16th International Conference on Wind Engineering

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Aerodynamic characteristics of a streamlined box girder under velocity shear flow with turbulence

College of Civil Engineering, Tongji University

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Contents

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Background

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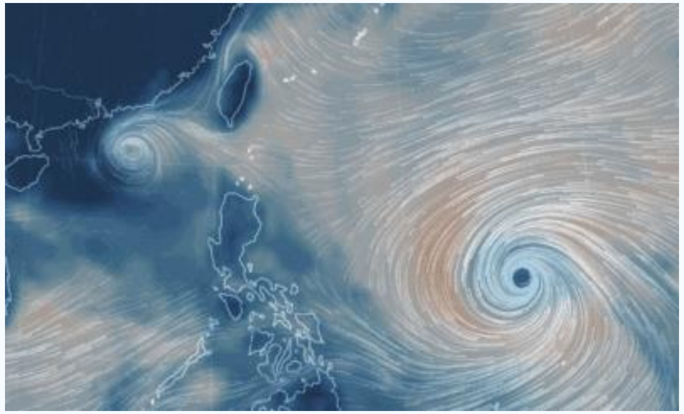
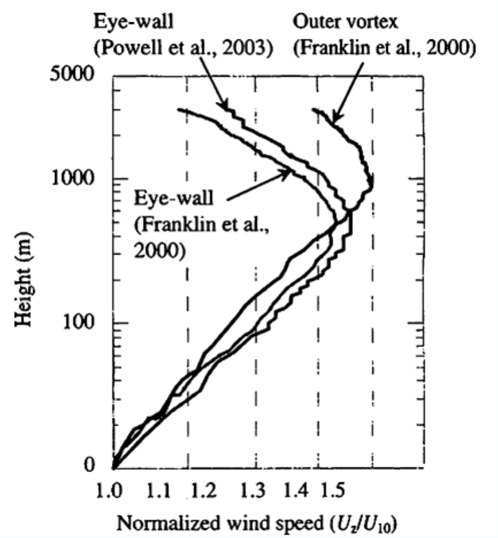
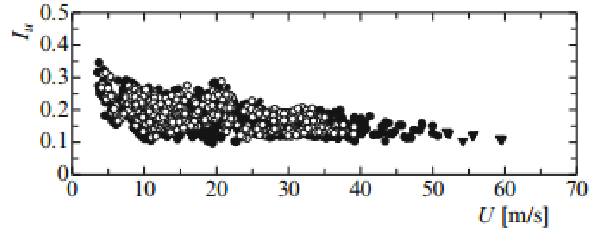
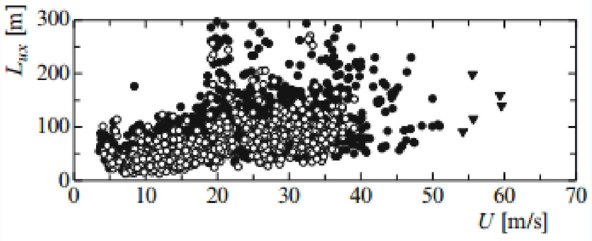
- Strong turbulence and large velocity shear rate

