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Effects of the reattachment on dry galloping in the critical Reynolds number range

Wenyong Ma[1,2], Qingkuan Liu[1,2] and Xiaobing Liu[1,2]

[1]The Key Laboratory for Health Monitoring and Control of Large Structure
Shijiazhuang Tiedao University, Hebei province, P.R.C

[2]Department of Wind Science and Engineering
Shijiazhuang Tiedao University, Shijiazhuang City, Hebei Province, P.R.C

Abstract

Large amplitude vibrations of circular cylinders in the critical Reynolds number range are reproduced in wind tunnels. Displacements and wind pressure for the cylinders are measured synchronously to reveal the characteristics of aerodynamic force for the vibrating cylinders in a Reynolds number range where flow re-attaches on the rear of the cylinder. Effects of these reattachments on the aerodynamic forces and the vibrations are discussed. The results show that the reattachment can produce unsteady aerodynamic force and excite large amplitude vibration when it forms unstable separation bubble at the early critical Reynolds number range. Once it develops stable separation bubble, the reattachment mitigates the vibrations by creating strong negative aerodynamic damping.

Introduction

Aerodynamics of circular cylinder in the critical Reynolds number range have attacked many attentions because of its complicated flow state and sensitivity to disturbances. “Drag crisis” is commonly used to designate fall in the drag coefficient to its minimum value In recent years, large amplitude vibrations of the dry inclined circular cylinder in the critical Reynolds number range have been observed in the laboratory [1, 2] and named as dry galloping [3]. Studies [4-10] have been made to clarify the mechanism of this vibration. The most of the tests of having large amplitude vibrations in the critical Reynolds number range carried out with skewed cable model in wind tunnel [1-5, 9]. This may imply that being skewed is a necessary condition for a circular cylinder to have a large vibration in the critical flow state. Matsumoto [3] explains that the axial flow on inclined cables can mitigate vortex shedding and excited the vibration. Another branch of the studies on this topic focus on effects of the surface roughness or lack of circularity on aerodynamics and vibrations. A. Benidir, O. Flamand [7] had carried out static wind tunnel tests on the circularity-defect cable model at normal wind to show the aerodynamic stability in the critical Reynolds number range. G.Matteoni and C. T. Georgakis [5] also carried out the dynamic tests to clarify the mechanism of dry galloping. Although these studies reveal a significant impact of the surface roughness on aerodynamic and instabilities, they all believe that dry galloping only occurs in the critical Reynolds number. As N. Nikitas and J.H.G. Macdonald [4] state, ‘The inherent flow pattern unsteadiness in the critical *Re* range and its interaction with turbulence and inclination are important in creating the dry galloping conditions’. However, the flow in the critical Reynolds number is not only one state. The discovery of a one-bubble regime by Bearman [11] in 1969 made a detailed classification of the critical Reynolds number. M.M.Zdravkovich [12] has summarized it. In the present study, the Reynolds number is from 1.2×10^5 to 4.3×10^5 which cross over the subcritical (TrSL3), precritical (TrBL0), one-bubble(TrBL1) and two-bubble(TrBL2) regimes. ‘Drag crisis’ normally occurs in a range of TrBL0 to TrBL2. On the other hand, characteristics of flow around the circular cylinder in each regime had been studied for many years, but the states between the regimes which normally is unsteady and easy changing have rarely been revealed. Several unique features in the transition of two regimes such as jump of the lift coefficients [7, 13] are worth further study. More importantly, the relation of the flow state and dry galloping needs to be clarified in more details.

This study aims to confirm which regime in the critical Reynolds number range may induce large amplitude vibration. A series of static and dynamic tests were carried out for a smooth circular cylinder at normal wind. The aerodynamic forces of the stationary model and displacement of elastic mounted model were measured. The characteristics of the aerodynamic force are discussed with much attention on the transition between two regimes in the critical Reynolds number range. The relation between flow state and dry galloping is revealed by comparing aerodynamic forces and large vibrations.

Experiment Set up

Static and dynamic tests were carried out to obtain the aerodynamic forces and displacements. To reduce an effect of uncertainties of the circularity, three angles of attack were adopted for both static and dynamic tests. They are termed as first, second and third test. The same model, end plates, wind velocity and other setups also were used in all tests in this study to improve the similarity of static and dynamic tests. The only man-made difference of static and dynamic tests is the supporting system in which four springs are used in dynamic tests instead of steel bar in static tests.

