Streaming numerical simulation of cylinder pier laminar flow and control measure research on external concave rib

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Abstract

This paper utilizes FIUENT Software to simulate the appearance, development and change of vortex shedding in cylinder streaming under low Reynolds number, calculates displacement of pressure coefficient and changing rules of lift and resistance coefficients on cylinder surface and introduces working conditions with 10 different rib heights on cylinder surface to do comparative calculation so as to acquire the control measures of concave rib streaming on cylinder surface. Calculation results show that the application of concave rib on cylinder surface could help effectively control vortex shedding of cylinder surface, reduce its resistance and restrain vibration. Calculation results of each parameter are consistent with those in literatures. When height of concave rib is 0.12D, effect of restraining streaming is the best. At this moment resistance coefficient of cylinder surface is 1.0849 which decreases about 39.609% comparing with its resistance coefficient without concave rib. Meanwhile lift coefficient reduces by 79.691%. The results above provide references for control measures of cylinder pier streaming.

Keywords: Low Reynolds Number; Surface Concave Rib; Cylinder Pier; Control Measure; Restrain Streaming;

1 Introduction

Except for being affected by wave, river-crossing and sea-spanning bridges are also affected by environmental loads like wind, water current, earthquake, etc. Researches show that response of bridge pier structure presents different levels of increasing when various random loads do coupling effect on wave. Reliability and security of structure may be influenced when serious. In terms of the current technical means, it is difficult to control vibration response of structure through directly changing the size of environmental load. Therefore, it becomes the hot spot in bridge research field among nations to control damage and destruction of environmental load on deep-water bridges. Research on controlling streaming damage of wave on bridge pier has become another difficult problem after scour and fatigue. Therefore mastering the streaming features of fluid is very important to engineering practice. With the rapid development of computer technology, numerical simulation has gradually become a new method to study cylinder streaming in recent years because it keeps advantages of simple modeling, short cycle, low cost and flow visualization[1]. This paper utilizes FLUENT Finite Element Software to do numerical simulation on cylinder streaming while Re is 400 (Reynolds number namely Re is the key factor to influence cylinder streaming. When it caters for $300 \leq Re \leq 3\times10^5$, this is called sub-critical zone. At this moment, boundary layer still keeps to be laminar separation while wake has become turbulent vortex street.). It also analyzes resistance coefficient, lift coefficient, position of separation point and changing rules of flow field of cylinder streaming. It studies the control measures of cylinder streaming through introducing concave rib on the surface of pier. It does comparative analysis on effectiveness of different heights of concave ribs and proposes optimizing suggestions to control rib height of cylinder streaming.

2 Similarity comparison of physical parameter models

Physical Model: In order to simplify calculation, it is supposed that height of the simulated water tank along the flow direction is 1000mm, width of it perpendicular to flow direction is 200mm, distance between upstream inlet boundary and center of bridge pier is 200mm and center of bridge pier is 800mm away from downstream outlet boundary. Being at left side and right side of cylinder center, sketch of physical model in fluid region is shown in Figure 1. Relevant modeling parameters and boundary conditions are seen as Follows.

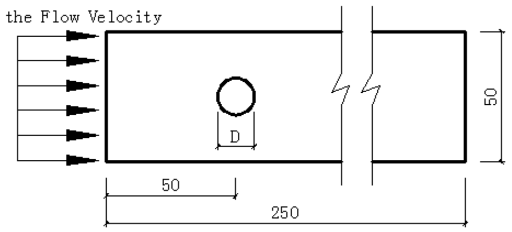

FIGURE 1 Sketch Of Physical Model In Fluid Region

Characteristic parameter: velocity u of upstream flow is 0.01m/s, its fluid density ρ is 1000kg/m^3, fluid dynamic viscosity coefficient u is 10^{-3}kg/m.s, diameter of cylinder d is 0.04m and $R_e = \rho u\, d/u$ is 400.

