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A Review on the Study of Wind Loads on Multiple Cylinders with Effects of Turbulence and Surface Roughness

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Abstract In the past decades, there have been a great number of studies concerning the flow around circular cylinders. Depending on the researcher's interests, these studies investigated various perspectives of the flow phenomenon, including the pressure distribution, force coefficients, vortex shedding, Strouhal numbers, flow patterns, etc. Most of these investigations were conducted by means of wind tunnel experiments, and only a few were carried out with full-scale measurements. These previous research work is reviewed in this paper. Since the mean drag and lift coefficients are of the most interest in these study, the data regarding these parameters constitutes the majority of the review work as well.

Keywords: *tandem cylinder, downstream wave, critical spacing, critical regime, drag coefficient, progressive transition*

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1. Introduction

Wind-resistant design of industrial structures has been given growing attention due to the possible catastrophic effects in case of failure, especially in the areas where extreme wind events are likely to occur. It may not only cause a huge economic loss, but also be devastating to the environment in some cases. Pipe-rack structures are commonly found in petrochemical plants, chemical plants, power plants, etc. In many cases, the calculation of the wind loads on pipe rack structures is not specifically addressed in the current design codes. There have been a great number of studies concerning different perspectives of the flow around circular cylinders (also mentioned as "pipes"). Of primary interest, the mean drag and lift force coefficients C_d and C_l are required to calculate the wind loads.

2. Flow around a Single Cylinder

The research about the flow around a single cylinder can be dated back to more than a century ago. For a smooth cylinder immersed in a disturbance-free flow, the characteristics of the flow are determined by many factors. The Reynolds number is usually singled out as the governing parameter, which is defined as:

$$Re = \rho V d / \mu$$

where, ρ, V and μ are the density, approaching velocity and dynamic viscosity of the flow respectively and d is the diameter of the cylinder. The Reynolds number essentially represents the ratio of inertial to viscous forces. Figure 1 shows the flow field around the single cylinder. Depending on Re, progressive transitions from laminar to turbulent flow take place in the wake behind the cylinder, the shear layer, the boundary layer and then become fully turbulent. The drag and lift coefficients are closely related to these transitions.

The function of C_d vs. Re has been well established through a great amount of research. Several flow regimes can be defined based on these variations of C_d. It is also demonstrated that the variations of C_d vs. Re may have different behaviors with changes in free-stream turbulence and surface roughness.

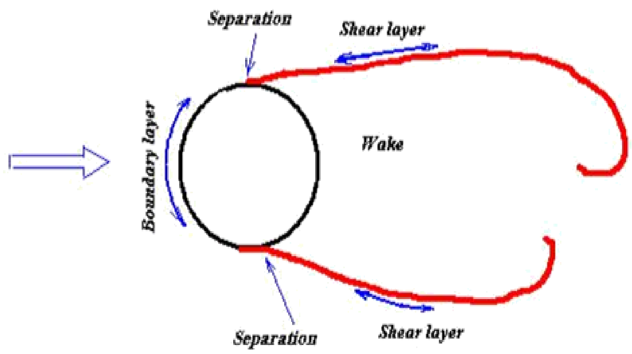

Figure 1. Flow Field around Circular Cylinder

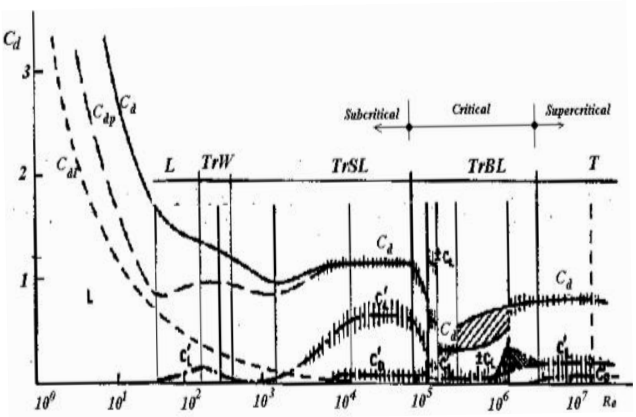

Figure 2. Variation of Cd and Flow Transitions for Single Cylinder Flow (reproduced from [5])

