# Benchmarking Toroidal Propellers on Efficiency and Noise Characteristics

Aritra Mukhopadhyay
*National Institute of Science Education and Research*
*Bhubaneswar, Odisha 751005, India*
*4th year, Integrated M.Sc. Physics*
*Roll No.: 2011030*
(Dated: April 26, 2024)

Drones are employed in various fields, including aerial photography, surveillance, and logistics. However, high-speed drone delivery requires quieter and more efficient propellers. High-speed rotation of drone propellers, while providing necessary lift, produces significant noise, not only leading to energy loss but also noise pollution concerns in populated areas. This report compares the noise reduction capabilities and efficiency of commercial two-blade and three-loop toroidal propellers across different power consumption levels.

Preliminary findings show that toroidal propellers offer superior noise reduction, making them appealing for minimal noise applications. However, this advantage comes at a cost of reduced efficiency compared to the commercial two-blade propellers.

## I. INTRODUCTION

Drones have revolutionized various industries, from spraying pesticides on agricultural fields to surveillance and aerial photography. Their versatility, agility, and ability to access remote or hard-to-reach areas have made them an indispensable tool in modern times. However, as drone technology continues to advance, the need for drone delivery of parcels has emerged as a promising application. This will help in the ultra-fast and cheaper delivery of emergencies like medicines and even casual things like food products. This necessitates the development of quieter and more efficient propellers, which are critical components in ensuring the success of such operations.

High-speed rotation of drone propellers is essential for generating the necessary lift to support the weight of the drone and its payload. However, this high-speed rotation comes at a cost - significant noise generation. This noise not only leads to energy loss and reduces the overall efficiency of the drone but also raises concerns about noise pollution in populated areas. The latter is particularly crucial, as excessive noise can be a nuisance to residents and even pose safety risks.

In light of these challenges, this report investigates the noise reduction capabilities and efficiency of two distinct propeller designs: commercial two-blade propellers and three-loop toroidal propellers. By comparing their performance across different power consumption levels, this study aims to provide valuable insights into the potential of toroidal propellers in addressing the noise and efficiency concerns associated with high-speed drone delivery.

## II. THEORY

### A. Why do propellers make noise

Propellers generate noise primarily due to the high-speed rotation of their blades. Consider a typical drone propeller (example numbers from our experiment) rotating at speeds ranging from 3000 to 8000 revolutions per minute (RPM). At these speeds, the tip of the propeller moves at a significantly higher velocity than the centre, reaching speeds of approximately 60 m/s for a propeller with a radius of 4.5 inches.

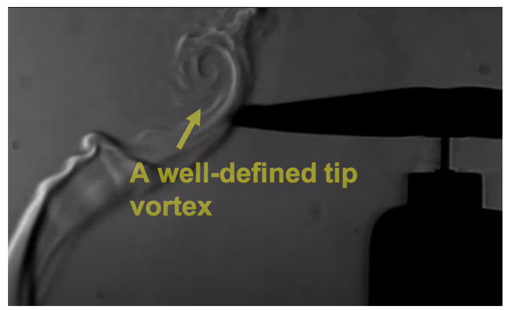



FIG. 1: Schlieren Visualization of Tip Vortex [1]

During operation, propellers actively create a pressure difference between the high-pressure region on one side and the low-pressure region on the other. As the propeller rotates, air not only moves perpendicular to the plane of the propeller but also radially along the blades, influenced by centrifugal force. This radial airflow creates two distinct streams along the two surfaces of the propeller—one with high pressure and the other with significantly lower pressure. These two streams collide at the propeller's tip, forming a vortex. This propeller tip vortex is shown with the help of the Schlieren imaging technique in Figure 1.

The creation of this vortex is a principal source of noise in propellers, contributing to increased drag and affecting overall efficiency. Toroidal propellers solve this issue by dramatically reducing vortex production due to their unique shape. Designed to direct the high and low-pressure streams in different directions, toroidal propellers prevent them from uniting at the tip, thereby minimizing vortex formation and reducing noise levels.