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Solution setup: model in this chapter utilizes FLUENT Fluid-solid Coupling Software to do analog computation. In order to simulate unsteady flow phenomena of Karman Vortex Street and vortex generation behind cylinder, Unsteady is chosen in time option and 2nd-order Implicit format is chosen in Unsteady Formulation to improve the computing accuracy [2]. Discrete format uses Second order Upwind [3].Pressure and velocity couplings apply SIMPLEC Algorithm to calculate disturbance of fluid, which may acquire high accuracy. Time step is set to be 0.5 and maximum iteration number of each step is set to be 40.

Boundary condition: water inlet in calculation region uses velocity inlet boundary condition Inlet. Fluid outlet boundary condition utilizes free outflow outlet. Surface of cylinder uses non-slip boundary condition. Upper and lower sidewalls in calculation region use wall boundary condition.

Mesh generation: do local refinement on meshes in the region near cylinder so as to improve the accuracy of calculation result.

2.1 SIMULATION OF MODEL

According to Literature [4], definition of circumferential average pressure coefficient C_P on the surface of cylinder is acquired as follows:

$$C_P = \frac{P - P_0}{0.5\rho u^2}. \quad (1)$$

In this definition, P stands for practical pressure value of each circumference point on cylinder surface whose unit is Pa. P_0 means incoming flow pressure from infinity whose unit is Pa. u is velocity of incoming flow whose unit is m/s. ρ is density of fluid being 1000kg/m^3.

According to computational analysis on models, we acquire the result of circumferential average pressure coefficient C_P on cross section of cylinder changing with angels. It is shown in Figure 2.

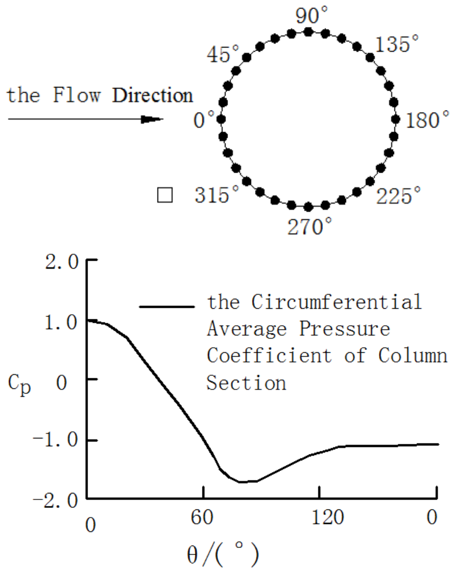


FIGURE 2 Mean pressure coefficient of cylinder surface

In Figure 2, distribution of circumferential average pressure coefficient on cross section of cylinder coincides well with experimental and computational results in Literature [4-8]. Theoretical standpoints of Nishimura and Taniika [9] say that separation point of fluid appears at the inflection point of average pressure coefficient. It is known from Figure 2 that separation point of model appears near 85° and 275°, which is basically accordance with condition of Literature [4, 5, 7]. Utilizing this model to simulate disturbance of fluid on cylinder pier keeps high simulation.

2.2 RESISTANCE COEFFICIENT AND LIFT COEFFICIENT

When streaming of fluid happens to cylinder, periodic alternating force on the surface of cylinder mainly comes from friction and pressure difference, which could be divided into resistance along direction of fluid motion and lift perpendicular to fluid motion [5]. Lift is the vertical component force of fluid's total force affected on streaming object in incoming flow direction. It mainly comes from the pressure difference of fluid. Resistance namely frictional resistance is the sum of shear stress affected on the surface of object in the direction of incoming flow [10]. In terms of cylinder in this chapter, both streaming resistance and lift should be taken into account. According to Literature [11], do non-dimensionalization on resistance and lift of each working condition during cylinder streaming process. Resistance and lift coefficients of each section along column length direction are shown in the following formula.

$$C_L = \frac{2F_L}{\rho U^2 D},\ C_D = \frac{2F_D}{\rho U^2 D}. \quad (2)$$

In this formula, F_L stands for the lift of unit axis of cylinder cross section and F_D is the resistance of it.

