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INTERACTION BETWEEN A THICK AXISYMMETRIC BOUNDARY LAYER AND A WAKE IN THE FLOW OVER A BENT CYLINDER

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ABSTRACT

Flow over the bend in a cylinder with one segment in axial flow and the other yawed has been investigated. When the boundary layer on the axial segment, which determines the end condition for the yawed segment, is laminar, regularly distributed streamwise strucures appear. Their lateral spacing is proportional to cylinder radius and independent of boundary layer thickness, cylinder Reynolds number and yaw angle. When the boundary layer is turbulent, its interaction with the cylinder wake is confined to a smaller region, and formation of streamwise structures is suppressed.

INTRODUCTION

Flow over a long cylinder with its axis parallel to the main stream results in the development of a very thick axisymmetric boundary layer. When the cylinder is slightly yawed to the main flow, the boundary layer becomes highly asymmetric and eventually turns into a vortex wake as the yaw angle is increased. The present investigation concerns bent cylinders with an upstream segment aligned with the main flow and a downstream segment yawed to the main flow. In this case an axisymmetric boundary layer develops on the upstream segment, while at locations remote from the bend, a vortex wake forms on the yawed segment. In the vicinity of the bend itself, an interaction between these two types of flow is to be expected, and attention is concentrated on this region (Fig. 1).

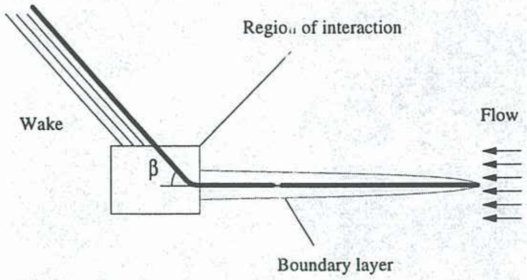


Figure 1: Location of the region of interaction.

THE EXPERIMENTS

The results presented here have been obtained by flow visualisation experiments carried out in a long water channel. Hydrogen bubbles continuously generated from a straight wire were used to visualise large regions of the flow, while a kinked wire was used to mark individual streak lines. Pulse-generated bubbles from straight wires were used to give time-lines. The models were of overall length 3 m. Each consisted of two circular-cylinder segments; four models (2.3 mm, 4 mm, 9.5 mm and 25 mm in diameter) had segments rigidly connected at an angle of 30°, and two models (6 mm and 16 mm in diameter) had a flexible joint which allowed the angle between the segments to be varied. In most cases, the length of the axially aligned upstream segment was x = 2000 mm.

Variations of Reynolds number (the primary effect of which is to determine the laminar, transitional or turbulent state of the axisymmetric boundary layer approaching the bend), cylinder diameter and angle β between the two cylinder segments have been investigated.

Flow speeds U_o ranging from 70 mm/s to 250 mm/s were used, corresponding to Reynolds numbers $Re_x = xU_o/\nu$ (where ν is the kinematic viscosity of the fluid) ranging from 1.4×10^5 to 5×10^5.

OBSERVATIONS

Typical flow structures for a laminar boundary layer approaching the bend

The flow pattern in the vicinity of the bend, with an approaching laminar boundary layer and the downstream segment of the bent cylinder yawed at an angle of $\beta = 36°$, is shown in Figure 2; the length of the upstream segment is x = 2400 mm and the Reynolds number $Re_a = U_o a/\nu$ (where a is the cylinder radius) is 280.

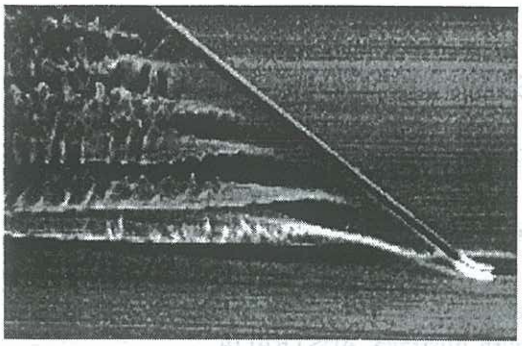


Figure 2: Streamwise structures in the wake of the yawed cylinder: β=36°, Re_a=270, x/a=800.