Maemi typhoon
Y. Tamura. 2013

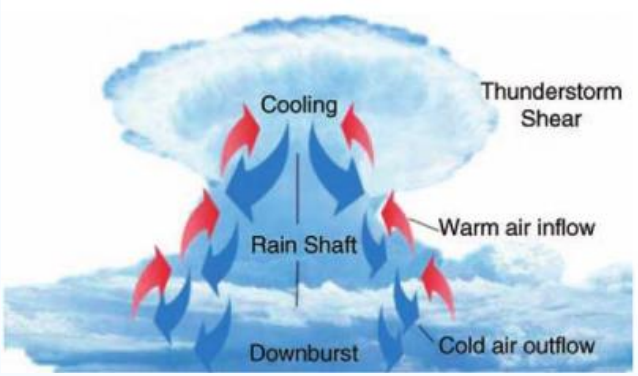


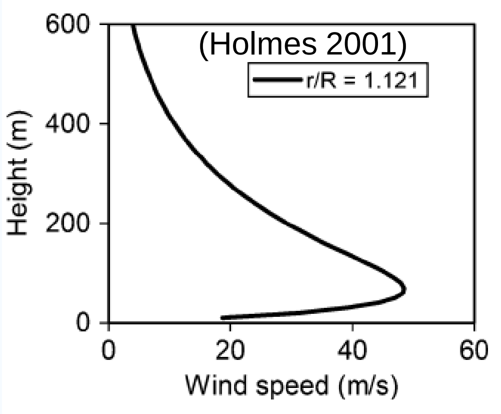






Typhoon

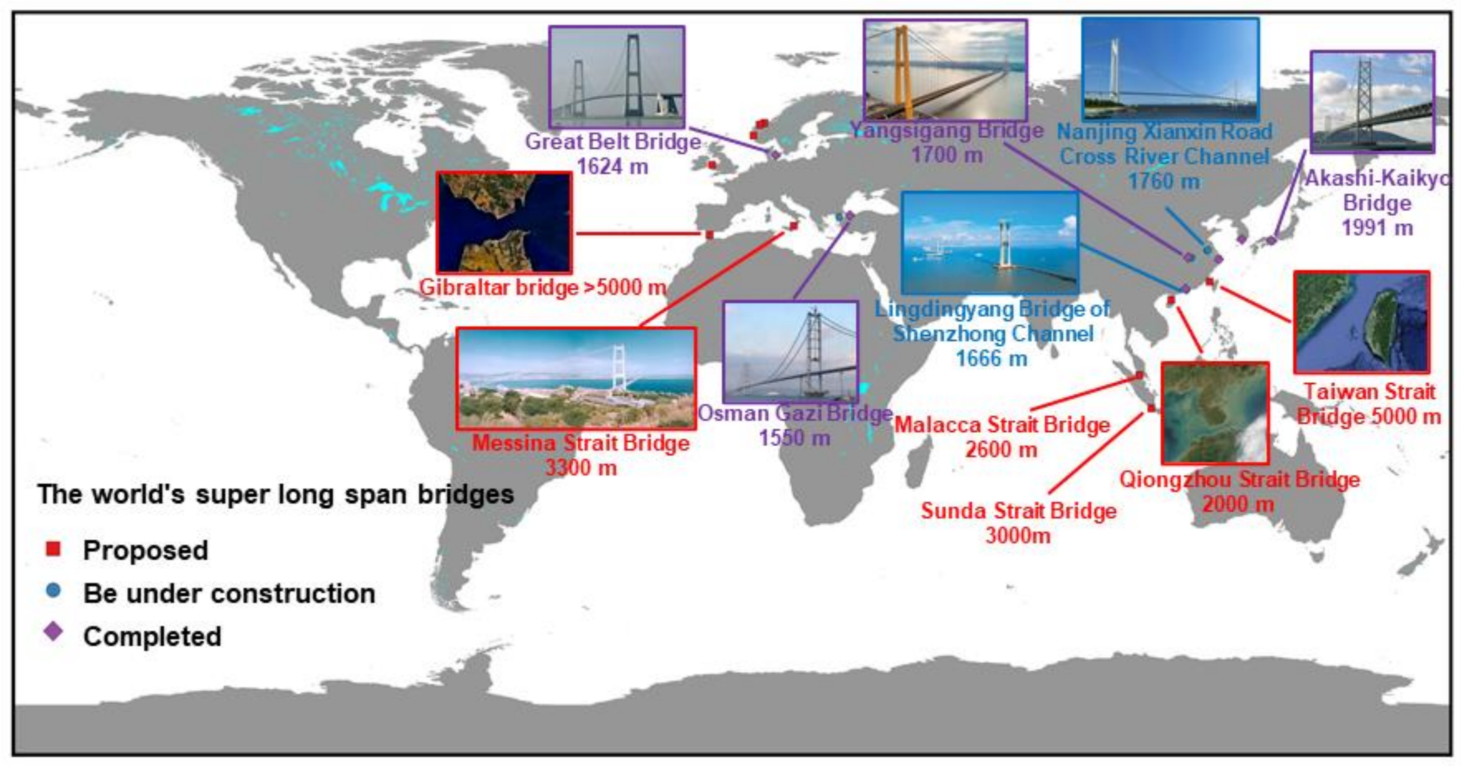




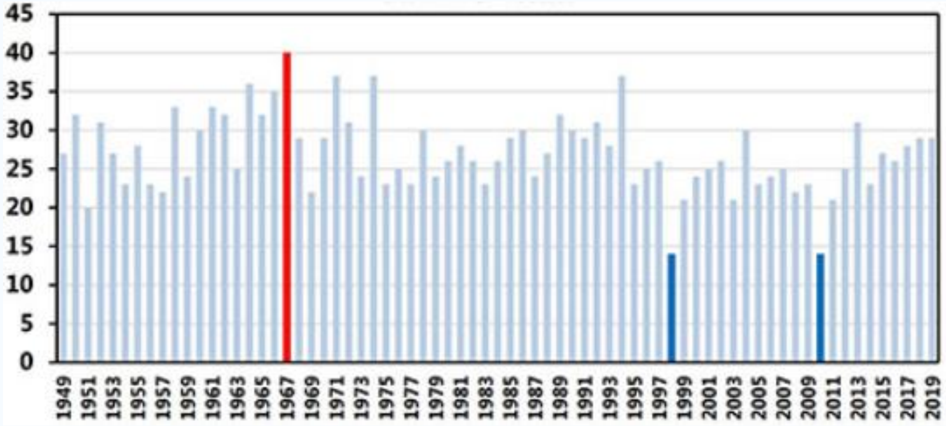
Downburst

Long-span bridge structures under non-synoptic wind

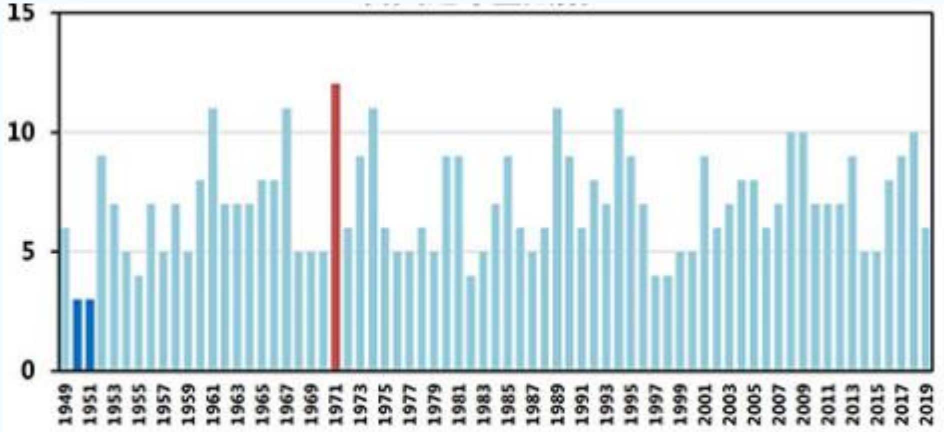
❖ Increasing span and frequent non-synoptic wind



Distribution of worldwide long span bridges



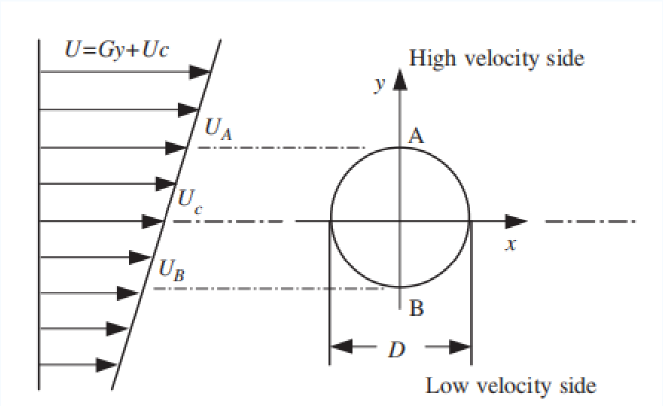
Number of typhoons generated annually



Typhoon landings per year

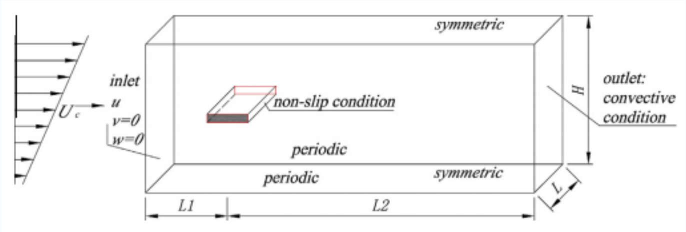
Structural aerodynamic characteristics

❖ Bluff structure under shear flow



S. Cao, et al. 2007

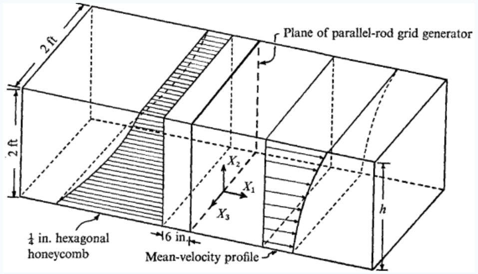
Circular cylinder



S. Cao, et al. 2014

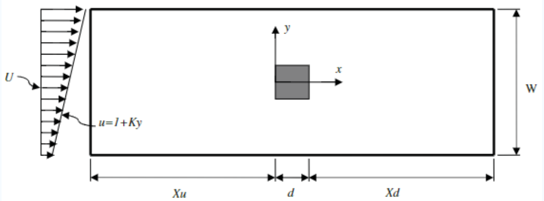
Square / Rectangular cylinder

Structural styles



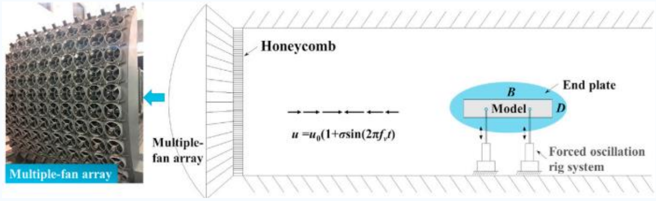
H. K. Richards and J. B. Morton. 1976

Quadratic mean-velocity



A. Lankadasu and S. Vengadesan. 2009

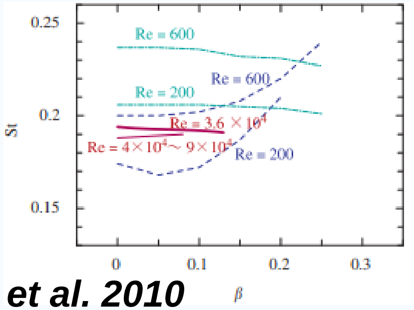
Planar shear flow



R. Ma et al. 2021

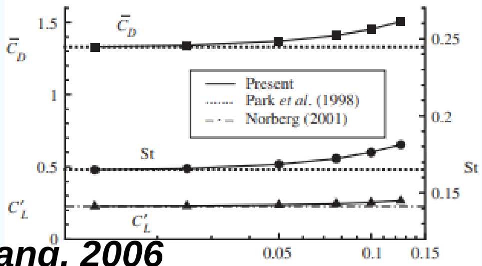
Sinusoidal streamwise stream

Velocity profiles



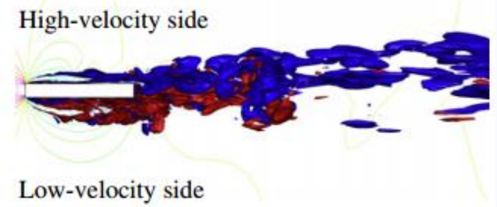
S. Cao, et al. 2010

Strouhal number



S. Kang. 2006

Aerodynamic force



S. Cao, et al. 2014

Instantaneous dynamic wake

Investigation interests

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Experimental design and numerical simulation

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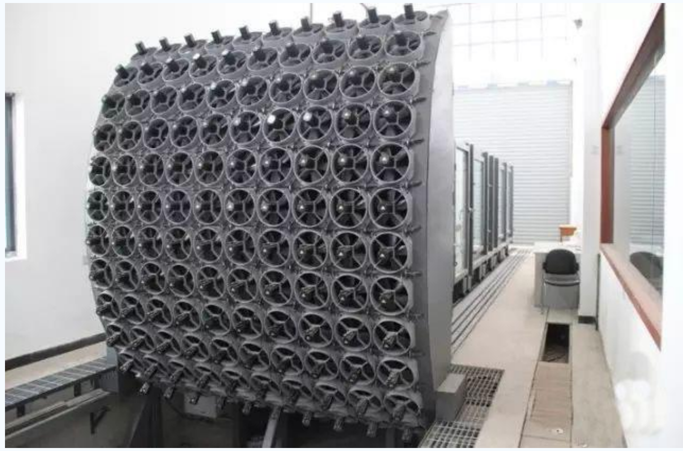
Experimental design

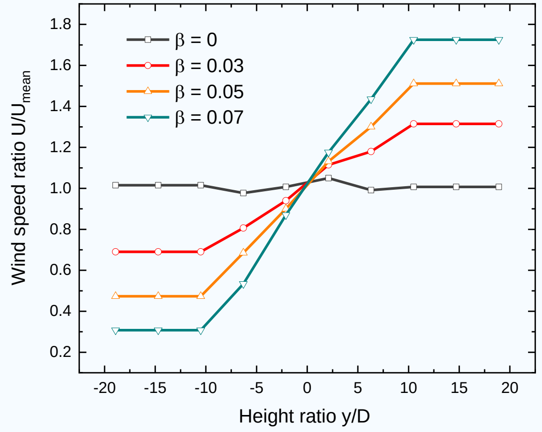
- Velocity shear and turbulence simulation

$$\beta = G \times \frac{H}{U_{mean}} = \left(\frac{dU}{dy}\right) \times \left(\frac{H}{U_{mean}}\right)$$