Figure 3 shows time history curves of resistance coefficient and lift coefficient on cylinder surface under the condition of Re being 400. Its calculation result basically coincides with Literature [6, 12]. There exists one boundary line in downstream vortex of cylinder. Fluid on the boundary line comes from vortex shedding on lower and higher surface of cylinder [13-17]. When periodic vortex shedding lies on higher part of cylinder, lift on its surface becomes the highest. At this moment, back vortex shedding gradually moves to downstream. When it reaches the center of cylinder, lift changes to zero. When vortex shedding reaches downstream, lift becomes the minimum negative value. Therefore, average value of lift coefficient is zero with vortex shedding continuing moving like this. After resistance coefficient becomes stable, its average value is 1.687. Based on periodic vortex shedding of flow behind cylinder, time history curves of lift coefficient C_L and resistance coefficient C_D are acquired. Lift and resistance coefficients present periodic changes. Vibration period of resistance coefficient is half of that of lift coefficient, which means that its vibration frequency is 2 times of that of lift coefficient. While stable amplitude of lift coefficient is far higher than that of resistance coefficient. Features of cylinder streaming are in line with Literature [7]. Figure 3 to Figure 7 show the pressure nephogram, velocity contour line, path line of flow field and vorticity of flow field included in the calculation results.

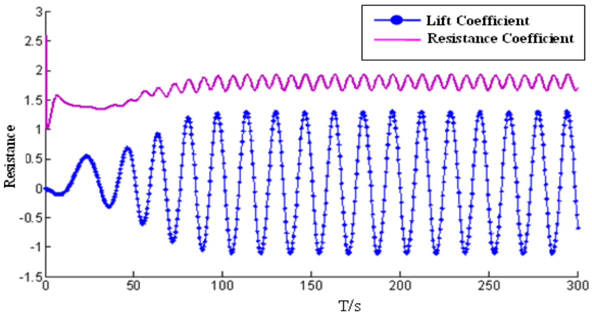


FIGURE 3 Resistance coefficient and lift coefficient of cylinder with reynolds number being 400

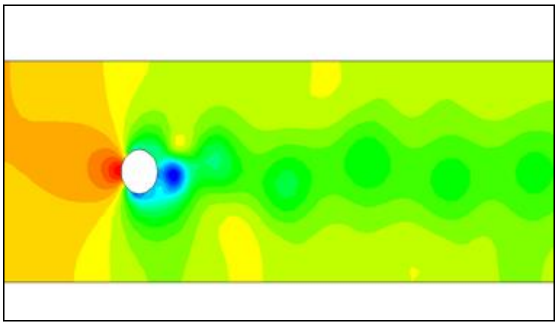


FIGURE 4 Pressure nephogram (unit: Pa)

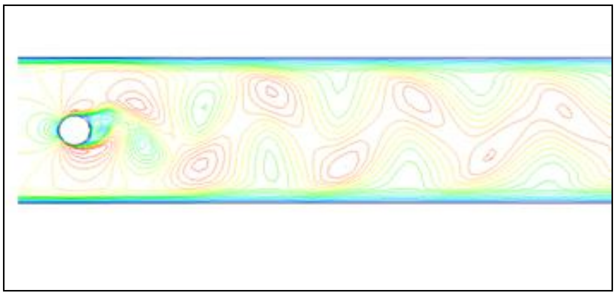


FIGURE 5 Velocity contour line (unit：m.s^{-1})

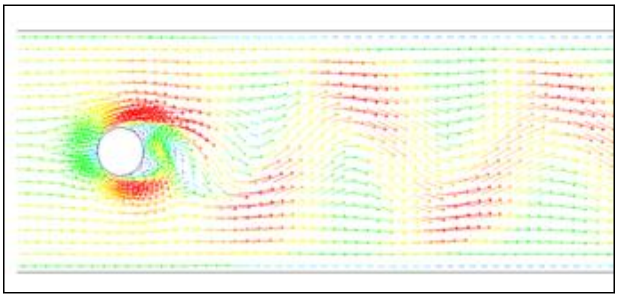


FIGURE 6 Path line of Flow Field (Unit:m.s^{-1})

