FM Lab Experiment-3: Visualization and quantification of free and forced vortices

Group - 2

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1. Answers to the questions posed in essential background

Q. What are free and forced vortices? Briefly discuss a few application/occurrences of such vortices.

A **free vortex** is a form of flow when the fluid mass rotates without needing external torque. For instance, when water drains from a container through the center hole in the base, a free vortex is created. Natural, free vortices include tornadoes and river whirlpools. On the other hand, an **artificially created vortex** is brought about by forces acting on the fluid called the **forced vortex**. It can be produced by paddling in fluid or rotating a vessel that contains fluid. A rotating flow produced by a pump's impellers illustrates a forced vortex in turbomachinery.

A thorough understanding of vortex behavior is necessary to study natural phenomena such as hurricanes, tornadoes, and whirlpools (free vortices). The ability to classify forced vortices produced by machinery, such as centrifugal pumps or turbines is crucial for engineers and designers. Understanding vortex behavior has allowed engineers to construct turbomachinery and hydraulic structures that make use of these phenomena. Vortices frequently have negative impacts, as observed during hurricanes, tornadoes, or scour holes generated downstream of a dam outlet. To separate solid materials from liquids, for instance, hydrodynamic separators based on vortex behavior (swirling flow) have been created. In water treatment plants, this kind of separation is employed.

Q. Can you quantify velocity profiles and the associated free surfaces for free and forces vortices?

Free Vortex

In a free cylindrical vortex, the velocity varies inversely with the distance from axis of rotation,

$$v = \frac{k}{r}$$

By using Bernoulli's theorem,

$$\frac{v^2}{2g} + z = C$$

$$\implies \frac{k^2}{2gr^2} + z = C$$

$$C - z = \frac{k^2}{2gr^2}$$

This is the equation of *hyperbolic curve,* $y = \frac{A}{x^2}$. Thus, the curve is asymptotic to line z=C and the axis of rotation.

In other words,

$$r \to \infty \implies z \to C$$

Thus, C is the value of z at the uppermost tangent drawn on the water surface.

Thus, from the experimental values

$$\Rightarrow C = 23.8\,cm$$

From the experimental values, we also know that r=1cm at z=0.

Thus,

$$k = \sqrt{2gC} * r = \sqrt{2 * 9.8 * 0.238} * 0.01 = 0.022m^2/sec$$

Forced Vortex

Known Parameters:

- ω → Angular Velocity in rpm
- g → gravity

Now, if the container and water are rotating with an angular velocity ω, then the velocity at any point can be given by,

$$v = \omega r$$

The velocity head can then be calculated as,

$$h_c = \frac{v^2}{2g}$$

Substituting $v = \omega r$ into this, we get

$$h_c = \frac{r^2 \omega^2}{2g}$$

The total energy can be written as,

$$H = h_o + h_c$$

where h_o is the pressure head at the lowest point of vortex. Substituing h_c gives,