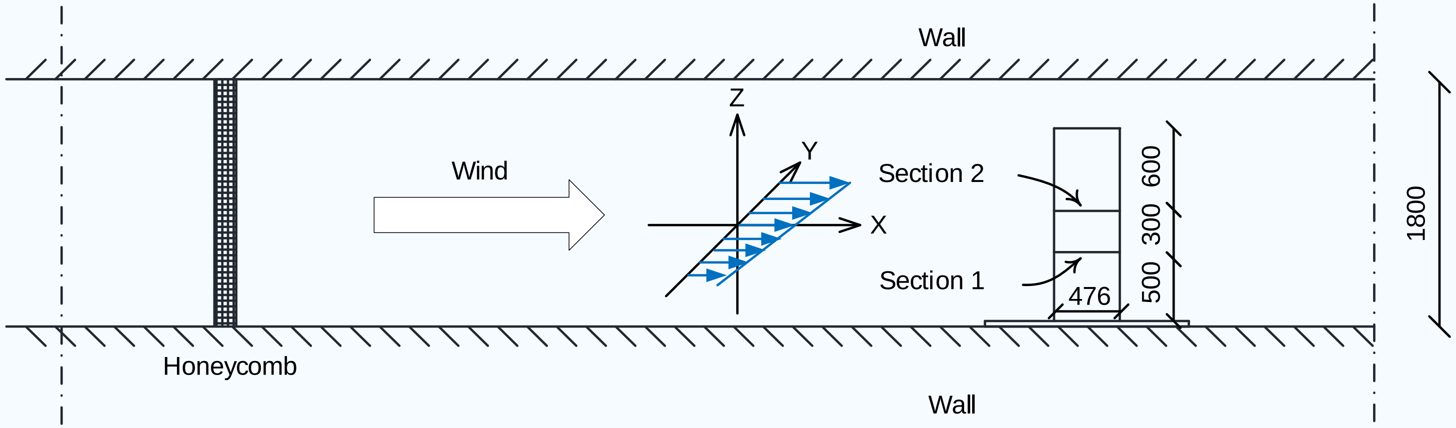


Inlet section

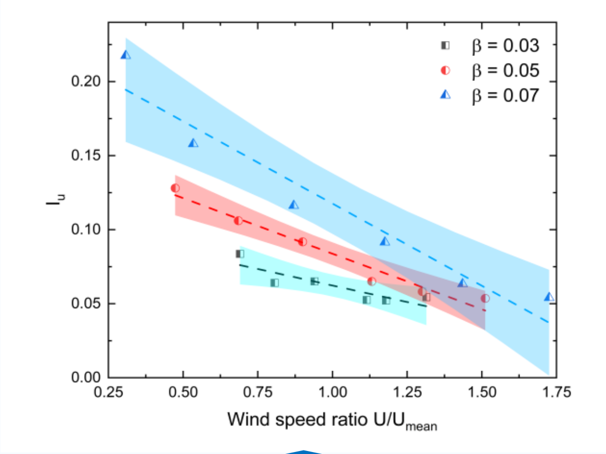
Streamlined box girder



Velocity shear simulation



Shear flow over streamlined box girder



Turbulence simulation

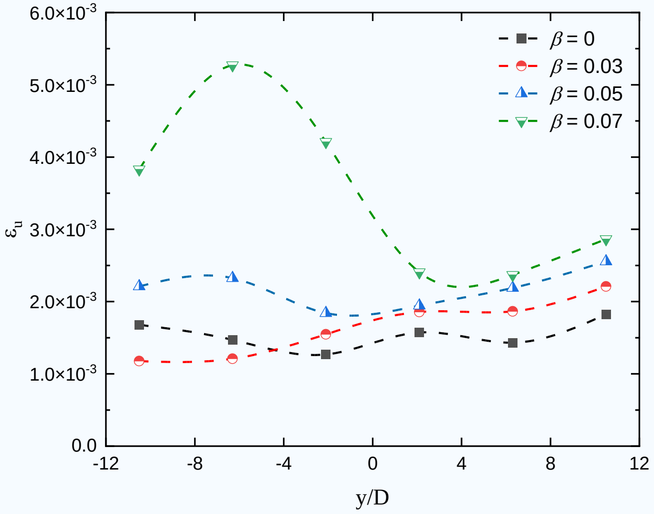
TJ-5 wind tunnel for velocity shear and turbulence simulation

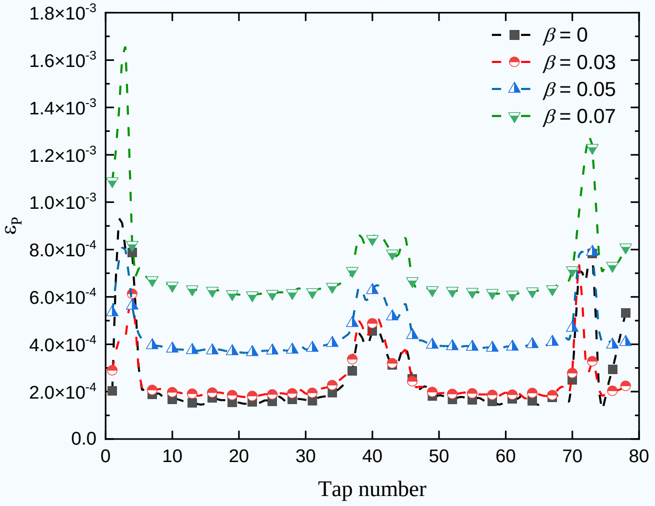
Experimental design

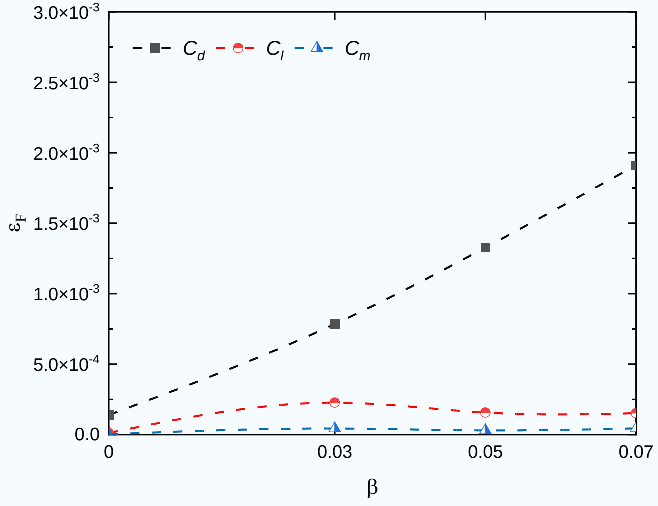
❖ Uncertainty analysis

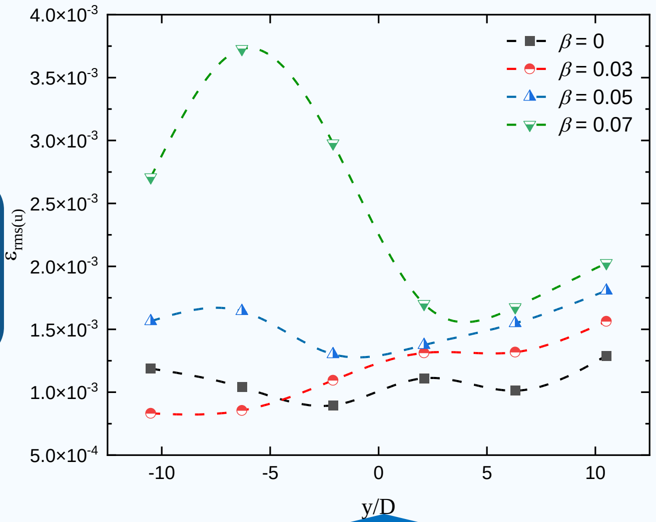
$$\varepsilon_u = \sigma_u \Big/ \sqrt{N}$$

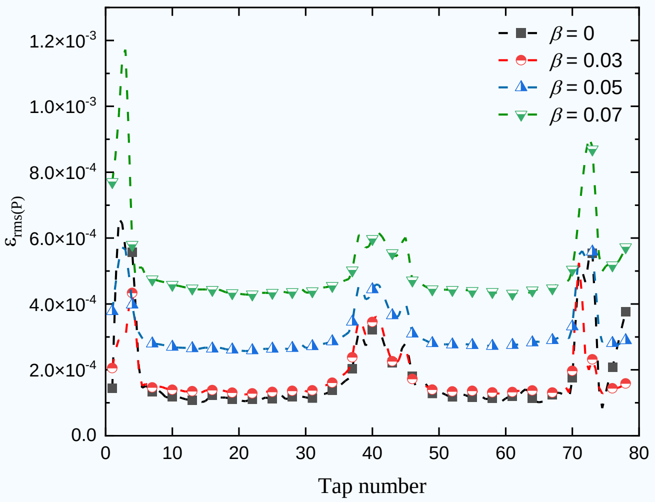
$$\varepsilon_{rms(u)} = \sigma_u \Big/ \sqrt{2(N-1)}$$