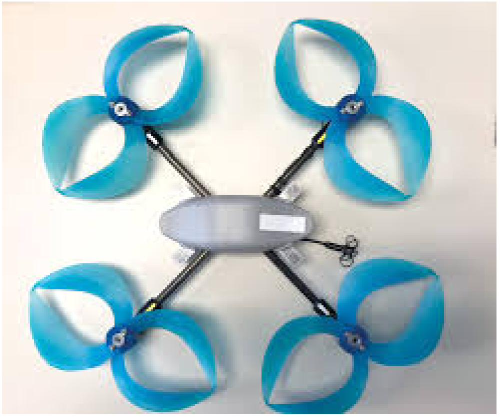


FIG. 2: Toriodal Propeller Fitted on a Drone []

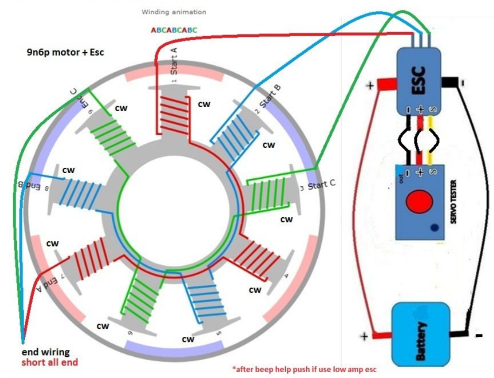



FIG. 3: BLDC Schematics

### B. Toroidal Propellers

Toroidal propellers, also known as ring-shaped or doughnut-shaped propellers, have gained significant attention in recent years due to their potential to improve efficiency and reduce noise. The concept of toroidal propellers was first proposed by researchers at the Massachusetts Institute of Technology (MIT) in 2017. These unique propellers feature a circular shape with a central hole, resembling a doughnut or a ring. Initially, toroidal propellers were designed for marine vessels, where they have proven to be highly efficient by reducing cavitation in water. However, MIT researchers also proposed the use of toroidal propellers for drones, claiming that they could significantly reduce noise and increase efficiency. Despite the promising results, the MIT team did not release any design files or specifications, leaving the drone community to experiment with their own designs and try to improve upon the concept. As a result, various enthusiasts and researchers have been exploring different toroidal propeller designs, testing their performance, and sharing their findings online. We can see such toroidal propellers being fitted in a drone in Figure 2.

### C. Brush Less DC (BLDC) motor

Although more complex and costlier, the Brush Less DC (BLDC) motor has several advantages over traditional DC motors, including higher efficiency, longer lifespan, and reduced maintenance. In the context of drones, BLDC motors are preferred over traditional DC motors due to their ability to provide high power-to-weight ratios, essential for achieving the necessary thrust while minimizing weight.

A typical BLDC motor consists of a stator and a rotor, with three wires emerging from the motor. These three wires correspond to the three phases of the motor (see Figure 3), which are responsible for generating the rotating magnetic field that drives the motor's rotation. These three wires are connected to the Electronic Speed Controler (ESC) which takes in input from the user as a Pulse Width Modulated (PWM) signal and translates it to signals necessary for the motor to work.

Here we generate the PWM input to be sent to the ESC with the help of an Arduino UNO. Our ESC has BEC (Battery Eliminator Circuit), so we do not need to power the Arduino separately; our ESC sends a backward current to power the Arduino. In Figure 3 we can see the schematics of the BLDC motor along with the Battery and the ESC. We use exactly same circuit except we use an Arduino and a potentiometer in place of the Servo Tester in the image. We also had to code the Arduino properly to make it act like the Servo Tester.

The working principle of a BLDC motor revolves around the periodic reversal of current direction in the motor windings. In traditional DC motors, this is achieved through the use of brushes, which make contact with the commutator to switch the current flow. In contrast, BLDC motors rely on an external controller to provide an alternating current (AC) signal that periodically reverses the current direction. This allows for precise control over the motor's rotational speed, as the frequency of the AC signal can be adjusted to achieve a specific RPM.

In our experiment, we utilized a 1,000 Kv (konstant voltage) BLDC motor, which is designed to operate at high speeds. When powered by a 12V supply, this motor can theoretically reach rotational speeds of up to 12,000 RPM. At its highest speed, the motor typically draws around 10-12 amperes of current, although this value can increase if the load on the motor is increased. The motor is rated for a maximum current draw of 20A, allowing it to handle demanding applications with ease.

### D. Noise Characteristics Analysis

We employed a comprehensive approach to capture and process the audio data to analyse the noise generated by the two propeller designs. First, we recorded the audio signals for 5 seconds using a our smartphone microphone positioned at a fixed distance behind the propeller (towards the direction of blowing air). This ensured that the captured data accurately represented the noise heard by a person on the ground when the drone is above them.