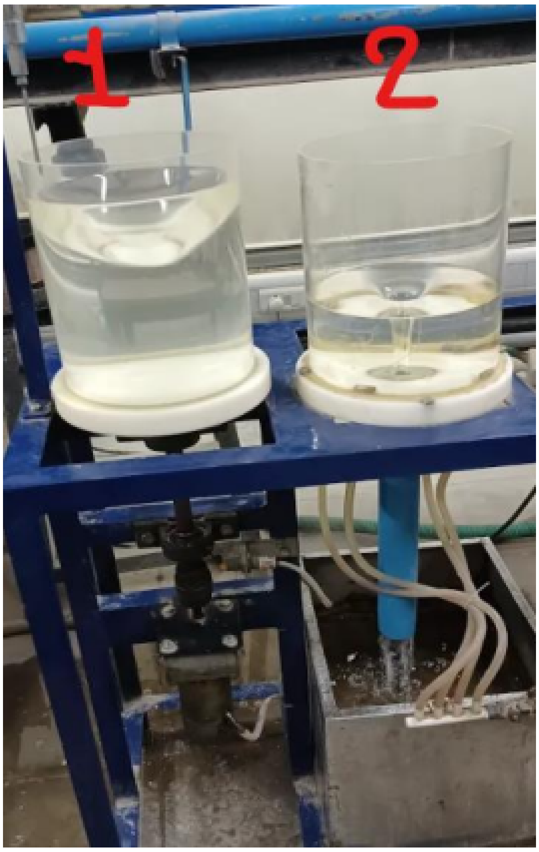
$$H = h_o + \frac{r^2 \omega^2}{2g}$$

Thus,

$$H = \frac{r^2 \omega^2}{2g}$$

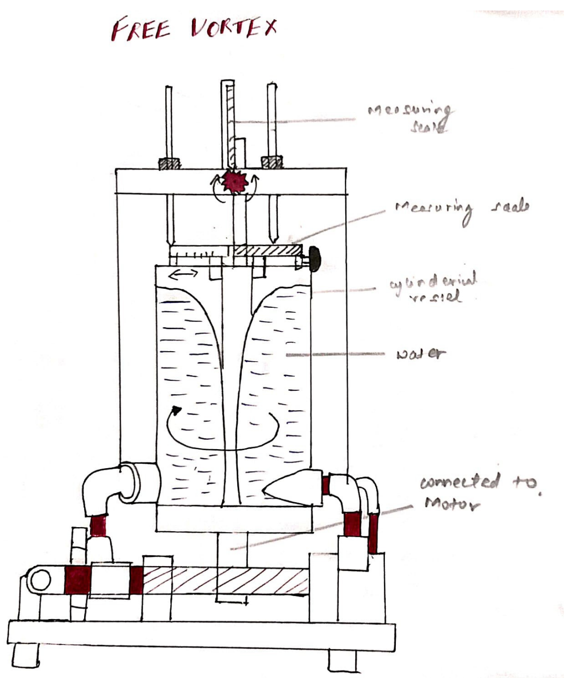
$$\omega = 2\pi \frac{rpm}{60}$$

2. Schematic of the experimental setup along with a photograph

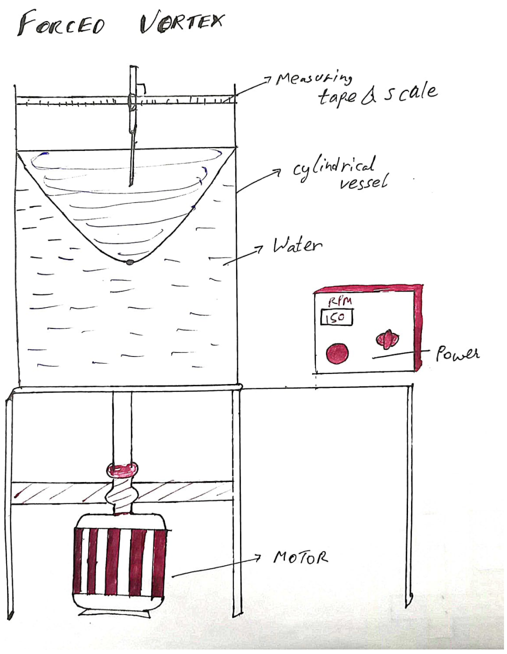


The experimental setup.

The experimental setup photograph shows both the forced (1) and free (2) vortex.



Free Vortex Schematic



Forced Vortex Schematic

3. Outline of experimental procedures

Forced vortex experiment is performed by rotating water in a container at high angular velocities without any other outside intervention. Before measuring and making observations, we try to achieve a steady state and maintain angular velocity without fluctuating more than 5 revolutions per minute (rpm). Steady state is characterized by minimal changes in water level at the periphery. Once achieved, we proceed to measure the x and y coordinates of various points on the free surface by using the scale attached to the setup.

The exercise is then repeated for other angular velocities.

For the **free vortex** experiment, we need a container with a small orifice at the bottom of about 1-2 cm in diameter. We then proceed to start supplying water tangential to the container at the bottom. Initially, we keep a high flow rate to quickly fill the container. Once filled, we then decrease the flow rate so as to maintain a constant level of water in the container. This constant level indicates steady state. We then proceed to measure and plot the surface of water using attached scales.

4. Experimental Observations

FREE VORTEX

X	Height(cm)
44.1	23.8
43	23.8
42	23.8
41	23.6
40	23.4
39	23.1
38	22.7
37.5	22
37.2	21.3
37.1	21
37	20.4
36.7	19
36.5	16.8
36.3	12.8
36	0
35	0
34	0
33.8	13
33.6	16.9
33	20.3
32.7	21.5
32.4	22.2
32	22.9
31	23.1
30	23.4
29	23.5
28	23.8
27	23.8
26.3	23.8

