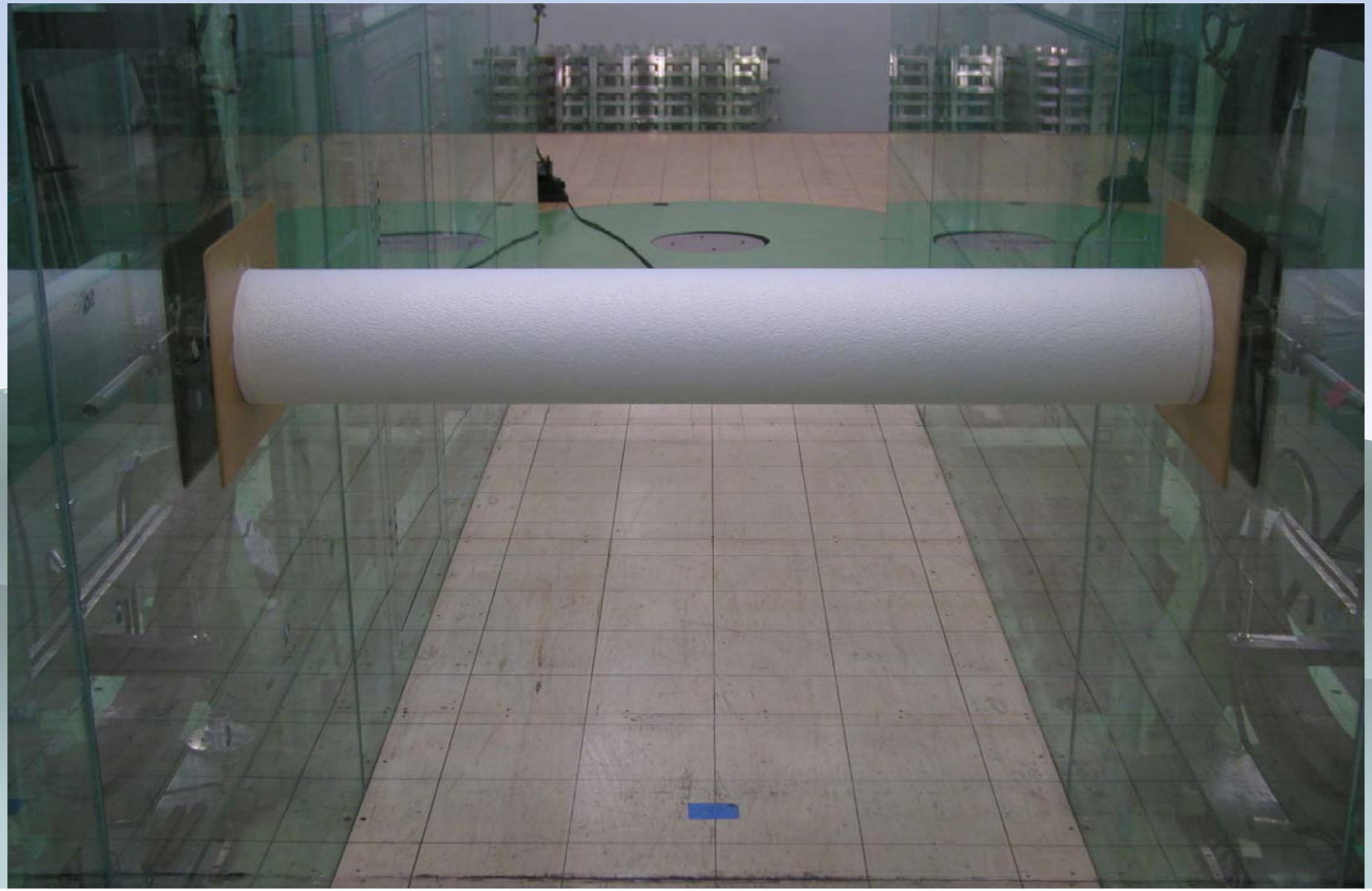
**High wind velocity**
Max.17m/s

**Larger diameter**
$D$=158mm

**Change of Reynolds number**

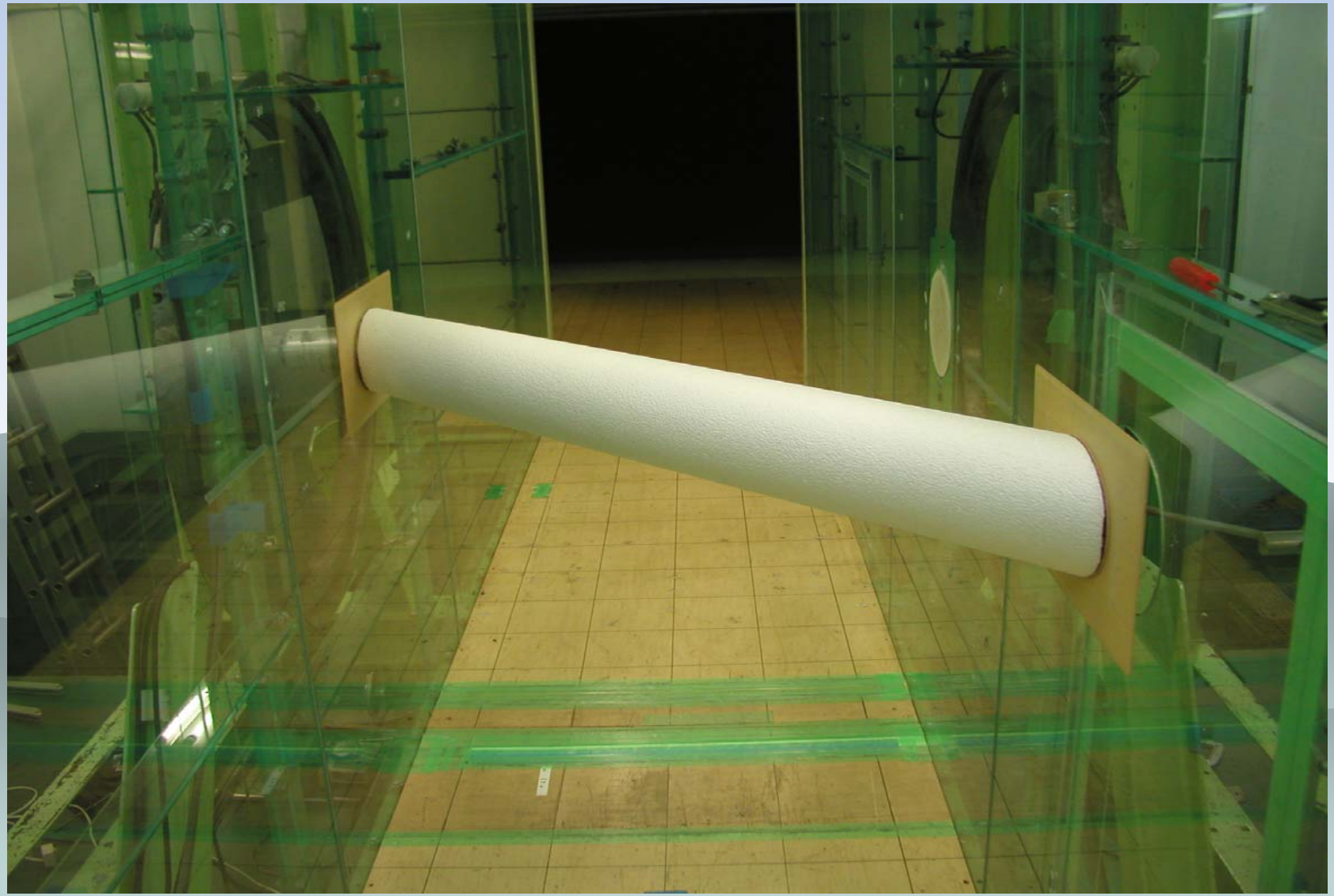
- **Cable Model with surface roughness (non-yawed state) (RE)**

# Cable Model (β=0°) with Surface Roughness (Styrene Foam)

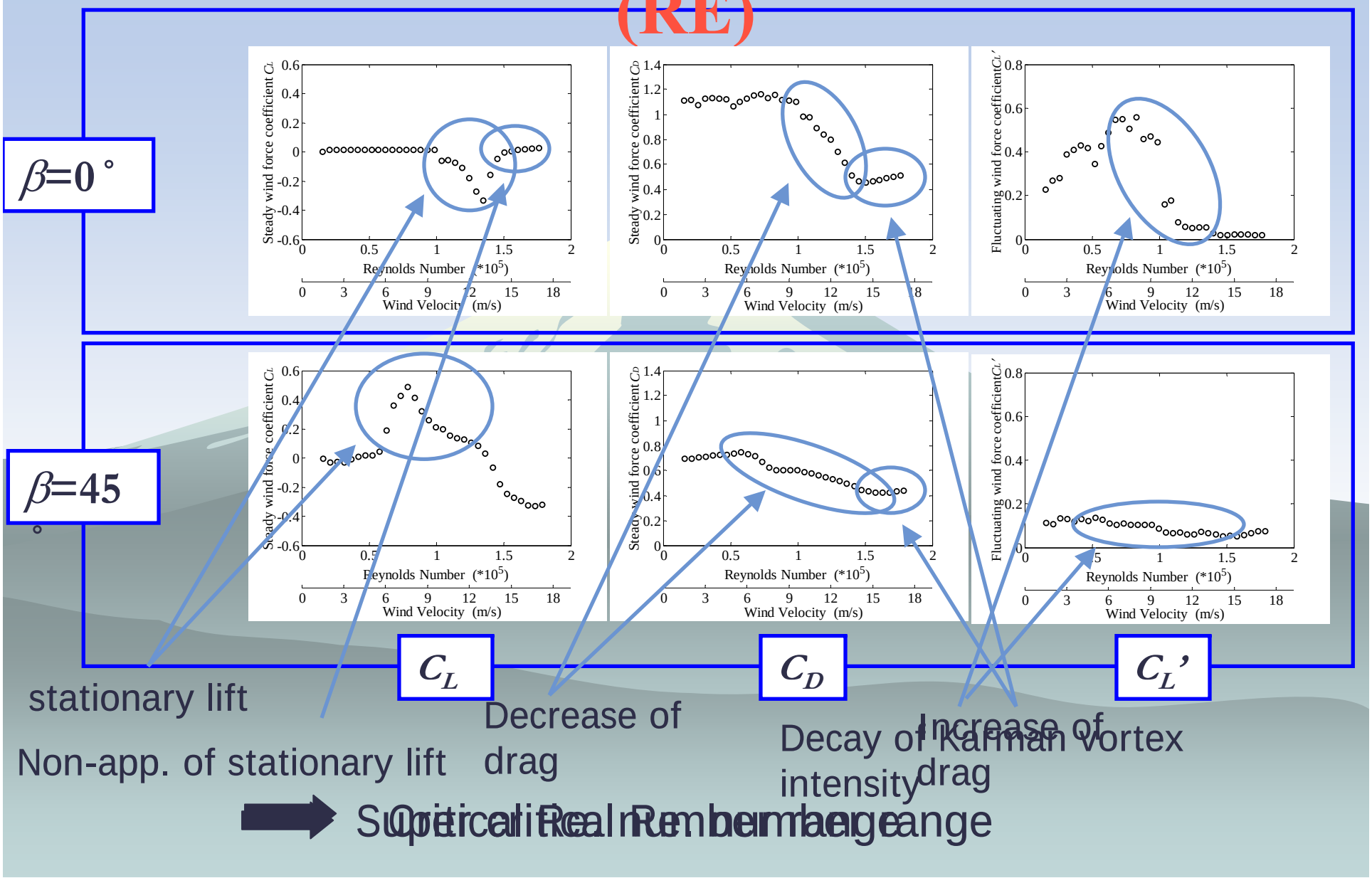


# Cable Model (β=0°)

# Cable Model (β=45°)

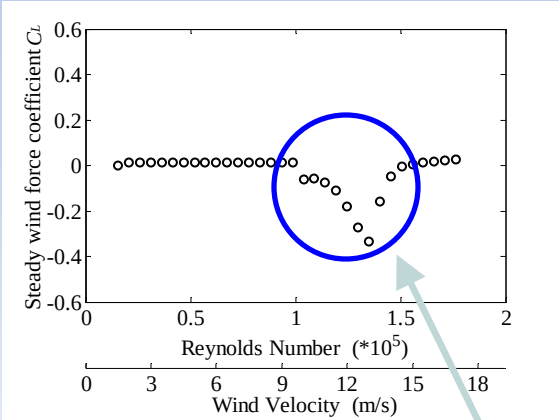


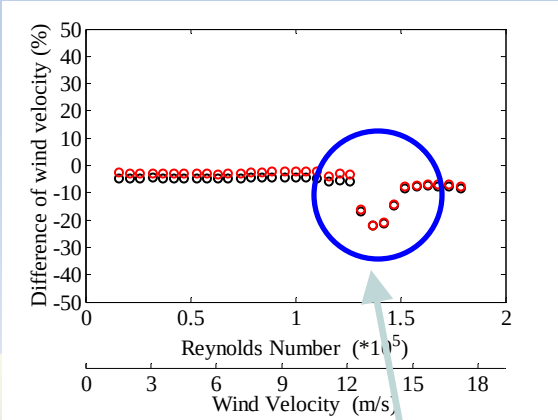
# Static forces with surface roughness (RE)



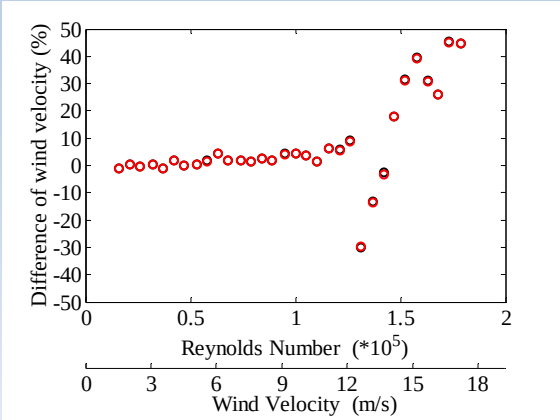
# Flow field with surface roughness

## $\beta$=0 (RE)

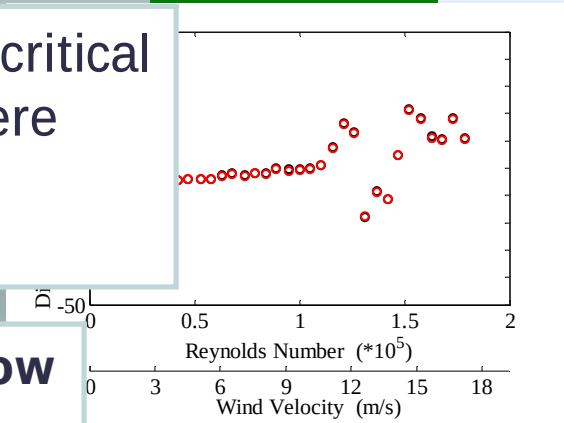


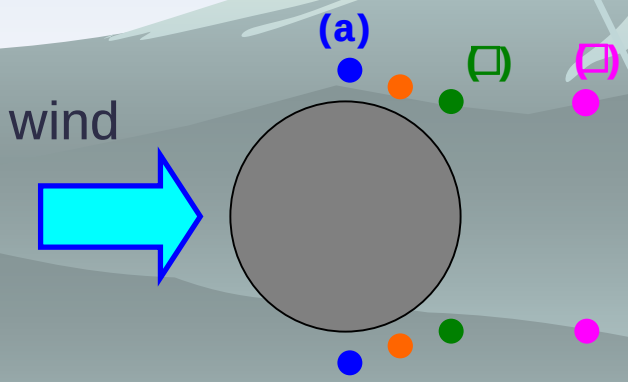

(a)




(b)