Based on the data of Bull and Dekkers (1992), an isolated yawed cylinder with β= 36° would be expected to shed vortices inclined at an angle of about 40° to the flow direction, and such vortices do occur at some distance away from the bend (Fig. 3).

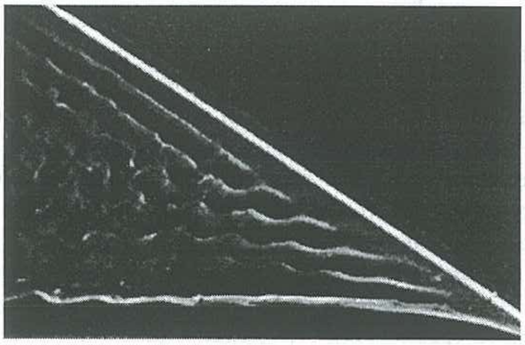


Figure 3: Coexistence of vortex shedding and streamwise structures: β=30°, Re_a=140, x/a=1000.

However, near the bend, streamwise vortex structures rather than oblique vortices are observed. The structures shown are made visible by a vertical bubble wire in front of the plane of the bent cylinder. A complementary similar set of structures can be identified by visualisation in a plane just behind that of the bent cylinder. A cross-section of the wake, in a view looking upstream, is sketched in Figure 4.

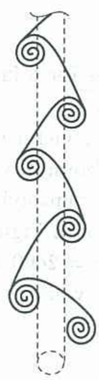


Figure 4: Schematic cross section of the wake.

The sequence of streamwise stuctures in Figure 2 is initiated by the presence of the bend. The lowermost structure seems to be generated by the interaction of fluid originating from the immediate vicinity of the bend, which is convected along the yawed cylinder segment, and vortex motion resulting from instability of the shear layers separating from the yawed cylinder. A bubble wire placed just downstream the bend reveals this convected fluid in helicoidal motion on the leeward side of the yawed cylinder (Fig. 5). The resulting vortex structure is eventually swept away by the main flow. Similar convective helicoidal motion is observed to feed into the subsequent structures, but in these cases the convected fluid originates from the mainstream rather than from the vicinity of the bend.

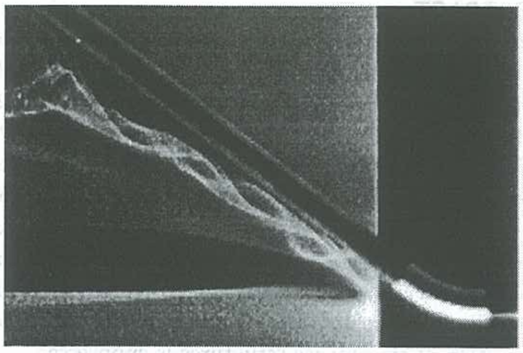


Figure 5: Secondary flow along the leeward side of the yawed cylinder: β=36°, Re_a=270, x/a=800.

A further striking feature of the flow apparent in Figure 2 is the presence of almost vertical striations on the streamwise structures. These are shown in more detail, in a perspective view of a pulse of hydrogen bubbles from a vertical wire in the wake, behind the plane of the bent cylinder, in Figure 6. They appear to be vortices on the braids of vortex sheet joining the main vortex cores, and seem to be similar to the streamwise vortices associated with the three-dimensional instabilities observed by Williamson (1996) in the vortex wake of a cylinder normal to the flow.

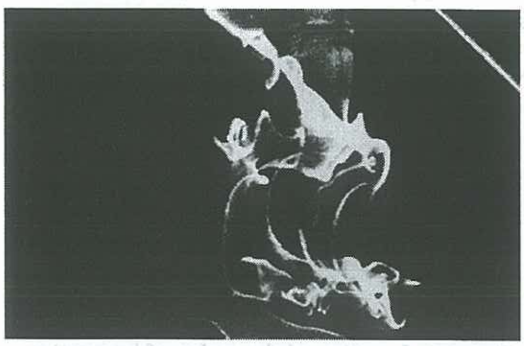


Figure 6: Instabilities in the shear layer: β=36°, Re_a=270, x/a=800.