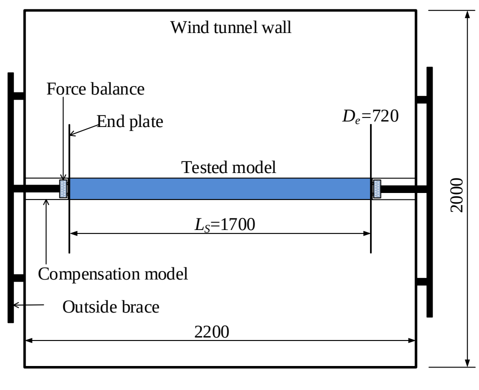


Figure 1. Sketch of wind tunnel arrangement.

All tests were carried out in a 2.2m wide, 2m high and 5m long working section in STDU-1 wind tunnel at Shijiazhuang Tiedao University. The wind velocity in this section was with in ±0.1%

and longitudinal turbulence intensity was around 0.1% at wind speed 56m/s. The model had length L=1.7m and diameter D=120mm. This set up had aspect ratio of 14 and blockage ratio of 6%. End plates with diameter D_e=6D were used at both ends to reduce the end effects Compensation models were also adopted in the static tests to cover high-frequency balances at both ends. Each elastic mounted end is made of four vertical springs and an end bar. This setup can provide single-degree-of-freedom of vertical vibration with natural frequency f=2.47Hz and structural damping ratio ζ=0.15%

Results

Fig. 2 shows the curve of aerodynamic force coefficients against Reynolds number. To reduce possible random error, the tests had been repeated three times under almost the same condition which is indicated by subscript in drag and lift coefficients in Fig. 2. In general, mean drag and lift coefficients can be reproduced very well in subcritical Reynolds number range shown in Fig. 2. At the critical Reynolds number, a small scatter is observed in drag coefficients at three measurements. Meanwhile, the lift coefficients have significant changes when Reynolds number is entering or leaving the critical Reynolds number range. The variation of mean drag coefficients with Reynolds number shows an obvious drop which is known as 'drag crisis.' Instead of continuously decrease during the whole process, the drag coefficients undergo six stages with increasing Reynolds number which is constant; the continuously decreases, the first sudden drop, the first step, the second sudden drop, the second step. Based on the M.M. Zdravkovich's classification, the continuously decrease corresponds to precritical Regime (TrBL0); the first step represents the one bubble regime (TrBL1), and the second step indicates the two-bubble regime. The scatter of drag and lift coefficients occur at the first and second sudden drops which represent transition form TrBL0 to TrBL1 and TrBL1 to TrBL2. CL1 in Fig. 1 shows a surprising variation in a Reynolds number range corresponding to the first sudden drop in drag coefficient by changes its value from -1.24 to 1.24. These will be discussed later.

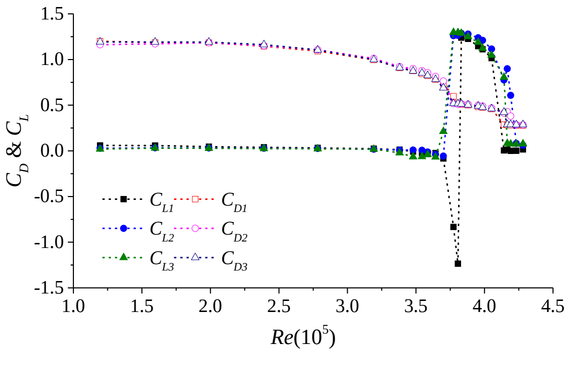


Figure 2. Variation of mean aerodynamic force coefficients with Reynolds number.

The dynamic tests were carried out by using the same model at the same wind velocities to check the possible vibrations in the critical Reynolds number range. The mean and standard deviation of the vertical normalized displacement are shown in Fig. 3. D_v and D_{vr} represent the mean and standard deviation of the vertical displacement.

Statistic results of displacement shown in Fig. 3 provide two important information. The flow state can be identified by the mean vertical displacement. The mean lift in one bubble regime (TrBL1) can change the balance position reflected as the nonzero mean vertical displacement in Fig. 3. Once flow enters two bubble regime (TrBL2), the cylinder will move back to the initial balance position. Large standard deviation of vertical displacement, which means the server oscillation, indicates that the oscillation occurs just before one bubble or two bubble regime (TrBL0-1 and TrBL1-2).