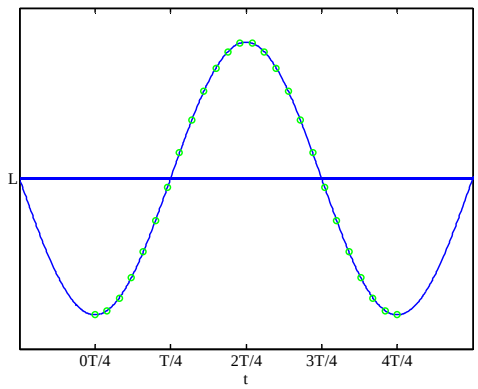

(c)



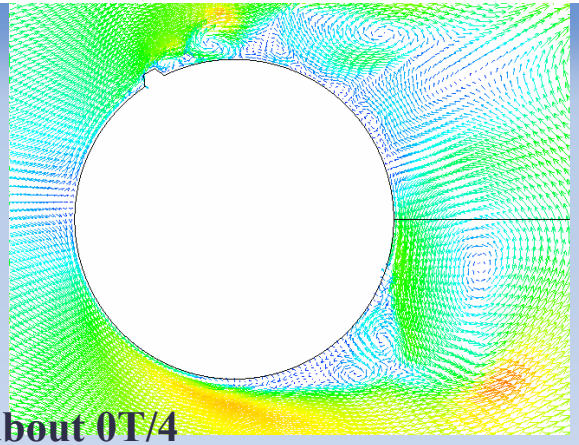

Velocity difference at critical Re number range where Karman vortex is suppressed

**Non-symmetry flow field**

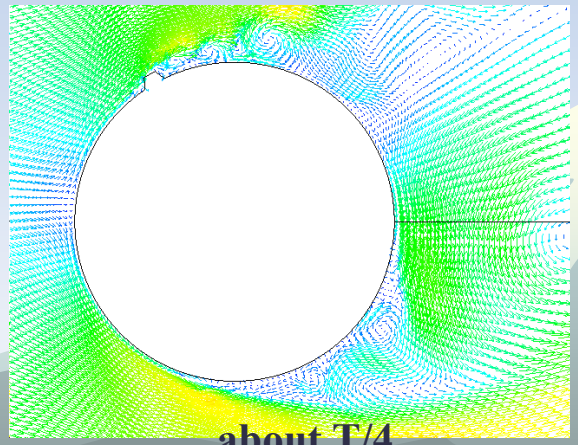
Appearance of Stationary lift



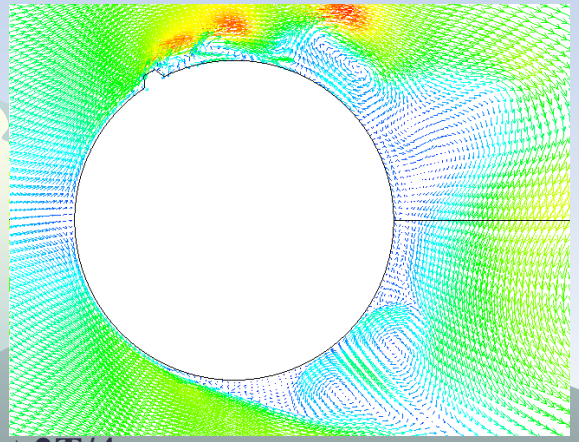

Fluctuating lift force



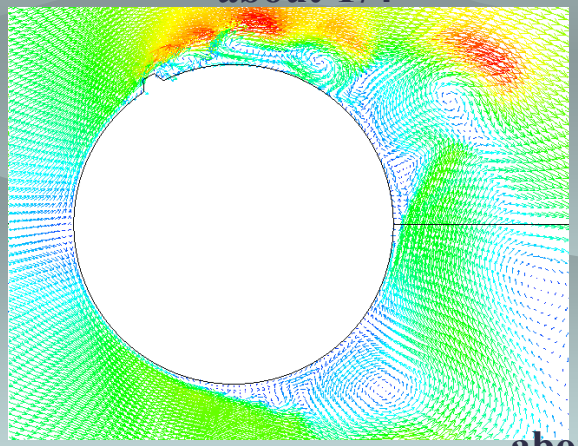
about 0T/4



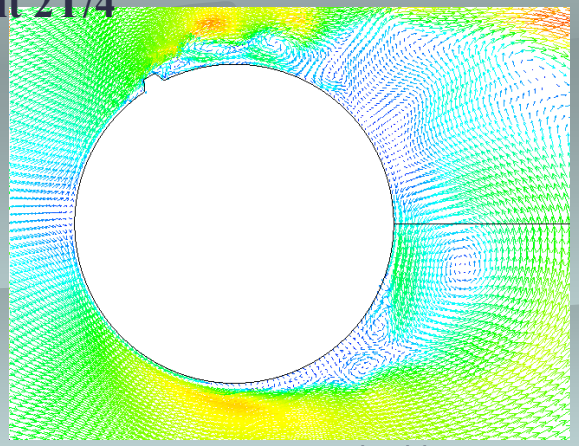
about T/4



about 2T/4



about 3T/4



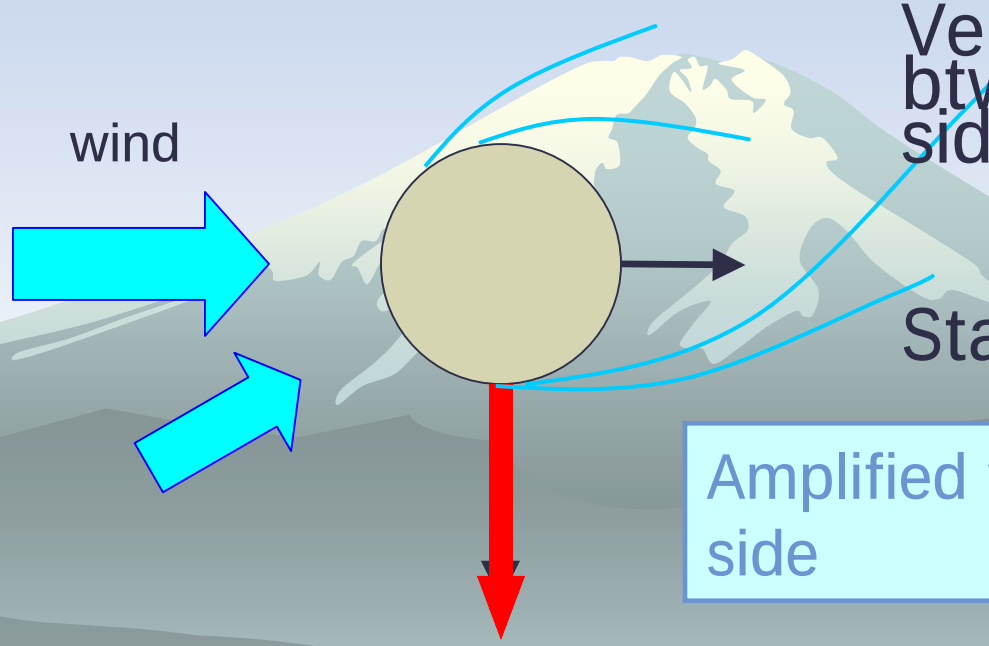
about 4T/4

Velocity vector around cable during one period of fluctuating lift force ($\theta$=60°) (WR)

# At critical Re. number range (RE)

Decrease of drag

Velocity-difference btw up and down sides




Stationary lift

Amplified velocity at down side

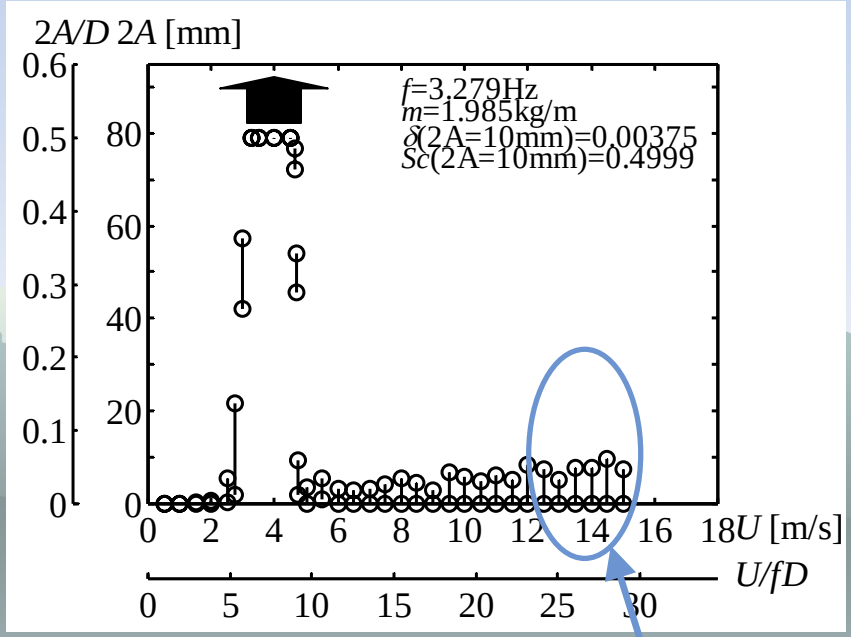
exciting force

Relative angle of attack due to vib.

# Aerodynamic derivative v.s. Re number (RE)

Frequency of forced heaving vibration was changed to change the reduced velocity under the fixed wind velocity to change Reynolds number.

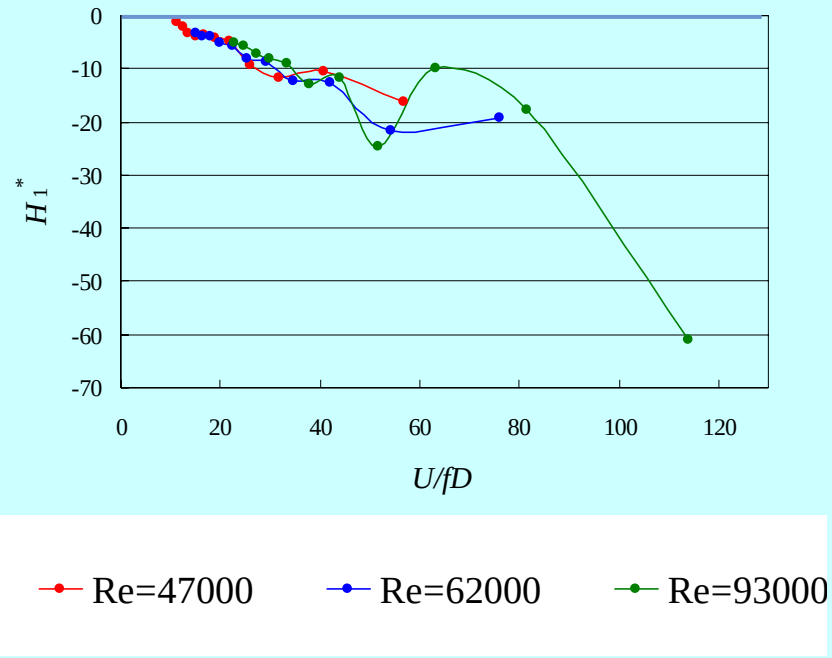
# Free vib. test□$\beta$=0°□(RE)

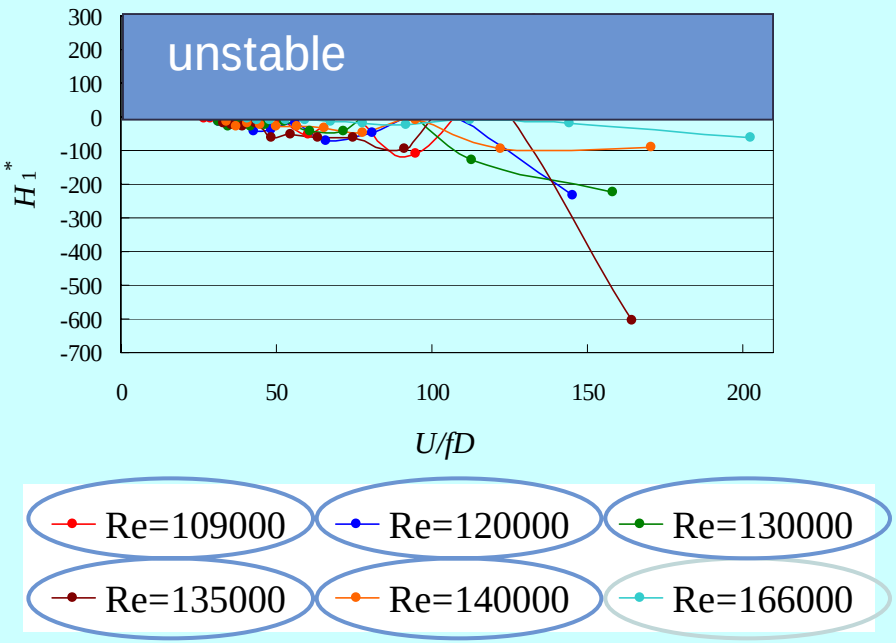



**w. Surface roughness**
**Wo. Surface**

**Response with unsteady amp. appears at cr. Re. number range**

# *Aerodynamic derivative* $H_1^*$ w. SR, $\beta$=0°, without rivulet (RE)




Sub-crtical Re. number range

Cr. Re number range

Super cr. Re number range

# Summary

# The Role of Karman Vortex on Inclined Cable Aerodynamics

# Karman Vortex Mitigation by

- Axial Flow
- Rivulet formation
- Critical Re number
- Turbulence
- The others

# The Role of Karman Vortex

Axial Flow(AF)

Water Rivulet (WR)

Vortex

Reynolds Number (RE)

Mitigation of

Karman

Galloping

High Spewed Vortex Exc.

# If Karman Vortex is controlled,

- **Low frequency fluctuation** component of flow field and lift appears. Which would excite the galloping or high speed vortex exc..

- **Non-symmetrical flow field** appears, then stationary lift force can be generated. Which would excite the galloping.

# Future Subjects

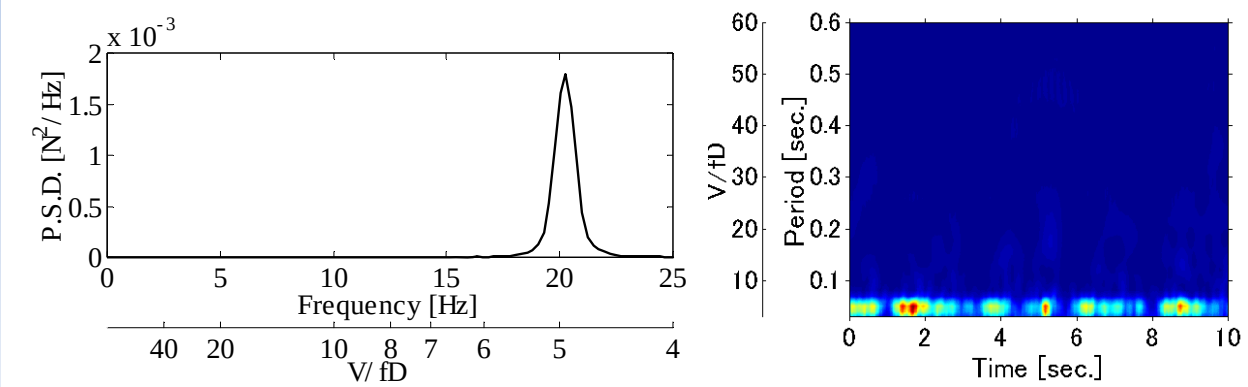
# How to Control the Cable Vib.?

- Mechanical Countermeasure ?
- Aerodynamic Countermeasure ?