Role of the laminar axisymmetric boundary layer in streamwise structure formation

The effect of the thickness of a laminar axisymmetric boundary layer approaching the bend is indicated by experiments on the series of models of different diameter, all with $\beta = 36°$ and axial segment of length x = 2000 mm. As the cylinder diameter is varied from 2.3 mm to 25 mm, the ratio of boundary layer thickness to cylinder radius δ/a varies from about 8 to about 1.2 . This appears to have no significant effect on the lateral spacing of the streamwise structures. Despite the variation in δ/a, the spacing between individual streamwise vortices is found to be directly proportional to the radius of the cylinder. In all cases, the average spacing σ between streamwise vortices is given by

$$\frac{\sigma}{a} \approx 8.$$

That the flow patterns are independent of the laminar boundary thickness is confirmed by experiments, at $Re_a = 140$, with different lengths of the axial segment of the bent cylinder. A 4-mm-diameter cylinder with $\beta = 30°$ was tested with x = 0, 50 mm, and 2000 mm, giving a variation in δ/a from zero to about 5.8. Again there is no discernible change in the spacing of the streamwise flow structures (Figures 7a and 7b).

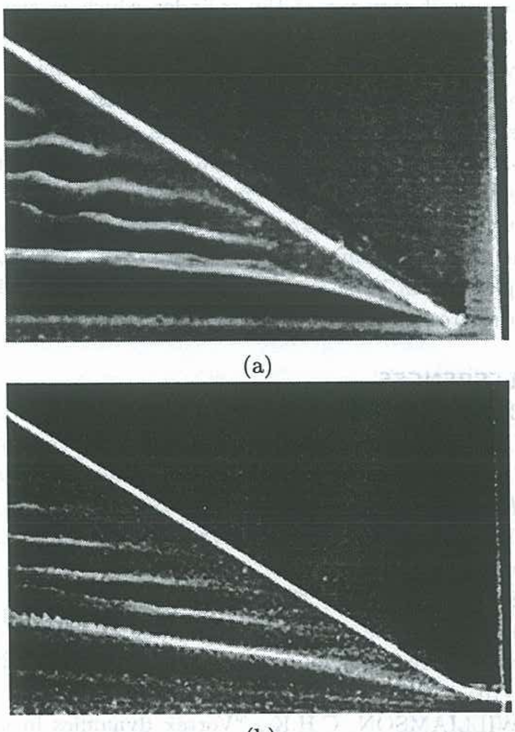


Figure 7: Effects of axial segment length on wake patterns: β=30°, Re_a=140
(a) x/a=0; (b) x/a=1000.

The "bent" cylinder with x = 0 corresponds to an isolated straight cylinder with a free end, as previously tested by Ramberg (1983) who obtained similar flow patterns.

The experiments indicating independence of δ/a also imply independence of Re_a for laminar boundary layer flow.

Influence of the angle of yaw

The influence of the angle of yaw on the structure of the wake has been investigated over a range of 90° to 15°.

For angles ranging from 90° (corresponding to the downstream segment of the model normal the the flow) down to 40°, the predominant feature of the wake is vortex shedding similar to that observed on long inclined cylinders. As the angle decreases below about 50°, a streamwise structure appears at the lower end of the vortex wake. As the angle is further decreased, additional streamwise structures appear, and the edge of the oblique-shedding region recedes from the bend.

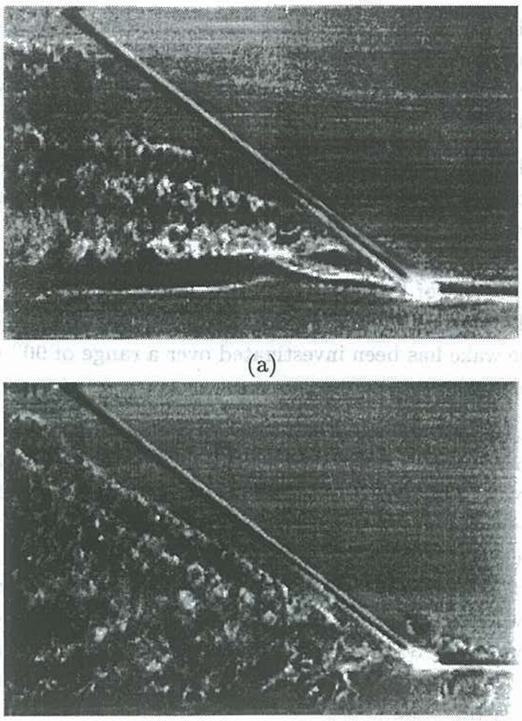
When β falls below 15°, the development length of the streamwise structures becomes so large that their interaction with the oblique vortices cannot be observed in the available length of the working section of the water channel.

