Indian Institute of Technology Gandhinagar

Visualization and Qualification of Free and Forced Vortices

ME 351: Mechanical Engineering Lab-I

Experiment Report

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Objectives:

(i) Generate forced and free vortices and visualize the associated free surfaces and compare the water surface profiles.
(ii) Measure the location of the free surface to compare with theoretical estimates.

The Essential background:

Free Vortex:

The fluid mass rotates in the free vortex flow without any externally impressed contact force. The entire fluid mass rotates due to fluid pressure or gravity. It occurs naturally in the flow and can be seen in a drain or the atmosphere of a tornado.

When water exits a vessel through a central hole in the base, it creates a free vortex. The degree of rotation is determined by the initial disturbance. In a free cylindrical vortex, velocity varies inversely with the distance from the rotational axis.

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

Bernoulli's theorem serves as the foundation for the equation regulating the surface profile:

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

Equation (1) into Equation (2) will result in the following new expression:

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

Or we can write it as,

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

which is the equation for a hyperbolic curve of nature, $y = \frac{A}{x^2}$.

Through $z = c$, this curve asymptotically approaches both the axis of rotation and the horizontal plane.

Forced Vortex:

A constant supply of energy or external torque was required for the forced vortex. is caused by external forces on the fluid, such as a pump's impeller

As a solid body, all fluid particles rotate at the same constant angular velocity. As a result, a flow or forced vortex is referred to as a solid body rotation. When water is made to rotate at a constant speed, the velocity remains constant and equals:

$$v = \omega r$$

Calculating the velocity head (or kinetic energy) is as follows:

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

Equation (5) is substituted into equation (6) to produce:

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

If the horizontal plane across the vortex's lowest point is chosen as the datum.

$$H = h_o + h_c$$

where, h_o is the datum's pressure head. Inputting h_c from above Equation which results in:

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

At $r = 0$, $H = 0$, which causes $h_o = 0$, and:

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

This is the equation for the parabola water surface profile.

The applications where free and forced vortices can be seen are:

- Free vortex occurrences include tornadoes, the flow of liquid around a pipe's oblique bend, whirlpools, and hurricanes.
- Turbomachinery, hydraulic structures, and pump impeller-induced fluid flow are examples of forced vortex phenomena.
- Applications: Solid waste from liquids can be separated using hydrodynamic separators in water treatment facilities.

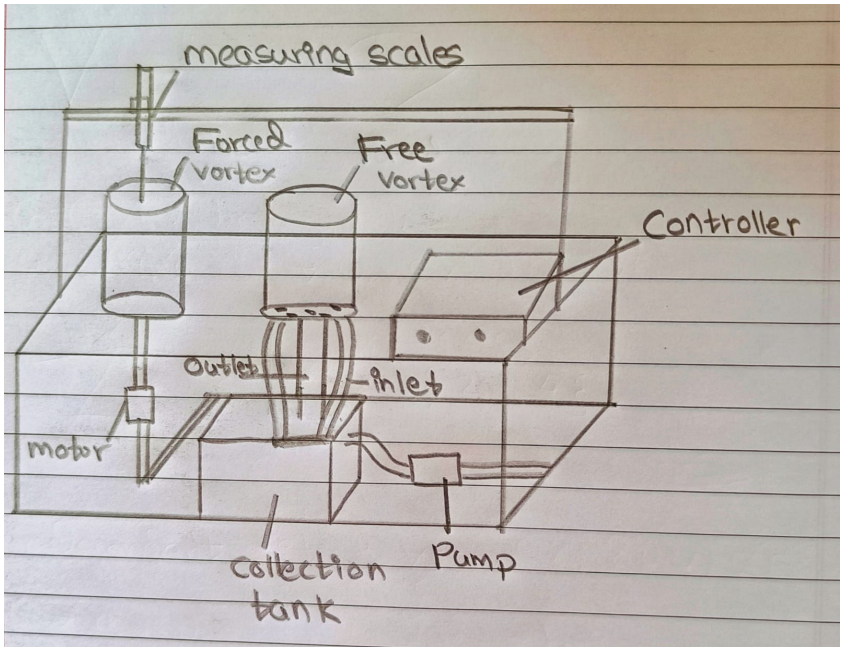
Velocity profiles and the associated free surfaces for free and forced vortices:

Velocity profiles and related free surfaces can be measured for free and driven vortices.