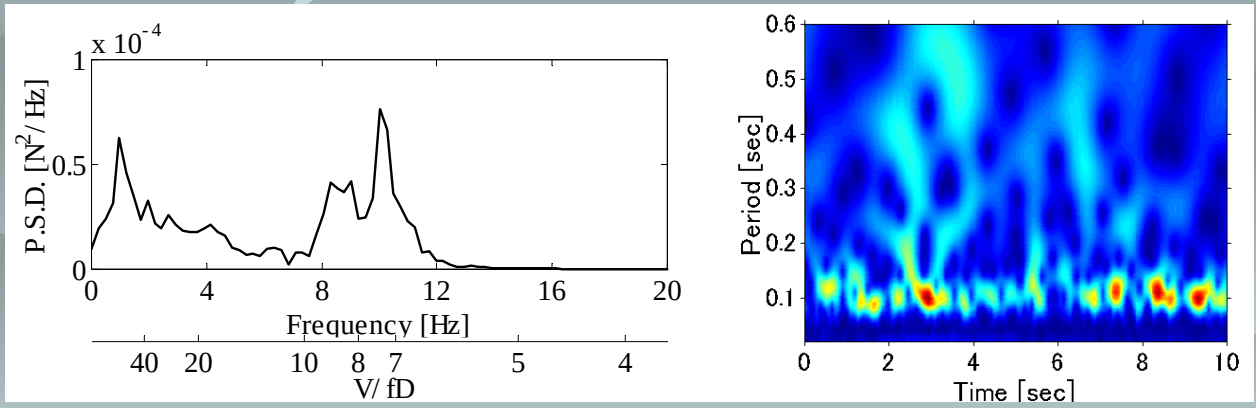
- How to encourage the 2D Karman Vortex?

**Thank you for your kind attention.**

# P.S.D. and wavelet analysis of the unsteady lift force on stationary cable model (without rivulet) (AX)

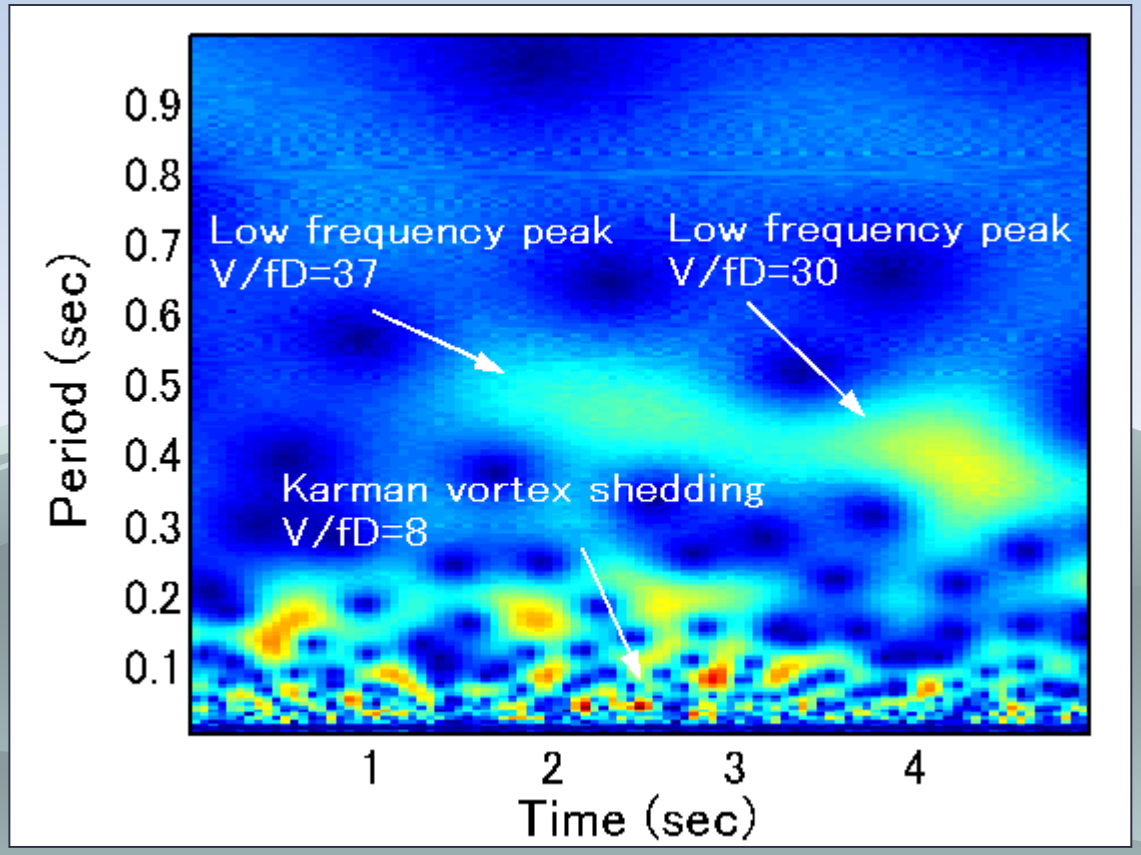



$\beta$=0°, in smooth flow, $V$=5.0m/s



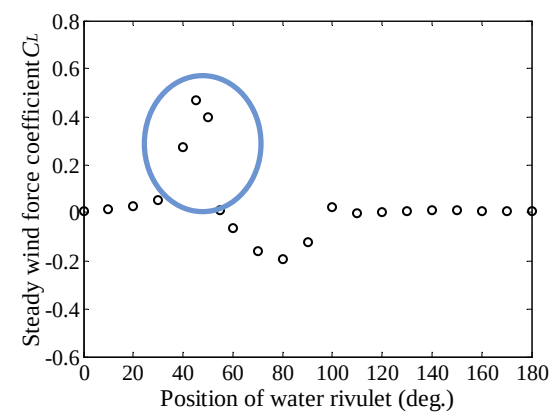

$\beta$=45°, in smooth flow, $V$=4.0m/s

# Wavelet analysis of fluctuating wind velocity in the wake of stationary yawed cable model (AX)

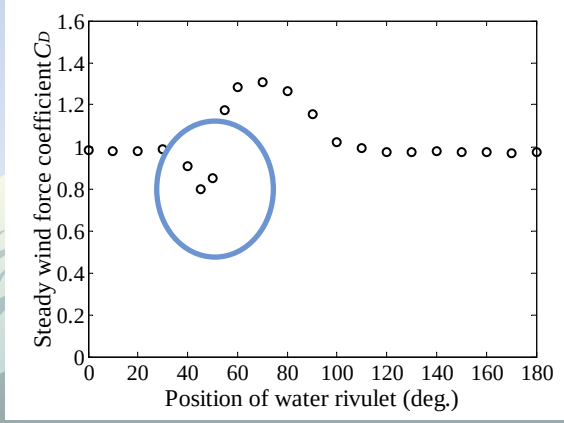



(without rivulet, $\beta$=45°, $V$=4m/s, in smooth flow)

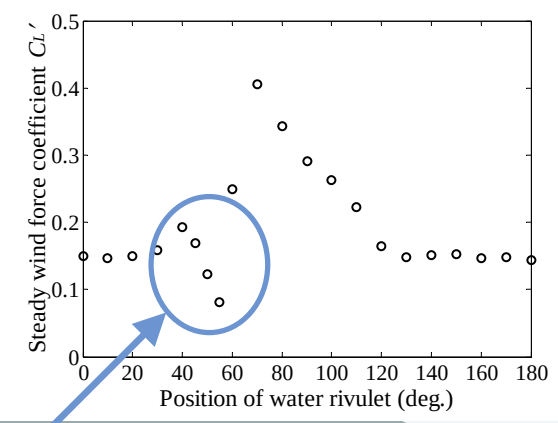
# Aerostatic/fluctuating force v.s. rivulet position□$\beta$=0°□(WR)




$C_L$



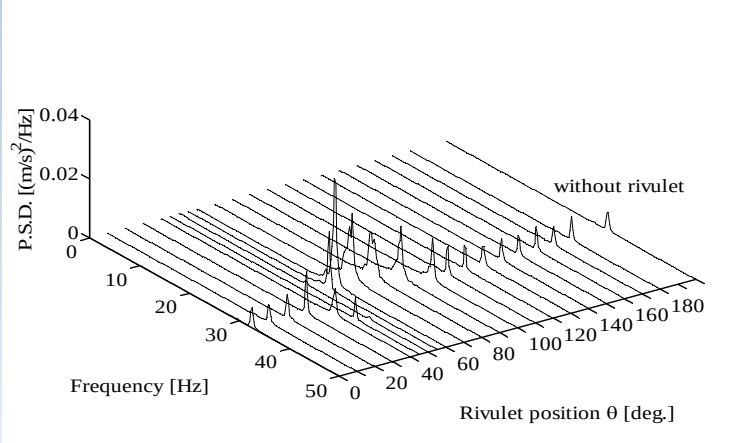

$C_D$



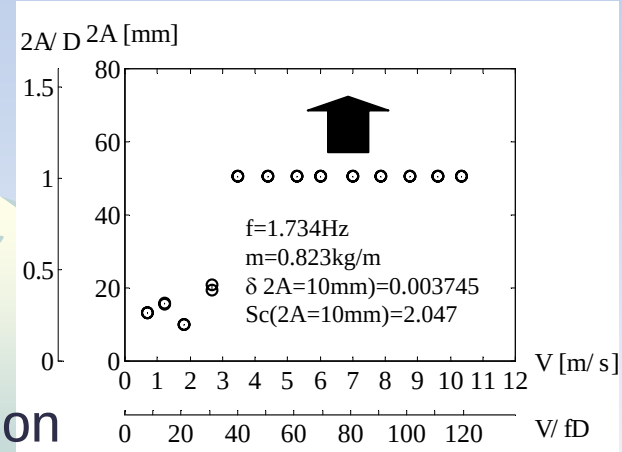

$C_L'$

**At near 50deg., Karman vortex becomes weak, then drag decreases and stationary lift appears.**

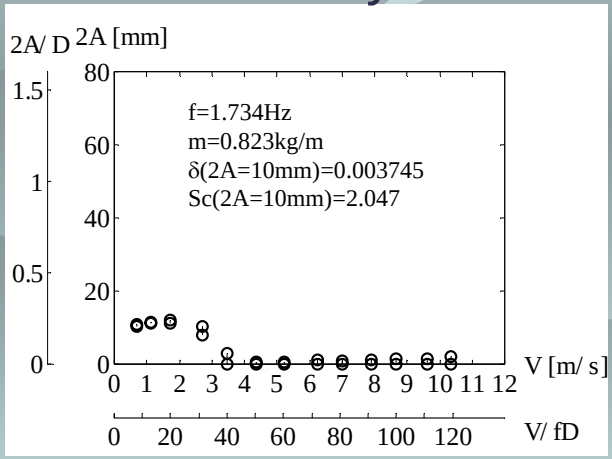
# Rivulet position effect on velocity-amplitude diagrams of non-yawed cable model ($\beta$=0°) (WR)