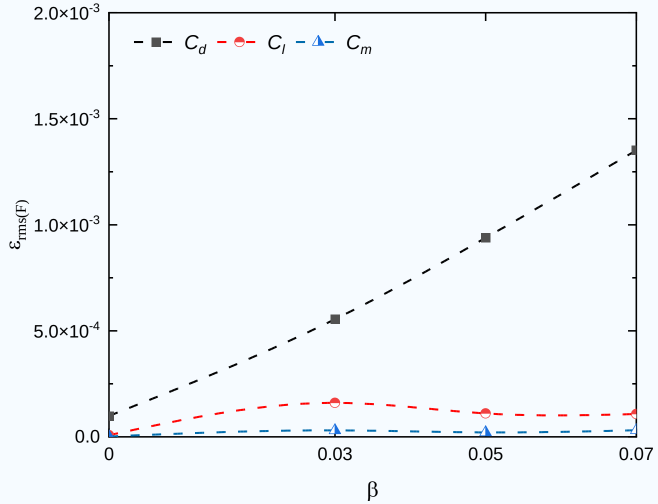








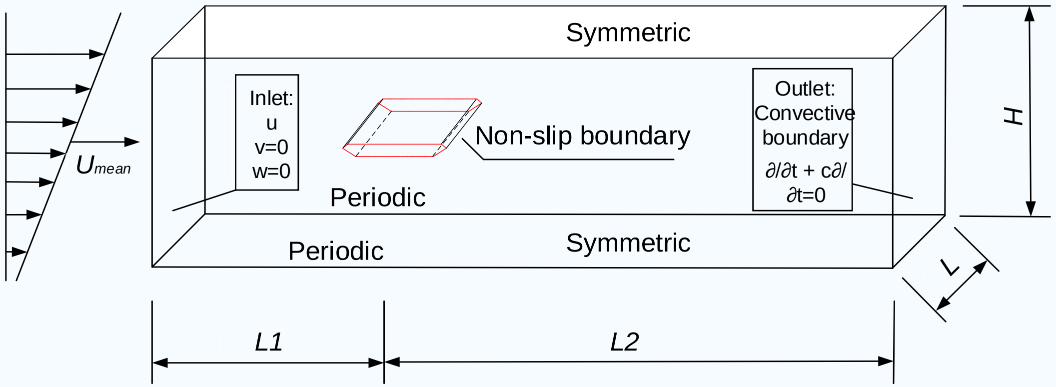




Velocity shear | **Pressure distribution** | **Aerodynamic force**

Numerical simulation

- LES method and model



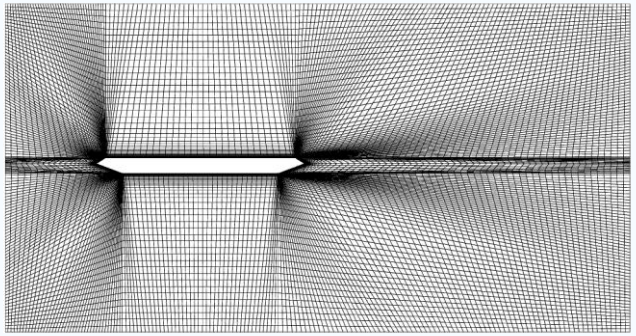
Computational domain and boundary

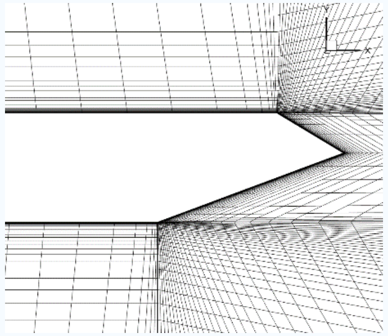
$$Re = \frac{U_{mean}B}{v} = 2.6 \times 10^5$$

$L_1 = 12.5D$ $\quad H = 21D$

$L_2 = 27.5D$ $\quad L = 2.94B$

Boundary size





Structural grid

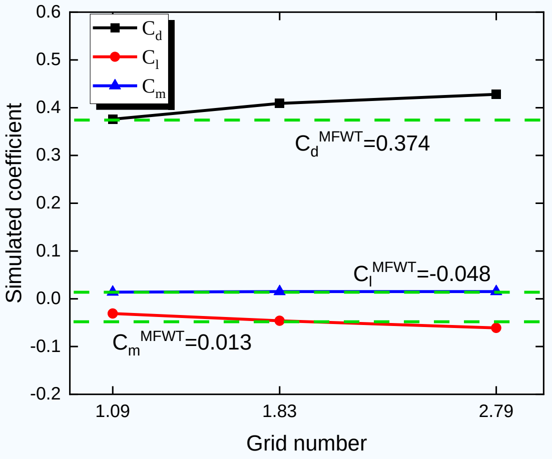
$\Delta x^+ = 42$ $\quad y^+ = 0.3$

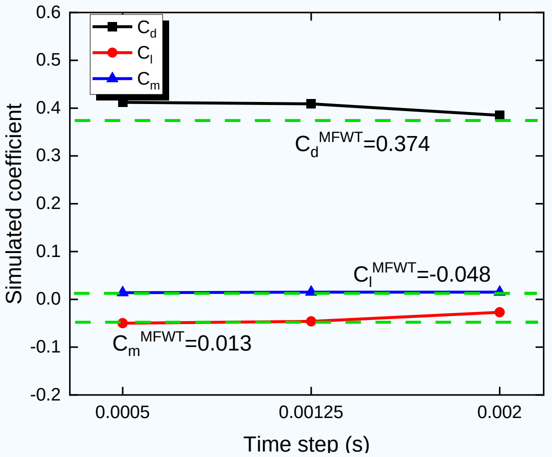
$\Delta z^+ = 12$ $\quad \Delta d/D < 0.1/\sqrt{Re}$

Mesh resolution

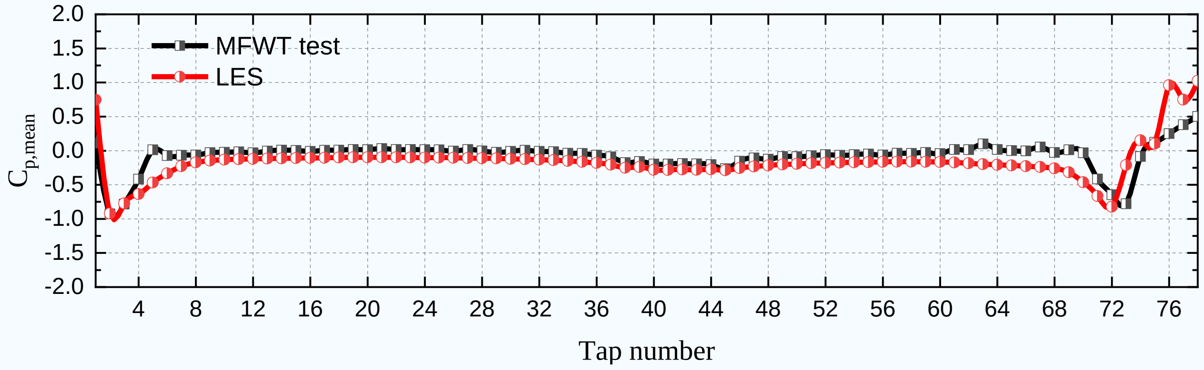
Numerical simulation

❖ Validation of LES method

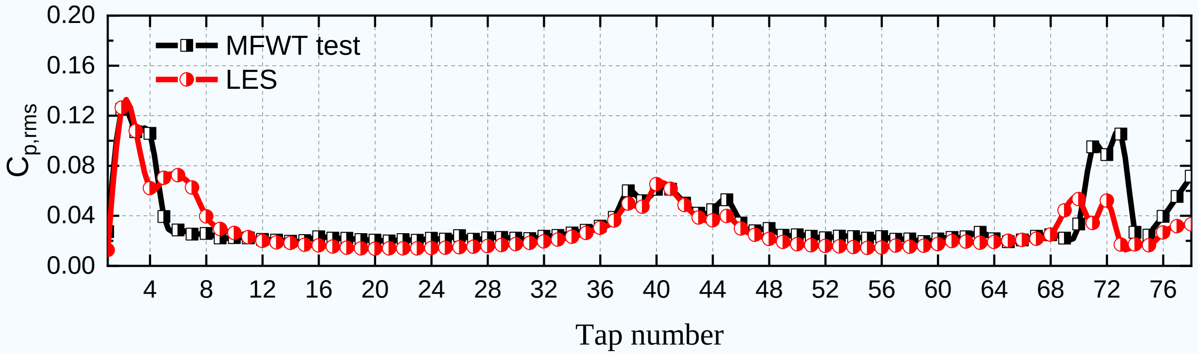




Grid and time step independence



Mean pressure distribution



Fluctuating pressure distribution

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Pressure distribution and aerodynamic forces