- Free Vortex: In a forced vortex, velocity $v = \frac{k}{r}$, where k is a constant, is inversely proportional to r.
- Forced Vortex: A fluid is made to revolve at a constant angular velocity ω. In this situation, $v = \omega r$. In this case, r denotes the distance from the vortex's centre.

Experimental setup:

1. **Schematic:**



Forced Vortex:

The vessel's bottom has an orifice directly above a water tank connected to a hydraulic pump. The pump wires connect to inlets that open tangentially into the vessel's bottom. These inlets are critical for preserving the free vortex (and keeping the free surface fixed). A valve connected to the hydraulic pump controls the rate of water flows into the vessel. A free vortex can be created by turning on the pump and opening the valve. A free vortex is formed as water flows out of the orifice.

Free Vortex:

The vessel's bottom is linked to an electrical apparatus that includes a "pump" and a stirrer. The speed of rotation of the vessel's bottom can be controlled by turning on the pump and adjusting the stirrer (thus applying an external torque to the fluid within it). This will result in the formation of a forced vortex.

Figure 1 : Forced Vortex

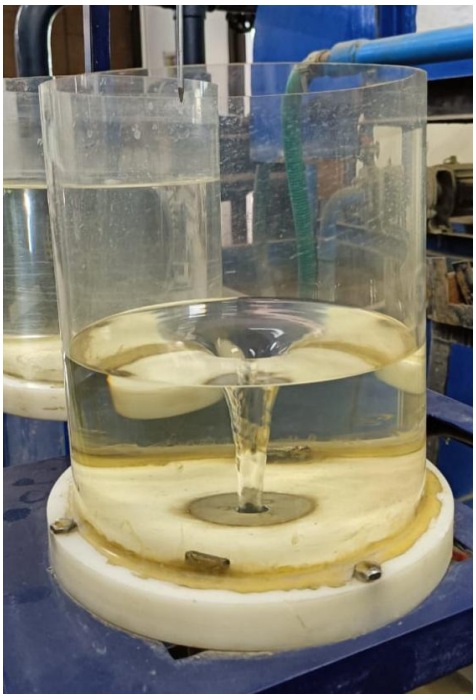


Figure 2 : Free Vortex

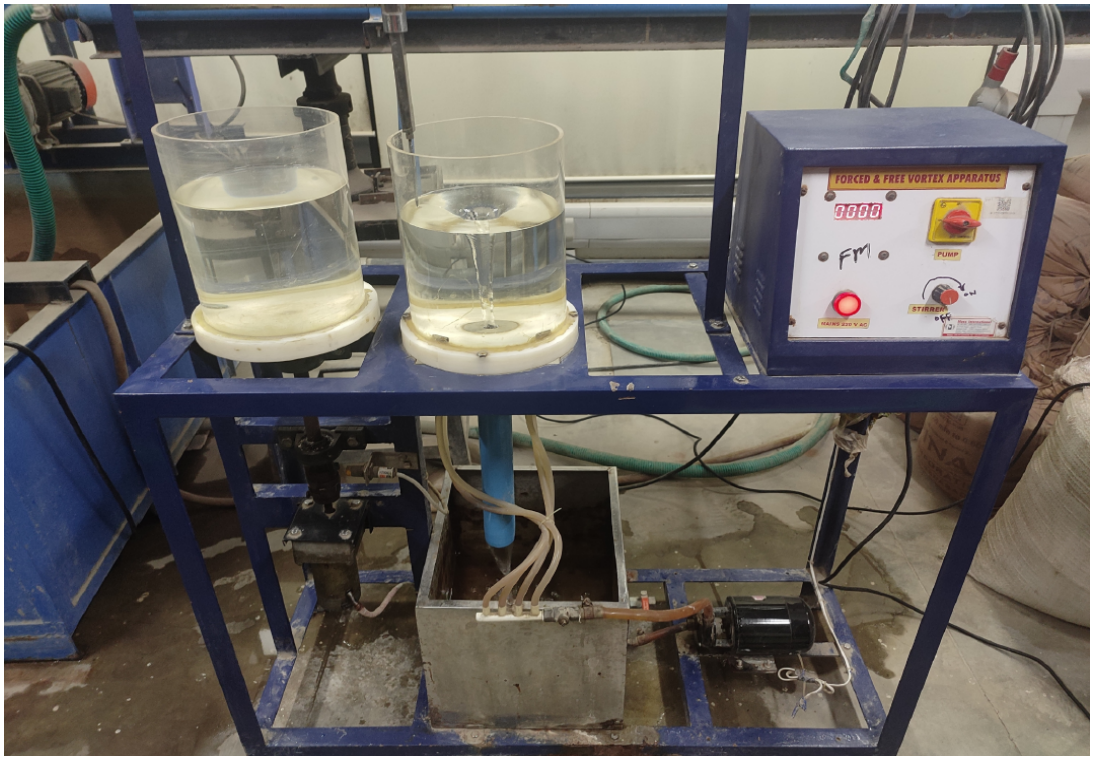


Figure 3 : Complete Experimental Set-Up

2. Experimental Procedure:

Free Vortex:

- Position the apparatus on the hydraulics bench so that the central outlet in the base of the vessel is located over the weir through.
- Close the bench outlet valve, and turn on the pump.
- When the vessel is slightly overflowing, open the outlet valve, so the water level maintains a stable height.
- After the steady water level is achieved, use a measuring caliper to record the vertical height from the water level.
- Record the horizontal and vertical distance when the needle simply contacts the water surface according to radii.
- Do this experiment by changing the horizontal distance for the remaining radii.
- After completing the measurements, close the bench valve, turn off the pump, and repeat the process twice.

Forced Vortex:

- Turn on the forced vortex device. To control the angular velocity, use the stirrer (displayed in rpm). While taking readings, keep an eye on the figures and don't let

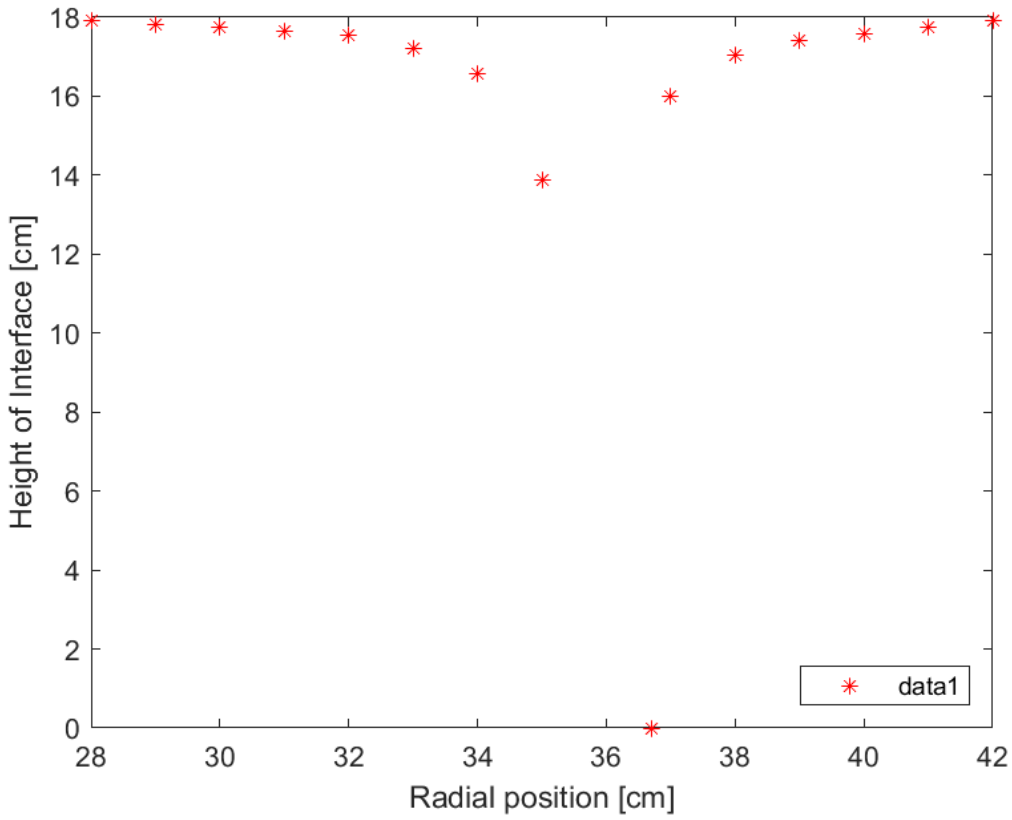
them go more than +5 or -5. After choosing an rpm, let the vortex stabilize (that is, the free surface must have a stable center that cannot be easily disrupted by the measuring needle)before taking readings.