3. Flow Field and Transitions around Single Cylinder

Smooth cylinders immersed in disturbance-free flow have been intensively studied for decades. The variation of C_d vs. Re has been well defined over a range of Re extending to over 10^7. Figure 2 presents this relationship as complied by Zdravkovich [5], where C_{df} (drag caused by the viscous friction along the surface) and C_{dp} (drag caused by asymmetric pressure distribution on the upstream and downstream side of the cylinder) are also shown. The total drag force is the sum of these two components. Roughly, classification of five flow transitions were suggested by Zdravkovich after he extensively reviewed the previous work and studied the flow characteristics at different Re, which are marked as "L", "TrW", "TrSL", "TrBL" and "T" respectively. "L" denotes a laminar flow at very low Reynolds number of Re<200. "TrW" denotes a flow transition in the wake behind the cylinder in 200<Re<400. At Reynolds number of 350~2×10^5, transition in shear layer occurs and is denoted as "TrSL". In the range of $3\times10^5<Re<6\times10^6$, a transition in boundary layer around the cylinder takes place, which is referred as "TrBL". At the even higher Reynolds number, the flow becomes fully turbulent, denoted by "T".

The last three regimes are of our greatest interests since most of the wind tunnel study and the real wind engineering applications fall in this range. It can be observed that in the upper region of TrSL transition, Cd remains constant at Cd =1.2 when $10^4<Re<2\times10^5$. This is usually mentioned as a subcritical regime. Then in the critical regime, Cd first drops rapidly and reaches the minimum value of about 0.2~0.3, and then bounces back. Beyond Re=3.5×10^6~6×10^6, Cd remains a relatively constant value of around 0.7~0.9 again, which is often called the supercritical regime.

4. Surface Roughness Effects

Drag coefficients for a single cylinder with surface roughness have a different behavior from the smooth cylinder case. A great variety of surface roughness has been tested by different scholars. Walsh and Weinstein (1979) used longitudinally ribbed surface. Nakamura and Tomonari (1982) classified and tested two types of roughness: distributed roughness and smooth cylinder with roughness strips. They also had compared the results from these rough cylinders with smooth cylinders. Ribeiro (1991) investigated roughness generated by sand paper, wire mesh screen and ribs. Since different roughness textures compose different roughness types, even the same physical scale may produce different roughness. Some scholars suggested that the equivalent roughness parameter Ks/d should be adopted. Fage & Warsap (1929), Achenbach [1], and Guven (1980) reported drag coefficient data for rough cylinders and the change of critical Re, where the critical regime starts, with Ks/d. Figure 3 shows the variations of C_d vs. Re at different surface roughness levels based on Guven's experiments, which was re-presented by Zdravkovich.

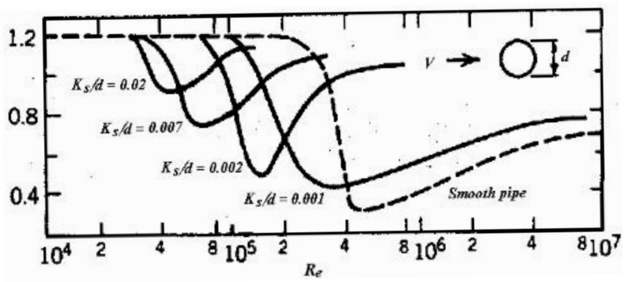

Figure 3. Effects of Surface Roughness on Drag

5. Flow Around Two Cylinders

5.1. Two Equal-Diameter Cylinders

For the case of two equal-diameter cylinders, three categories of arrangements can be classified based on the angles of the center connection line of the cylinders relative to the wind direction as shown in Figure 4: in tandem (0°), side by side (90°), and staggered (between 0° and 90°).