Next, we applied a Fast Fourier Transform (FFT) to the recorded audio data, effectively transforming it from the time domain to the frequency domain. This step enabled us to visualize and analyze the noise levels across various frequencies. The resulting spectra revealed that the toroidal propeller exhibited lower noise levels compared to the 2-blade propeller, indicating a quieter operation. Furthermore, the curve corresponding to the toroidal propeller was observed to be relatively flatter, suggesting that the noise is distributed more evenly across all frequencies. This characteristic is reminiscent of white noise, which is often perceived as background noise and can be naturally eliminated by the human ear.

Upon closer inspection, we noticed a slight increase in amplitude towards the lower frequency range compared to the higher frequencies. This phenomenon is beneficial, as lower frequencies tend to decay faster than higher frequencies, reducing noise pollution over time.

### E. Efficiency Calculation

To calculate the efficiency of the propeller designs, we employed a straightforward approach that involved measuring the current drawn by the motor and the corresponding thrust produced. We connected a series of ammeters with the ESC to the power supply, allowing us to accurately measure the current being drawn by the motor. Throughout the experiment, the voltage was fixed at 12V.

Since power consumption (P) is directly proportional to current ($I$), as described by the equation $P = VI$, where $V$ is the potential difference (constant here), we can use the measured current as a replpacement for power. This simplifies our analysis, as the constant voltage ensures that any changes in current directly indicate changes in power.

In our setup, we measured the thrust produced by the propeller at multiple current values. We defined efficiency as the ratio of thrust to current, which can be mathematically represented as:

$$\text{Efficiency} = \frac{\text{Thrust}}{\text{Current}} \tag{1}$$

This equation enables us to quantify the efficiency of each propeller design and compare their performance.

## III. EXPERIMENTAL SETUP

We established a controlled experimental setup to conduct a comprehensive analysis of the propeller designs. The BLDC motor was securely fastened to a tower, which was then placed on top of a weighing machine. This arrangement enabled us to measure the thrust produced by the motor accurately. The tower was necessary to ensure unrestricted flow of air to the propeller. The experimental setup is shown in Figure 4.

FIG. 4: Experimental Setup

The motor was connected to a power supply in series with an ammeter, allowing for precise measurements of the current drawn by the motor. Additionally, we connected the Electronic Speed Controller (ESC) to the motor. We linked the signal wires of the ESC to Pin 9 of an Arduino board, which is capable of generating Pulse Width Modulation (PWM) signals.

To control the speed of the motor, a potentiometer was connected to the Analog Input Pin A0 of the Arduino board. The Arduino was programmed using the following code:

```
#include <Servo.h>  // BLDC and Servo same for
    arduino; both work on similar signal

const int potPin = A0;
const int BLDCpin = 9;

Servo myBLDC;

void setup() {
  Serial.begin(9600);
  myBLDC.attach(BLDCpin);
}

void loop() {
  int potValue = analogRead(potPin);
  int bldcAngle = map(
      potValue,  // value
      0, 1023,   // from range
      0, 180     // to range
  );

  myBLDC.write(bldcAngle);
  Serial.println(potValue);
  delay(15);  // controlled delay
}
```

This experimental setup enabled us to systematically measure the thrust produced by each propeller design and analyze their performance.

### A. Methodology

**Measuring Efficiency:** To quantify the efficiency of each propeller design, we measured the thrust produced by each motor at various current levels. We then plotted two graphs: one illustrating the relationship between thrust and current, and another showing the efficiency versus thrust, as defined in Equation 1. This enabled us to visualize and compare the performance of both propellers across different operating conditions.

**Measuring Noise:** To assess the noise characteristics of each propeller design, we recorded the audio signals for 5 seconds at different current levels. We then applied a Fourier transform to the recorded signals, which allowed us to plot the noise amplitude spectra for both propellers. Additionally, we integrated the noise amplitude across all frequencies for different current values. This facilitated plotting noise levels versus current graphs for both propellers, enabling us to compare and contrast their noise characteristics.

### B. Apparatus

- a BLDC Motor
- Propellers to be tested
- ESC (preferably one with BEC) rated for 18A
- A servo tester (can be replaced by an Arduino UNO and a Potentiometer)
- A power source capable of providing 15A current and 15V potential.
- Weighing Machine (max 1kg) to measure the thrust
- An ammeter (multi-meter) to measure the current
- A cylindrical tower to attach the motor onto, such that it is positioned high above the flat surfaces like the table top.

