ME 207: FLUID DYNAMICS

DESIGN AND DEMONSTRATION OF HORIZONTAL AXIS MINI WIND TURBINE

Group - 13

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Introduction

Horizontal Axis Wind Turbines (HAWTs) are among the most efficient configurations for converting wind energy into electrical power. This project focuses on the design and demonstration of a mini horizontal axis wind turbine, aimed at understanding the fundamental principles of wind energy conversion and exploring compact, efficient designs suitable for educational, low-power applications.

By analyzing blade geometry and aerodynamics, this project attempts to optimize a small-scale HAWT system that can perform effectively in moderate wind conditions. The design integrates key aerodynamic features such as airfoil selection, blade tapering, twist, and pitch angle for maximum efficiency.

Problem Statement

While large-scale wind turbines are well-established, there is a gap in accessible and efficient small-scale wind energy solutions, particularly for low-resource or remote areas. This project addresses the challenge of designing a cost-effective, efficient, and demonstrable mini wind turbine that can operate at low to moderate wind speeds. The goal is to explore how aerodynamic optimization and lightweight construction can make small-scale wind energy viable for off-grid or educational purposes.

Objectives

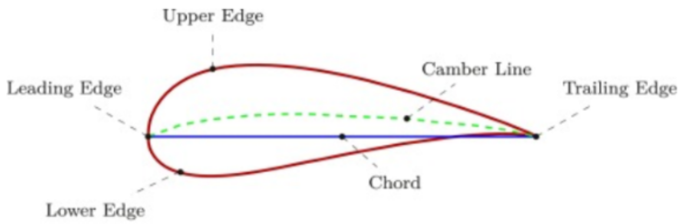
- To quantify the useful work done by the mini wind turbine with the help of a pulley-mass system.
- To test different types of wind turbines (in our case by changing the pitch angle of the turbine) for various wind speeds.
- To analyze efficiency and tip speed ratio of each wind turbine for different wind speeds.

Theoretical Discussion

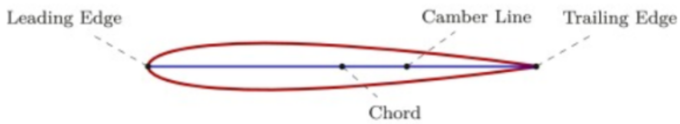
The rotation of a wind turbine depends on the lift and drag forces acting on it. These forces mainly depend on different factors like Angle of Attack, Pitch Angle, Camber of an airfoil, and the cross-section of wind acting on it.

- **Angle of Attack**: The angle between the direction of wind and the chord line of the airfoil.
- **Pitch Angle**: The angle between the chord line and the cross section of rotation of the wind turbine.
- **Camber Line**: The locus of the centroids of an airfoil from the leading edge to the trailing edge.

To design this wind turbine, we chose airfoil blades of zero camber, i.e., a symmetric airfoil. In a symmetric airfoil, the camber line coincides with the chord line (as shown in Fig. 3.1), so that the distance between the chord and the camber line is zero, making it a zero-camber profile.



(a) An asymmetric airfoil



(b) A symmetric airfoil

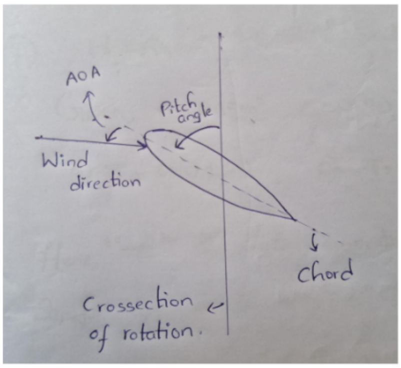
Fig : 3.1

Twist in Blade Design

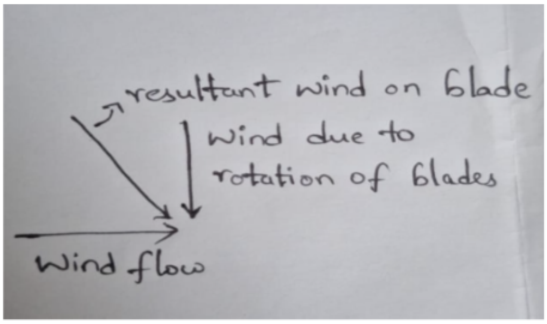
We need more lift and less drag to rotate the wind turbine. The lift increases with the Angle of Attack (AoA), but only up to a certain point. Beyond that, the airfoil stalls, leading to an increase in drag force on the blade, which is undesirable. The optimal AoA, which provides a higher lift-to-drag ratio, typically lies between 25° and 35°.