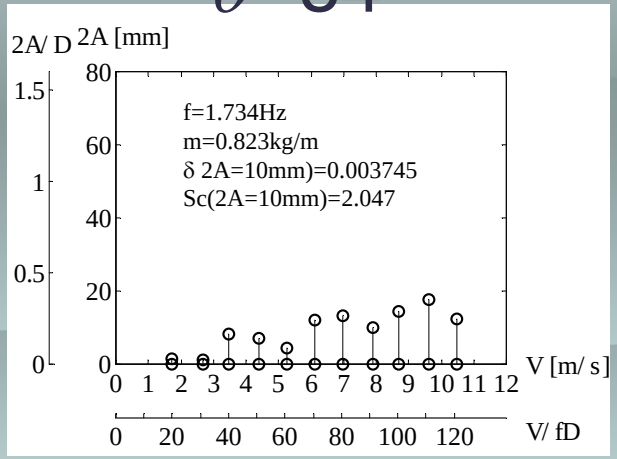

P.S.D. of the fluctuating lift force on stationary cable model



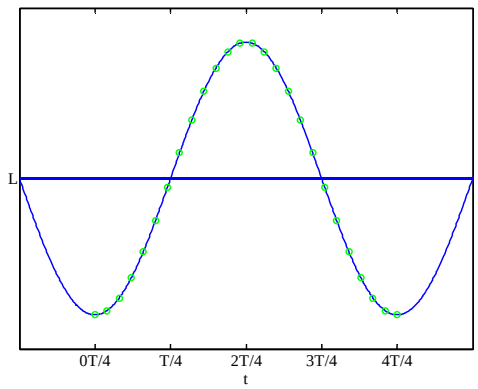

$\theta$=54°



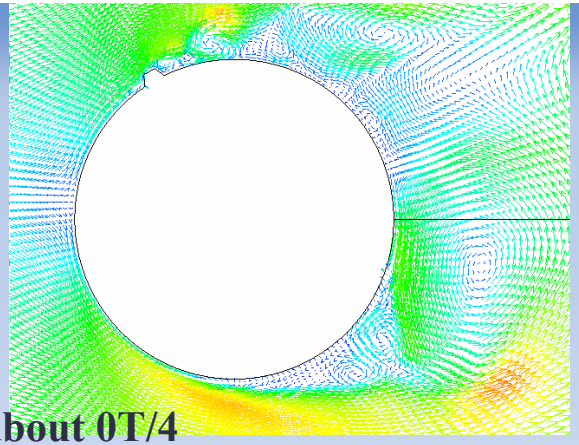

$\theta$=47°



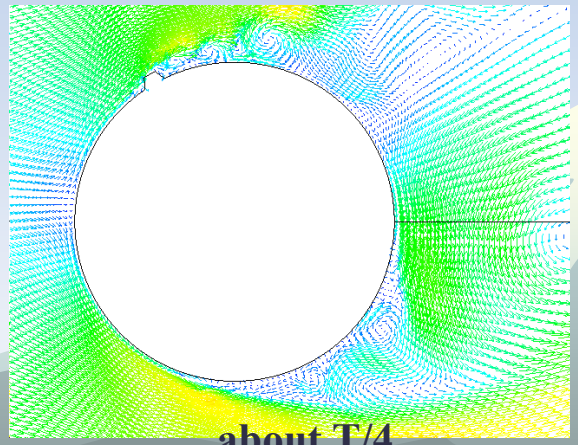

$\theta$=58°



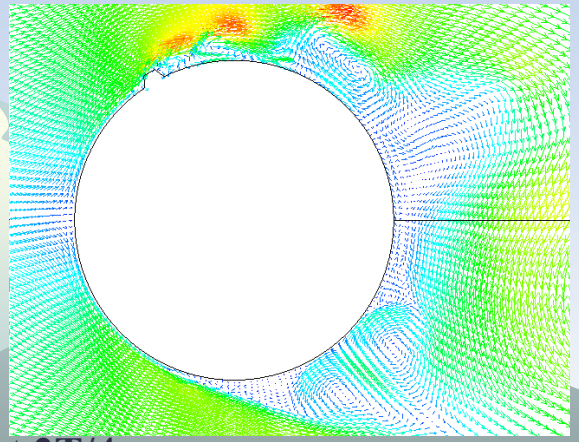

Fluctuating lift force



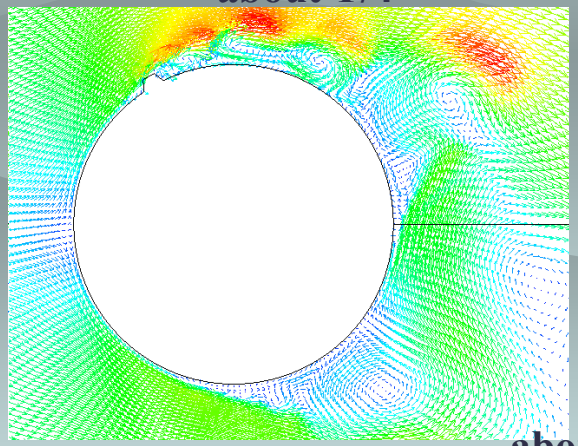
about 0T/4



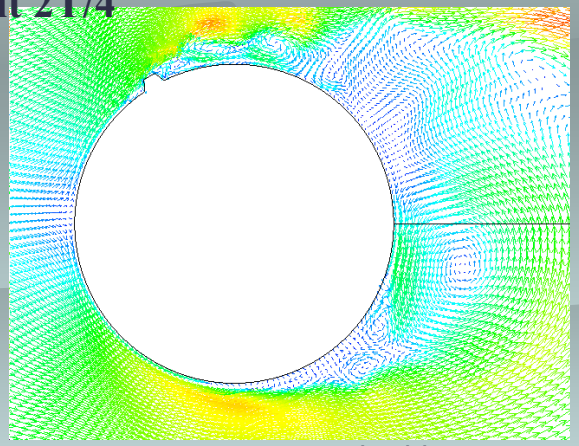
about T/4



about 2T/4



about 3T/4

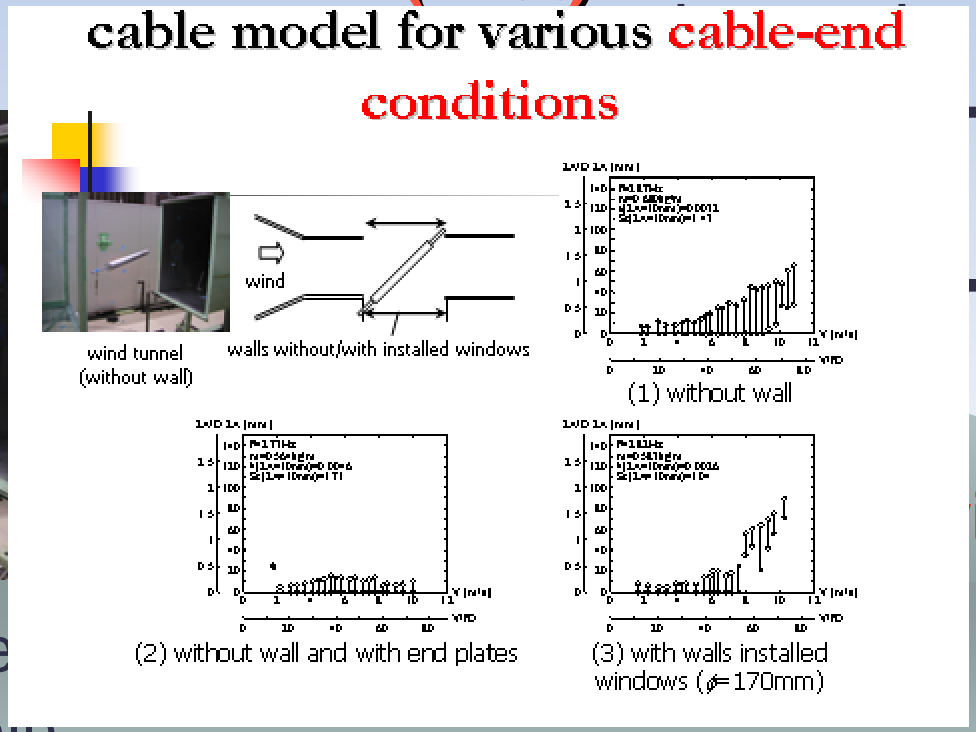


about 4T/4

Velocity vector around cable during one period of fluctuating lift force ($\theta$=60°) (WR)

# Experimental set up (three end conditions) (without rivulet) (yawing angle=45deg) (AX)

wind tunne
(without wall)

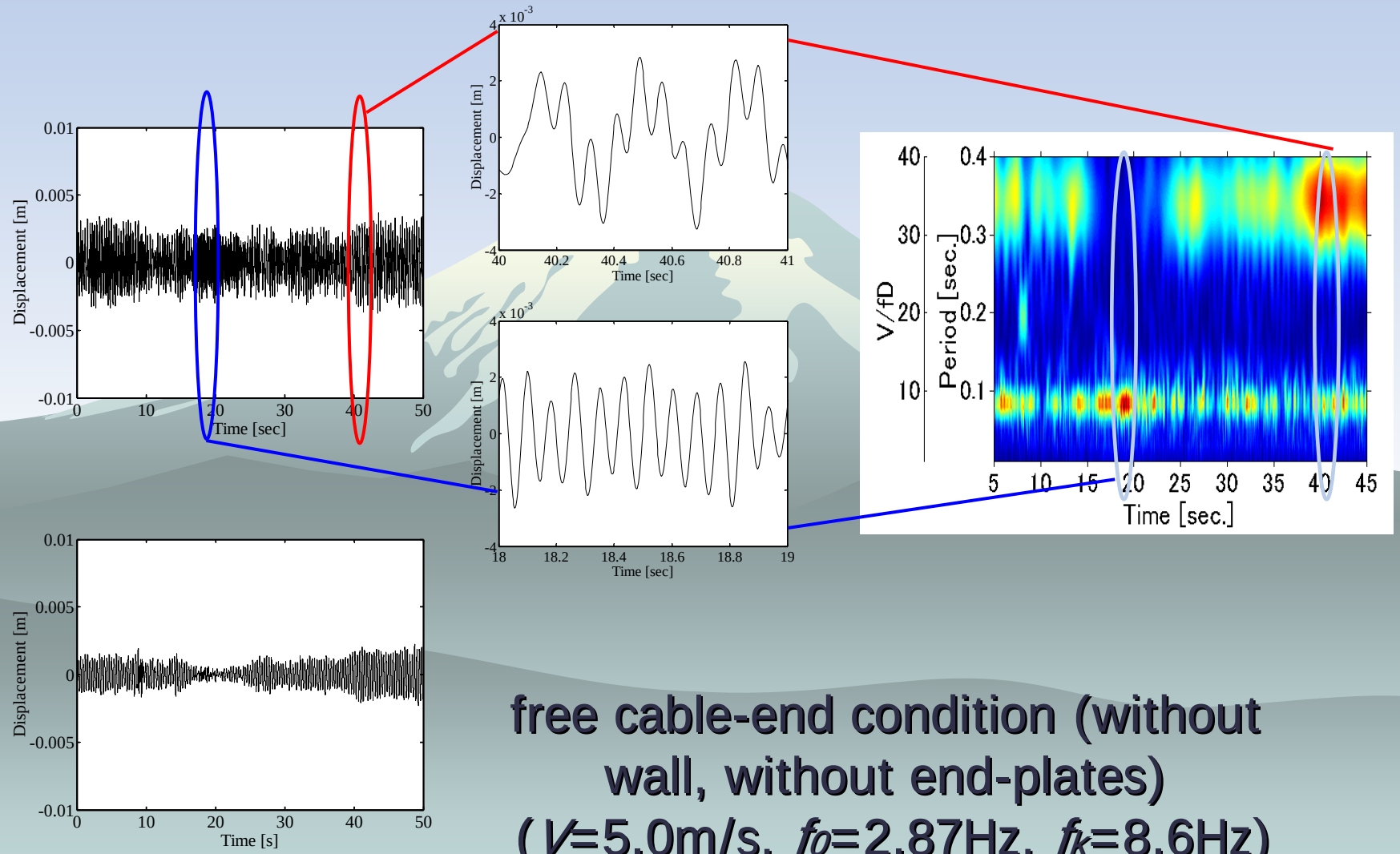



indows

three end conditions

1. without wall
2. without wall and with end plates
3. with walls installed windows ($\phi$=170mm)

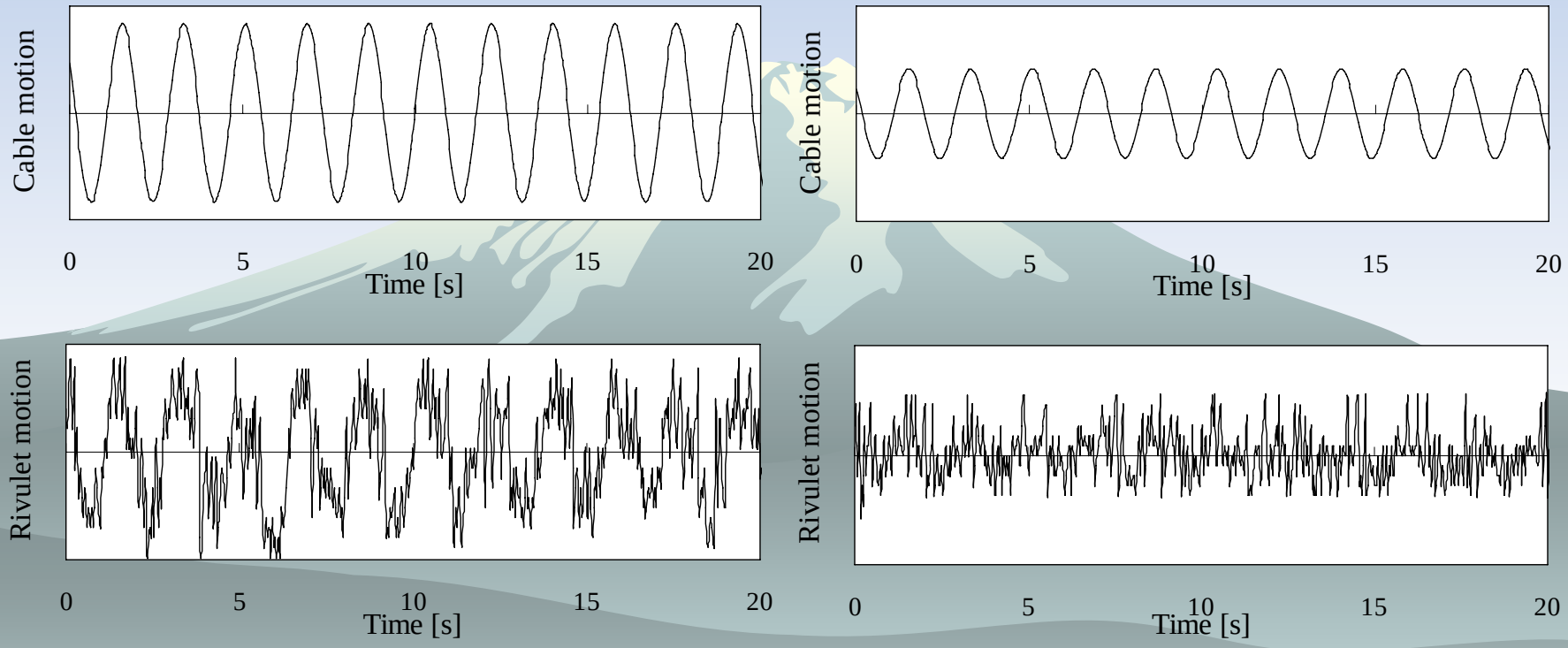
# Time history and the wavelet analysis of the unsteady cross-flow displacement (unsteady galloping)




free cable-end condition (without wall, without end-plates)
($V$=5.0m/s, $f_o$=2.87Hz, $f_k$=8.6Hz)

# Observed water rivulet movement on prototype scale cable model during rain-wind induced vibration

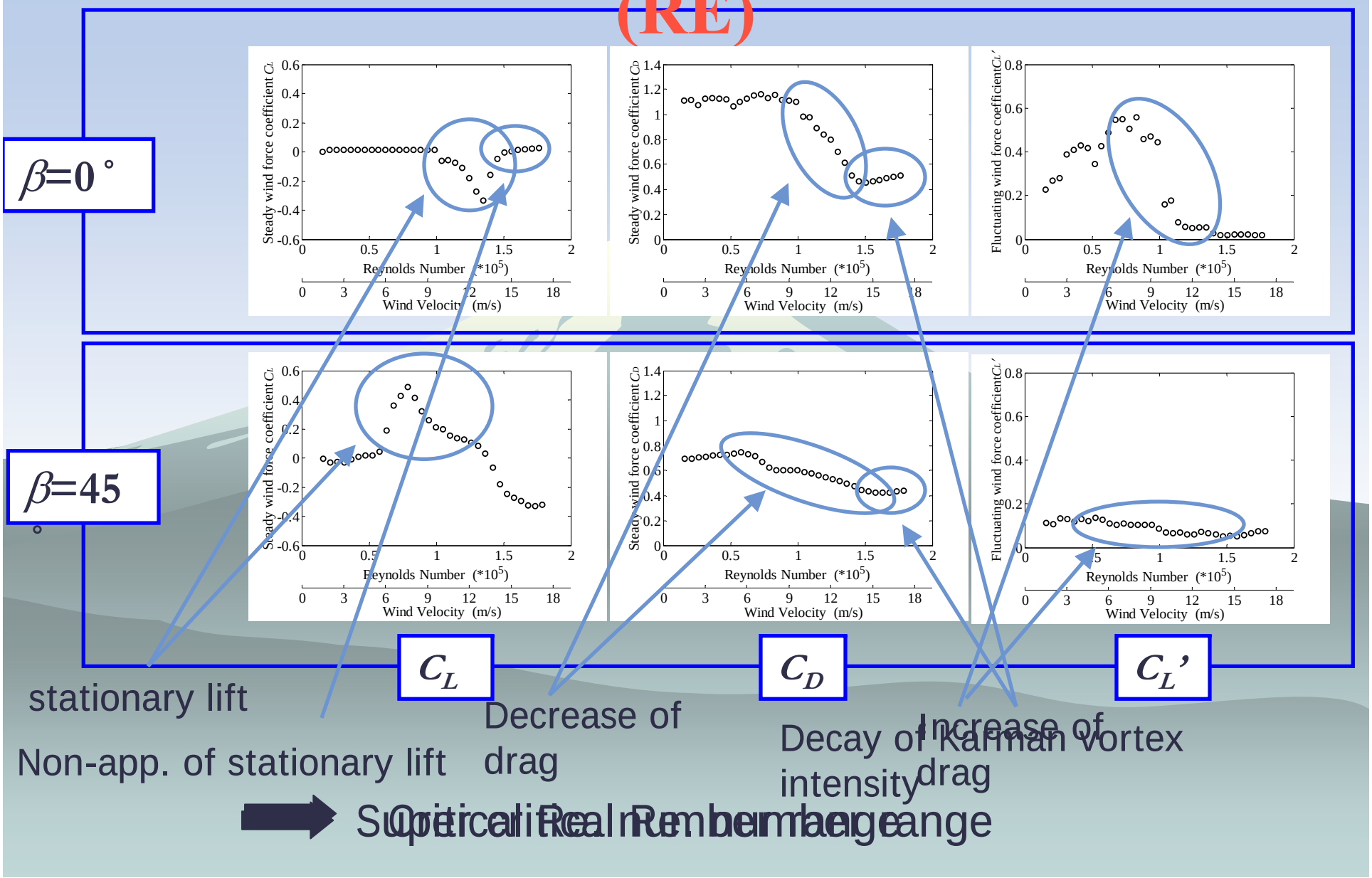
# The time history of cable vibration and rivulet movement




(intensive cable response)

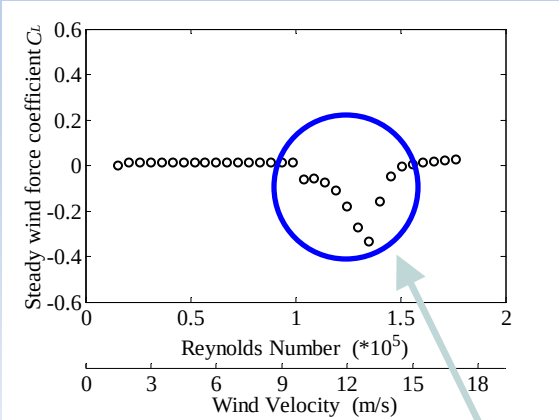
(weak cable response)

