

## CYLINDERS (AND OTHER “BLUFF BODIES” IN BOUNDARY LAYERS)

### Advice on essays

Questions in these weekly assignments are introduced in increasing order of need for background. The requested parts of the assignment are highlighted in **boldface type**. Answers are better organized in general by rearranging the order of the questions. Make at least a mental list of the questions or requests for information. Answer them in the order that allows you to organize most economically, not the order in which they are introduced.

### Review and introduction

Last week we got our first exposure to flows. The aim was to begin to become familiar with the characteristics of the three stages of flows. Today's purpose is to make sure that you see how boundary layers work and to see how they interact with even simple objects to make fully three-dimensional flows. It is also to get you ready to think about interactions of shear stresses and pressure forces producing net forces on objects (including organisms) in flows.

Now that you have seen eddy shedding, you might also find another nondimensional number useful, the Strouhal number,  $St$ . For a cylinder (of radius  $r_0$ ) in cross flow or a cylinder extending into a boundary layer, the eddy shedding frequency,  $n$ , is a strong function of flow velocity and only a weak function of  $Re$ . Over most of the natural flow ranges in the ocean  $St$  is  $\sim 0.2$ . Frequency has dimensions of inverse time [ $T^{-1}$ ] so  $1/n$  would be the time between eddies. Therefore, one can use the frequency of shedding as a good indicator of flow velocity ( $u$ , either in the uniform flow hitting the cylinder in cross flow or at the top of the cylinder in the case of the cylinder protruding into the boundary layer):

$$St = \frac{n2r_0}{u} \approx 0.2; 0.2u \approx n2r_0; n \approx \frac{0.1u}{r_0}$$

In the case of the cylinder on the flume bottom, the relevant velocity is the upstream flow velocity just below the top of the cylinder; this fastest flow velocity characterizing the interaction tends to dominate eddy shedding.

Over most flow velocities in the flume that I constructed, a smooth-turbulent boundary layer results. It would be characterized with a small to moderate roughness Reynolds number,  $Re_*$ . To get a rough-turbulent boundary layer with the velocities that this flume can deliver would take a gravel bottom (which is hard on the Plexiglas). The flume is constructed to give a fairly well developed boundary layer by the time the flow reaches the bottom cut-out (working section). **Just upstream of that well, use dye to identify the viscous sublayer and a turbulent outer layer. What evidence do you see of the intermediate flow regime and in what range of depth layer(s)?**

**Now put in the flat plate at a height of about 2 cm. Compare the heights above the plate where these transitions occur with the heights you observed above the flume bottom. Do so near the leading (upstream) edge of the plate and near (but not right at) the rear. If for a small organism (1 mm high and wide or less) there were an advantage to living with less shear stress on it, would it prefer to live near the leading edge or near the middle and why?**

I've provided a couple of squat cylinders that for most flow velocities will extend into the lower log layer. First, use dye to establish the gross pattern of flow around the object. The height of the cylinder matters because it determines the fastest flow that the cylinder will encounter. In order to get an identical flow pattern requires matching not only the cylinder  $Re$  (defined in the usual way, but using mean velocity at the top of the cylinder) and  $Re_*$ , but also the ratio of height of the tube,  $h$ , to roughness height,  $z_0$ .

You already made related observations last week. What I would like you to **focus on** this week, however, are **the flow patterns that you would not expect of a cylinder in cross flow far from the wall**, that is, on the patterns of flow that have some upward or downward components. **Where do you see upward or downward components of flow (either vertical or at some smaller angle**

**to the bottom), and what do you suppose is driving them?** Think about locations of attachment lines and points. (You will want to wait until lecture to make sure that you get the terms you need.) **Describe not only the location but the pattern of flow.** If you release dye at the bottom, one cylinder diameter upstream of the tube, it will not penetrate a region of fluid just upstream of the tube. That observation tells you that the fluid on the bed in front of the tube does not arrive there by going straight downstream, *i.e.*, it likely has a vertical (in  $z$ ), lateral (in  $y$ ) and(or) upstream ( $-x$ ) component. **Describe where it comes from and where it goes as well as the flow pattern along the way.** Also try out the corn starch. It does not track the flow because it has slight excess density. Areas of the bottom where it immediately gets flushed away thus are likely to have higher mean shear or higher maximal shear in flow fluctuations than places where it stays longer.

Now add dye through the top of the cylinder. The holes are small, and the only significant driver of flow is the pressure difference between the locations of the four holes. **Use the device to rank the back, front, top and sides of the cylinder in pressure.** You know that shear stress is greatest where flow is fastest close and parallel to the cylinder surface.

To consolidate a little more what you have learned, **compare the 1D flow over the bottom with the largely 2D flow around the cylinder in cross flow (from last week) and the 3D flow around the cylinder projecting into the bottom boundary layer, and look for the common features.** The bigger the length scale and the higher the velocity scale, the more turbulent the flow. Right at the bottom in 1D and right at the surface of the cylinder in cross flow or at the bed, flow is laminar. In the 1D flow, however, at some distance from the bottom, viscosity is no longer strong enough to keep the flow from becoming turbulent, and the flow literally rips free of the orderly, laminar flow pattern. Inertia of the mass of fluid deflected by the cylinder in cross flow similarly becomes great enough to overcome viscous forces, and the flow “separates” from the cylinder rather than successfully decelerating after passing. At moderate  $Re$  this separation is moderately orderly, producing the (von) Kármán vortex streets that you observed last week, but at higher  $Re$  the wake becomes fully turbulent.

To complete the exercise, **draw a side view of the cylinder, indicating flow direction at a number of points. Show an arrow indicating the direction of the net force that you think the flow applies to the cylinder.** According to Newton, the force that the cylinder applies back has to be equal and opposite. Justify the reasons for your choice of direction based on shear stresses and pressures. **Also, give a rough approximation of how many cylinder diameters upstream, downstream and cross-stream the flow appears to be affected by the presence of the cylinder.** Don't be fooled by residual dye patterns way downstream; check for downstream effects by injecting the dye there.

The flow patterns that you are observing are qualitatively similar to what you would observe around a small house or other structure on the ground, and how far away the flow is affected by the structure will determine where to place your windmill for power generation or water pumping. You might be tempted to put your windmill by the side of the house where the air is accelerated, but you will find that the wind changes direction, and uniform flow is far more efficient in turning blades (doing useful work) than is turbulent flow produced by friction with roughness features on the house. In general, you are stuck putting a windmill where it won't be affected even if the house is upwind and high enough to be unaffected by both the wake of the house and friction with the ground (or more typically by the trees and shrubs on the ground).

Don't consider what you see around a cylinder as terribly idealized and irrelevant to nature. Nature uses a lot of cylinders, and flow around the cylinder is qualitatively characteristic of flow around any bluff body. (Be careful to include the  $L$  in your spelling!) A bluff body is one that is not well streamlined. A consequence at intermediate to high  $Re$  is that accelerations and decelerations of flow around it are relatively abrupt, as they are around the cylinder on the flume bottom.