In a wind turbine blade, the velocity of the blade changes across its length—it increases with the radius, i.e., $V \propto r$. As a result, the direction of the relative wind changes along the blade (as shown in Fig: 3.2(b)), where the vertical component of velocity increases, shifting the resultant wind vector towards it. This shift leads to a variation in the AoA across the blade.

To maintain a constant AoA across the blade length, a twist is introduced along its radius. This twist causes the pitch angle to vary along the blade's length. However, as long as the AoA remains constant, the turbine continues to experience good lift.



(a) Blade without twist (constant pitch angle)



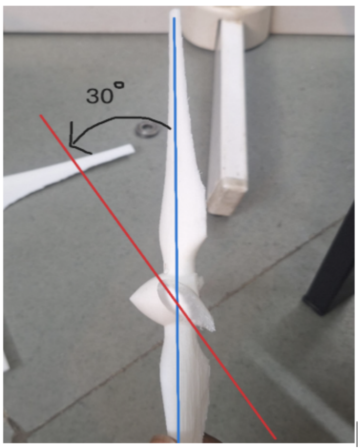
(b) Blade with twist (constant AoA)

Fig. 3.2 – Effect of Twist on Angle of Attack along Blade Radius

But due to an increase in the velocity of the blade towards the tip, the tip of the blade gets a better lift than the root of the blade. So to increase the lift at the root of the blade we used a tapered design. The cross section of the airfoil at root will be larger than the cross section at the tip (we can clearly see the tapered shape in Fig:3.3b). This increases the lift at the root of the blade.

We used two different wind turbines with different pitch angles (measured at tip of the blade): one is of 3° and the other is of 30° (Fig:3.3). For the blade of 3° pitch angle, the AoA will be greater than the optimal value, whereas with 30° pitch angle, AoA is closer to its optimal value compared to 3°. Therefore, the wind turbine with 30° pitch angle should show more lift and rotate freely than the turbine with 3° pitch angle.