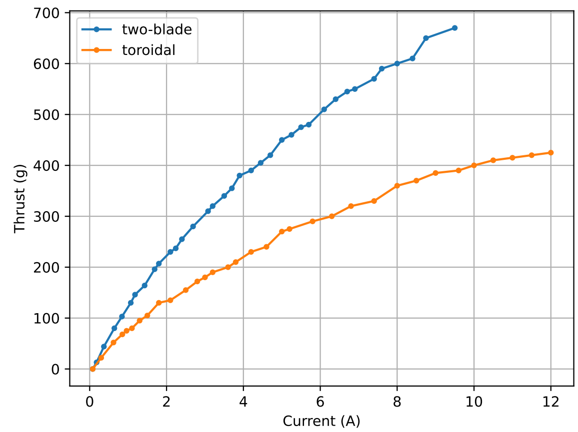
## IV. OBSERVATION

| | Propeller Type | Diameter (cm) | Pitch (degrees) | # of Blades | Weight (g) | Fabrication Process |
|---|---|---|---|---|---|---|
| 1 | Two Blade | 25.4 | 15 | 2 | 12.0 | Injection Moulded |
| 2 | Toroidal | 22.0 | 15 | 3 | 12.6 | 3D Printed |

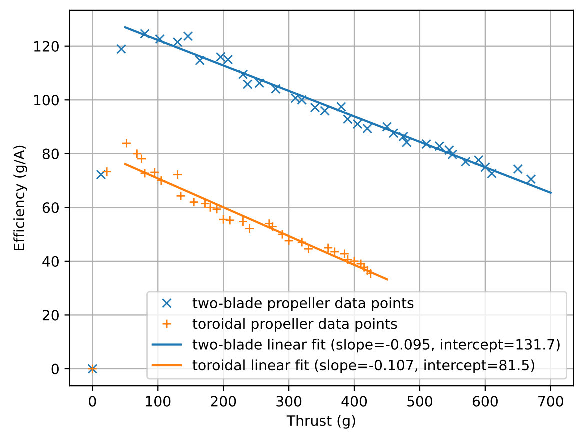
TABLE I: Specifications of the propellers used

**Motor Specifications**

- **Rated Voltage:** 12 V
- **Maximum Current:** 18 A
- **Theoretical RPM/V:** 935 kV




(a) Thrust vs Current for the different types of propellers



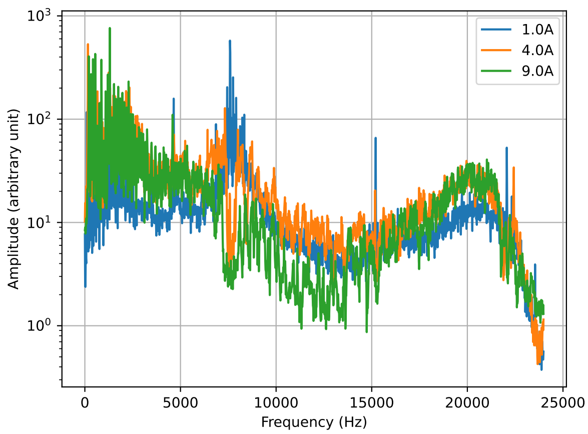

(b) Efficiency vs Thrust for the different types of propellers

FIG. 5: Performance characteristics of different propeller types

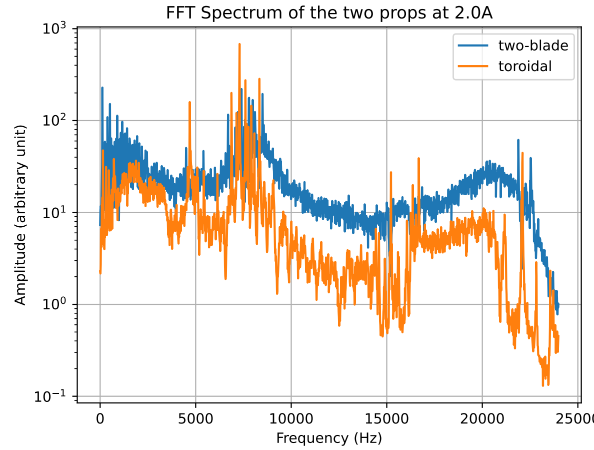
### A. Efficiency Comparison

Figure 5a illustrates the relationship between thrust and current (a direct measure of power). A growing trend is observed, although it appears to saturate at a certain value without reaching a plateau. Notably, the curve for the Two-Blade Propeller consistently exceeds that of the Toroidal propeller across all current (power) levels. **Therefore, we can conclude that the Toroidal propeller exhibits inferior efficiency compared to the Two-Blade Propeller at every current (power) level.**