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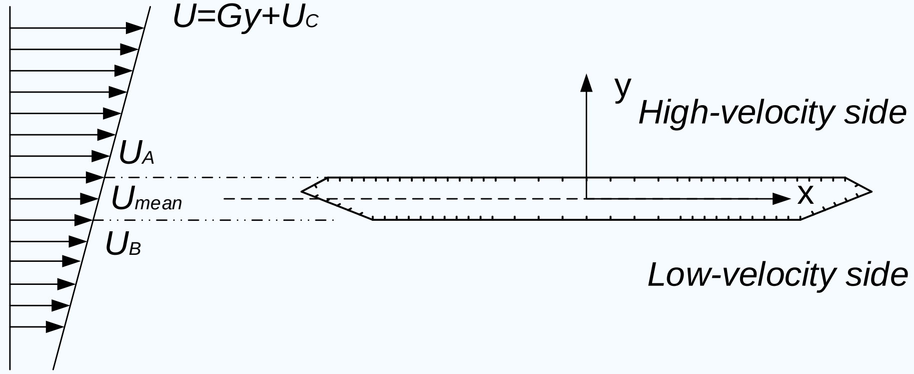
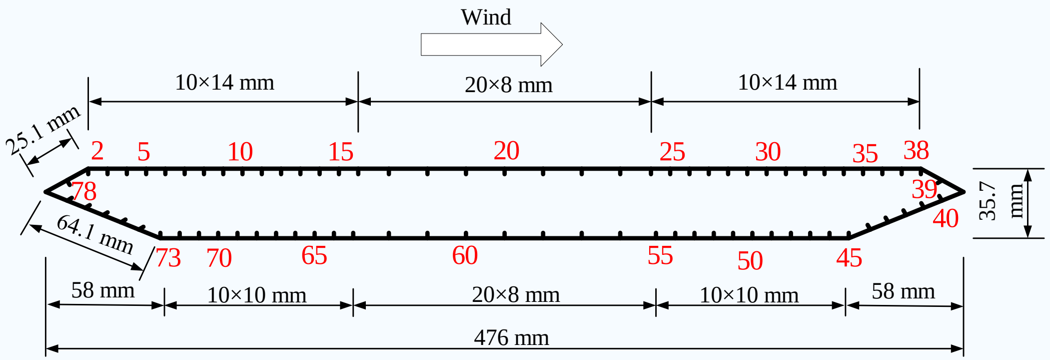
Pressure distribution

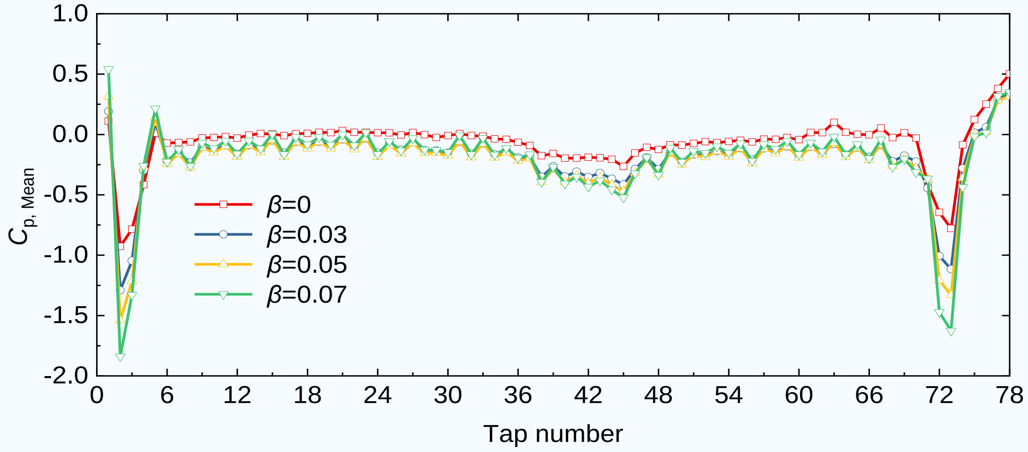
❖ Pressure distribution under shear flow without oncoming turbulence