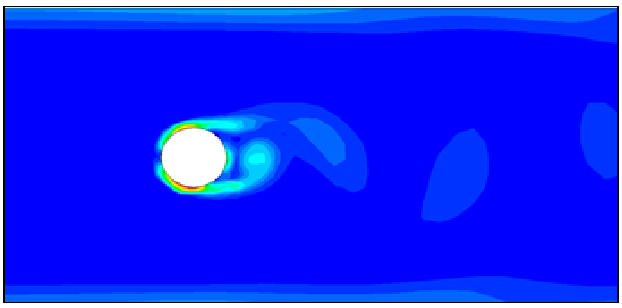


FIGURE 7 Vorticity of flow field (Unit:s^{-1})

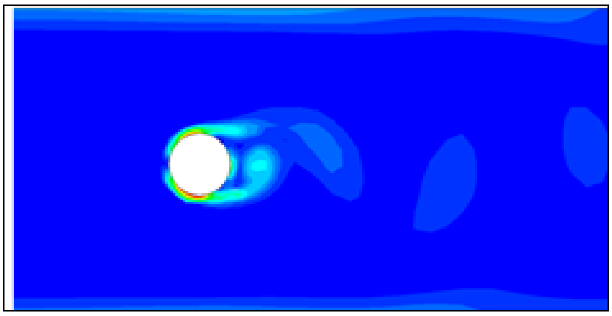
3 Longitudinal concave rib added on pier surface

Using control measures of aerodynamics for reference, vibration characteristics of pier affected by flow could be improved through changing the roughness of pier surface. This section utilizes the way of adding concave ribs to improve its vibration characteristics. Comparative analysis is done between the original pier models and 10 groups of others with different rib heights under fluid-solid coupling effect. This verifies feasibility and applicability of the measure.

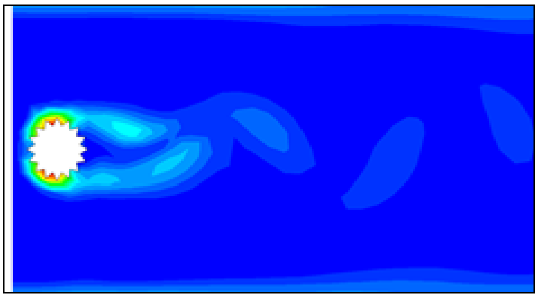
Ten groups of pier models with different rib heights are established under the premise of not weakening the original carrying capacity. Except for the changing of rib height, other conditions are all the same. For the purpose of leading model research achievement to have authenticity, cross section models under 6 different working conditions are established according to different ratios between rib height h on pier surface and diameter d of relevant cross section. Table 1 shows these cross section models and calculation results. It is seen from analysis on these working conditions that both resistance coefficient and lift coefficient present different levels of reduction when circumference utilizes concave rib cross section. Meanwhile the lower value of lift coefficient is still higher than resistance coefficient. This illustrates that changing cross section of cylinder to be concave rib under the same external diameter could help effectively control streaming. Further analysis on the 10 working conditions in the table tells that effect of controlling streaming becomes the best when concave rib height is 0.12D. In the meantime resistance coefficient on cylinder surface is 1.0849 which is 39.609% lower than the number without concave rib. Lift coefficient also reduces by 79.691%.

TABLE 1 Calculating results under different rib heights

Condition	High Heel	resistance coefficient	resistance Influence coefficient (%)	lift coefficient	resistance Influence coefficient (%)
1	0.000D	1.6870	0.000	1.3029	0.000
2	0.07D	1.1342	-32.768	0.5208	-60.028
3	0.080D	1.0582	-37.273	0.3284	-74.795
4	0.09D	1.0162	-39.763	0.3913	-69.967
5	0.100D	1.0246	-39.265	0.3234	-75.178
6	0.110D	1.0802	-35.969	0.3681	-71.748
7	0.120D	1.0188	-39.609	0.2646	-79.691
8	0.130D	1.0401	-38.346	0.3903	-70.044
9	0.140D	1.0849	-35.691	0.4052	-68.900
10	0.150D	1.0567	-37.362	0.7472	-42.651