(a) Blade with 3° pitch angle



(b) Blade with 30° pitch angle

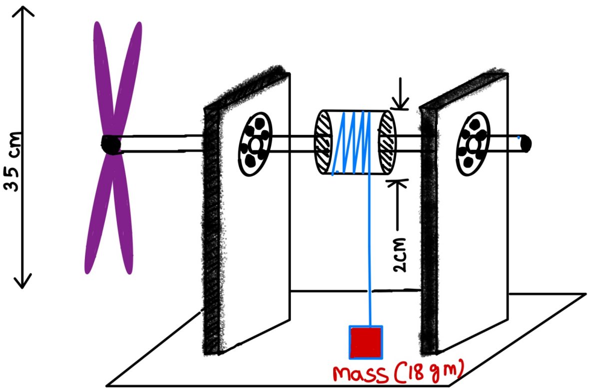


Figure 3: Schematic of the setup

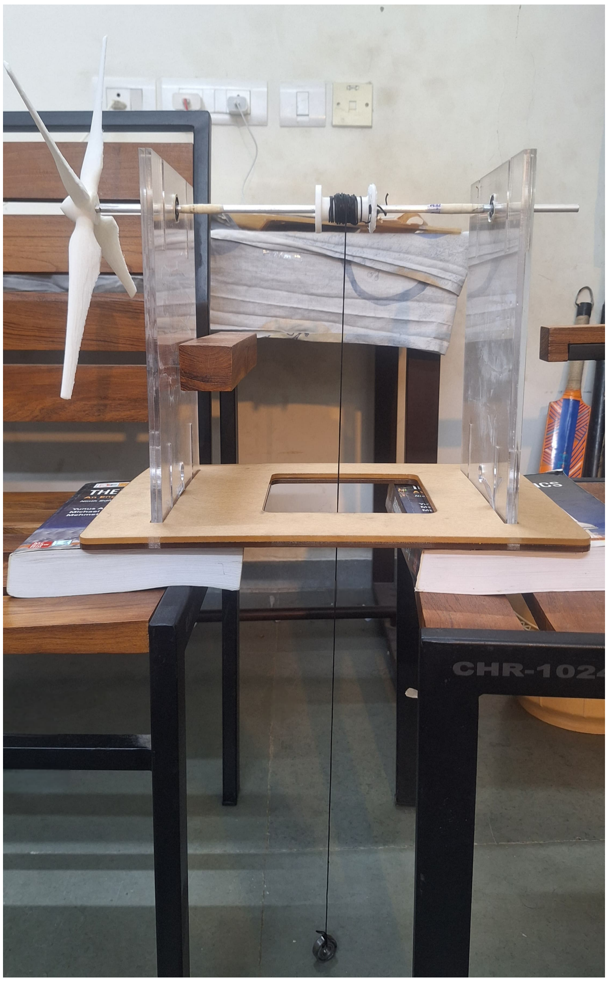


Figure 4: Experimental setup

Details of the Setup

The turbine blades were designed using 3D printing. The length of each blade is 17.5 cm. Our design has a total of four blades for each wind turbine.

Two types of turbine blades were used, i.e., 3° and 30° pitch angle, respectively.

An aluminium rod is connected to the turbine, which rotates along with the blades.

To ensure the rod remains stable without any wobbling, it was fixed between two MDF sheets.

To enable free rotation of the rod, two frictionless ball bearings were installed on the MDF sheets.

Between the MDF sheets, a pulley (radius = 1 cm) is placed where the load is suspended. The suspended load has a mass of 18 g.

The entire setup is supported by a base with a central gap through which the load can pass.

Experimental Methodology and Results

Two different wind speeds were generated using a tabletop fan, sufficient to rotate the turbine blades and produce useful mechanical work.

A pulley-mass system was used to visualize and quantify the useful work output of the wind turbines.

The output power was defined as the rate of change of gravitational potential energy using the formula:

$$P_{\text{exp}} = \frac{m \cdot g \cdot h}{t}$$

where:

- $m = 0.018\,\text{kg}$ (mass of test weight)
- $g = 9.81\,\text{m/s}^2$ (gravitational acceleration)
- $h = 0.75\,\text{m}$ (height the mass is lifted)
- t = average time taken for the mass to reach the pulley

A pulley was fixed 75 cm above the ground and connected to the turbine shaft via a string.

A test weight of 18 grams was used in this experiment.

The mass was lifted vertically as the turbine blades rotated. The time taken for the mass to rise to the pulley was recorded for multiple trials and averaged.

Two different wind turbine blade designs were tested:

- Blade with pitch angle of 3°

- Blade with pitch angle of 30°

(Both blade sets had the same dimensions.)

Each blade was tested under both wind speeds to analyze how pitch angle affects turbine performance.

From the experimental data, the following were calculated for comparison:

- Efficiency of each blade design (ratio of experimental to theoretical power)
- Angular velocity of the turbine shaft
- Tip speed ratio (ratio of blade tip speed to wind speed)

Data Collection

Table 1: Lift Times for Different Wind Speeds and Pitch Angles

Wind Speed	**3-degree Pitch Angle**	**30-degree Pitch Angle**
2.8 m/s Wind Speed	No data (This reading set is just to depict that this speed for a 3-degree pitch angle blades is insufficient to lift the 18g)	t1 = 3.8 s t2 = 5 s t3 = 6.2 s **Approx Avg. Time = 5 s**
3.8 m/s Wind Speed	t1 = 9 s t2 = 10 s t3 = 11 s **Approx Avg. Time = 10 s**	t1 = 4.2 s t2 = 4.2 s t3 = 3.7 s **Approx Avg. Time = 4 s**