FORCED VORTEX

130 Revolution Per Minute

150 Revolutions Per Minute

X	Height(cm)
19.4	29.5
18.4	28
17.4	26.5
16.1	25.35
15	24.1
14	23.2
13	22.8
12	22
11.2	21.5
9.8	21.6
10.5	21.3
9	22.2
8	23
7	23.5
6	24
5	24.9
4	25.8
3	27.1
2	29
1.7	29.5

X	Height(cm)
19.9	30.1
19.3	28.6
18.1	27.4
16.9	25.4
15.9	24.5
14.2	22.2
12.3	20.8
10.8	20.3
10.2	20.4
8.9	20.7
7.3	21.7
6.3	22.8
5.3	23.7
4.1	25.5
3.1	27.5
2.1	29.5
1.6	30.5

5. Interpretations or Tasks 3.2

Q. Measure shape of the free surface for a free vortex at steady state for various orifice sizes (if available).

Various orifice sizes were unavailable.

Q. Measure the position of the free surface for the forced vortex for multiple angular velocities of the platform.

Measured for 130 and 150 rpm. Listed in experimental observations section.

Q. Theoretically compute the free surface shapes for free and forced vortices. Jot down all the assumptions necessary. Now compare your computed free surface shapes to the experimental observed ones. You should quantify experimental uncertainties and errors.

The Below tables show the computed theoretical and experimental values along with the error.