- Using the measuring calipers, determine the water surface profile: Adjust the horizontal and vertical positions using the screws, with the vertical rod's needle just touching the water's surface (but not disturbing the vortex). Take note of the X- and Y-dimensions at various locations along the concave surface.
- For accurate readings, ensure the vertical needle is at a straight angle to the horizontal measurement rod.
- The forced vortex equipment should be turned off once the readings have been recorded.

Task 3.2:

A. We Measured the shape of the free surface for a free vortex at a steady state for various orifice sizes and the following table shows the different readings for one orifice size:

Distance X (cm)	Y1 (cm)	Y2 (cm)	Y3 (cm)	Average Y (cm)
28	18.0	17.9	17.8	17.900
29	17.9	17.8	17.7	17.800
30	17.8	17.7	17.7	17.733
31	17.7	17.6	17.6	17.633
32	17.6	17.5	17.5	17.533
33	17.1	17.2	17.3	17.200
34	16.4	16.5	16.8	16.567
35	13.7	13.8	14.1	13.867
36.7	0	0	0	0
37	16.1	16.0	15.9	16.000
38	17.3	16.9	16.9	17.033
39	17.4	17.5	17.3	17.400
40	17.8	17.5	17.4	17.567
41	17.9	17.6	17.7	17.733
42	18.0	17.8	17.9	17.900



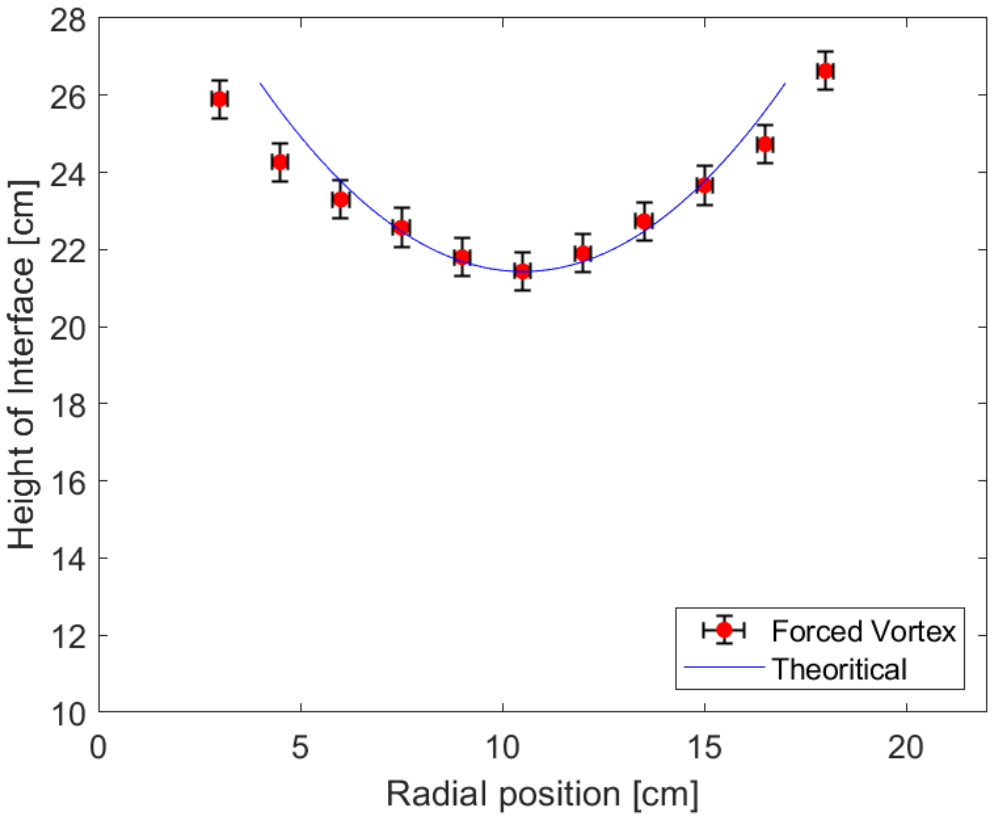
B. Observations for a Forced vortex:

We took the readings for two different angular velocities of the platform.