Rotational Inertia

$$I_1 = M\left\{\frac{l^2}{12} + \frac{b^2}{12}\right\}$$

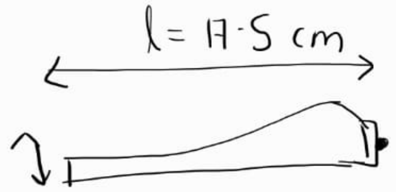
$$I_2 = I_1 + M\left(\frac{l}{2}\right)^2$$

$$I_2 = \frac{Ml^2}{3} + \frac{Mb^2}{12}$$

$l = 17.5$ cm

$b = 2.5$ cm

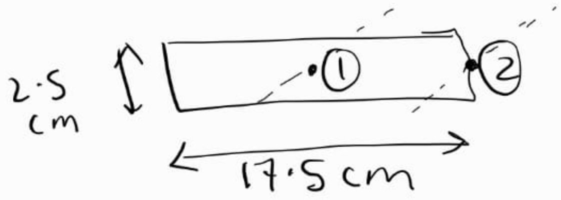
$m = 25$g



average width = 2.5cm

⇓

Model it as a Rectangle



mass of each blade = 25g

$I_2 = 2.6 \times 10^{-4}$ kgm^2

4 blades

$\Rightarrow I = 4I_2 = 10.4 \times 10^{-4}$ kgm^2

(inertia due to rod /axle and pulley is negligible)

$\Rightarrow$ Rotation energy $= \frac{I\omega^2}{2} = (5.2 \times 10^{-4})\,\omega^2$ J

$\Rightarrow$ Kinetic energy of mass $= \frac{(M_{mass})\,V_{mass}^2}{2}$ J

$\Rightarrow$ Potential energy of mass $= (M_{mass})\,g\,(h)$ J

(Kinetic energy is negligible)

$$\Rightarrow \underset{\text{efficiency}}{\eta} = \frac{\Delta PE}{\left(\frac{1}{2}\rho A V_{wind}^3\right) \times t} = \frac{mgh}{\left(\frac{1}{2}\rho A V_{wind}^3\right) t}$$

$\left[\because \text{Power generated by turbine} = \frac{1}{2}\rho A V_{wind}^3\right]$

$$\Rightarrow \underset{\substack{\text{including loss}\\ \text{due to rotational}\\ \text{inertia}}}{\eta} = \frac{\Delta PE + (5.2\times10^{-4})\,\omega^2}{\left(\frac{1}{2}\rho A V_{wind}^3\right) \times t}$$

in these formulae; $v = \frac{h}{t}$; $\omega = \frac{v}{r_{pulley}} = \frac{h}{rt}$

$h = 75\,cm$; $r_{pulley} = 1\,cm$

$m_{mass} = 18g$

$\Rightarrow$ V_{mass} and ω_{pulley} have been tabulated below.

$\Rightarrow$ Following this, the respective efficiencies η and $\eta_{with\ loss}$ have been tabulated.

Blade design	Wind speed 2.8 m/s	Wind speed 3.8 m/s
Pitch angle 3 degrees	No data; Just for depiction	Avg Time taken = 5 s
		Velocity of mass = 0.075 m/s
		Axle Angular velocity = 7.5 rad/s
Pitch angle 30 degrees	Avg Time taken = 5 s	Avg Time taken = 4 s
	Velocity of mass = 0.15 m/s	Velocity of mass = 0.186 m/s
	Axle Rotational velocity = 15 rad/s	Axle Rotational velocity = 18.6 rad/s

Table 2: Comparison of blade design performance at different wind speeds and pitch angles.

Calculation of the power coefficient:

- Each blade will have its own power coefficient, and is calculated using the formula:

$$\eta_{\text{out}} = \frac{\frac{mgh}{t}}{\frac{1}{2}\rho A v^3} = \frac{\text{Output power}}{\text{Input power}}$$

- Generally, we consider output power as the useful work that could be obtained from this process.

- But in our case, since the turbine setup is very small, we were not able to get significant power output, so we calculated two efficiencies, one with only the output power and the other with the sum of the output power and the power made use to increase the rotational energy of the blade-axle system. (Kinetic energy of the mass is very small and insignificant).

$$\eta_R = \frac{\frac{mgh}{t} + \text{Rotational kinetic energy rate}}{\frac{1}{2}\rho A v^3}$$

Type of blade design	Velocity of wind (in m/s)	Power coefficient η_{out} (in %)	Power coefficient η_R (in %)
3-degree pitch angle	2.8	No data	No data (only depiction)
	3.8	0.41	0.512
30-degree pitch angle	2.8	2.5	3.92
	3.8	1.01	2.5

- Here the efficiencies for the same blade design **vary** large due to several energy losses in the system and this says that the blade can give a significant for only **upto** certain range of speeds.
- We can observe there are no significant changes in the power coefficients when rotational kinetic energy rate is included in the output term.