150 rpm

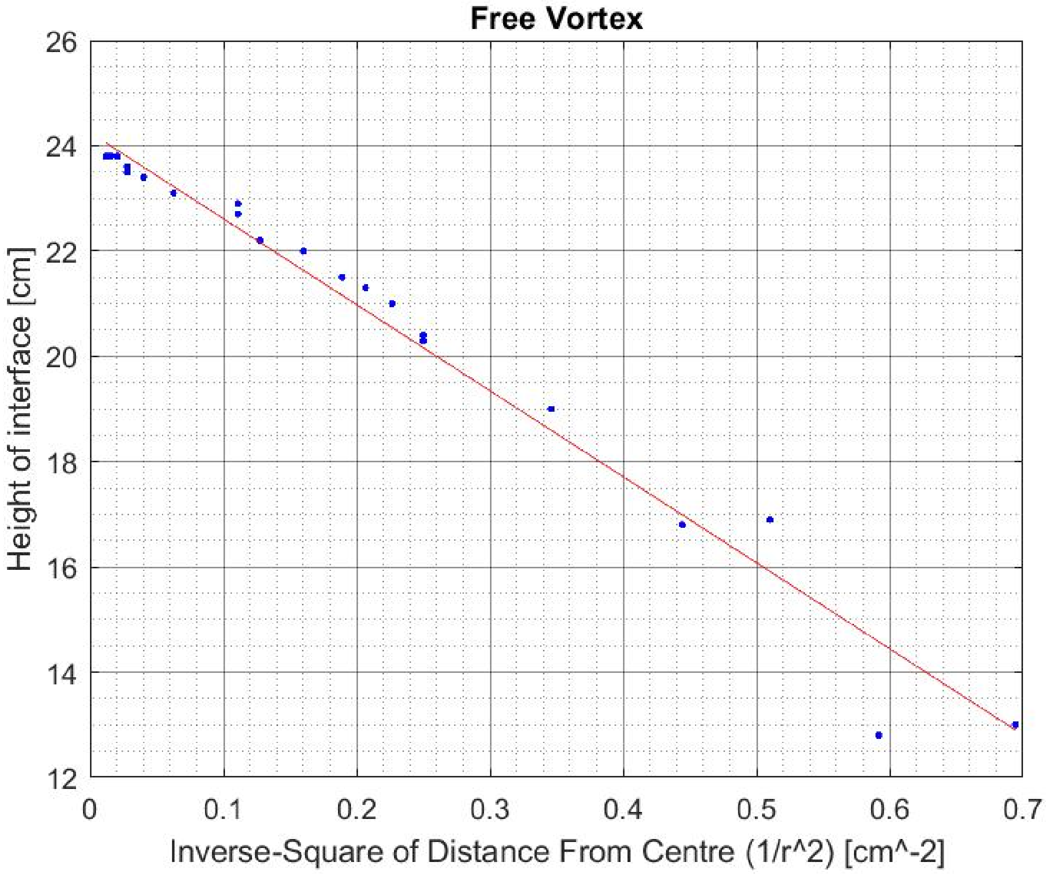
130 rpm

X	Height(cm)	Theoritical_Height(cm)	error
19.9	30.1	30.7142025	0.019997
19.3	28.6	29.38617474	0.026753
18.1	27.4	27.00176128	0.014749
16.9	25.4	24.97953719	0.016832
15.9	24.5	23.57102291	0.039412
14.2	22.2	21.75378796	0.020512
12.3	20.8	20.58296046	0.010545
10.8	20.3	20.3	0
10.2	20.4	20.34527367	0.00269
8.9	20.7	20.75399434	0.002602
7.3	21.7	21.8405625	0.006436
6.3	22.8	22.84664413	0.002042
5.3	23.7	24.10424617	0.016771
4.1	25.5	25.94537556	0.017166
3.1	27.5	27.7563225	0.009235
2.1	29.5	29.81878985	0.010691
1.6	30.5	30.94434367	0.014359
rpm	150		
gravity	9.8		
Avg per. Error	1.357592		

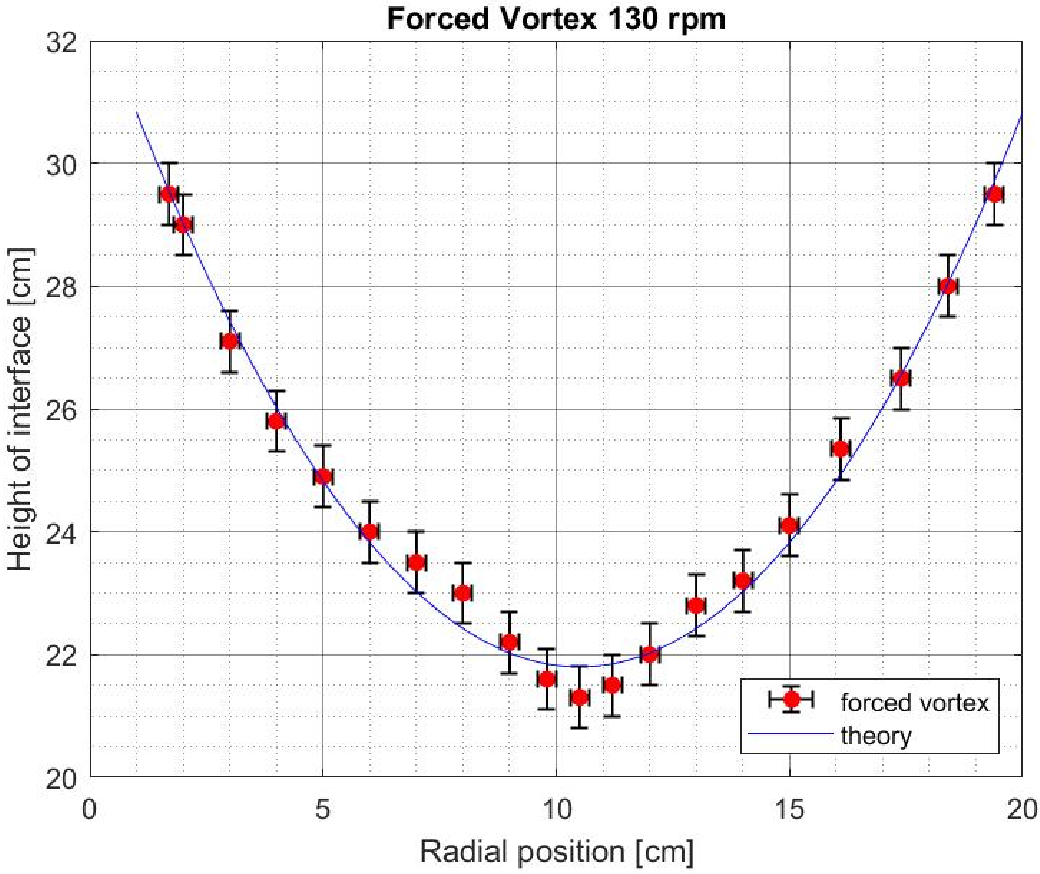
X	Height(cm)	Theoritical_Height(cm)	error
19.4	29.5	28.78216762	0.02494
18.4	28	27.19524152	0.029592
17.4	26.5	25.7972352	0.027242
16.1	25.35	24.26226204	0.044833
15	24.1	23.2128127	0.03822
14	23.2	22.45713361	0.033079
13	22.8	21.89037429	0.041554
12	22	21.51253474	0.02266
11.2	21.5	21.34628534	0.007201
9.8	21.6	21.34628534	0.011886
10.5	21.3	21.3	0
9	22.2	21.51253474	0.031956
8	23	21.89037429	0.05069
7	23.5	22.45713361	0.046438
6	24	23.2128127	0.033912
5	24.9	24.15741157	0.03074
4	25.8	25.29093021	0.020129
3	27.1	26.61336862	0.018285
2	29	28.12472681	0.031121
1.7	29.5	28.61497362	0.030929
rpm	130		
gravity	9.8		
Avg. per. Error	2.877026		

Further analysis and comparison is done by plotting the graphs of theoretical and experimental values.

