CH211P - Fluid Mechanics and Heat Transfer Laboratory

Group 7:

M KEDHAR REDDY, CH23B024

MAYANK DHYAWANA, CH23B023

M PRAMOD, CH23B022

Project Title:

ROTATING FLUIDS

Submission Date:

Friday, 16 May 2025

भारतीय प्रौद्योगिकी संस्थान तिरुपति

TIRUPATI

Department of Chemical Engineering

Indian Institute of Technology Tirupati

ROTATING FLUIDS

1. INTRODUCTION:

Background:

- Rotating fluids are a fundamental topic in fluid dynamics, with applications in meteorology, oceanography, astrophysics, and engineering.
- The study of rotating fluids helps in understanding phenomena such as:
    - Atmospheric circulation (e.g., cyclones, anticyclones)
    - Ocean currents (e.g., the Coriolis effect)
    - Industrial processes (e.g., centrifugal separators, rotating machinery)

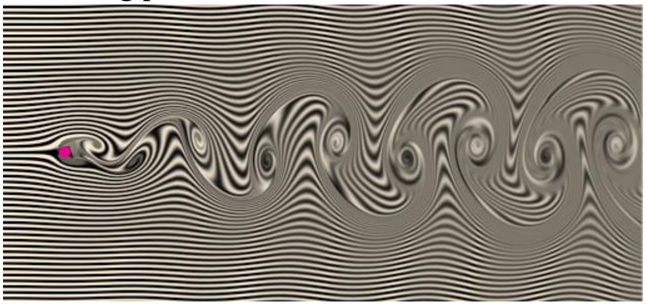

Fig 1 – Vortex in Fluid

Objective:

- The primary objectives of this experiment are:
    - To observe the behaviour of fluids under rotation.
    - To study the effects of the Coriolis force and centrifugal forces on fluid motion.
    - To analyse the formation of Taylor columns, Ekman layers, and other rotational flow structures.

Importance:

- Understanding rotating fluids is crucial for:
    - Predicting weather patterns and ocean circulation.
    - Designing efficient turbomachinery and mixing devices.
    - Modelling geophysical and astrophysical flows.

2. THEORY:

Definition:

- A **forced vortex** is a type of rotational flow in fluid dynamics where the fluid rotates as a solid body.
- This means every particle in the fluid has the same angular velocity.
- It differs from a **free vortex**, where angular momentum is conserved and the angular velocity decreases with increasing radius.

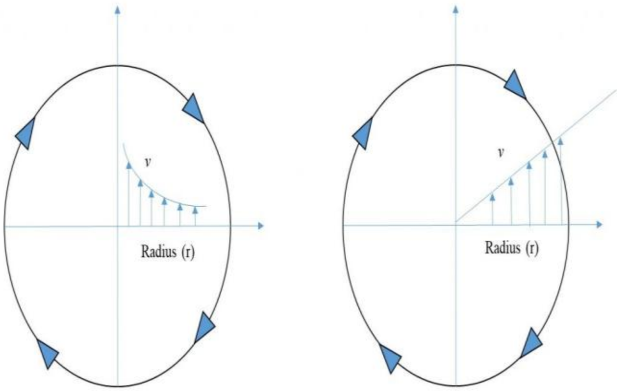

Fig 2 – Velocity profile of Free (left) and Forced (right) vortex

Key features of a Forced Vortex:

- **External Torque Applied**: An external force (like a mechanical stirrer or rotating cylinder) is needed to maintain the rotation.

- **Solid Body Rotation**: The fluid rotates like a rigid body, so:

$$v = r\omega$$

Where,

$v - tangential\ velocity$

$r - \ radial\ distance\ from\ the\ axis\ of\ rotation$

$\omega - angular\ velocity\ (constant)$

- **Pressure Distribution**: The pressure increases radially outward due to the centrifugal force. From the balance of centrifugal force and pressure gradient:

$$\frac{dP}{dr} = \ \rho\omega^2 r$$

- **Surface Shape**: In an open container, the free surface of the fluid forms a **paraboloid of revolution** due to the varying pressure. The height h of the surface at radius r is given by:

$$h(r) = \frac{\omega^2 r^2}{g}$$

Physics:

- All fluid particles have same angular velocity.
- No shear stress between adjacent fluid elements (like a solid body).
- **Examples:** forced vortex, spinning fluid elements (like a solid body).