(i) For ω = 135 RPM

Distance X (cm)	Y1 (cm)	Y2 (cm)	Y3 (cm)	Average Y (cm)
3.0	25.8	26	25.9	25.900
4.5	24.3	24.3	24.2	24.267
6.0	23.3	23.4	23.2	23.300
7.5	22.6	22.6	22.5	22.567
9.0	21.9	21.6	21.9	21.800
10.5	21.5	21.2	21.6	21.433

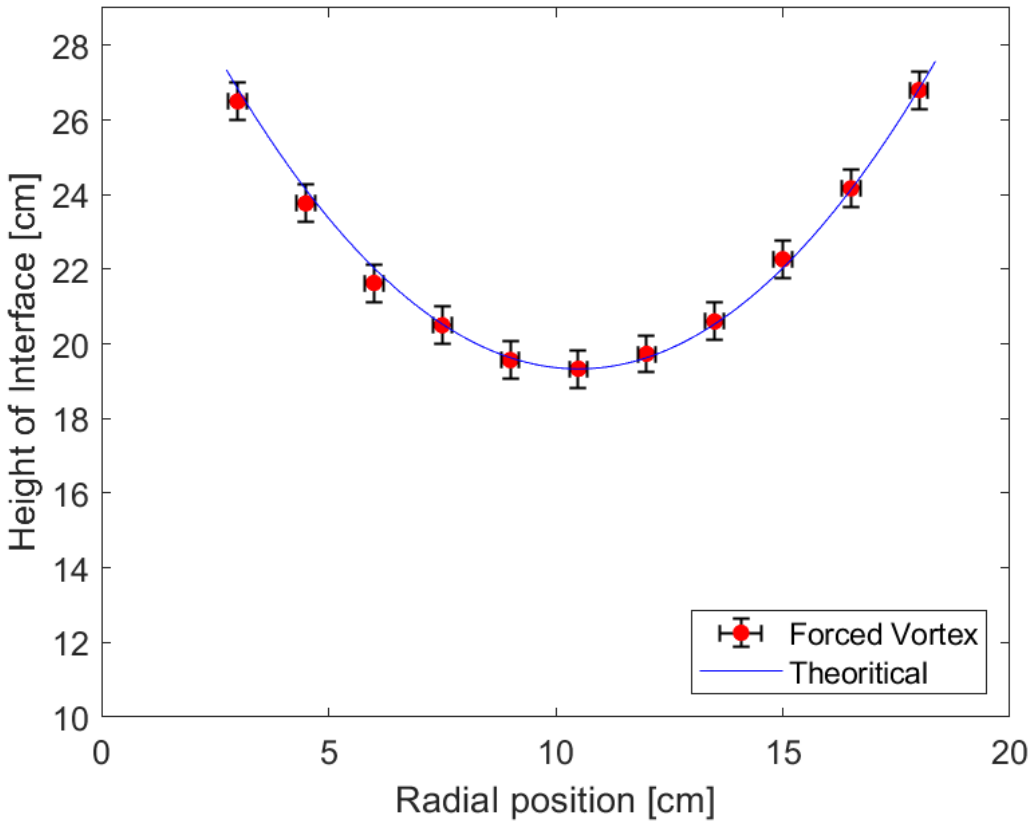
12.0	22.3	21.5	21.9	21.900
13.5	22.7	22.9	22.6	22.733
15.0	23.7	23.8	23.5	23.667
16.5	24.9	24.7	24.6	24.733
18.0	26.6	26.8	26.5	26.633



(ii) For ω = 150 RPM

Distance X (cm)	Y1 (cm)	Y2 (cm)	Y3 (cm)	Average Y (cm)
3	26.5	26.5	26.5	26.500
4.5	23.8	23.7	23.8	23.767
6	21.6	21.7	21.6	21.633
7.5	20.5	20.6	20.4	20.500

9	19.6	19.5	19.6	19.567
10.5	19.3	19.4	19.3	19.333
12	19.6	19.7	19.9	19.733
13.5	20.6	20.5	20.7	20.600
15	22.2	22.4	22.2	22.267
16.5	24.2	24.1	24.2	24.167
18	26.7	26.9	26.8	26.800



C. Theoretical Computations:

Free Vortex:

We need to find values of heights at different values of distance from orifice. Now,

