REVIEWS ON
BLUFF BODY FLOW AROUND
PRISMS AND GIRDERS

Prepared by Le Thai Hoa

2005
REVIEWS ON BLUFF BODY FLOW AROUND PRISMS AND GIRDERS

1. Around-flow patterns of bluff bodies under either steady or turbulent ongoing flows have been formed by either 1 shear layer or 2 shear layers on one side or both sides of bodies due to the flow-body interactions. Depending on characteristics of bluff bodies (sectional shape and dimension) and characteristics of ongoing flow (steady or unsteady, wind velocity, attack angle) and even in-flow movement of body, the around-body flow shear layer can be either stability or instability.

2. The flow-body interaction phenomena consists of: separation bubble, non-reattachment and reattachment flows, vortex-shedding (1 shear layer or 2 shear layers).
Branches of shear layer on around-body flow

Noting should be born in mind that:

+ No separation flow: Shear layer does not exist (Airfoil or thin plate only)
+ Separation flow: Shear layer (1 shear layer or 2 shear layers) always exists
+ Shear layer stability: *No separation bubble and no vortex shedding* form on the surface or in the wake of bodies. It means that *no flow-body interaction* occurs.
+ Shear layer instability: *Separation bubble and vortex shedding* form on the surface or in the wake of bodies. The *flow-body interaction* occurs

+ Two shear layer instability usually occurs for the most bluff bodies or bridge sections.
3. **Around-body flow patterns based on characteristics of flow shear layers**

   +) 1 shear layer stability: No formation of separation bubble and vortex-shedding

   ![Diagram of 1 shear layer stability]

   *Aerodynamic phenomena:* Galloping instability; Unsteady buffeting

   +) 1 shear layer instability: Formation of separation bubble and vortex-shedding on the one surface of bluff body (must study more this type).

   ![Diagram of 1 shear layer instability]

   *Vortex-shedding*  
   *Separation bubble*

   *Aerodynamic phenomena:* Vortex-induce Vibration (Lock-in resonance or motion-induced vibration); Unsteady buffeting; Low-speed torsional flutter

   +) 2 shear layer stability: No formation of separation bubble and vortex-shedding

   ![Diagram of 2 shear layer stability]
Aerodynamic phenomena: Galloping instability; Unsteady buffeting

+) 2 shear layer instability: Formation of separation bubble and vortex-shedding

\[ \text{2 shear layer instability: formation of bubble} \]

\[ \text{2 shear layer instability: formation of vortex} \]

Aerodynamic phenomena: Vortex-shedding vibration; Torsional and coupled flutters; Unsteady buffeting

4. Around-body flow patterns and vortex-induced vibration

According to Matsumoto (1999), the vortex shedding around bluff bodies can be classified by some following kinds:

1) Karman vortex shedding (periodic shedding)
2) Symmetrical vortex shedding in two shear layer
3) Vortex shedding associated with 1 shear layer instability
4) Axial vortex shedding
5) Tip vortex shedding

4.1. Karman vortex shedding: The Karman vortex has been shed periodic in the wake of body. The frequency of Karman vortex shedding can be estimated by the Strouhal number.
\[
S_t = \frac{f_v D}{U} \quad \text{or} \quad f_v = \frac{S_t D}{U}
\]

The Strouhal number depends on i) Reynold number; ii) Shape and dimension of body; and iii) Wind velocities

+ ) *Increase of Reynold number*: Strouhal number increases or decreases in certain range of Reynold number

+ ) *Increase of dimension (D)*: Strouhal number increases

+ ) *Increase of velocity (U) and change of attack angle*: Strouhal number decreases

Effect of Reynold number on Strouhal number: It should be noted that the Strouhal number can be influenced by the Reynold number in some cases:

+ ) *Circular cylinders*: The Strouhal number seems to stay constant on the certain range of Reynold number between \(1.5 \times 10^2\) and \(1.5 \times 10^5\) [Blevin(1977), Simui&Scanlan(1978)].