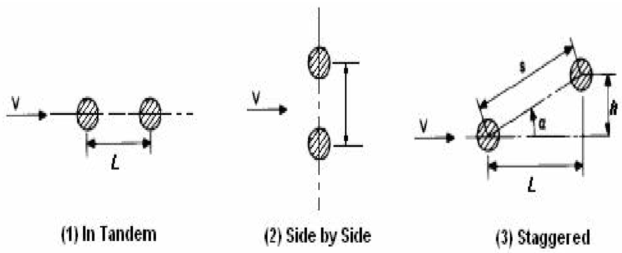

Figure 4. Schematic Diagram of Two-cylinder

Zdravkovich [4] reviewed more than 40 papers and presented a comprehensive assessment of the studies on flow around two equal-diameter cylinders at various arrangements. For two cylinders arranged in tandem, the measurements of the front gap pressures of the downstream cylinder (pressures measured at the front position of the cylinder) and the base pressures (pressure measured at the back position) of both cylinders at various spacing revealed a discontinuous jump at some critical spacing. The discontinuity was interpreted as the result of an abrupt change from one stable flow pattern to another at the critical spacing, that is, a bi-stable state. A schematic diagram shown in Figure 5 demonstrates the change of flow field with the spacing for two tandem equal-diameter cylinders. When the spacing between the two cylinders is larger than the critical spacing, the flow pattern is referred as co-shedding type, with both cylinders shedding vortices. When the two cylinders move closer, the shear layers that separated from the upstream cylinder just reattach onto the downstream cylinder at the critical spacing. Then the flow will suddenly change from co-shedding type to the reattached type.

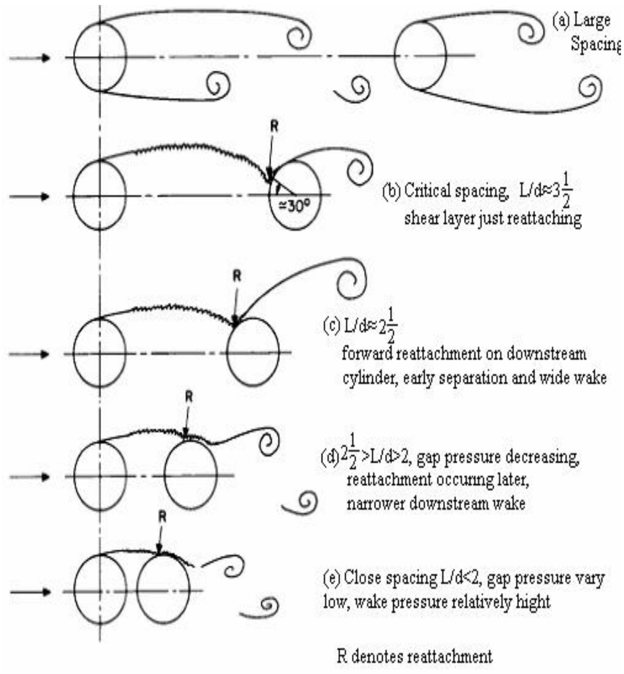

Figure 5. Flow around Tandem Pairs (reproduced from ESDU, 1984)

For side by side arrangements, a discontinuous change of drag and lift force with varying of spacing between cylinders was also observed. The bi-stable values of the drag forces coupled with two alternative values of the lift force was observed.

5.2. Two Unequal-Diameter Cylinders

Compared to the equal-diameter case, significantly fewer studies have been reported for unequal diameter arrangements. Baxendale & Barnes [3] conducted an investigation of the two unequal-diameter cylinders, in which the diameter of the downstream cylinder was two times that of upstream cylinder. The tested Reynolds number was 1.45×10^4 and the turbulence intensity was less than 1%. They studied various arrangements with different stagger angles between 0^o and 45^o. For the in-tandem case, a step change of drag coefficient for the downstream cylinder was observed, which showed a similar behavior to the equal diameter case. Luo and Gan (1992) presented their experimental work of two tandem cylinders with diameter ratio of 0.33 (upstream cylinder to downstream cylinder). The tested Reynolds number range was 3.15×10^4~8.81×10^4 based on the larger diameter. A critical spacing of 1.8d~2.2d was observed as well, where the diameter referred to the downstream diameter.