Governing Equations:

- Momentum equation in cylindrical coordinates includes centrifugal acceleration:

$$\frac{dv_\theta}{dt} = r\omega^2$$

- Rigid body assumption, no internal deformation:

$$\nabla \times \vec{v} = 2\omega$$

- The **rotating Navier-Stokes equation** (in a frame with angular velocity **Ω**):

$$\frac{D\vec{V}}{Dt} = \ -\vec{\nabla}p + \ \mu\nabla^2.\vec{V} + \gamma\vec{g} - 2\vec{\Omega} \times \vec{V}$$

- Key Dimensionless numbers:
  - **Rossby number** ($Ro = U/\Omega L$): Ratio of inertial to Coriolis forces.
  - **Ekman number** ($Ek = \nu/\Omega L^2$): Viscous vs. rotational effects.

Case Studies:

- **2D motion of a rigid body in perfect incompressible fluids** (Boulakia et al., arXiv 2019): Reformulation of Newton-Euler dynamics for fluid-rigid body interaction. arXiv:1902.07082
- **Asymptotic stability of rigid bodies with viscous fluid cavities** (Galdi et al., 2014): Internal fluid motion damps initial disturbances and leads to uniform rotation. arXiv:1405.6596

Key Phenomena:

Concept	Description	Example
Coriolis Force	Deflects fluid perpendicular to motion (right in NH, left in SH).	Hurricane spin direction.
Taylor Columns	Vertical rigid-body structures in rapidly rotating fluids ($Ro \ll 1$).	Jupiter's banded storms.
Ekman Layers	Boundary layers where viscosity balances rotation ($Ek \ll 1$).	Ocean floor's drag effects.

Fig 3 – Key Phenomena involved in Vortex studies

EXPERIMENT:

Components:

- Arduino UNO R3
- Breadboard
- Stepper motor, 17HS4410S
- A cylindrical structure
- Motor driver, A4988 (Fig)
- Jumper Wires
- Fluid (Water), with no stains
- Ink/Dye (Tracer) and Injection system (Syringe)

Procedure:

1. The properties of the rotating fluids can be observed using the following procedure:
    - Get a power supply.
    - Check the polarity of the stepper motor, using a Multimeter.
    - Fix the motor driver, A4988, on the breadboard.
    - Make the necessary connections to the driver motor, via breadboard, as mentioned in Fig 5 .
    - Connect the other ends of the jumper wires to the Arduino, (VDD to 5V, GND to GND, dir to pin 2, and step to pin 3).

- Connect the stepper motor, 17HS4410S, to the motor driver, using jumper wires, with proper pairing of the wires.
- Fix a cylindrical structure on the stepper motor, and stick them firmly, so that it does not slip or topple over.
- Fill the cylinder with water (fluid) and inject ink (tracer) from the walls of the cylinder to observe the formation of vortex.
- Boot up the Arduino with the given code (Fig 6)

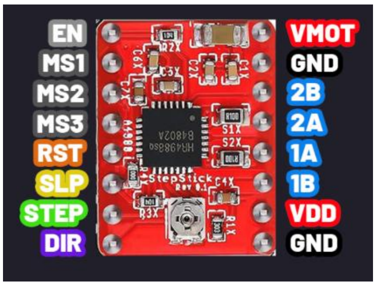

Fig 4 – A4988 motor driver

- These steps can be repeated for different speeds (revs/sec) of the stepper motor.