From equation (3),

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

We will find k as

$$\frac{k^2}{2gr_1^2} + z_1 = \frac{k^2}{2gr_2^2} + z_2$$

So this implies,

$$k^2 = 2g\,(z_2 - z_1) \,/\, (\frac{1}{r_1^2} - \frac{1}{r_2^2})$$

Using two values of r and H/z, we can find the constant k.
Then,

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

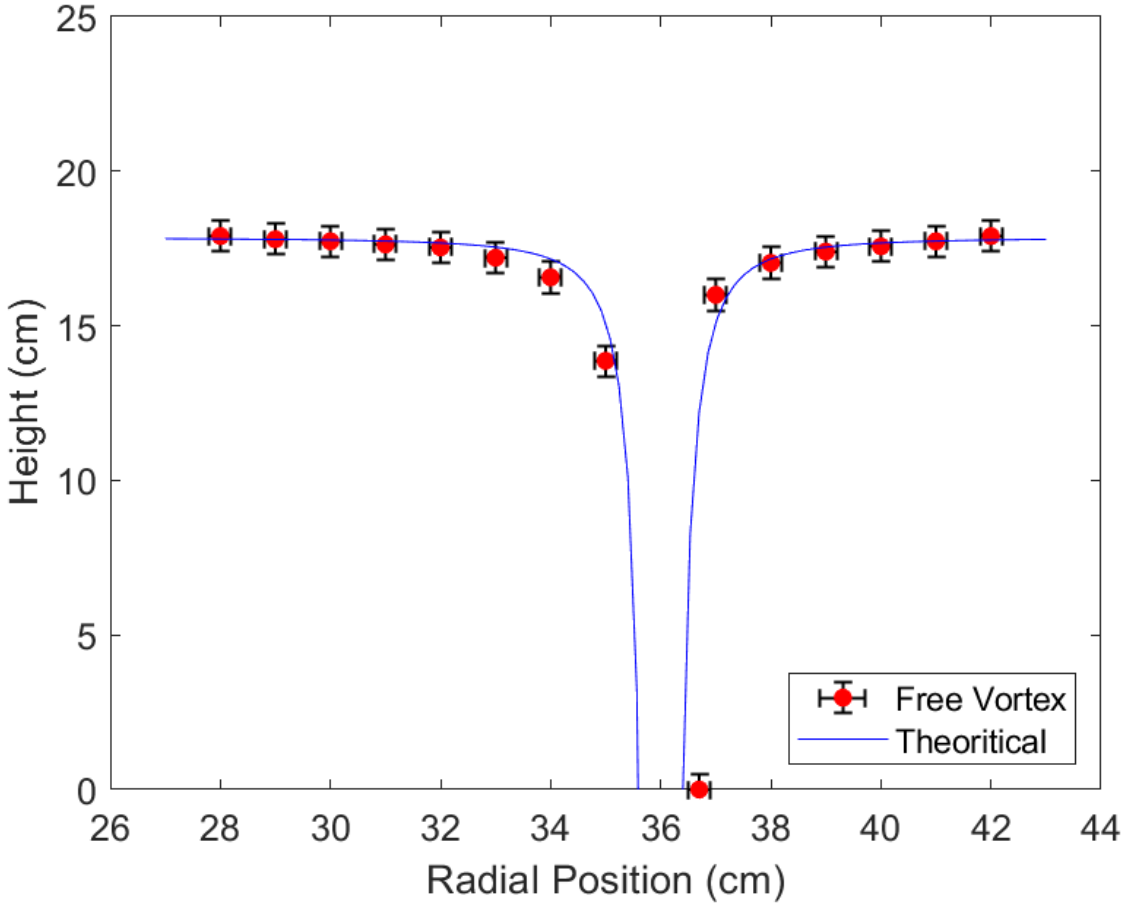
From hit and trial method, we found that:
k = 7.348469228
c = 17.85

Distance in x	Y1	Y2	Y3	Y_avg	$z_0 = \frac{k^2}{2gr^2}$	$z = z_0 + c$
28	18	17.9	17.8	17.9	0.04300458716	17.80695153
29	17.9	17.8	17.7	17.8	0.05616925669	17.79377343
30	17.8	17.7	17.7	17.73333333	0.07645259939	17.77346939
31	17.7	17.6	17.6	17.63333333	0.1100917431	17.73979592
32	17.6	17.5	17.5	17.53333333	0.1720183486	17.67780612
33	17.1	17.2	17.3	17.2	0.3058103976	17.54387755
34	16.4	16.5	16.8	16.56666667	0.6880733945	17.16122449
35	13.7	13.8	14.1	13.86666667	2.752293578	15.09489796
36	0	0	0	0	-	-
37	16.1	16	15.9	16	2.752293578	15.09489796
38	17.3	16.9	16.9	17.03333333	0.6880733945	17.16122449
39	17.4	17.5	17.3	17.4	0.3058103976	17.54387755
40	17.8	17.5	17.4	17.56666667	0.1720183486	17.67780612
41	17.9	17.6	17.7	17.73333333	0.1100917431	17.73979592
42	18	17.8	17.9	17.9	0.07645259939	17.77346939

NOTE: For x = 36 cm, asymptotes will be formed around the perimeter of the orifice.