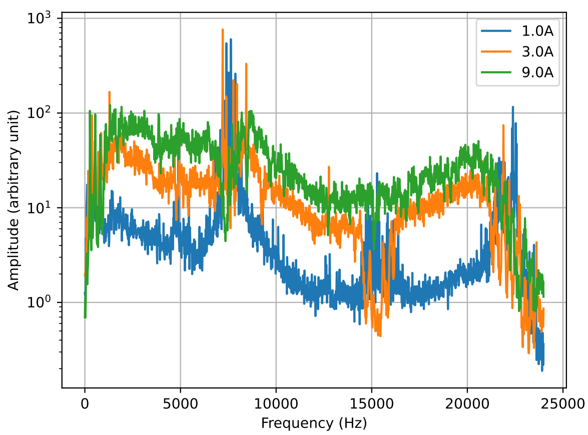
Figure 5b reveals a linear correlation between Efficiency and Thrust. Both propellers demonstrate maximum efficiency at low speeds. The negative slope observed for both propellers is expected, as increased propeller speed results in higher air drag, hence decreasing efficiency. While numerous online resources [2, 3] explain the de-




(a) Amplitude vs Frequency for the different current values for Two-blade propeller

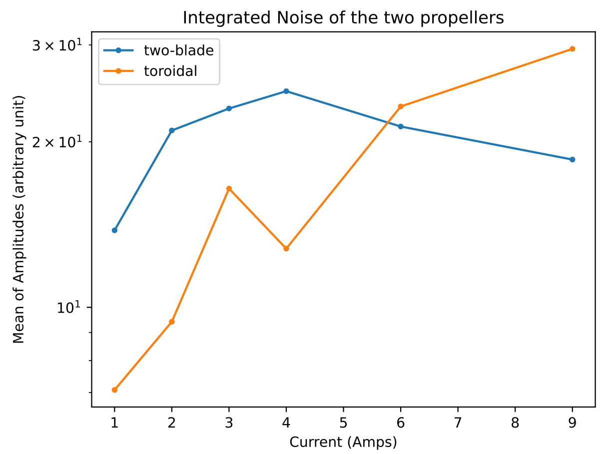



(a) Noise comparison between Toroidal and Two-blade propeller for the same current




(b) Amplitude vs Frequency for the different current values for Toroidal propeller

FIG. 6: Amplitude-frequency variation for two propeller types at various currents




(b) Integrated Noise Comparison between Toroidal and Two-blade Propeller

FIG. 7: Noise Comparisons

crease in efficiency with increasing throttle or power output, the linearity of the relationship between Efficiency and thrust remains an unexplored topic.

### B. Noise Analysis

We can see in Figure 6 how the noise profiles in the frequency domain of the two propellers vary for the two-blade and the toroidal propellers. We can see how unlike the toroidal the noise profile for the two blade remains same for the whole range. Noise for toroidal increases as it spins faster. This observation is more easily seen in Figure 7b, where we see the two blade propeller had almost same level of noise level throughout the range, while the toroidal shows an overall growing trend. In the toroidal propeller in Figure 7b at 3A we can see a sudden peak, probably this might be a resonating frequency of the setup at which the noise is getting amplified.

Both Figures in 7 suggest that the toroidal propeller has much less noise properties than the two-blade propeller for the major part of the distribution. At 6A current the the curves cross each other and the noise of the toroidal surpasses the two-blade noise.

## V. FUTURE WORK

- **Design Exploration:** Explore a wider range of exotic propeller designs, including variations of toroidal propellers with different pitches, diameters, weights, and number of blades to gather more comprehensive datasets and facilitate meaningful comparisons.

- **Alternative Propeller Designs:** Consider other low-noise propeller designs, like the 2-blade asymmetric propeller by Zipline, which claims significant noise reduction, and evaluate their performance in comparison to traditional two-blade and toroidal propellers. This could involve conducting further experiments or simulations to validate the results and identify potential areas for improvement, such as optimizing blade angles or tip shapes to minimize noise generation.
- **Material Innovations:** We could have utilized innovative materials like *foaming PLA* filaments, which expand upon cooling after melting during 3D printing, to create lightweight propellers that would be ideal for applications where weight reduction is crucial.
- **Surface Finish Improvement:** Investigate methods for improving the surface finish of 3D printed propellers, which currently exhibit rough surfaces due to layer lines, thereby increasing drag and compromising their aerodynamic performance. One potential approach is to apply a thin layer of coating, such as nail polish, to smooth out the surface and reduce noise generation. Other techniques, like chemical etching or mechanical polishing, were deemed infeasible since they would compromise the structural integrity of the already thin propeller blades.