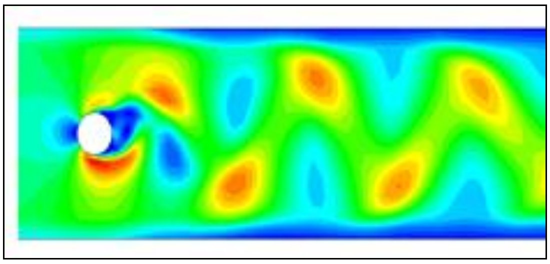


(a) Condition 1

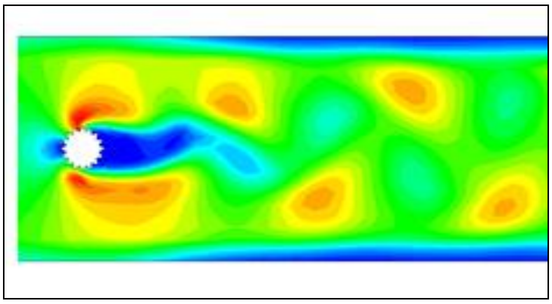


(d) Condition 7

FIGURE 8 Vorticity of flow field (Unit:s^{-1})

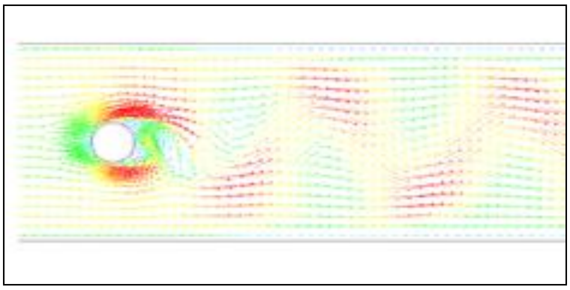


(a) Condition 1



(b) Condition 7

FIGURE 9 Dynamic pressure nephogram (unit: Pa)



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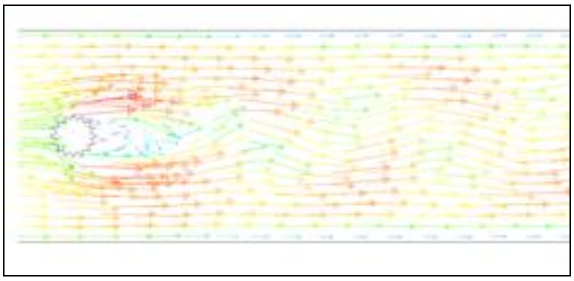

(d) Condition 7

FIGURE 10 Path line of flow field (Unit: $m.s^{-1}$)

Figure 8 to Figure 10 show vorticity of flow field, pressure of flow field and path line of flow field under 7th working condition being with concave rib and 1st working condition being without concave rib. These figures tell that regular vortex shedding appear behind the cylinder when fluid flows past it. After cylinder is changed into concave rib, wake flow of cylinder obviously becomes narrower and wake of vortex shedding becomes longer. It means that period of vortex shedding becomes longer and Strouhal number changes to be lower. It is known from Figure 10 that the existing of concave rib delays and weakens the interaction of wake flow on top and bottom junction zone of cylinder back. This helps better control cylinder streaming.

4 Conclusions

In terms of cylinder streaming with Re being 400, the application of cylinder and fluid field model in this chapter helps better simulate distribution of average pressure coefficient on cylinder surface and predict position of separation point and formation of vortex shedding. Its calculation results of lift coefficient and resistance coefficient on cylinder surface have high accuracy.

Being without concave rib, regular vortex shedding would appear when fluid flows past cylinder. Being with concave rib, wake flows of each working condition become narrower and weaker in different levels when fluid flows past cylinder. Wake of vortex shedding also becomes longer to various degrees. This explains that vibration period of vortex shedding becomes longer.

Side-to-side vibration regularity of pressure path line in the tail part of cylinder obviously becomes weaker after it is designed to be concave rib. Pressure amplitude of fluid on cylinder surface also becomes lower in different levels.

It is seen from path line of flow field in which deflector is set that under the condition of slit width being equal to or less than 0.12D, this deflector delays interaction of wake flows in junction zone between top and bottom parts of cylinder and also weakens its velocity. Therefore, the effect of choosing rib height to be 0.12D is the best on the basis of not weakening carrying capacity of bridge pier.

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