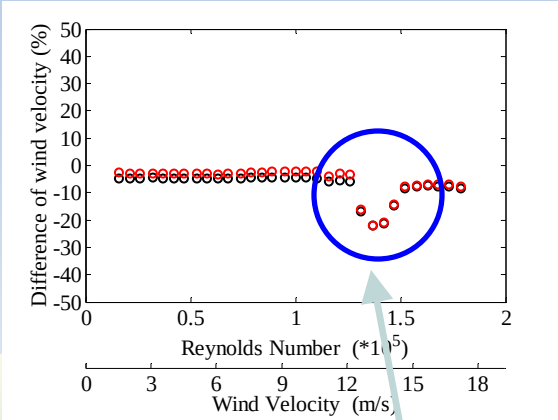
# Static forces with surface roughness (RE)



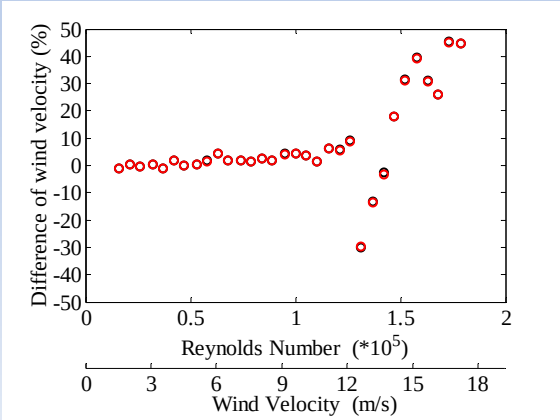
# Flow field with surface roughness

## $\beta$=0 (RE)

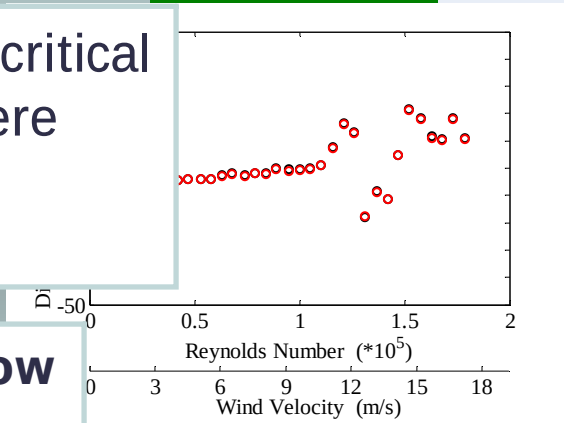


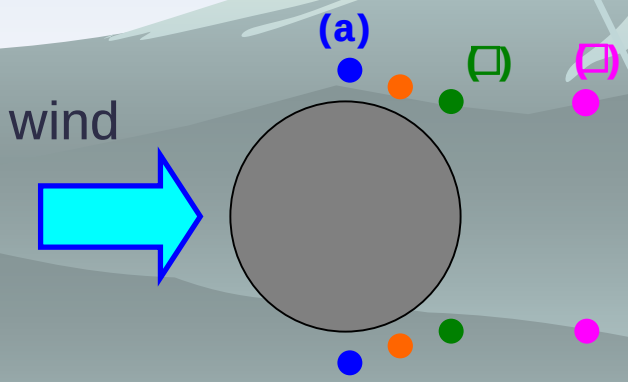

(a)




(b)




(c)




Velocity difference at critical Re number range where Karman vortex is suppressed

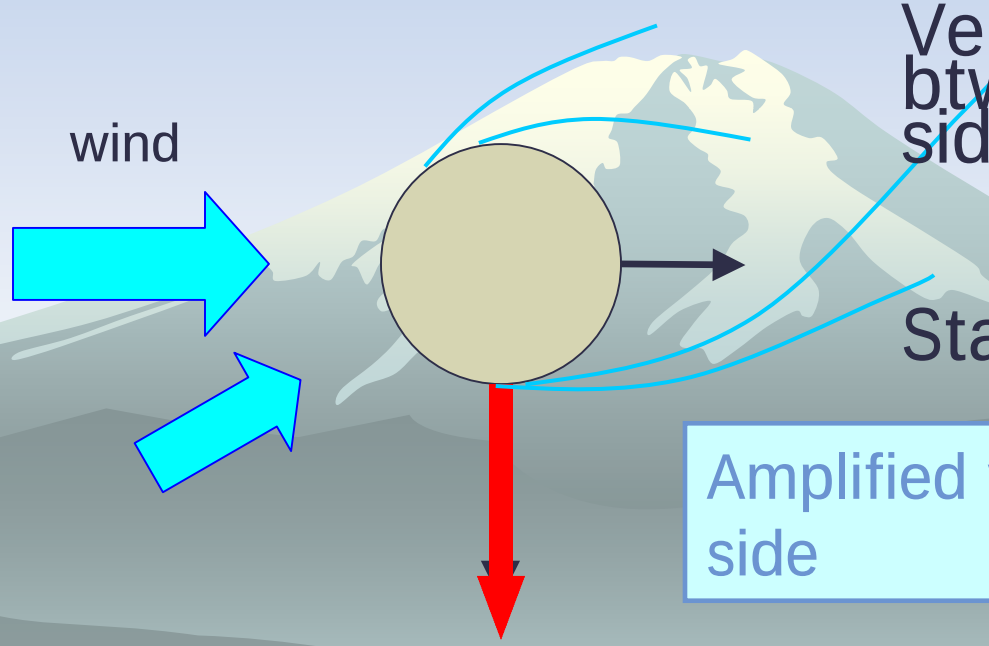
**Non-symmetry flow field**

Appearance of Stationary lift

# At critical Re. number range (RE)

Decrease of drag

Velocity-difference btw up and down sides




Stationary lift

Amplified velocity at down side

exciting force

Relative angle of attack due to vib.

# Future Subjects

# How to Control the Cable Vib.?

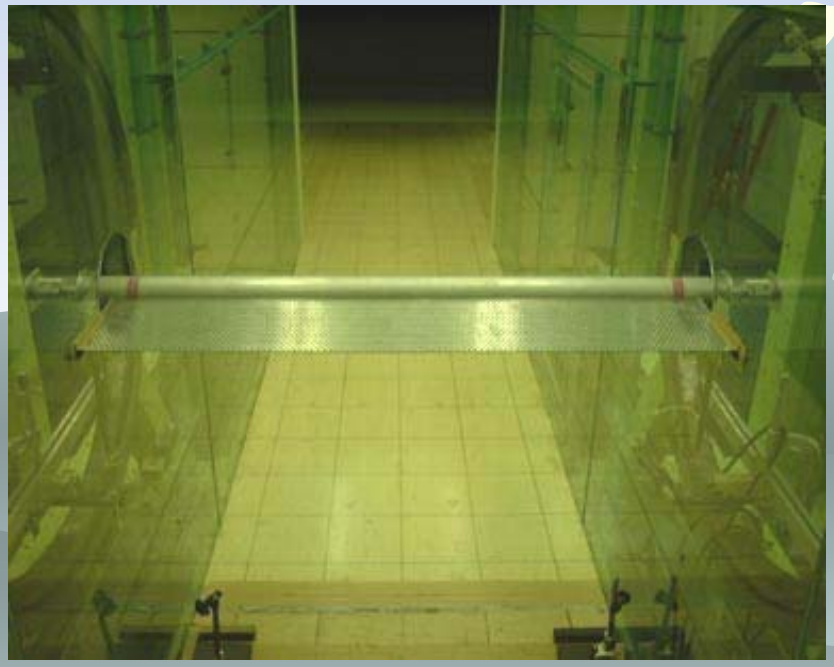
- Mechanical Countermeasure ?
- Aerodynamic Countermeasure ?

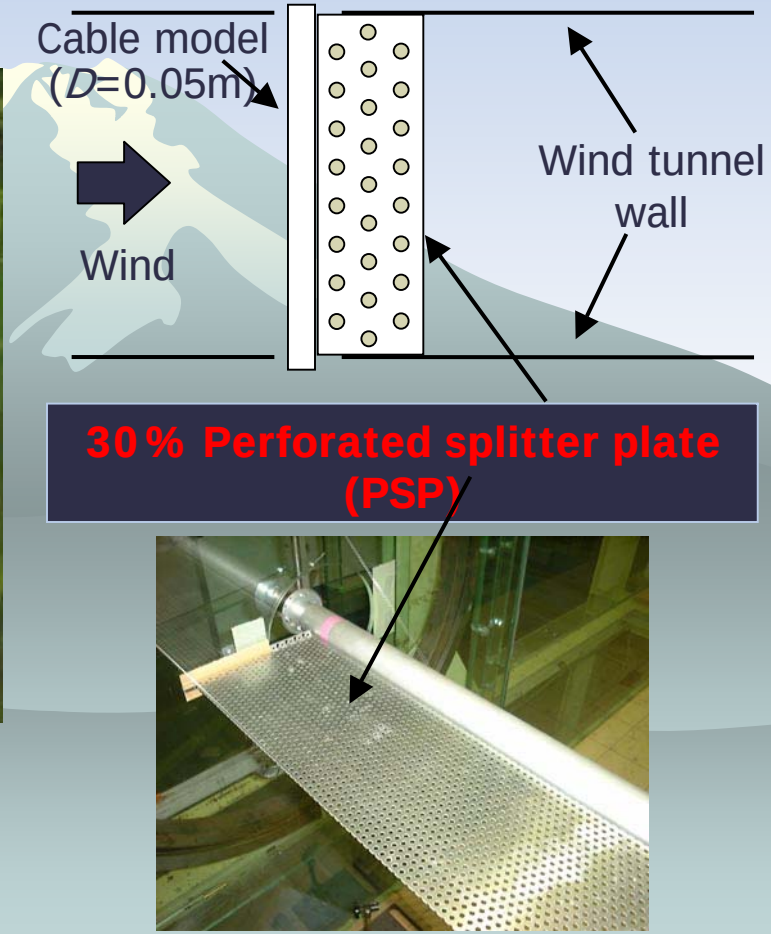
- How to encourage the 2D Karman Vortex?

**Thank you for your kind attention.**

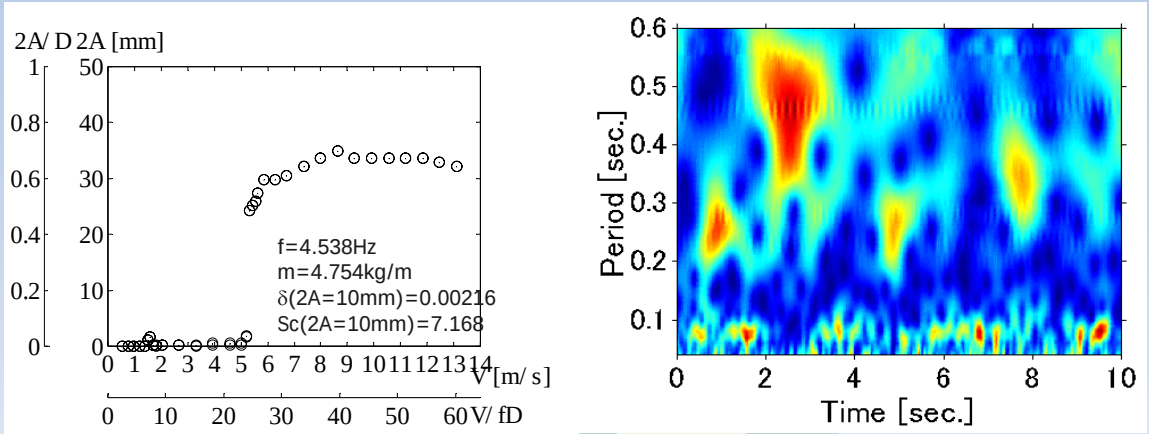
- **Quasi-Steady Theory for Inclined Cable with Fixed rivulet ?**

# Axial Flow Simulation by a Perforated Splitter Plate(30%) (QS)



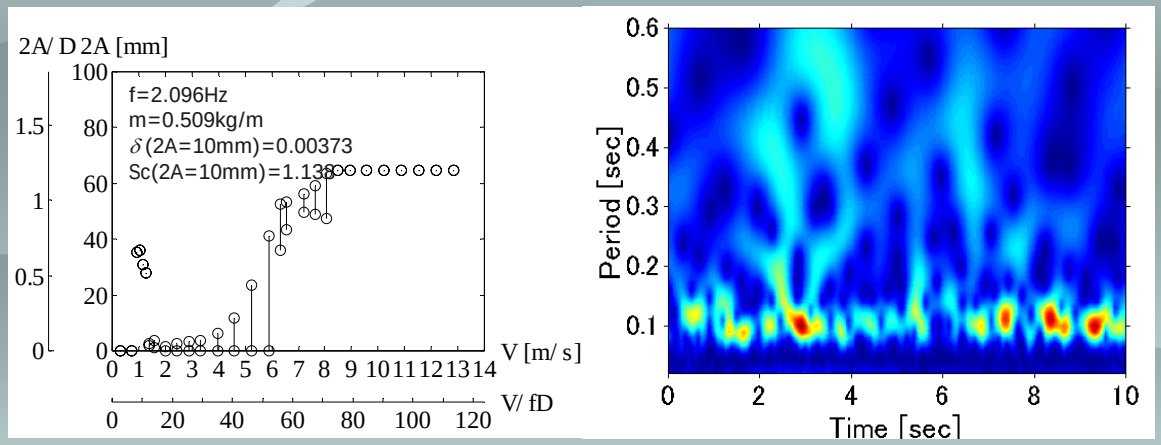


# Cross-flow Vibration affected by PSP (QS)




V-A diagram wavelet analysis of the lift force

$\beta$=0°, with a 30% perforated splitter plate




V-A diagram wavelet analysis of the lift force

$\beta$=45°, without a splitter plate

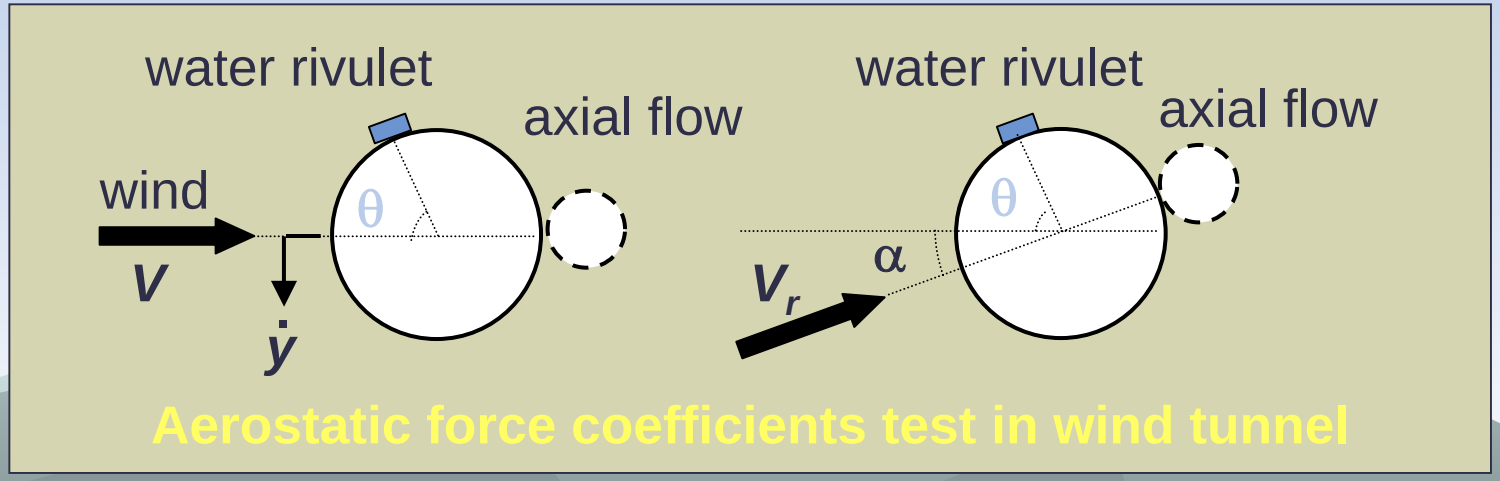
- **Probably PSP for non-yawed cable would be simulated to yawed cable aerodynamics from the point of axial flow effect. (QS)**