Effect of Reynold number on Strouhal number for 2D circular cylinder [Blevin(1977)]
Effect of Reynold number on Strouhal number for 2D circular cylinder [Simui&Scanlan(1978)]

+) **Rectangular cylinders**: The Strouhal number can be affected by the Reynold number with rectangular cylinders of various B/D [Okajima(1991)]. However, the influence of Reynold number on the Strouhal number to some extent can be considered as the minor effect.

Effect of Reynold number on Strouhal number for 2D rectangular cylinders with various slenderness ratios B/D=0.8-4 and B/D=5-9 [Okajima(1991) from Matsumoto(2000)]

As can be seen from Fig. above that:

+) B/D=0.8-4 and Re=10^2-10^5: Strouhal number seems to be constant

+) B/D=5-9 and Re=10^4-10^5: Strouhal number seems to be constant
+) **Rectangular cylinders with cutting corners**: The Strouhal number can be strongly affected by the Reynold number. Concretely, the Strouhal number seems to gradually increase with the increase of Reynold number.

Effect of Reynold number on Strouhal number for 2D rectangular cylinders with different cutting corners [Okajima(1991) from Matsumoto(1999)]

Lock-in phenomenon or frequency resonance: At the critical condition \( f_b = f_c \) or frequency resonance can be well known as the ‘Lock-in’ phenomenon:

![Graph showing the relationship between velocity and Reynolds number](image)

The Karman vortex might be generated under such following conditions:

+) Circular cylinders, rectangular section with low B/D; streamlined cross-sections

+) Low reduced velocities \( U_{re} = \frac{U}{fD} \) and low Reynold number \( R_e = \frac{UD}{\nu} \)

\[ \nu = \frac{\mu}{\rho} \]: Kinetic viscosity, \( \nu = 0.15 \text{cm}^2/\text{sec} \) (at 20\(^\circ\))
Shimada & Meng(1998) investigated using CFD technique for 2D rectangular cylinders with various B/D between 0.5 and 7 pointed out that:

+) B/D=0.5-4: Vortex shedding occurs
+) B/D>4 (5-8): Vortex shedding disappears or weaken.

It is generally agreed that it is very difficult and even impossible to simulate the Reynold number on wind tunnel experiments to fully respect to the full scale structure. About effect of the Reynold number on the Strouhal number can affect on evaluation of vortex-induced vibration, it should be noted the influence of the Reynold on the Strouhal number in such certain cases:

+) Generally, the Reynold number slightly influences on the Strouhal number, thus large discrepancy of the Reynold number between full-scale structure and wind tunnel model can be neglected.
+) In the some cases the Reynold number considerably affects on the Strouhal number, the difference between full-scale structure and wind tunnel model can affected on the error evaluation of the vortex-induced vibration using tool of wind
tunnel. The technique for compensating the influence of the Reynolds number difference between full scale structure and experimental model should be required.

4.2. *Symmetrical vortex shedding in two shear layers:* has been observed by King (1977) for the 2D stationary circular cylinder in the water flume and by Knisely & Matsumoto (1986) for stationary 2D rectangular cylinder in the weak fluctuating flow. Noting that both of them occurred at reduced velocity 

\[ U_{re} = \frac{U}{fD} = \frac{1}{4S_f} \]

that much lower than reduced velocity 

\[ U_{re} = \frac{U}{fD} = \frac{1}{S_f} \]

at the Karman vortex shedding appeared.

![Symmetrical vortex shedding](image)

Symmetrical vortex shedding for 2D rectangular cylinder B/D=0.5 in fluctuating flow at reduced velocity U<sub>re</sub>=1/4St [Okajima & Matsumoto (1986)]

4.3. *Vortex shedding generated by one shear layer instability:* This kind of vortex shedding can be generated by the enhancement of one shear layer instability under conditions of the harmonic fluctuating flow and motion itself.