Equation:

$$y = 17.85 - \frac{54}{19.6\,(x-36)^2}$$



Forced Vortex:

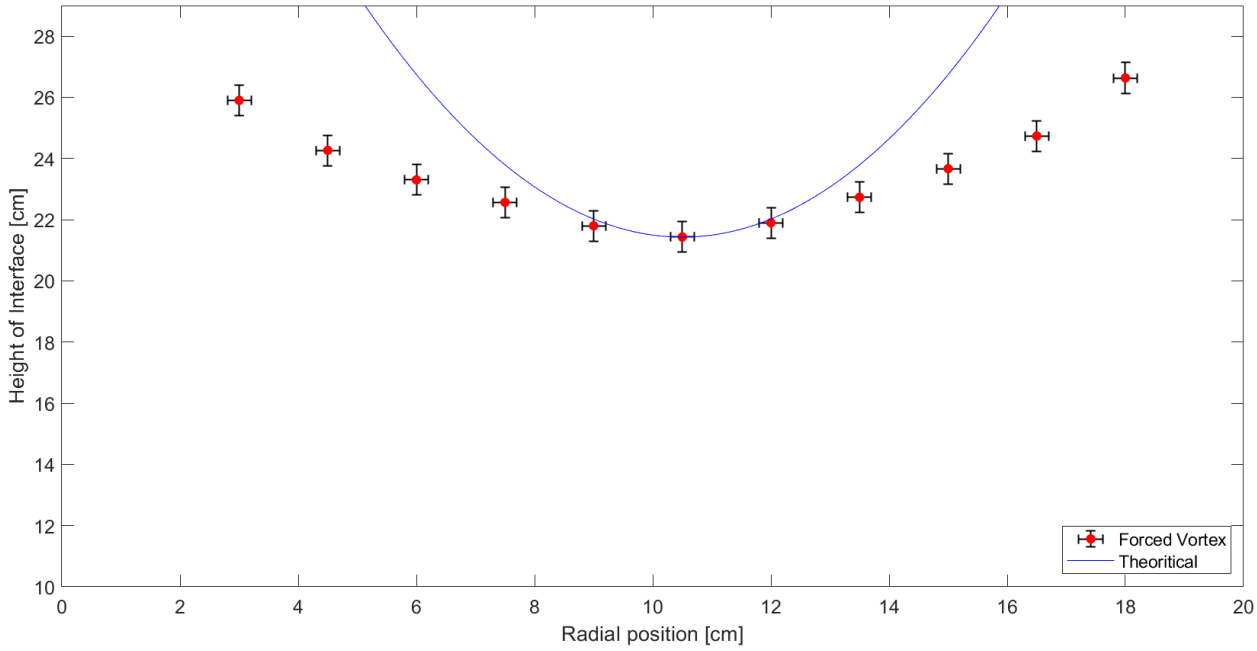
From the equations derived above, when we try and approach the theoretical values for the assciated data points we get the following result:

For ω = 135 rpm:

Distance X (cm)	Y_avg (cm)	R (cm)	V = rw	h=h0 + $\frac{v^2}{2g}$	Standard Deviation in y (%)
3	25.9	7.5	17.01696021	36.25927292	39.99719274
4.5	24.26666667	6	13.61356817	30.94593467	27.52445605
6	23.3	4.5	10.21017612	26.81333825	15.07870494
7.5	22.56666667	3	6.806784083	23.86148367	5.737741509
9	21.8	1.5	3.403392041	22.09037092	1.331976683
10.5	21.43333333	0	0	21.5	0.3110419907
12	21.9	1.5	3.403392041	22.09037092	0.8692735926
13.5	22.73333333	3	6.806784083	23.86148367	4.962538125
15	23.66666667	4.5	10.21017612	26.81333825	13.29579543
16.5	24.73333333	6	13.61356817	30.94593467	25.11833424
18	26.63333333	7.5	17.01696021	36.25927292	36.14245151