# Observed water rivulet movement on prototype scale cable model during rain-wind induced vibration

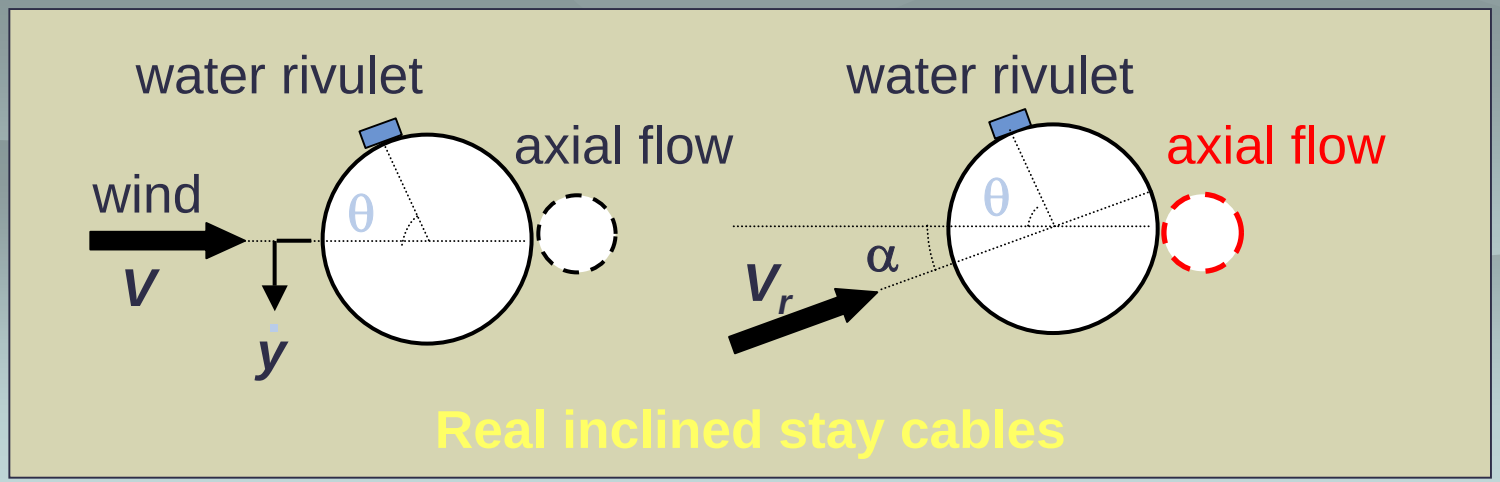
*V*=10m/s

# Observed water rivulet movement on prototype scale cable model during rain-wind induced vibration

# The Problems of the Stationary Lift and Drag Forces in Applying to Quasi-steady Theory (QS)

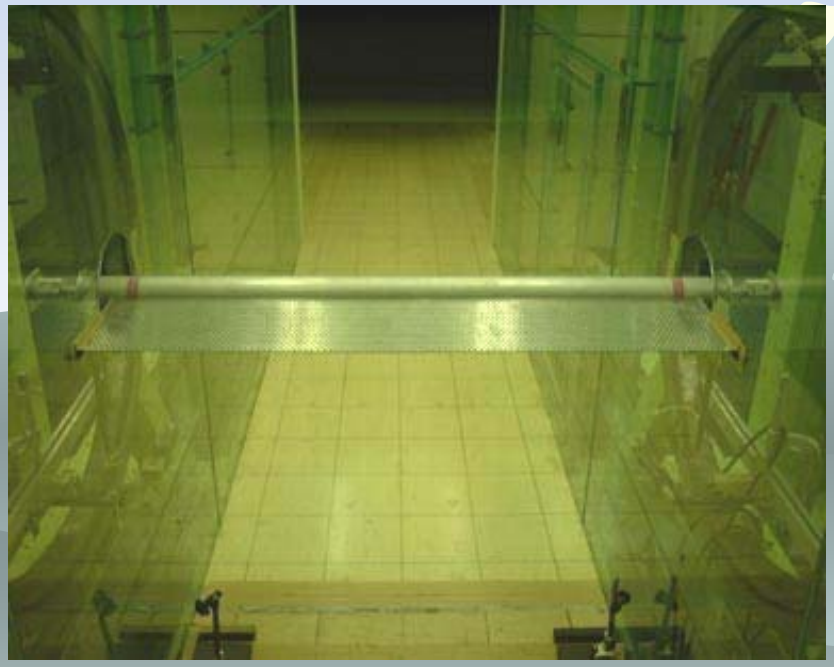


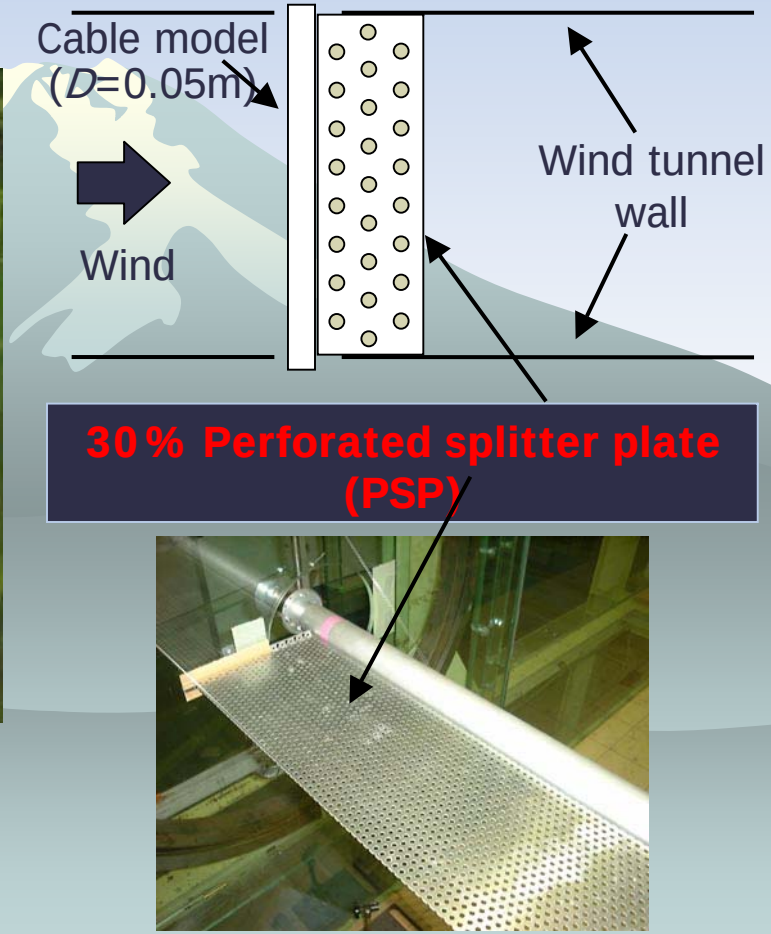

Aerostatic force coefficients test in wind tunnel



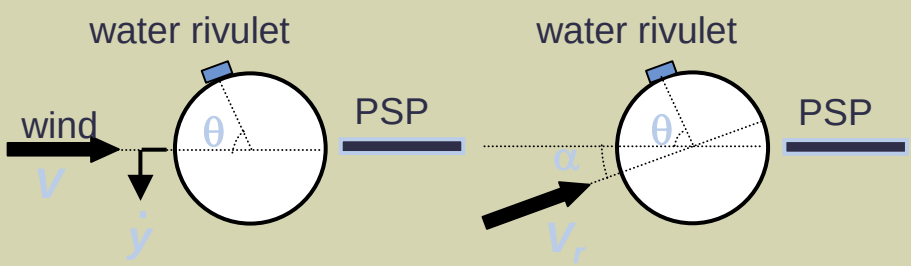

Real inclined stay cables

# Axial Flow Simulation by a Perforated Splitter Plate(30%) (QS)

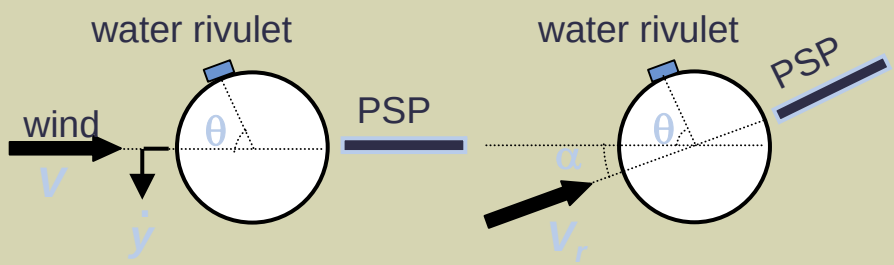




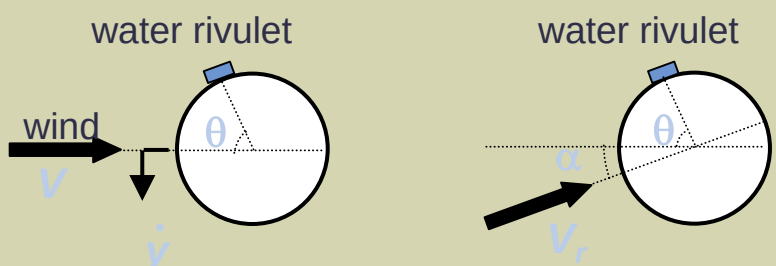
# Various situations ( Position of water rivulet, axial flow and PSP ) (QS)



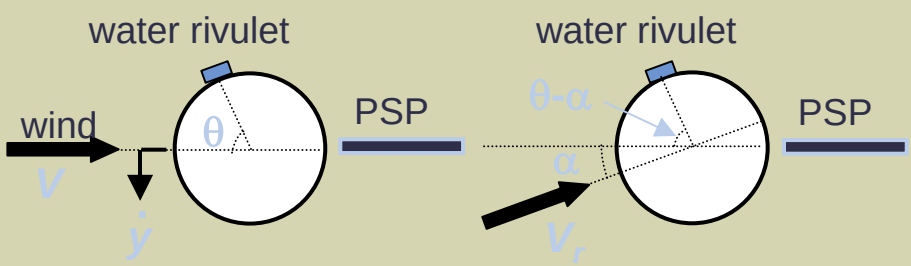

(a) Wind tunnel tests situation, β=0°, with PSP



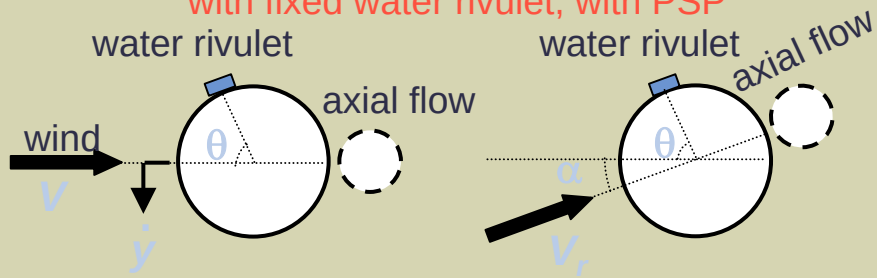

(b) Wind tunnel tests situation, β=0°, with fixed PSP (ε=180°)