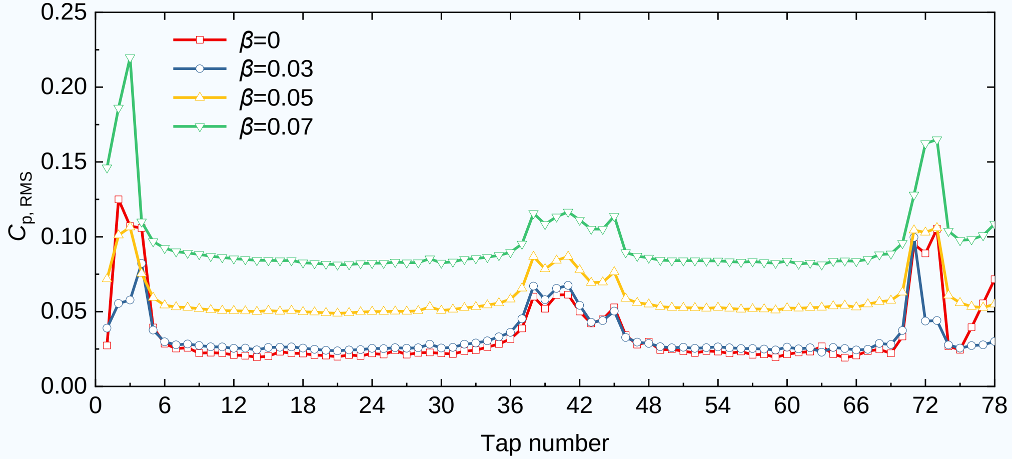


Shear flow without oncoming turbulence



Measured taps around box girder

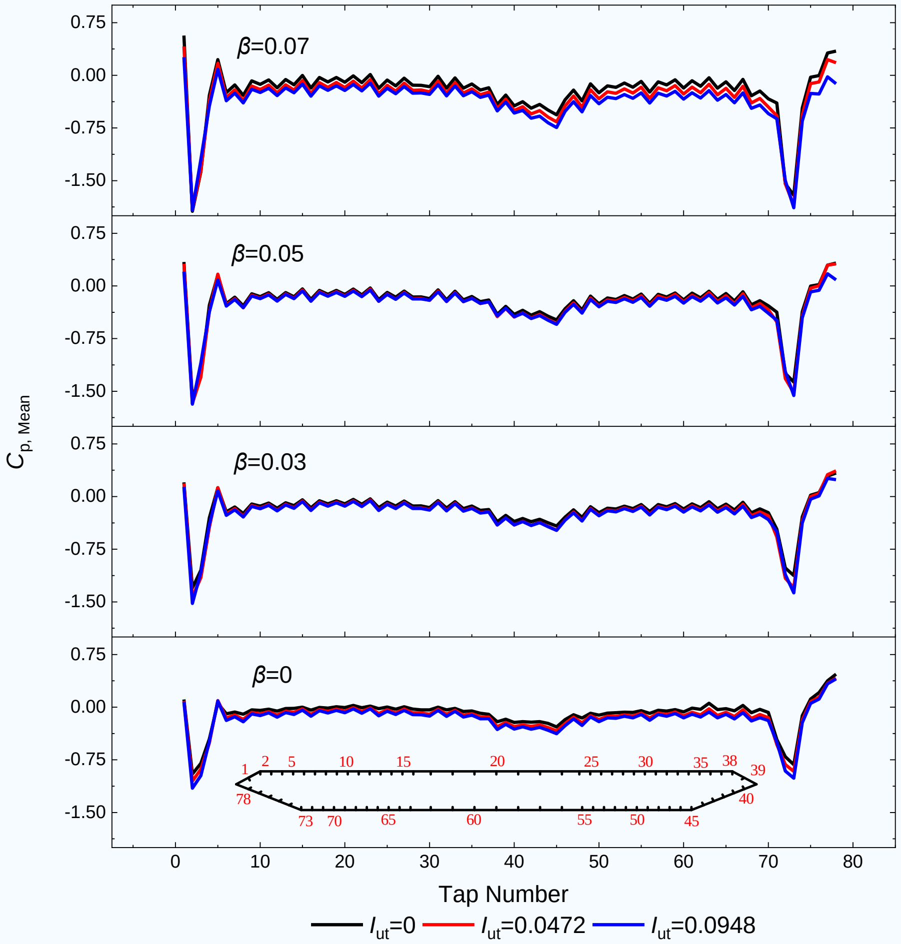


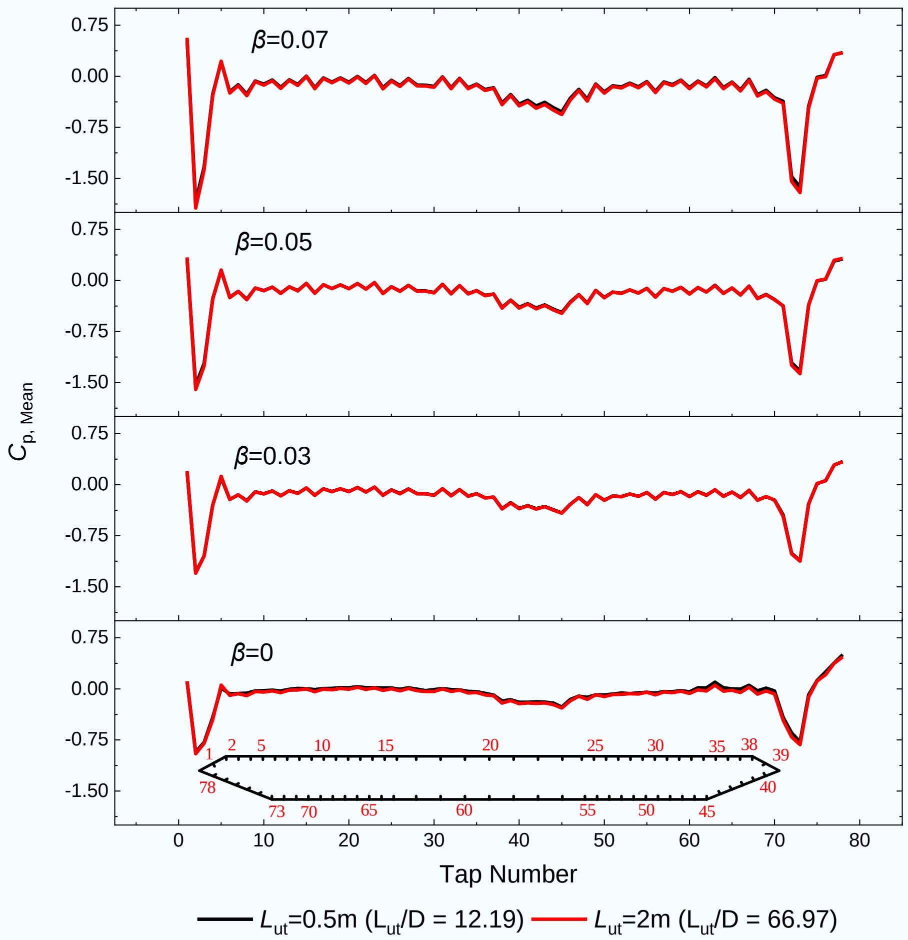


Pressure distribution

Pressure distribution

❖ Pressure distribution under shear flow with oncoming turbulence



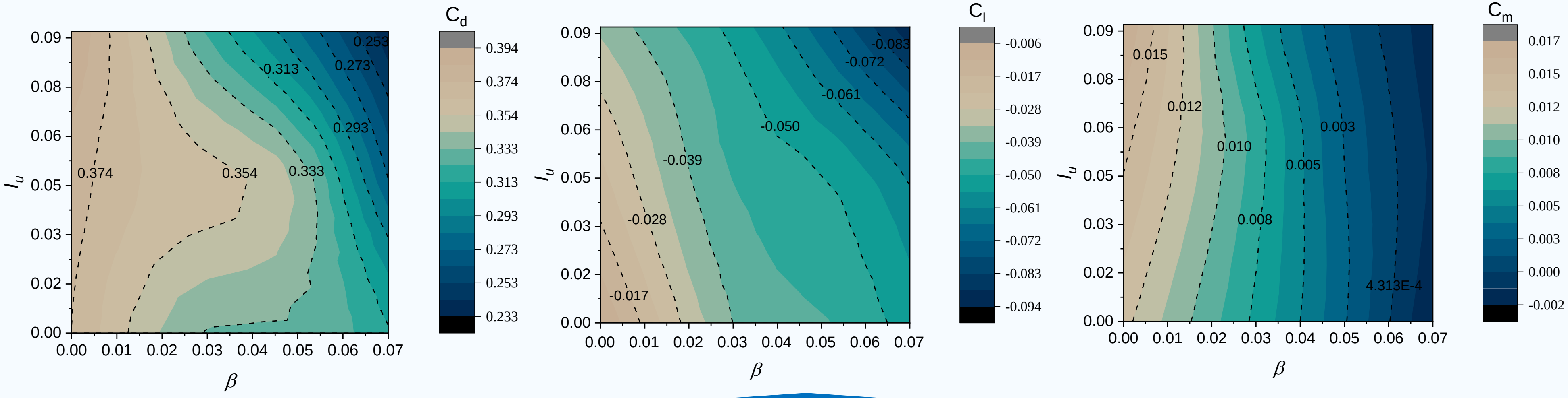


Pressure distribution influenced by velocity shear and turbulence intensity

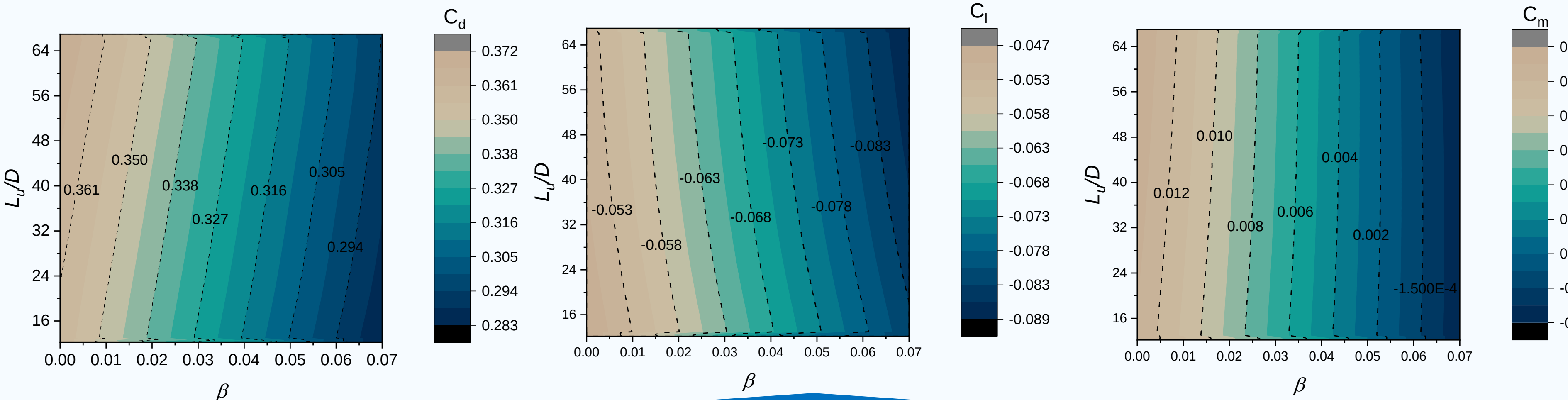
Pressure distribution influenced by velocity shear and turbulence integral scale

Aerodynamic forces

❖ Aerodynamic forces under shear flow with oncoming turbulence



Aerodynamic forces influenced by velocity shear and turbulence intensity



Aerodynamic forces influenced by velocity shear and turbulence integral scale

- Strongly nonlinear drag force
- Lift force increased with shear rate and turbulence intensity
- Moment force decreased with shear parameter
- Weak influence of integral scale on aerodynamic forces

Aerodynamic forces

❖ Empirical relationship

$$\begin{cases} C_d = \alpha_0 + \alpha_1\beta + \alpha_2 I_u + \alpha_3 \beta I_u + \alpha_4 I_u \left(\frac{L_u}{D}\right) + \alpha_5 I_u^2 + \alpha_6 \left(\frac{L_u}{D}\right)^2 + \alpha_7 \beta I_u^2 \\ C_l\ (or)\ C_m = \alpha_0 + \alpha_1\beta + \alpha_2 \left(\frac{L_u}{D}\right) + \alpha_3 I_u^2 \end{cases}$$

Fitted parameter	C_d $(R^2 = 0.9621)$	C_l $(R^2 = 0.9750)$	C_m $(R^2 = 0.9840)$
α_0	(0.2212 $\pm$ 0.0478)	(-0.0294 $\pm$ 0.0054)	(0.0210 $\pm$ 0.0013)
α_1	(3.3085 $\pm$ 1.0019)	**(-1.1887 $\pm$ 0.1378)**	**(-0.2312 $\pm$ 0.0263)**
α_2	(7.2230 $\pm$ 1.8905)	(-0.002 $\pm$ 0.0002)	(-1.41E-05 $\pm$ 3.48E-05)
α_3	**(-67.0307 $\pm$ 30.0376)**	**(-2.0069 $\pm$ 0.5199)**	**(-0.1394 $\pm$ 0.0642)**
α_4	(0.0360 $\pm$ 0.0168)	--	--
α_5	**(-77.5930 $\pm$ 17.0623)**	--	--
α_6	(-2.51E-05 $\pm$ 1.59E-05)	--	--
α_7	**(830.8719 $\pm$ 227.2152)**	--	--

- Drag force dominantly affected by βI_u, I_u^2, and βI_u^2 term
- Lift force dominantly affected by β and I_u^2 term
- Dominant terms of moment force are similar to lift force