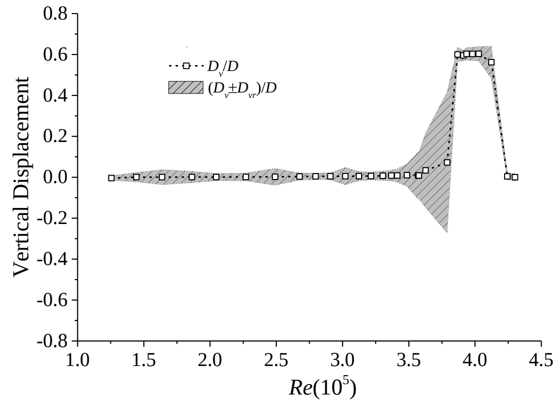
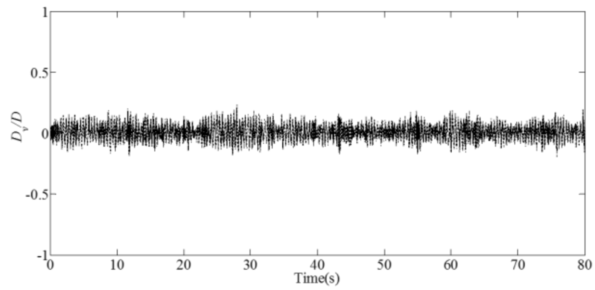
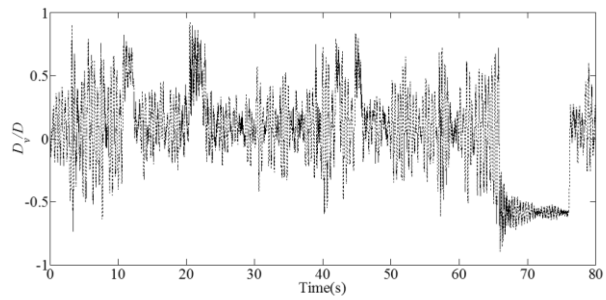


Figure 3. Variation of mean aerodynamic force coefficients with Reynolds number

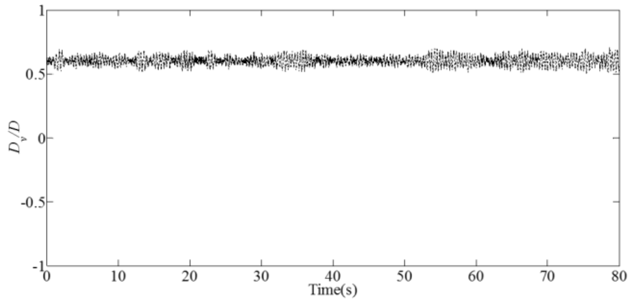
Fig. 4 shows the time histories of the vertical normalized displacement in TrBL0-1 at Re=3.8×10^5. The oscillation is not stable, and the cylinder jumps from initial balance position to new position. The amplitude is much larger when the cylinder oscillates at the initial position. An obvious decay can be found once the cylinder moves to a new position due to the mean lift; otherwise, the oscillation becomes stronger when the cylinder moves back to the initial position. This implies that the oscillation can not be excited or sustained in one bubble regime. The large oscillation is more likely induced in TrBL0-1 regime. When the transition occurs very close to the rear of the cylinder, the regular vortex shedding is destroyed, and the stable reattachment is not formed yet. The oscillation is excited by occasionally reattaching in short time and limited length, and flow around the cylinder may be influenced by the oscillation with interaction. This oscillation disappears as the Reynolds number enters one bubble regime with a stable reattachment on one side of the cylinder.