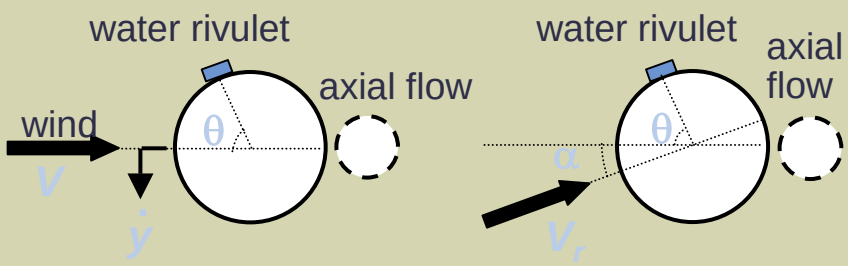

(c) Wind tunnel tests situation, β=0°, without PSP




(d) Wind tunnel tests situation, β=0°, with fixed water rivulet, with PSP

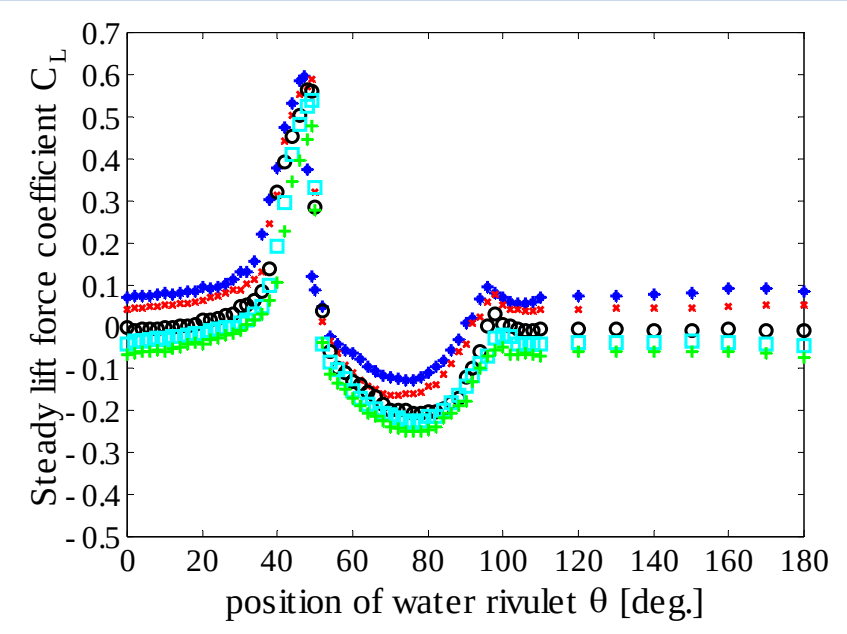


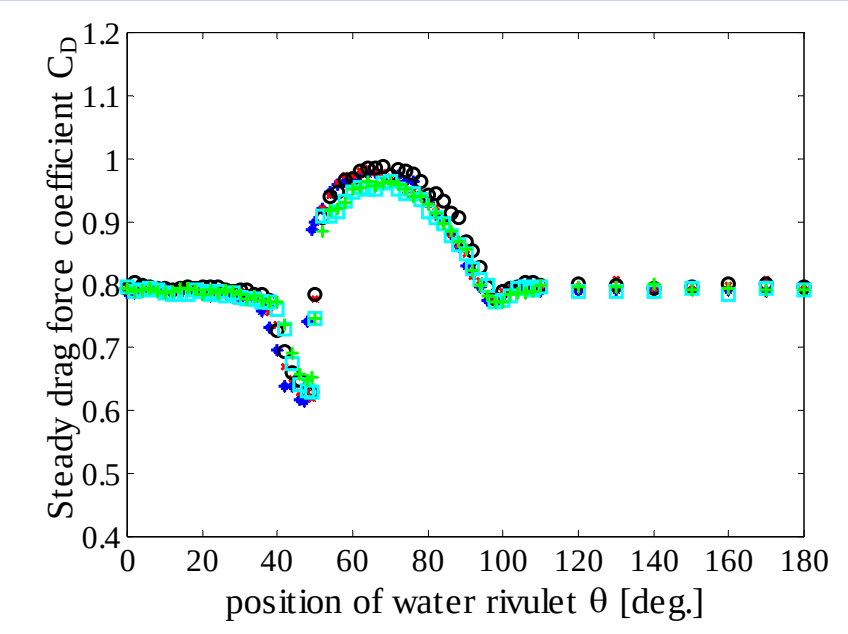

(e) Wind tunnel tests situation, β=45°, without PSP




(f) Actual situation

# The Stationary Lift and Drag Coefficients (β=0°, in smooth flow, *V*=8.0m/s ) (QS)

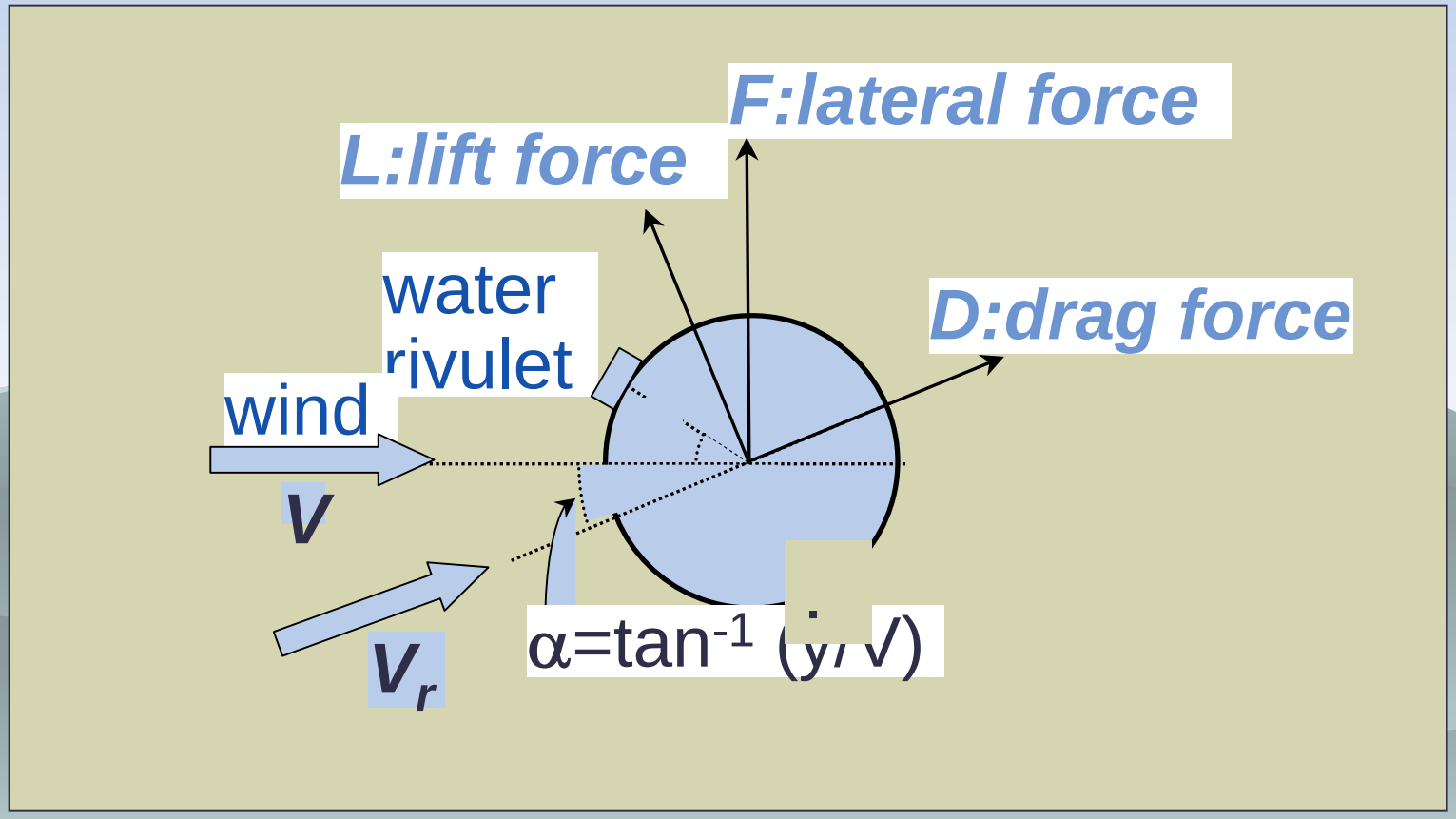


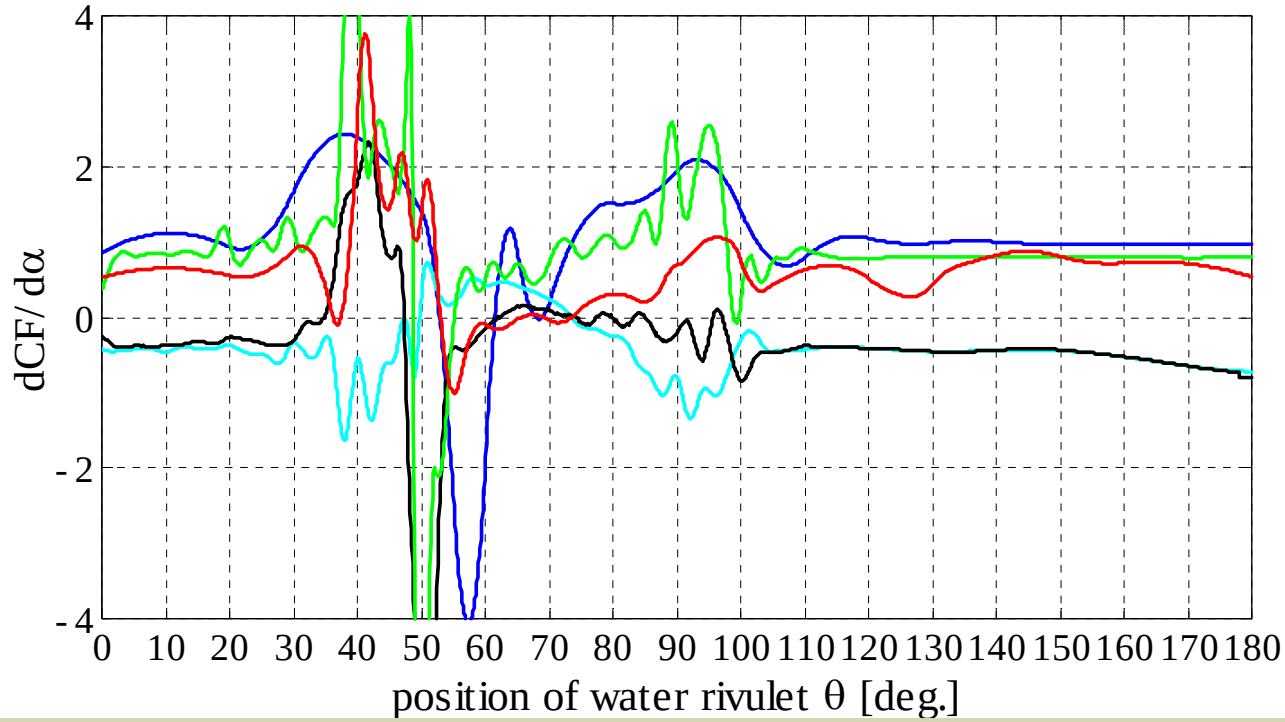

Position of PSP

*:ε =176° x:ε =178° o:ε =180° □:ε =182° +:ε =184°

# Angle of Attack, Drag, Lift and Lateral Forces (QS)



# $dC_F/d\alpha$ diagrams under various situation (QS)




(a) Wind tunnel tests situation, β=0°, with PSP

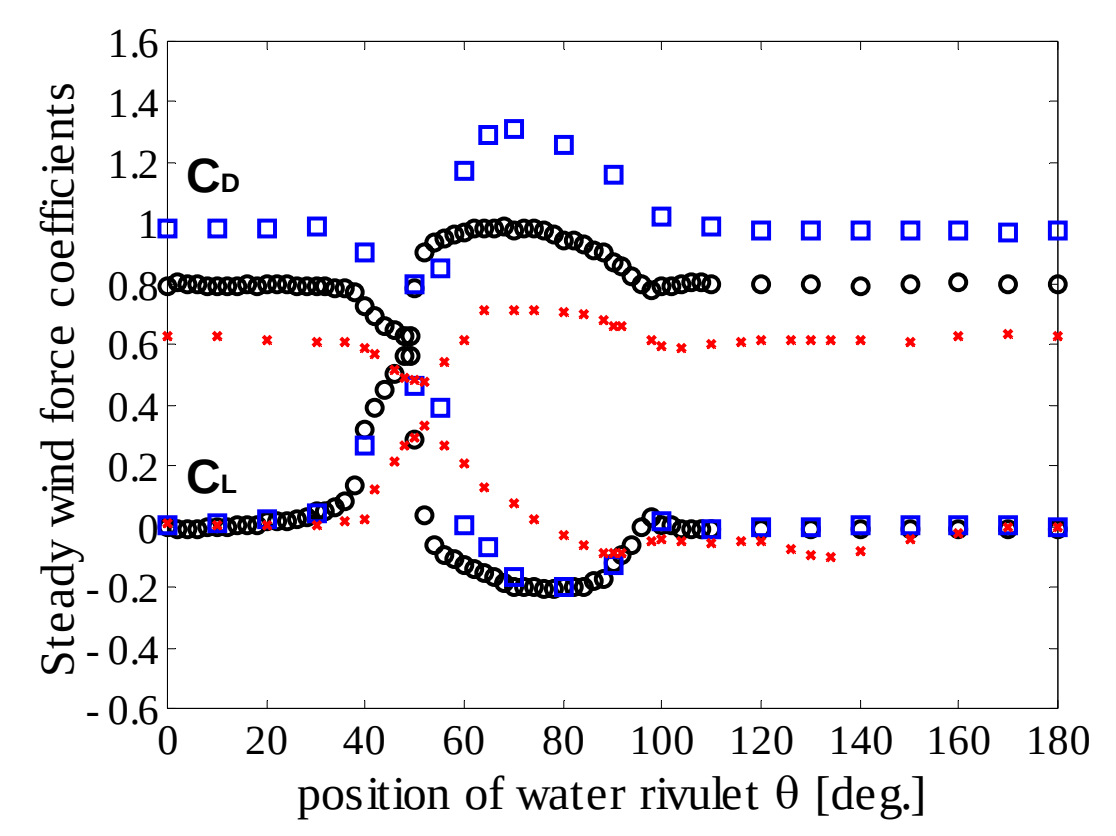
(b) Wind tunnel tests situation, β=0°, with fixed PSP (ε=180°)