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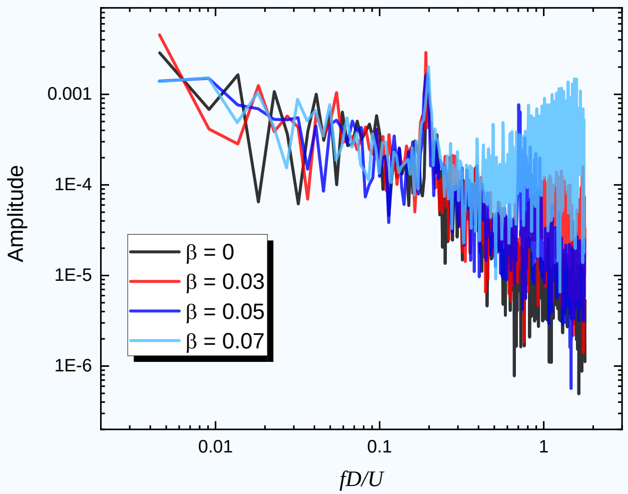
Aerodynamic spectrum and vortex shedding

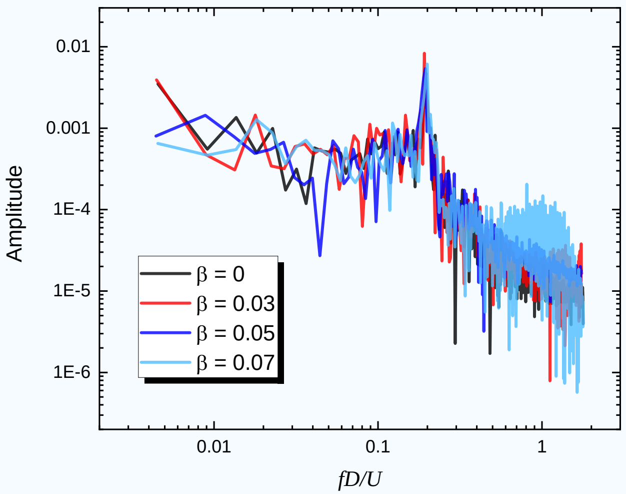
4

Aerodynamic spectrum

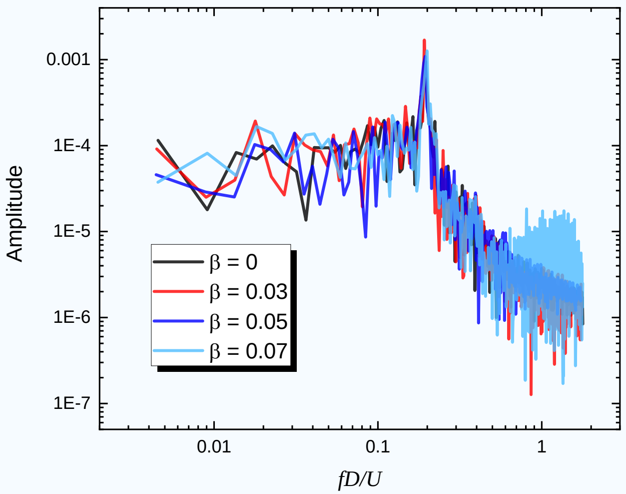
❖ Aerodynamic spectrum under different shear parameters



Drag coefficient



Lift coefficient

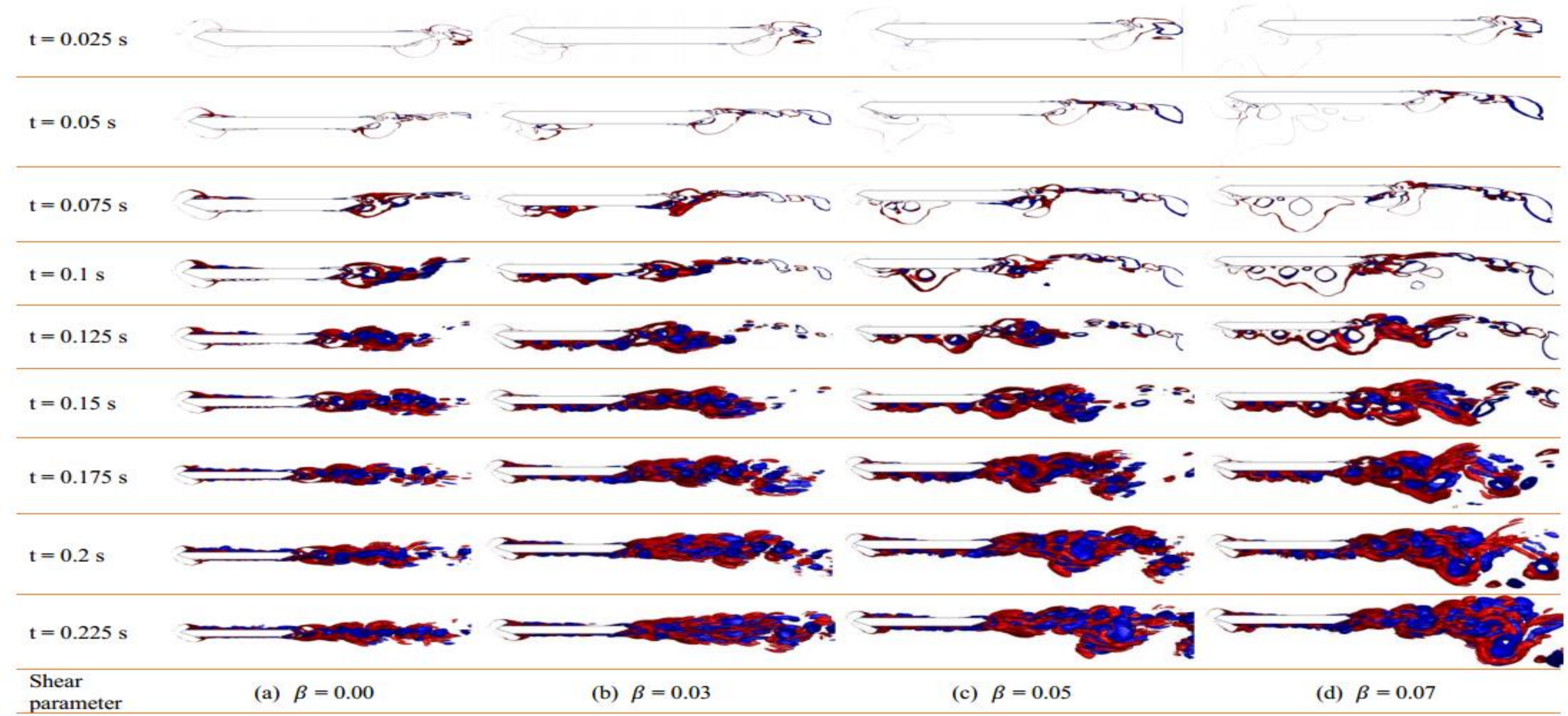


Moment coefficient

- Weak influence of velocity shear on dominant frequency
- Large shear parameter results in increased amplitude of aerodynamic forces at high-frequency band

Instantaneous dynamic wake

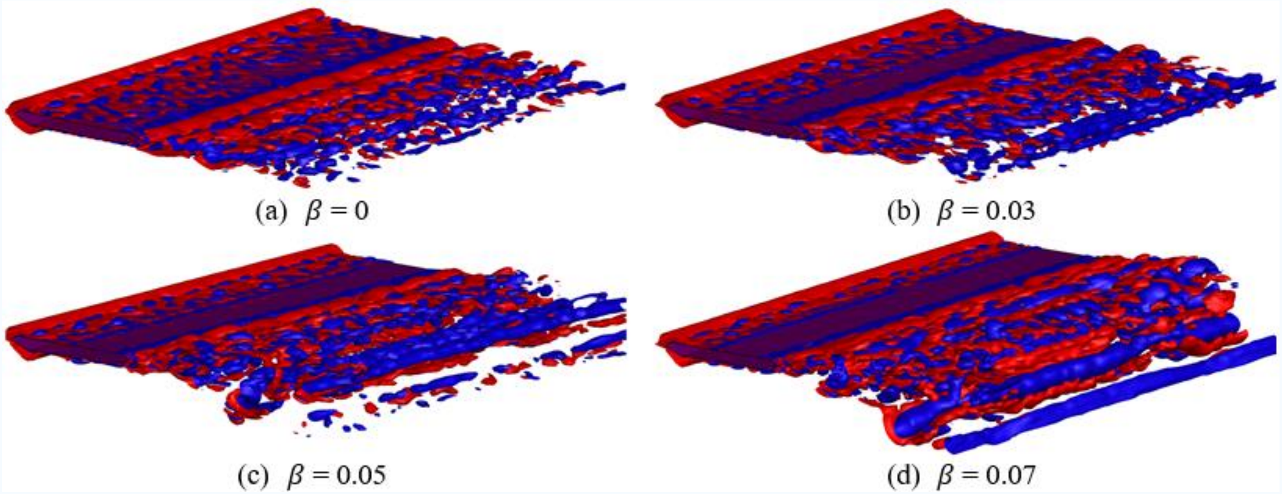
❖ Instantaneous dynamic wake under initial period