Calculation of Tip Speed Ratios (TSR)

The tip speed ratio (TSR) is defined as the ratio of the tangential speed at the tip of a blade to the actual speed of the wind:

$$\lambda = \frac{\omega R}{v} \tag{1}$$

where:

- ω is the angular velocity of the turbine blades (in rad/s),
- R is the radius of the area covered by the wind turbine blades (in meters),
- v is the velocity of the wind (in m/s).

The angular velocity ω can be determined by measuring the number of revolutions made by the pulley. It is calculated as the ratio of the length of the string wound around the pulley to the circumference of the pulley, which gives the number of revolutions:

$$n = \frac{l}{2\pi r} \tag{2}$$

where:

- n is the number of revolutions,
- l is the length of the string wound (in meters),
- r is the radius of the pulley (in meters).

The number of revolutions per unit time can also be expressed as:

$$n = \frac{2\pi}{t} \tag{3}$$

where t is the average of the time periods in which the mass moves from the ground to the pulley.

Type of blade design	Velocity of wind (in m/s)	Angular Velocity (in rad/s)	TSR
3-degree pitch angle	2.8	0	Couldn't be obtained
	3.8	7.5	0.41
30-degree pitch angle	2.8	15	2.5
	3.8	18.6	1.01

Comparison Between 3° and 30° Pitch Angle Wind Turbine Blades

To better understand how blade pitch affects the performance of a small horizontal-axis wind turbine, we carried out a simple yet insightful experiment using two blade designs: one with a pitch angle of 3° and the other with 30°. Both blades were tested under the same wind conditions provided by a tabletop fan, and their ability to do useful work—lifting a small weight via a pulley—was compared.

1. Power Output

- The 3° pitch blade struggled to lift the weight. It produced very little torque, and in most trials, it could not raise the mass consistently.
- The 30° pitch blade performed much better. It was able to lift the weight quickly and reliably, generating more useful mechanical energy.

This clearly showed that the 30° blade was better suited for our setup, especially at the low wind speeds used in our experiment.

2. Airflow and Lift Behavior

- Although 3° seems like a small pitch and should typically be efficient, in our case, the effective angle of attack was too high, likely approaching or even crossing the stall angle. As a result, it did not generate enough lift.
- The 30° blade, despite having a steeper pitch, maintained a more effective angle of attack relative to the airflow (that is, below the stall angle). This allowed the flow to stay attached to the blade surface and generate stronger lift and torque.

3. Torque and Efficiency

- The 30° blade spun faster and more powerfully, which directly translated to higher torque and a greater rate of energy conversion.
- When we calculated efficiency—based on how quickly and smoothly the mass was lifted—it was clear that the 30° blade outperformed the 3° one, even though that might seem counterintuitive at first glance.

The performance of a wind turbine blade is influenced not solely by its pitch angle, but by how effectively that pitch interacts with factors such as wind speed, blade geometry, and the overall experimental setup. In this study, the blade with a 30° pitch demonstrated superior performance, likely because it maintained an angle of attack that was favorable for lift generation while remaining below the stall threshold.