(c) Wind tunnel tests situation, β=0°, without PSP

(d) Wind tunnel tests situation, β=0°, with fixed water rivulet, with PSP

(e) Wind tunnel tests situation, β=45°, without PSP

# Steady Wind Force Coefficients (QS)

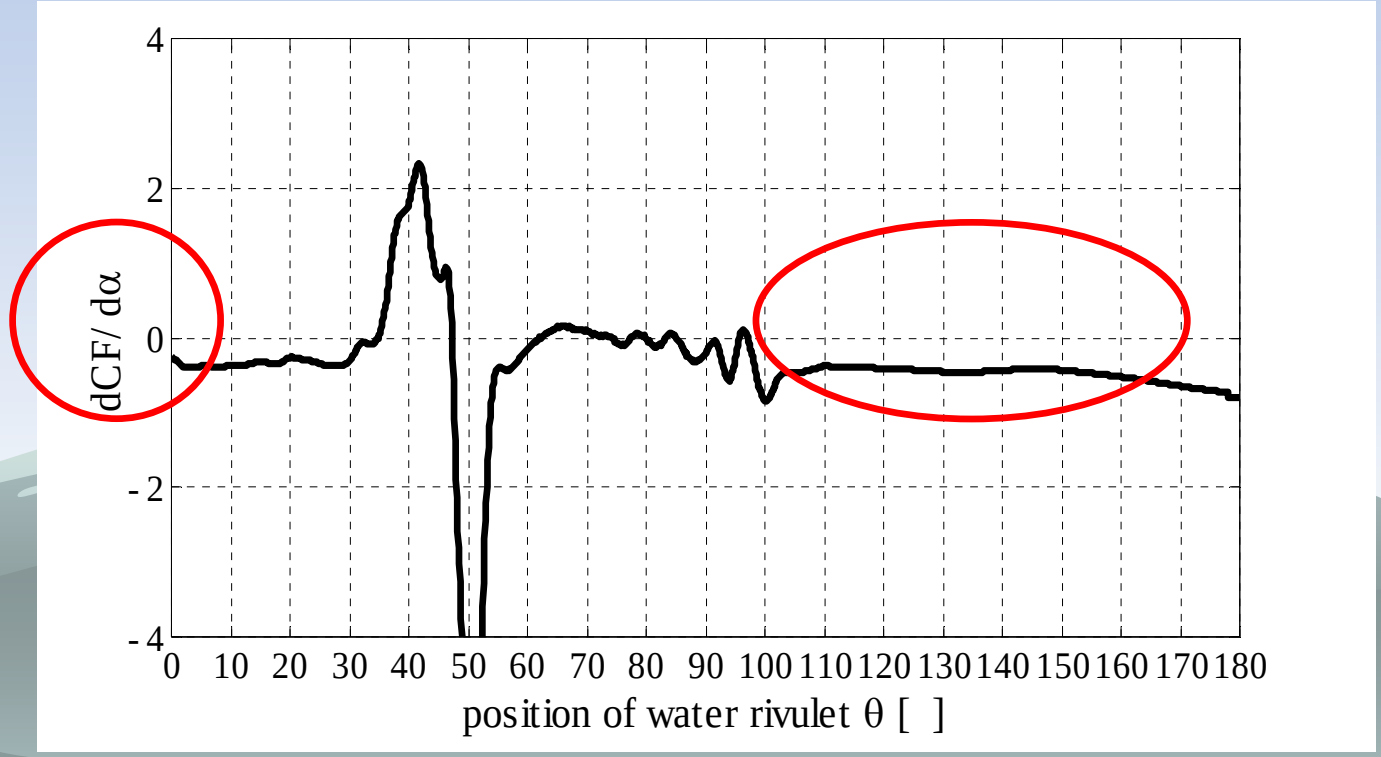



o:β=0°, without windows, with PSP

□ :β=0°, without windows

x:β=45°, with 110mm windows

# $dC_F/d\alpha$ Diagram (β=0°, with PSP) (QS)

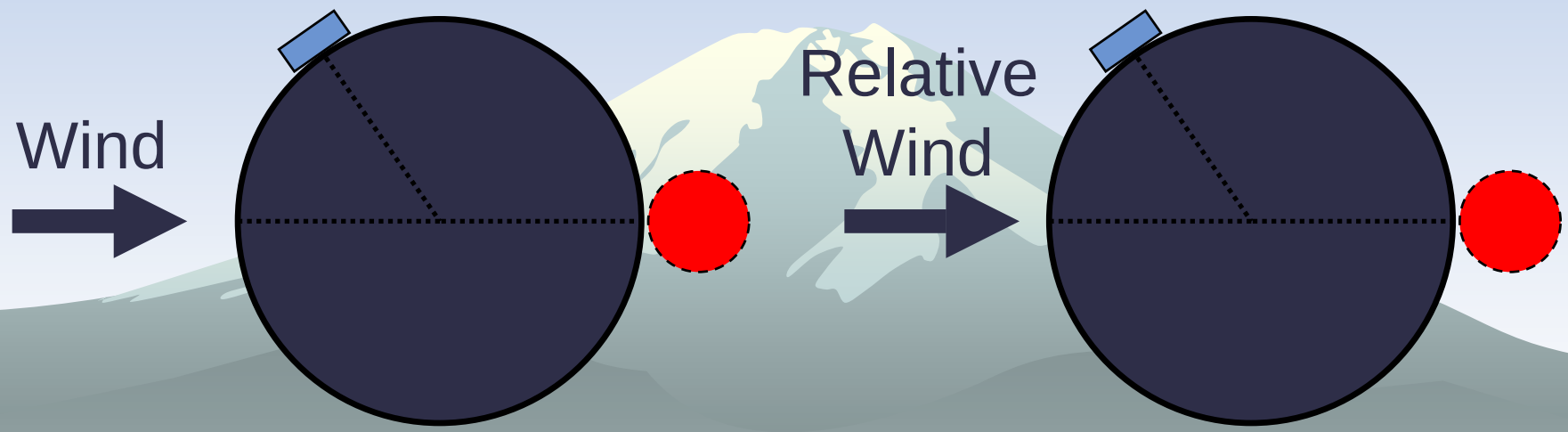



Quasi-steady theory

Galloping ⟷ $dC_F/d\alpha < 0$

# Quasi-steady Approach

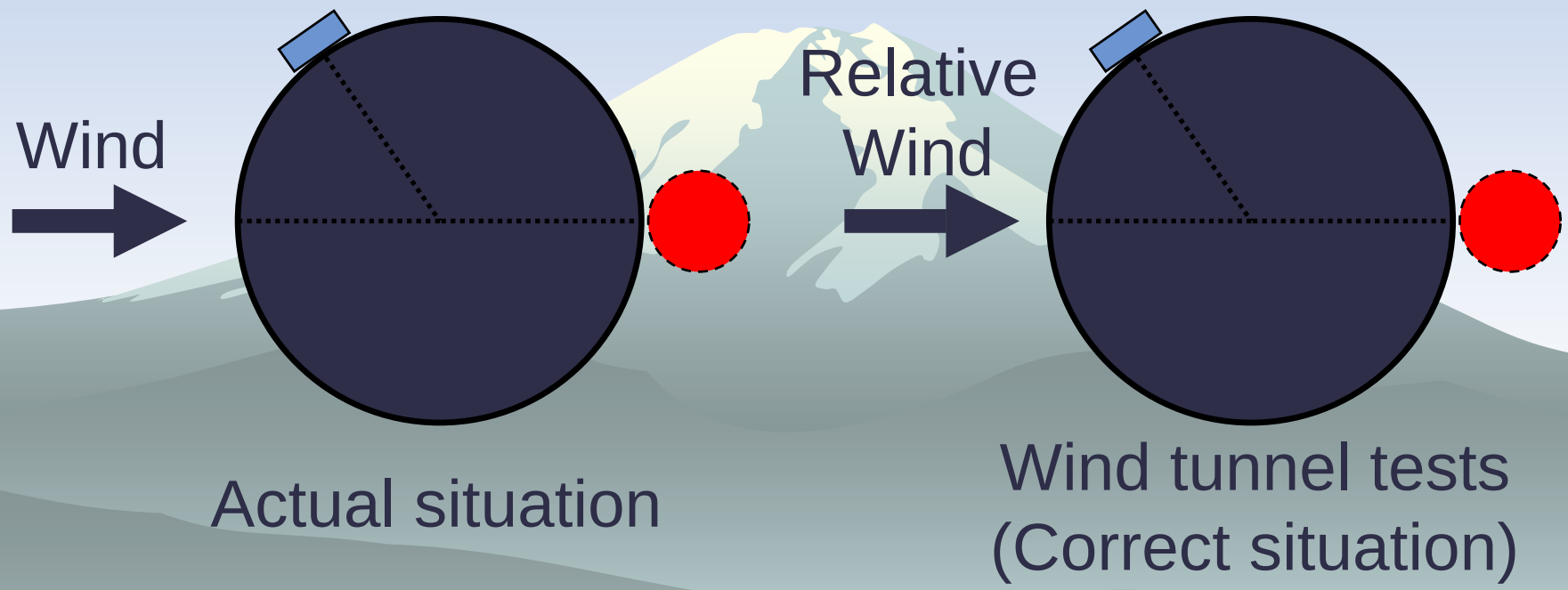
**Using yawed cable model (QS)**




Actual situation

Wind tunnel tests
(ex. $\beta$=45° situation)

# Quasi-steady Approach (QS)



# The non-linear analysis based on the quasi-steady theory (QS)

$$C_F = A_1 + A_2\alpha + A_3\alpha^2 + A_4\alpha^3 + A_5\alpha^4 + A_6\alpha^5 + A_7\alpha^6 + A_8\alpha^7$$

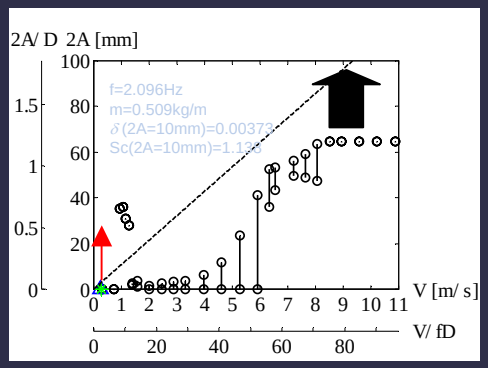
$$\alpha = \tan^{-1}(\dot{y}/V)$$

$$= (\dot{y}/V) - (1/3)(\dot{y}/V)^3 + (1/5)(\dot{y}/V)^5 - (1/7)(\dot{y}/V)^7$$

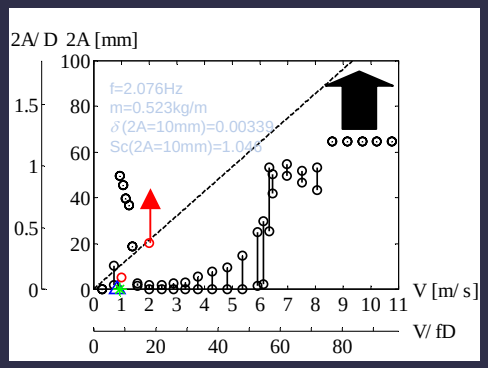
$\alpha$ : angle of attack

$\dot{y}$ : the cross-flow response velocity

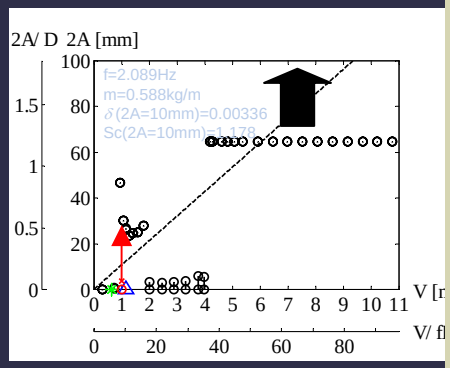
# Comparison of V-A diagrams ; wind tunnel tests (β=45°) and the quasi-steady analysis (CF:β=0°,with PSP) (QS)



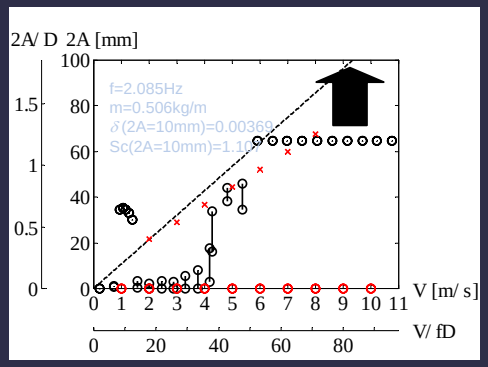

(a) without water rivulet



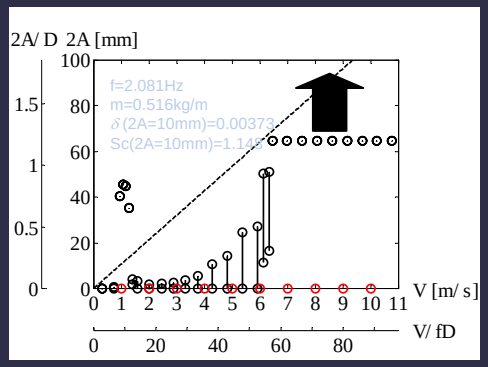

(b) θ=0°



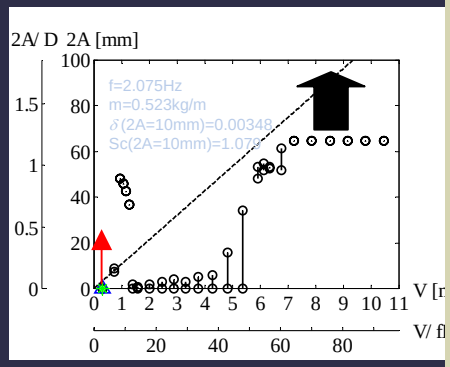

(c) θ=56°




(d) θ=66°




(e) θ=72°




(f) θ=180°

**O** : wind tunnel test (β=45°)

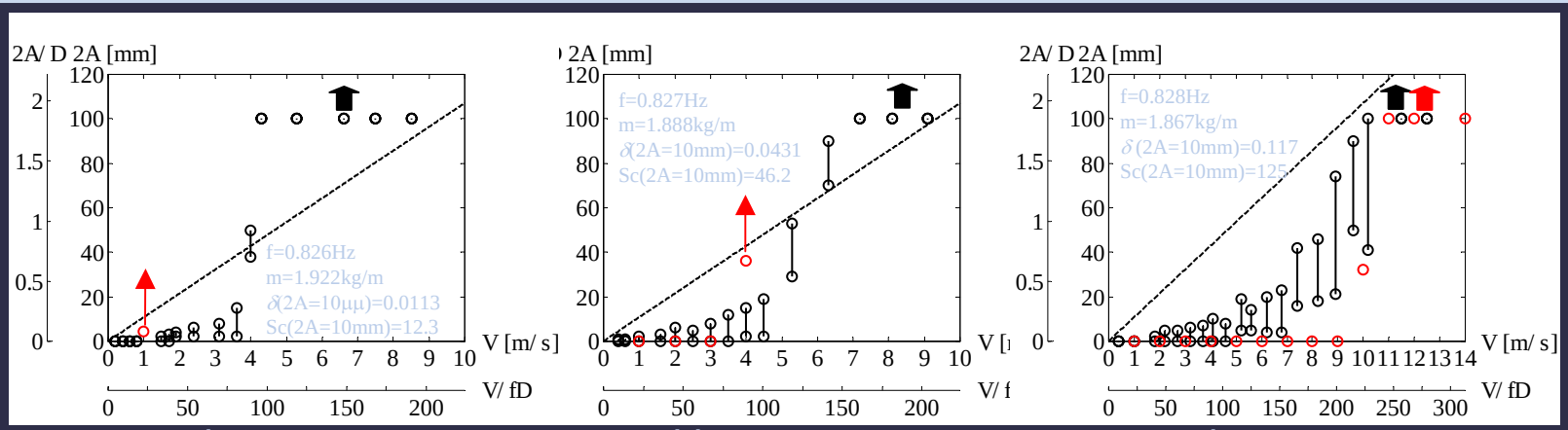
**O** : quasi – steady analysis ($C_F$:β=0°,withPSP)

**X** : limit cycle

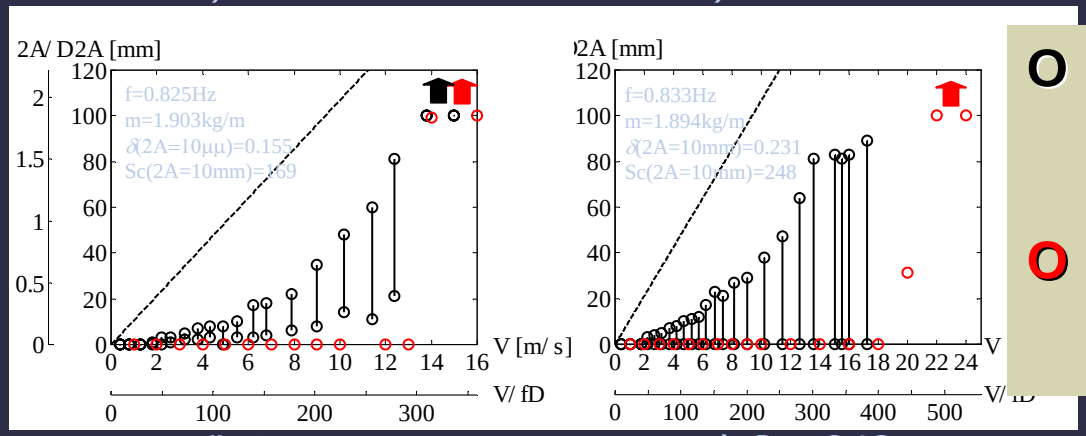
**Δ**: $V_{rcr}$ (Parkinson)

*****: $V_{rcr}$ (Den Hartag)

# Comparison of V-A diagrams ; wind tunnel tests (β=45°,without rivulet) and the quasi-steady analysis ($C_F$:β=0°,with PSP) (QS)




a) Sc=12.3 b) Sc=46.2 c) Sc=125

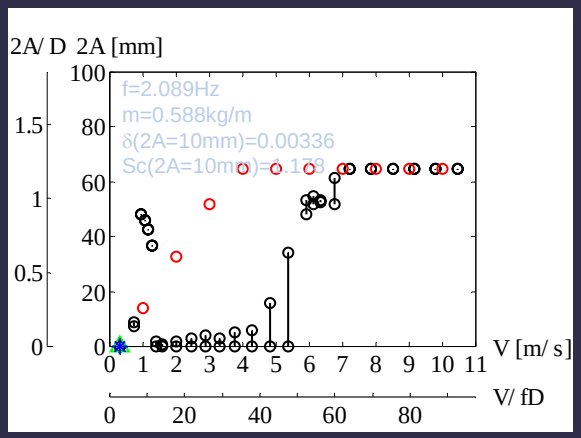



d) Sc=169 e) Sc=248

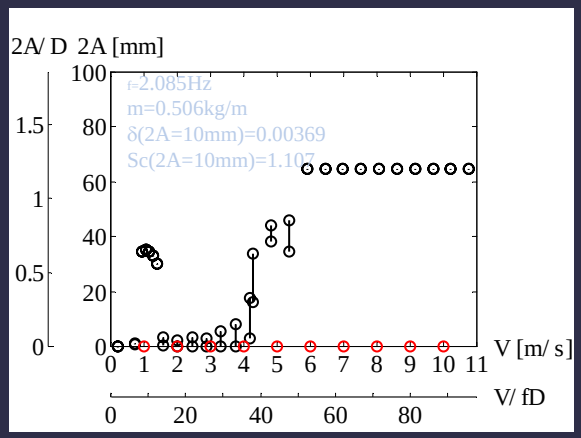
**O** : wind tunnel test (β=45°)

**O** : quasi-steady analysis ($C_F$:β=0°,with PSP)

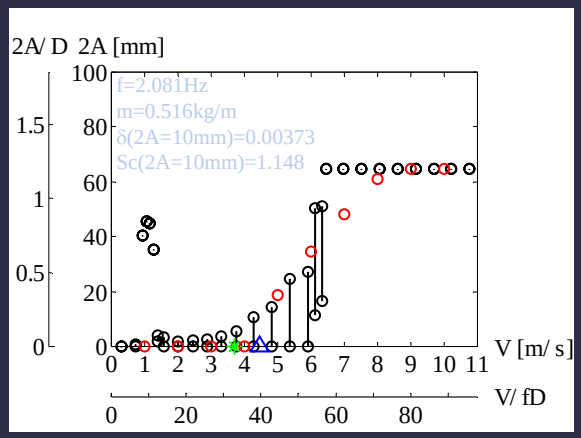
# Comparison of V-A diagrams ; wind tunnel tests (β=45°) and the quasi-steady analysis ($C_F$:β=45°,without PSP) (QS)




(a) θ=56°




(b) θ=66°




(c) θ=72°

**O** : wind tunnel test (β=45°)

**O** : quasi-steady analysis ($C_F$:β=45°,without PSP)

Δ : $V_{rcr}$ (Parkinson) , * : $V_{rcr}$ (Den Hartag)

# Quasi-Steady Theory (QS)

- Still we have to discuss more in application of Quasi-Steady Theory.