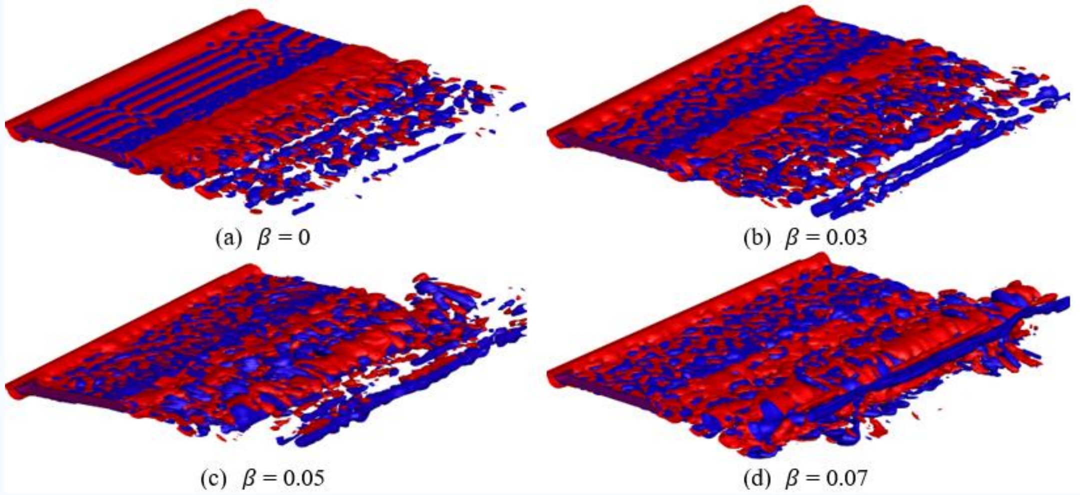


- Velocity shear suppresses the generation of vortex structures at high-speed side , and the suppression effect increases with the increase in shear parameters
- Vortices always generate, develop, and detach from the low-speed side to the downstream side in velocity shear flow

Instantaneous dynamic wake

❖ Three-dimensional instantaneous dynamic wake vortex under shear flow



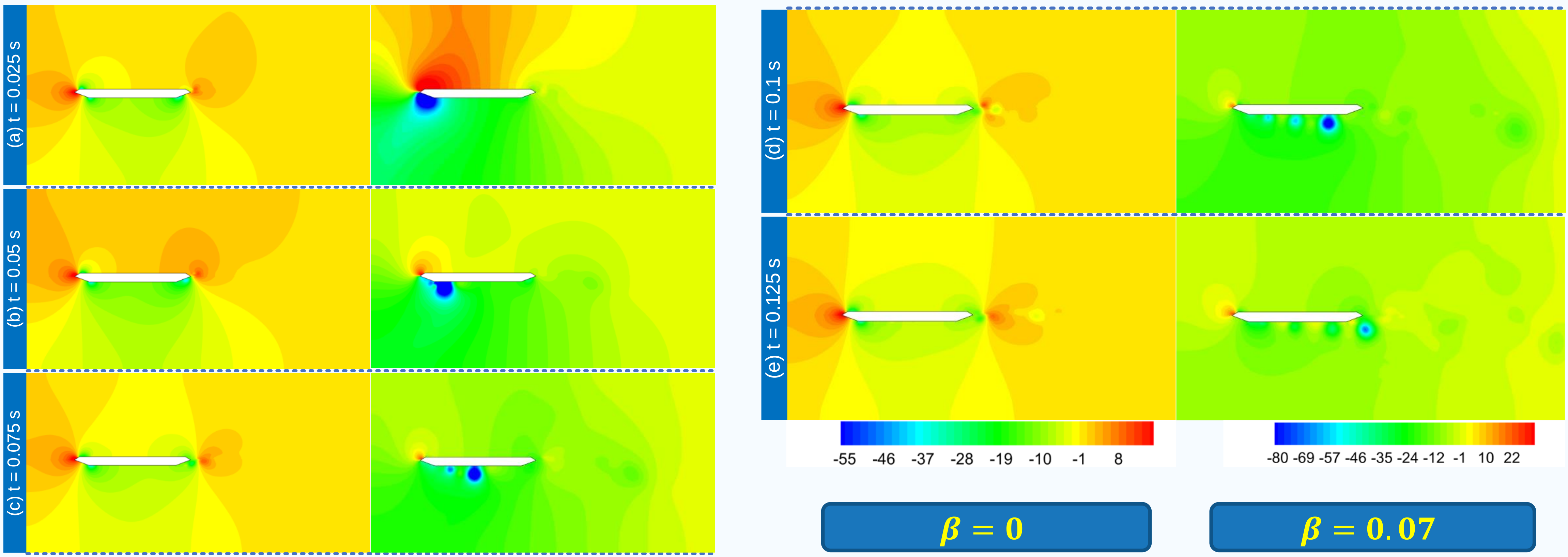


Instantaneous vortex on the high-speed side (t=0.225s) | **Instantaneous vortex on the low-speed side (t=0.225s)**

- Counterclockwise (red) vortex dominates on the windward side, corresponding to the positive pressure measured in MFWT
- The vortex on the high-speed side of the box girder is suppressed, forming a "vacuum" zone by double vortex isolation
- The low-speed side vortex of the box girder changes from alternating regular Karman vortices to fragmented irregular vortex structures with increasing shear parameters

Instantaneous pressure distribution

❖ Instantaneous pressure distribution in uniform flow and velocity shear flow



- The pressure distribution in uniform flow field is relatively stable
- Instantaneous local extreme negative pressure occurs in the velocity shear flow due to the generation and drift of vortex on the low-speed side

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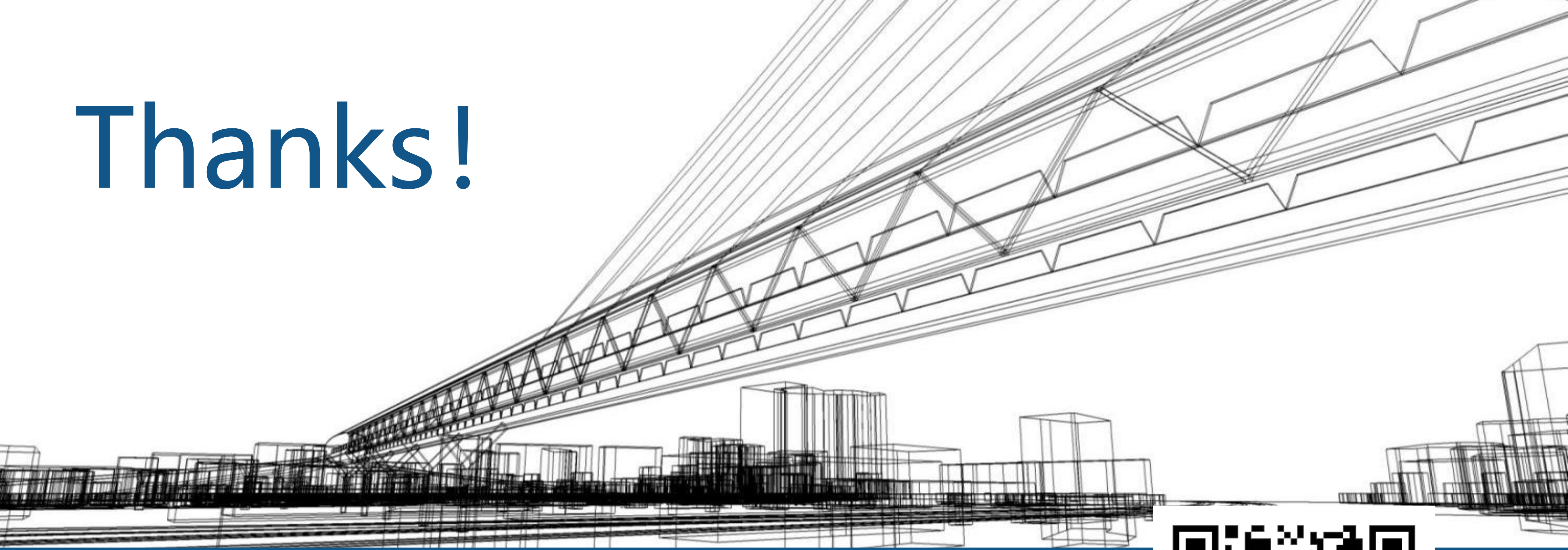
Conclusions 5

Conclusions

- The **fluctuating pressure** significantly increases with the increase in shear parameters, indicating that the velocity shear flow is self accompanied by **turbulence effect**
- The **turbulence intensity** only increases the mean pressure of the streamlined box girder when the shear parameters are high; the **turbulence integral scale** has almost no contribution to the pressure distributior
- The turbulence intensity exhibits **strong nonlinearity** in the drag force of the box girder; the integration scale has a **weak influence** on the aerodynamic forces
- The velocity shear **suppresses** the generation of vortex structures of the high-speed side, and the vortex structures always first generate and develop from the low-speed side

Thanks!



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