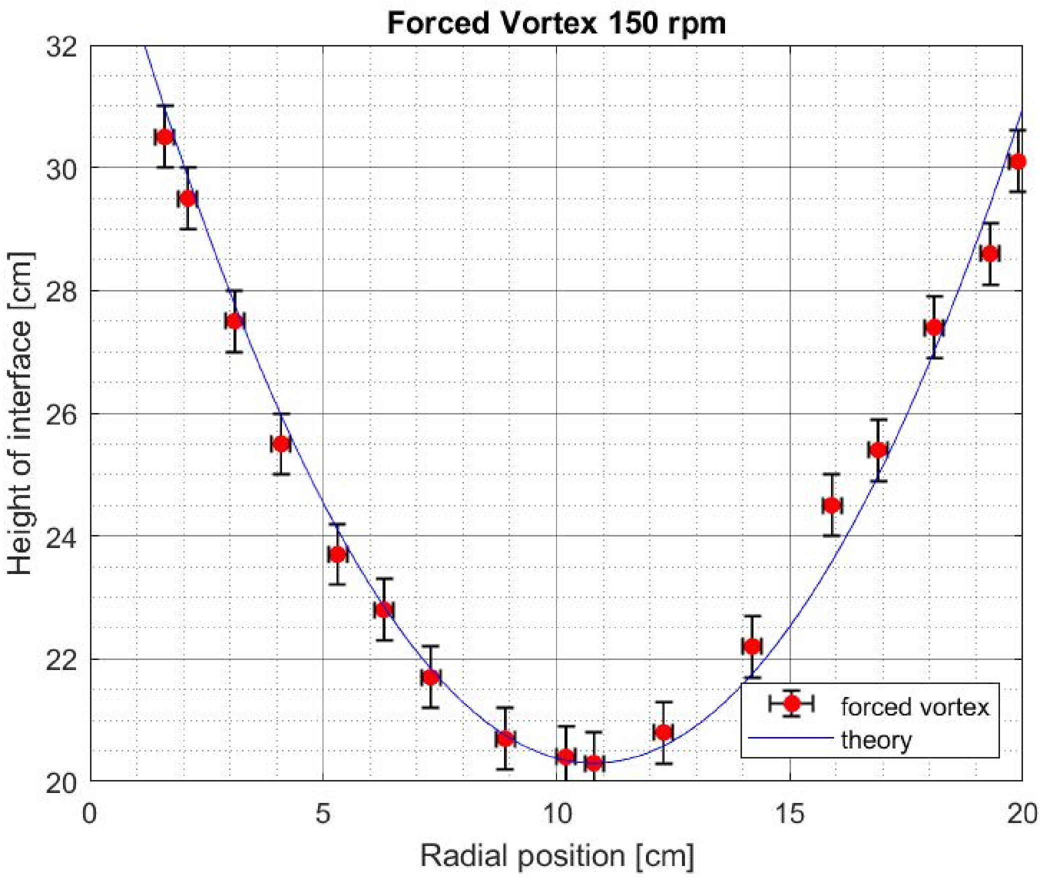
Free Vortex



Forced Vortex



Forced Vortex 130 rpm
Height of interface [cm]
Radial position [cm]
forced vortex
theory



Forced Vortex 150 rpm
Height of interface [cm]
Radial position [cm]
forced vortex
theory

Q. In case there are mismatches between observed and the calculated forces, can you specify some reasons which may cause these mismatches?

On average, there was 1.35% and 2.87% error for the forced vortex experiment for 150rpm and 130rpm respectively. There might be following reason for mismatches,

1. There are some frictional losses associated with the flow. Along with the turbulence and surface tension, they affected the shape of the surface.
2. The principal axis of the container was not stationary. It was also rotating with some velocity about the vertical axis due to the container not being exactly vertical. (1 or 2 degree change). It made the formed vortex to rotate in a circle.
3. The angular velocity also didn’t remain constant for the observations, and varied by about 5-10 rpm for the experiment.