Equation :

$$y = 21.43 - 0.2623870741\,(x - 10.5)^2$$

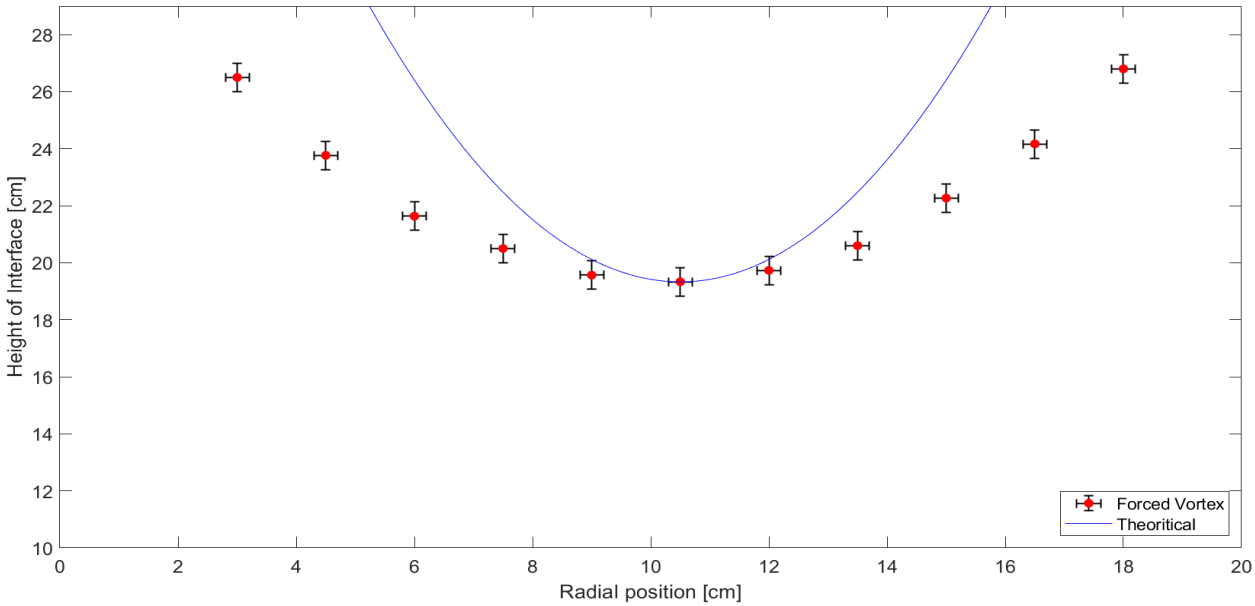


For ω = 150 rpm

Distance in X	Y_avg	R	v=rw	h=h0+v^2/2g	Standard Deviation in y (%)
3	26.5	7.5	19.63495408	38.94991957	46.98082856
4.5	23.76666667	6	15.70796327	31.87594852	34.12040052
6	21.63333333	4.5	11.78097245	26.37397104	21.91357956
7.5	20.5	3	7.853981634	22.44398713	9.482864053
9	19.56666667	1.5	3.926990817	20.08599678	2.654157322
10.5	19.33333333	0	0	19.3	-0.1724137931
12	19.73333333	1.5	3.926990817	20.08599678	1.787145858
13.5	20.6	3	7.853981634	22.44398713	8.951393839
15	22.26666667	4.5	11.78097245	26.37397104	18.44597774
16.5	24.16666667	6	15.70796327	31.87594852	31.90047665
18	26.8	7.5	19.63495408	38.94991957	45.33552077

Equation:

$$y = 19.33 - 0.3493319034\,(x - 10.5)^2$$



Standard Deviation in y indicates the error in heights calculated theoretically and experimentally, i.e.,

$$\text{S.D.} = \left(\frac{h - y_{avg}}{y_{avg}}\right) * 100\%$$

D. Reasons for Mismatches:

- The applied torque is not constant and varies between -4 to +4 throughout the experiment.
- Errors in measuring the height of the water level.
- Inflow from the Pump is changing.
- Human error while reading the instrumental apparatus for vertical rod (Y) and horizontal reading (X).
- At 135 rpm, if the measurement tool touched the water's surface, the vortex would get disturbed, and we would get an error while calculating.

Conclusion:

In a free vortex, the orifice's radius increases, the velocity decreases, and a larger orifice diameter result in a larger vortex. However, due to human error, the product of velocity and radius is not constant as it should be. The height from the top of the measuring gauge to the bridge h increases together with the angular velocity of the forced vortex. Since the flow function created by the forced vortex is parabolic, the slope of the curve rises as angular velocity does.