6. Experiments of Three or More Cylinders

Very few experimental works on three or more cylinders were reported. Dalton and Szabo (1977) conducted an experimental investigation on groups of two and three cylinders. Several stagger angles from 0^o and 90^o were tested. They found that the middle and downstream cylinder drag values were affected by the stagger angle noticeably more than the upstream cylinder for three-cylinder case, and these drag values strongly relied on the spacing especially when the spacing ratio is less than 4.0. The Re for their experiments ranged from 2.8×10^4 to 7.8×10^4. Sayers (1987) performed experiments on three-cylinder case with the three equal diameter cylinders arranged as an equilateral triangle, and the spacing range in $1.25<S/d<5.0$. Test were conducted at Re $=3\times10^4$ with a turbulence intensity of 0.4%. It was found that for the tested three-cylinder cluster, either the total force coefficient or the force coefficients acting on any one of the cylinders were strong functions of spacing and orientation angle.

7. Experiments of Multiple Cylinders Arranged in Tandem Conducted by Narasimhan

In the precedence study, wind tunnel experiment was conducted in the LSU Aerodynamic Wind Tunnel on a series of cylinder combinations of up to four cylinders by Narasimhan [6]. Multiple cylinders arranged in tandem were studied for both equal diameter and unequal-diameter combinations. The tested Reynolds number range was 1.1×10^4~9.0×10^4. Smooth pipe models and low turbulence flow condition were used in his study. Narasimhan found that the combined drag coefficient (based on the total force and the projected area) was much less than the basic sum of individual cylinders for all the cases, especially in the close spacing range. For the two-cylinder case, the effects of the upstream cylinder to the downstream cylinder could still be detected even at the large spacing of L/d=20. The combined drag coefficient values were suggested based on the spacing configurations for two, three and four-cylinder combinations. That study provided a preliminary insight to the wind loads on multiple cylinders arranged in tandem, although these conclusions are not directly applicable for the design because of the low Re range and smooth flow condition for the test.

8. Conclusion

All these studies demonstrated the same trend: an increase in the surface roughness will modify the flow by increasing the minimum drag coefficient and shift the critical Reynolds number to lower values. Moreover, it was observed that at Reynolds numbers lower than $2\sim3\times10^4$, the surface roughness did not have a significant effect on the drag coefficient. However, in the supercritical regime, the drag coefficient became a function of surface roughness only and was independent of cylinder Reynolds number.

Apart from that, it can be noticed that this specification (Design Code of ASCE7-02 for Pipe Rack Structures) was completely derived from the single cylinder case (Figure 3). There are no further specifications particular for pipe-rack structures, nor is the spacing configuration considered as a parameter for multiple pipes (or other structures with circular cross section) case. In the current practice of wind load design, the multi-cylinder case may be treated as the sum of independent cylinders, or often only the largest cylinder in the group was considered, depending on the judgment of the engineer. This is also the reason for the large variation in the estimation of wind loads on pipe racks.

Nomenclature

L:	Distance between the adjacent cylinders from center to center in wind direction
C_d:	Mean drag coefficient for individual cylinder
C_{df}:	Mean drag coefficient when drag is caused by the viscous friction along the surface
C_{dp}:	Mean drag coefficient when drag is caused by asymmetric pressure distribution on the upstream and downstream side of the cylinder
Re:	Reynolds number based on the diameter of the largest cylinder in the combination
K_s/d:	Equivalent Roughness Parameter
TrSL:	Transition in shear layer
TrW:	Flow transition in the wake
R:	Reattachment in flow around tandem pairs
TrBL:	Transition in boundary layer

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