## VI. CONCLUSION

In conclusion, the results obtained in this experiment are dependent upon various factors, including the motor used, the experimental setup, and the exact design of the propeller. The performance of the 3D printed propellers is also influenced by the printing material, layer thickness, and surface finish. Therefore, it is essential to consider these parameters when interpreting the results and making comparisons with other studies.

I would like to extend my gratitude to Ayush Singhal for his invaluable assistance in carrying out this experiment. Additionally, I would like to thank the Robotech Club for providing the necessary equipment and resources that enabled us to conduct this study. Their support was instrumental in the successful completion of this project.

[1] L. Science, Schlieren visualization of propeller tip vortex (2021), youTube video.
[2] Selecting a propeller, accessed on March 31, 2023.
[3] P. Devi, What is the relationship between thrust and fuel efficiency in aircraft engines?, https://qr.ae/pskESG, accessed on March 31, 2023.

| Two-blade propeller | | | Toroidal Propeller | | |
|---|---|---|---|---|---|
| **Current (A)** | **Thrust (g)** | **Efficiency (g/A)** | **Current (A)** | **Thrust (g)** | **Efficiency (g/A)** |
| 0.078 | 0 | 0.00 | 0.08 | 0 | 0.00 |
| 0.18 | 13 | 72.22 | 0.3 | 22 | 73.33 |
| 0.37 | 44 | 118.92 | 0.62 | 52 | 83.87 |
| 0.642 | 80 | 124.61 | 0.85 | 68 | 80.00 |
| 0.84 | 103 | 122.62 | 0.96 | 75 | 78.13 |
| 1.07 | 130 | 121.50 | 1.1 | 80 | 72.73 |
| 1.18 | 146 | 123.73 | 1.3 | 95 | 73.08 |
| 1.43 | 164 | 114.69 | 1.5 | 105 | 70.00 |
| 1.69 | 196 | 115.98 | 1.8 | 130 | 72.22 |
| 1.8 | 207 | 115.00 | 2.1 | 135 | 64.29 |
| 2.1 | 230 | 109.52 | 2.5 | 155 | 62.00 |
| 2.24 | 237 | 105.80 | 2.8 | 172 | 61.43 |
| 2.4 | 255 | 106.25 | 3 | 180 | 60.00 |
| 2.69 | 280 | 104.09 | 3.2 | 190 | 59.38 |
| 3.08 | 310 | 100.65 | 3.6 | 200 | 55.56 |
| 3.2 | 320 | 100.00 | 3.8 | 210 | 55.26 |
| 3.5 | 340 | 97.14 | 4.2 | 230 | 54.76 |
| 3.7 | 355 | 95.95 | 4.6 | 240 | 52.17 |
| 3.9 | 380 | 97.44 | 5 | 270 | 54.00 |
| 4.2 | 390 | 92.86 | 5.2 | 275 | 52.88 |
| 4.45 | 405 | 91.01 | 5.8 | 290 | 50.00 |
| 4.7 | 420 | 89.36 | 6.3 | 300 | 47.62 |
| 5 | 450 | 90.00 | 6.8 | 320 | 47.06 |
| 5.25 | 460 | 87.62 | 7.4 | 330 | 44.59 |
| 5.5 | 475 | 86.36 | 8 | 360 | 45.00 |
| 5.7 | 480 | 84.21 | 8.5 | 370 | 43.53 |
| 6.1 | 510 | 83.61 | 9 | 385 | 42.78 |
| 6.4 | 530 | 82.81 | 9.6 | 390 | 40.63 |
| 6.7 | 545 | 81.34 | 10 | 400 | 40.00 |
| 6.9 | 550 | 79.71 | 10.5 | 410 | 39.05 |
| 7.4 | 570 | 77.03 | 11 | 415 | 37.73 |
| 7.6 | 590 | 77.63 | 11.5 | 420 | 36.52 |
| 8 | 600 | 75.00 | 12 | 425 | 35.42 |
| 8.4 | 610 | 72.62 | | | |
| 8.75 | 650 | 74.29 | | | |
| 9.5 | 670 | 70.53 | | | |

TABLE II: Efficiency Calculation Data