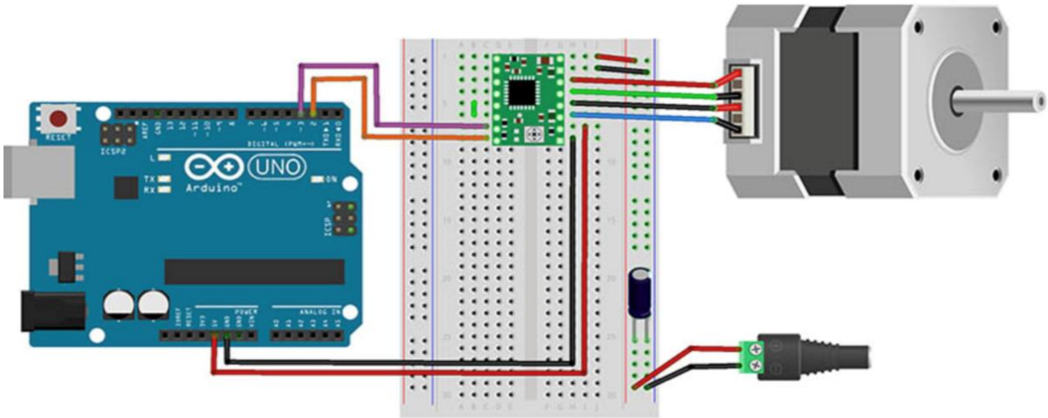

Fig 5 – Circuit diagram of the turntable setup

Arduino Code to Rotate the cylinder:

```
const int dp = 2;
const int sp = 3;
void setup() {
    pinMode(dp, OUTPUT);
    pinMode(sp, OUTPUT);
    digitalWrite(dp, HIGH);
}
void loop() {
    digitalWrite(sp, HIGH);
    delayMicroseconds(500);
    digitalWrite(sp, LOW);
    delayMicroseconds(500);
}
```

Fig 6 – Arduino Code for rotation

RESULTS AND OBSERVATIONS:

In lab experiments, a rotating tank setup shows:

- Paraboloidal rise of water surface.
- Pressure rise from centre to wall.
- Uniform particle rotation (visualized using dye (tracers)).
- The different paths followed by the fluid particle (dye) shows:
  - The direction of rotation of the vortex.
  - Coriolis effects on the particle.