Matsumoto (1999) pointed out that:

i) *this vortex shedding is usually associated with the ‘lock-in’ phenomenon, furthermore, almost streamlined close boxed sections and rectangular sections with B/D=2-6 can be favorably exhibited under this vortex shedding of one shear layer instability in the low range of reduced velocities.*
This ‘lock-in’ vibration can be called by the ‘motion-induced vibration’, because the generated aerodynamic forces in the ‘lock-in’ state are self-controlled ones.

ii) Onset critical velocity can be determined by approximation formula:

\[ U_{re} \approx 1.67(B/D) \]
iii) The formation of separated vortex on model surface and movement from leading edge to trailing edge. The velocity of surface vortex movement is roughly 60% of velocity of ongoing wind flow.

iv) The formation of secondary vortex at trailing edge

v) The formation of smaller vortex comes along with larger one on model surface

4.4. Axial vortex shedding: generated at the near wake and behind side of inclined cables under the rainy and windy conditions. Apart from the formation of Karman vortex shedding on the wake of inclined cables, another specified vortex shedding forms and moves along the centerline of inclined cable [Matsumoto et al. (1998)], then author named as the ‘axial vortex shedding’. This type of vortex shedding can be considered as 3D flow.

![Visualization of around inclined cable flow by liquid paraffin](Matsumoto et al. (1998))

According to Matsumoto et al. (1998), the axial vortex shedding around inclined cables have some following characteristics:

+) Axial vortex shedding is formed at the near wake and the behind side of inclined cables due to the rain-wind-induced vibration

+) Axial vortex shedding is always formed along with the Karman vortex shedding
+) Frequency of axial vortex shedding is approximately *three times higher than the frequency of Karman vortex shedding*.

+) Axial vortex shedding might be enhanced by the upper water rivulet on the cable surface.

+) Axial vortex shedding, Karman vortex shedding and the upper water rivulet play very important role to amplify the large amplitude of the rain-wind-induced vibration at very high reduced velocities (approximately 20 multiply) Ur=20, 40, 80,....

4.5. *Tip vortex shedding*: can be observed at near free end of circular columns and towers. Similarly to the axial vortex shedding, this type of vortex shedding occurs at very high range of reduced velocities and also moves along the centerline of columns or towers. Furthermore, the tip vortex shedding can excite at the critical reduced velocity that is three-time higher than the critical reduced velocity of Karman vortex shedding.

5. **Around-body flow patterns and galloping instability**

The mechanism of the Galloping instability is generated by the formation of inner circulation flow under the two shear layer stability that produces the *negative surface pressure*. This negative surface pressure might be created by the fluid interaction of shear layer stability from leading edge to trailing edge.

Visualization of around circular cylinder with splitter plate under forced vibration
Galloping instability has some following features on 2D rectangular cylinders with various slenderness ratios and reduced velocities:

i) \( \frac{B}{D} \leq 0.6 \): Galloping occurs at the reduced velocity lower than critical reduced velocity of the conventional Karman vortex shedding. It named as the ‘Low speed galloping’.

ii) \( 0.6 \leq \frac{B}{D} \leq 2.8 \): Galloping occurs at the reduced velocity higher than critical reduced velocity of the Karman vortex shedding. It named as the ‘High speed galloping’.

6. **Around-body flow patterns and flutter instability**

Matsumoto(1996,2000) convinced that the mechanism characteristics of generated self-controlled aerodynamic forces might be depended much on such following reasons:

i) simultaneous modification of approaching flow and around-structure flow by structure’s shape, scale, movement and wind’s velocity, relative attack angle.
ii) local pressure distribution at leading edge zone of structure surface played very important role to explain in generation mechanisms of aerodynamic phenomena and wind-induced vibrations.

Flutter branches of 2D H-shaped section are based on around body flow patterns [Matsumoto et al (1996)]:

Reference