Free Shear Flows – Introduction:

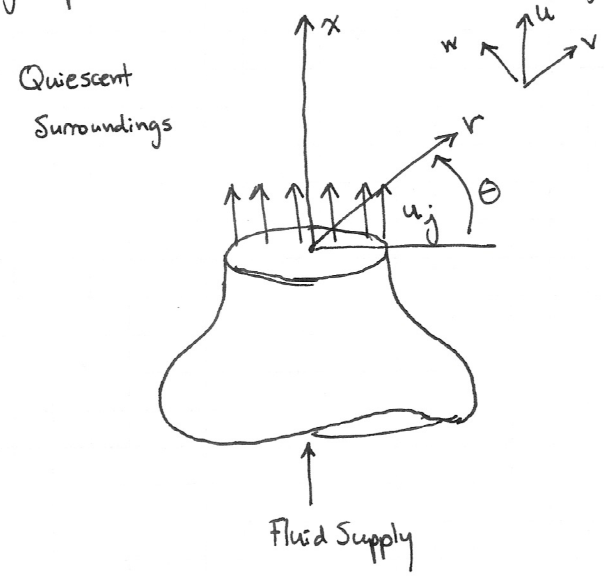
Shear flows are flows that result from mean-velocity differences. Free shear flows are shear flows that are remote from walls. Some examples of shear flows include wakes, jets, and mixing layers.

Free shear flows often exhibit turbulence in the region of mean shear. Outside this region, the flow is approximately irrotational and consequently not turbulent. We have two objectives in studying turbulent shear flow:

1. We wish to understand the turbulent statistics within the region of mean stress.
2. We wish to understand the boundary between the turbulent region and the irrotational outer region.

We will focus on point 1 above, but we will also discuss point 2 in detail.

Turbulent shear flows exhibit many important characteristics. These may be seen by examining experimental results for a turbulent round jet:



x = axial direction
r = radial direction
θ = circumferential direction

u = axial velocity
v = radial velocity
w = circumferential velocity

u_j = (initial) jet-speed

A collection of experimental plots for a turbulent round jet are available in a PDF on D2L at the link:

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Analyzing these plots, we notice the following things:

1. The flow field is statistically stationary and axisymmetric. Hence:

$$\bar{u} = \bar{u}(x,r) \qquad \langle (u')^2 \rangle = \langle (u')^2 \rangle (x,r)$$
$$\bar{v} = \bar{v}(x,r) \qquad \langle (v')^2 \rangle = \langle (v')^2 \rangle (x,r)$$
$$\bar{w} = 0 \qquad \langle u'v' \rangle = \langle u'v' \rangle (x,r)$$

2. The turbulent statistics are self-similar:

Mean Axial Velocity: $$\frac{\bar{u}(x,r)}{u_0(x)} = \bar{f}\left(\frac{r}{r_{1/2}}\right) = \bar{f}(\eta)$$ Similarity variable!

Mean Lateral Velocity: $$\frac{\bar{v}(x,r)}{u_0(x)} = \bar{h}\left(\frac{r}{r_{1/2}}\right) = \bar{h}(\eta)$$

Reynolds Stress: $$\frac{\langle u'v' \rangle}{u_0^2(x)} = \bar{g}\left(\frac{r}{r_{1/2}}\right) = \bar{g}(\eta)$$

Above, $u_0(x)$ is the centerline velocity:

$$u_0(x) = \bar{u}(x,0)$$

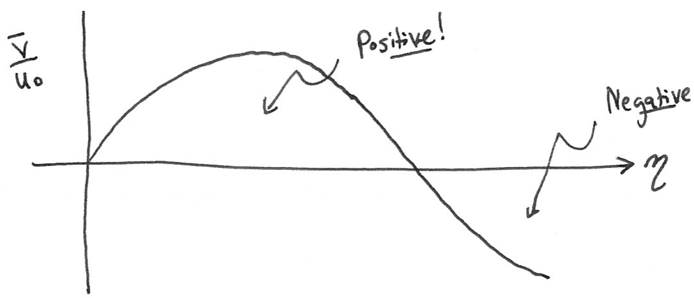
and $r_{1/2} = r_{1/2}(x)$ is the jet half-width defined by:

$$\bar{u}(x, r_{1/2}) = \frac{1}{2} u_0(x)$$

3. The centerline velocity varies inversely with x.

4. The half-width varies linearly with x.

5. The mean lateral velocity profile looks as follows:



Hence, near the centerline, fluid is pushed away from the center of the jet. This is why the half-width increases with x. At the edge of the jet, $\bar{v}$ is negative. This indicates that the ambient fluid is pulled into the jet and being entrained.

6. The root mean square (standard deviation) of axial velocity is 25% of the mean at the centerline, and the ratio of the r.m.s. to the mean goes to infinity as $r \to \infty$.

7. There is a positive turbulent viscosity ν_T such that:

$$\langle u'v' \rangle = -\nu_T \frac{\partial \bar{u}}{\partial r}$$

Remark: All of the above characteristics are for a fully developed turbulent jet. Near the nozzle, the flow is not self-similar. Nonetheless, our basic understanding of turbulent shear flows comes from fully-developed flows as they are amenable to theoretical analysis.

In this class, we will focus our studies on planar shear flows that are two-dimensional in the mean:

$$\bar{u} = (\bar{u}(x,y), \bar{v}(x,y), 0)$$

This will allow us to use the two-dimensional Reynolds equations, a considerable simplification.