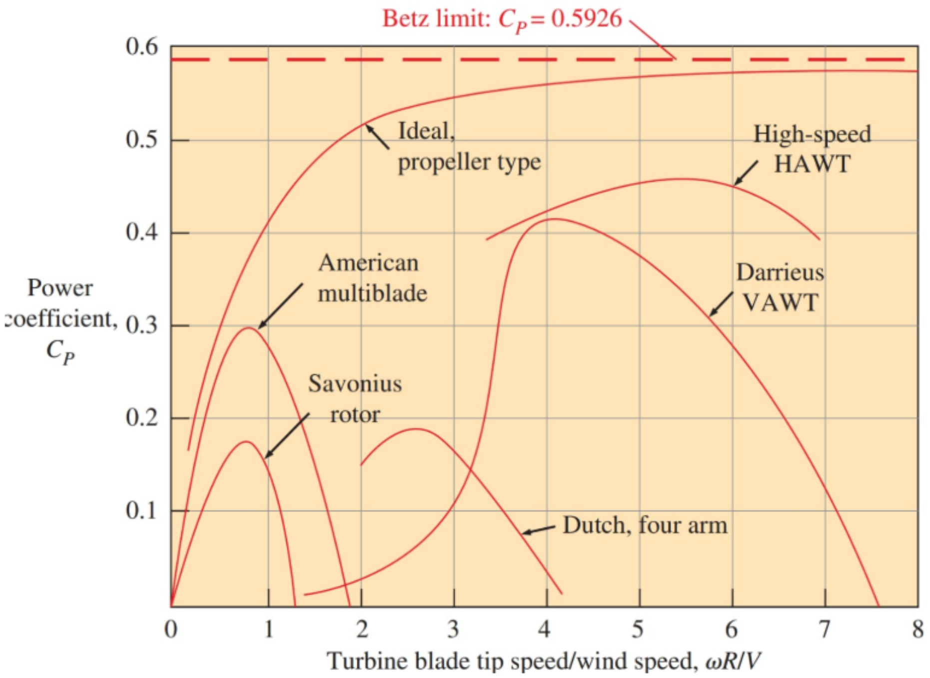


Figure 5: Comparison of the power coefficient (C_P) versus tip speed ratio ($\omega R/V$) for different wind turbine types. The Betz limit ($C_P = 0.5926$) is shown as a reference.

Source: Fluid Mechanics, Yunus A. Çengel, John M. Cimbala

- With the available wind speeds, we have the tip speed ratios of 0.41, 2.5, and 1.01 for both blades.

- From the above chart, we can see that a significant power coefficient for horizontal axis wind turbines is achieved only in the range of 3.5–7 TSR ratio, which is the optimal TSR ratio for HAWT. However, we couldn't obtain these TSR values because we have limited wind velocities. A significant power coefficient cannot be achieved outside the specified range (optimal TSR range) for HAWT, as seen in our case.
- We ended up getting low efficiencies as our TSR ratios don't lie in the specified range for HAWT.

Conclusion

In this experiment, we investigated the impact of blade pitch angle on the performance of horizontal axis wind turbines (HAWTs), specifically comparing blades pitched at **3** and **30**. Using a tabletop fan to simulate wind conditions and a **pulley–mass system** to measure useful mechanical work, we were able to assess the effects of pitch angle on key performance parameters such as **power output, efficiency, angular velocity, and tip speed ratio (TSR)**.

Despite the simplicity of the setup, the results clearly demonstrated that **pitch angle plays a crucial role** in determining turbine effectiveness. The **30** pitched blades consistently outperformed the **3** pitched blades, especially at wind speeds around **3.8 m/s**.

- Also, the aerodynamic torque from the blades isn't sufficient to lift larger weights as the blades are lighter, which is also a reason for getting lower power coefficient values in our case.
- From these results, we found that the turbine should be heavier, needs higher wind speeds, and an effective pitch angle design for blades that aligns with an angle of attack at which the lift is maximum. Then we could achieve the Optimal TSR range mentioned in the plot for HAWT.

Key Takeaways

- **Underperformance of 3° Pitch Blades:**
  Although the 3° pitch might seem more aerodynamically favorable at first glance, it resulted in a **higher angle of attack (AOA)** in our setup, likely **near or beyond the stall angle**. This caused **flow separation** and **poor lift generation**, ultimately reducing torque and overall performance.

- **Better Performance of 30° Pitch Blades:**
  In contrast, the 30° pitch blades, despite their higher pitch, achieved a **lower and more controlled AOA**, which remained **below stall**. This allowed for **smoother airflow**, better lift, and consequently **higher torque and efficiency** under the same wind conditions.

- **Tip Speed Ratio (TSR) and Efficiency Limits:**
  The TSR values observed (**0.41, 2.5, and 1.01**) were below the optimal range (**3.5–7**) for typical HAWTs. These suboptimal TSRs, influenced by limitations in wind speed and turbine design, likely constrained the achievable **power coefficients**.

- **Minimal Impact of Rotational Inertia:**
  When accounting for **rotational kinetic energy** (moment of inertia of blades and shaft), the change in efficiency was minimal. This suggests that **mechanical losses**, such as friction at bearings and in the shaft, played a more significant role in overall efficiency loss.

- **Context-Driven Blade Design:**
  The findings reinforce the idea that **blade performance is context-dependent**. In small-scale systems or at lower wind speeds, maximizing torque—even at higher pitch angles—may result in better energy capture and overall performance.

Acknowledgement

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