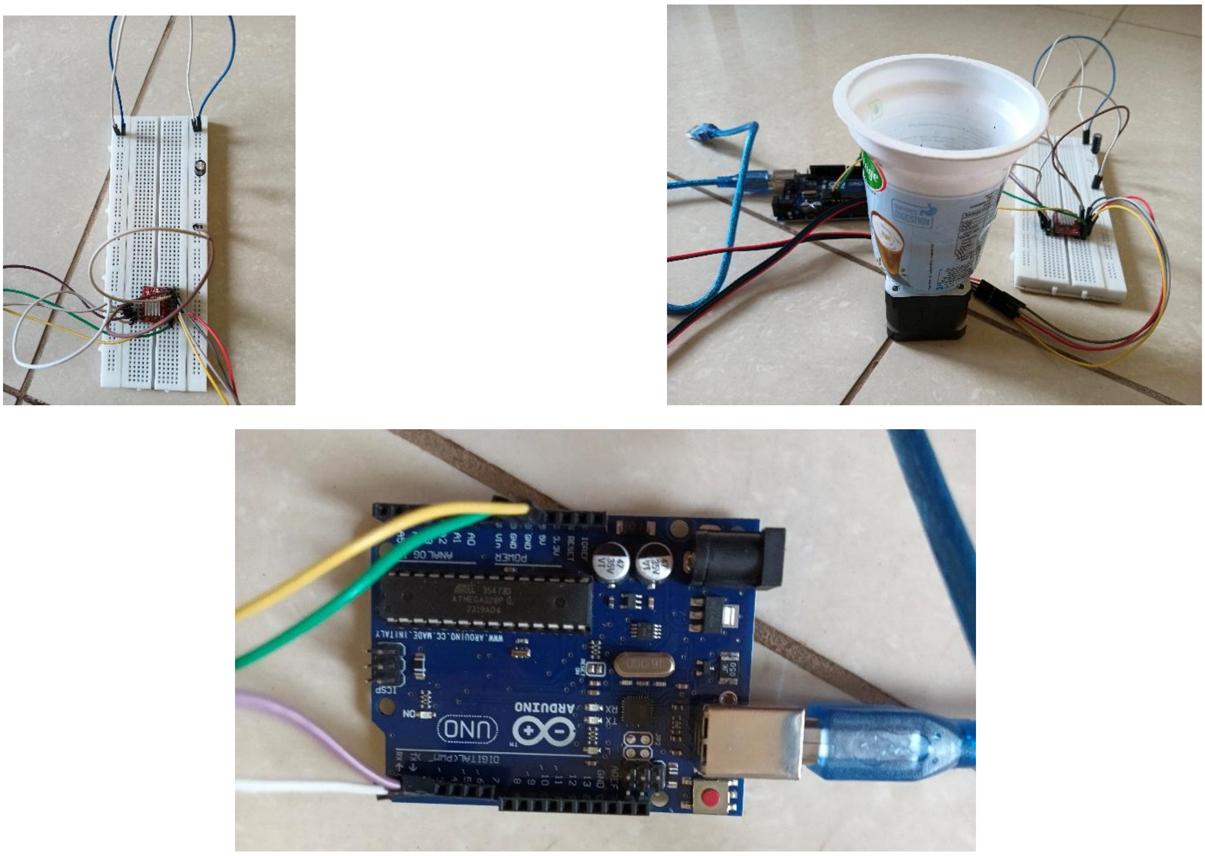

Fig 7 – Experimental setup

APPLICATIONS:

- **Industrial mixing**: Uniform rotation ensures even mixing.
- **Centrifuges**: Exploit pressure gradient in forced vortex for phase separation.
- **Meteorology**: Cyclonic storms show vortex structures.
- **Aerospace**: Used in fluid tanks of spacecraft.

CONCLUSIONS:

- Forced vortex is an engineered condition mimicking rigid body motion in fluids. Rigid body dynamics within fluids are crucial for understanding multi-phase systems, spacecraft behaviour, and rotating machinery.
- When a fluid is rotated in a container, the surface of the fluid eventually forms a parabolic shape. This is because of the centrifugal force.
- The process by which the entire fluid mass comes into rotation is gradual. The fluid near the container walls starts rotating first due to friction, then this motion is transmitted inward through viscous forces until the whole fluid rotates uniformly.
- The time it takes for the entire fluid to reach a steady rotational state depends on its viscosity. More viscous fluids (like oil) spin up faster than less viscous fluids (like water), as the viscous forces transmit the rotational motion more efficiently.
- In rotating fluids, secondary flow patterns develop, such as Ekman layers near the bottom and sides of the container. These thin layers are where frictional, Coriolis, and pressure gradient forces balance, leading to characteristic inward and upward flows along the boundaries and more complex circulations in the interior.
- When vortices are generated in a rotating fluid, their motion is affected by the rotation of the system (i.e.) vortex rings do not travel in straight lines but instead follow curved paths due to the background rotation.

Summary:

- The surface of a rotating fluid forms a paraboloid.
- Viscosity controls how quickly the fluid comes into uniform rotation.
- Ekman layers and secondary flows are critical features in rotating systems.
- Rotating fluids exhibit unique wave and vortex behaviours not seen in non-rotating systems.

ACKNOWLEDGEMENT:

This report is being submitted as an observation report on the Course project, ROTATING FLUIDS, for the course, CH211P,under the guidance and instruction of Prof. Anki Reddy Katha, IIT Tirupati, and Dr. Narendra Singh, IIT Tirupati, by Group 6.

REFERNCES:

1. Antipov, A.A. et al. (2022). *Particle Visualization in Forced Vortices*. MDPI Symmetry. DOI: 10.3390/sym14102016
2. Galdi, G.P. & Czubak, M. (2014). *Asymptotic Stability in Fluid-Filled Cavities*. arXiv:1405.6596
3. Boulakia, M. et al. (2019). *Dynamics of Rigid Bodies in 2D Incompressible Flow*. arXiv:1902.07082
4. ScienceDirect Topics. *Vortex Flow*. https://www.sciencedirect.com/topics/engineering/vortex-flow

5. https://racheldebarros.com/arduino-projects/control-nema17-with-a4988-arduino-wiring-and-code-guide/
6. robu.in
7. amazon.in