(a) Re=3.5×10^5 in TrBL0 regime



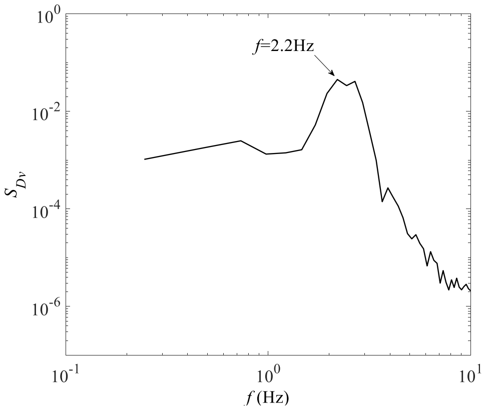
(b) Re=3.8×10^5 in TrBL0-1 regime



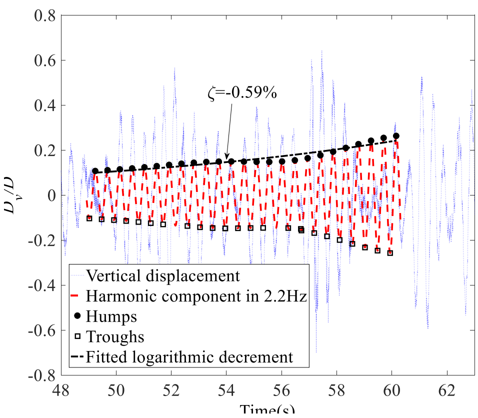
(c) Re=4.0×10^5 in TrBL1 regime

Figure 4. Time histories of the oscillation at various Reynolds number (a) Re=3.5×10^5 in TrBL0 regime, (b) Re=3.8×10^5 in TrBL0-1 regime and (c) Re=4.0×10^5 in TrBL1 regime

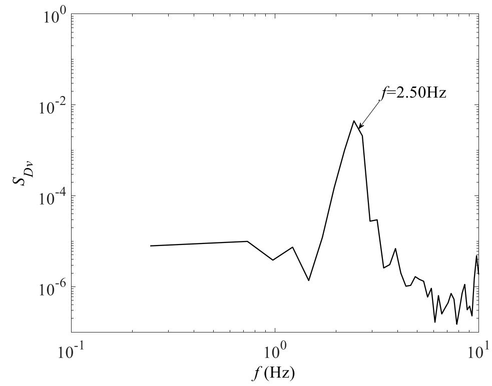
Two short period vibration in TrBL0-1 at Re=3.8×10^5 are selected to illustrate their spectra of normalized displacement and damping ratios shown in Fig. 5. The amplitude of oscillation at the initial balance position (the mean of the displacement is zero) in Fig. 5 (a) and (b) is large, and it is mainly contributed by a relatively wide band of frequency around f=2.2Hz. The damping ratio of this harmonic components is -0.59% which means the oscillation is excited with negative aerodynamic damping. On the other hand, amplitude of the oscillations at the new balance position at which the mean of normalized displacement is -0.58 in Fig. 5 (c) and (d) and decrease with time. The band of dominant frequency is narrow, and their harmonic components mainly reduce the oscillations with damping ratio 1.75%. These damping ratios are much larger the structural damping ratio 0.15%. The large positive damping ratio confirms that separation bubble can reduce the vibration with positive aerodynamic damping.



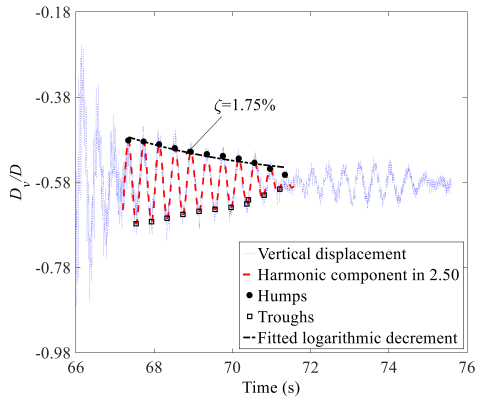
(a) Spectrum of normalized vertical displacement in t=48s-63s



(b) Damping ratio in t=48s-63s



(c) Spectrum of normalized vertical displacement in t=66s-76s



(d) Damping ratio in t=66s-76s

Figure 5. Spectra of normalized vertical displacement and damping ratios in TrBL0-1 regime at Re=3.8×10^5 at the various period.

Conclusions

Aerodynamic forces in the transitions between the three flow regimes precritical (TrBL0), one-bubble (TrBL1) and two bubbles (TrBL2) in the critical Reynolds number range show significant differences with in these three regimes. The spikes and jumps in lift coefficients imply that the reattachment is not stable in the transitions which make no regular vortex shedding and possible large amplitude vibration. Large amplitude oscillations are only observed in the transitions in the present study. They agree well with the results of static force test. By comparing the both, the large amplitude oscillation in the critical Reynolds number regime is more likely induced by unstable reattachment instead of stable separation bubble. On the contrary, a stable separation bubble reduces the amplitude of oscillation by the positive aerodynamic damping.

Acknowledgments

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