This series of experiments also indicates that the spacing of the streamwise structures does not depend on the yaw angle.

Influence of the boundary layer turbulence

When the boundary layer approaching the bend is turbulent, there is still oblique vortex shedding from the yawed cylinder, but the regular pattern of streamwise structures no longer occurs. At most there is a suggestion of one rather ill-defined such structure, but it is difficult to distinguish between a turbulent streamwise vortex structure and the turbulent wake generated by the axisymmetric turbulent boundary layer from the upstream segment of the cylinder.

A transitional boundary layer, which is intermittently laminar and intermittently turbulent, produces wake patterns which are alternately typical of laminar boundary layer flow (Fig. 8a) and typical of turbulent boundary layer flow (Fig. 8b) as described above.



(a)

(b)

Figure 8: Effects of approaching boundary layer state on wake patterns: β=36°, Re_a=270, x/a=800; (a) laminar; (b) turbulent.

INTERPRETATION

To explain the formation of the three-dimensional streamwise structures, we can make use of an extrapolation of the two-dimensional mechanism of vortex shedding in the wake of a cylinder normal to the flow, as described for instance by Perry, Chong and Lim (1982). In laminar two-dimensional flow, a recirculating bubble forms on one side of the leeward region of the cylinder and grows until it is released into the main flow. At this moment a new bubble starts to form on the other side and develops in the same way. Repetition of this process results in the alternate shedding of counter-rotating vortices from the two sides of the cylinder, forming the well know von Kármán vortex street.

In the present situation, we envisage a similar process taking place. However, the recirculating fluid in the cylinder wake is convected along the leeward side of the yawed segment, away from the bend, by a favourable pressure gradient the origin of which will be explained later. This mechanism generates a helicoidal fluid motion, as shown in Figure 5. This secondary flow is continuously fed by recirculating fluid resulting from the separation of two shear layers from the surface of the yawed cylinder, until it is released into the main flow. The axis of the helicoid progressively bends, eventually becoming parallel to the main flow and forming the streamwise vortices shown in Figure 2. Such a mechanism might be seen as the transposition of a two-dimensional unsteady vortex wake into three-dimensional steady flow, where the time dependence of the former is replaced by a spatial dependence in the latter through convection.

The proposed mechanism of the formation of streamwise vortices is based on the assumption that a pressure gradient exists along the yawed cylinder. The pressure gradient is seen as that between the free stream static pressure in the boundary layer approaching the bend and the suction pressure at the base of the yawed segment. The pressure gradient along the yawed segment will fall to zero at large distances from the bend, and the effects of the bend will then fade out, giving way to oblique vortex shedding. When the boundary layer approaching the bend is turbulent, it can be expected that a turbulent boundary layer separation will occur locally from the yawed segment of the cylinder. This will produce an accompanying rise in base pressure, leading to a reduction in the oblique pressure gradient and suppression of streamwise structure formation.

CONCLUSION

The present investigation has shown that the structure of the wake downstream of the yawed cylinder is highly dependent on the state of the boundary layer flow over the bend. The structure formed appears to be strongly dependent on the pressure gradient along the yawed segment of the cylinder which is generated by the flow. In the case of a laminar boundary layer approaching the bend, the gradient appears to be large, and regularly-spaced streamwise vortices are generated in the vicinity of the bend. The transverse spacing of the structures is proportional to the cylinder radius and is independent of boundary layer thickness, cylinder Reynolds number and yaw angle. When the gradient is small, as in the case of an approaching turbulent boundary layer, the regular streamwise structure is suppressed.

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