The Kinematics of Falling *Pterocymbium Tinctorium* Seeds

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Abstract

*Pterocymbium tinctorium (*Thai:ปออีเก้ง, Por-Ae-Keang) is a tree found in Thailand and other Southeast Asian countries. The fruit, containing a single seed with an attached single wing extending to one side and a hollow boat-shaped structure that braces the wing in flight, is known as a samara. The vertical terminal velocity and spin frequency of the falling samara were studied for a representative sample of the population. The effect of mass on terminal velocity and spin frequency was then investigated for a single typical seed. The motion was recorded with a high-speed camera. The terminal velocity and spin rate were determined and the coefficient of lift was estimated. In the population study, no significant correlation was found between seed mass, wing area, terminal velocity, and frequency. It is concluded that parameters such as angle of attack or wing curvature are likely have a larger impact on the aerodynamics. As the mass of one selected seed was increased, terminal velocity, frequency, and lift force also increased, following the trend found elsewhere for *Dipterocarpus Alatus* samaras. It was shown that 80-90% of the vertical retarding force generated during the fall was from lift and that the coefficient of lift for the seed used was close to constant, varying between about 0.3 and 0.4.

Keywords: *Pterocymbium tinctorium*, winged seed, mass, population variability, terminal velocity, aerodynamic lift

I. INTRODUCTION

Plants have several means of seed dispersal, including edible seeds transported by animals, buoyant fruit carried on water, ballistic fruit launching seeds, and winged or plumed fruit travelling in the air[1]. There are several types of winged seeds, or samaras, including single-winged seeds, and multi-winged seeds. Common examples are *Pterocymium tinctorium*, *Acer sassarinum* (Maple), *Dipterocarpus alatus*, and *Pinus Sylvestris*, respectively, shown in Figures 1 and 2.[2,3] The species investigated here is *P. tinctorium* in the Malvaceae family: a deciduous tree about 50 meters tall with a cylindrical bole up to 90 cm in diameter.[4] It is indigenous to Southeast Asia and is used for fiber, wood and dyestuff.[4] The samara (Figure 1), has a round fruit at its base with a curved wing extending to one side and a hollow boat-shaped central structure that braces the single wing in flight, allowing it to spin like a helicopter as it falls. Here, we first investigate the variability in falling behavior in a sample population and then determine the effect of varying the mass of a single seed.

Figure 1. *Pterocymbium tinctorium* seed, with its single wing.

Figure 2. Other types of samara. *Acer sassarinum* (Maple) (1), *D. Alatus* (2), and *Pinus Sylvestris* (3)[5,6,7]

Many studies have been conducted on the behavior of winged seeds. A study in population of Pinus Sylvestris (Figure 2) by Debain et al showed a positive correlation between wing area and seed mass.[8] In addition, seed mass was shown to be positively correlated with terminal velocity.[8] In general, seeds with wings or plumes tend to have increasing wing area with increasing seed mass.[9]

Green conducted an experiment with sample populations of 7 different flat-winged samara species, including several types of maple, in which he measured terminal velocity and angular velocity. He showed a variation of about 10-18 % in terminal velocity and 13-28 % in angular velocity within the populations of each species, along with a positive correlation between terminal velocity and the square root of the wing loading (the ratio of weight and wing surface area).[10] No population studies of curved wing samara species similar to *P. tinctorium* were found in the literature.

Turning to the second part of this investigation, a similar study by Song, who investigated the aerodynamics of the two-winged seed, *D. Alatus* (Figure 2), showed that terminal velocity, frequency, and lift force all increase, as the mass of a seed is increased.[6] Also, it was shown that 80 – 95 % of the retarding force is generated from the lift force, as seen in Figure 3.[6] The coefficient of lift of the samara, estimated between 1.3 to 1.6, increased with increasing wing velocity.[11]

A samara experiences three different forces while falling; the downward gravitational force, and the two upward forces of the aerodynamic drag and the aerodynamic lift of the wing. At its terminal velocity,

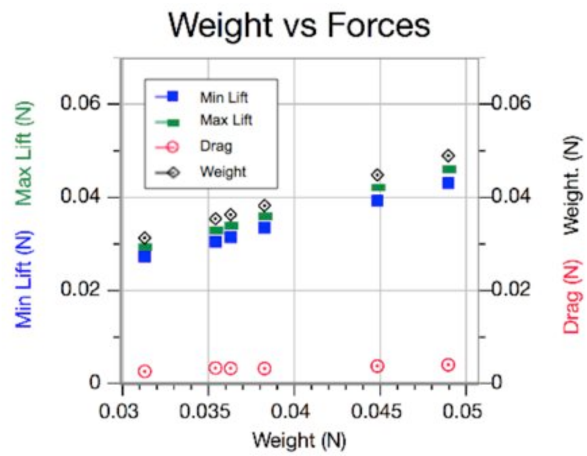


Figure 3. The relationship between weight and the drag and lift forces for a falling *D. Alatus* samara.[6]

the force of gravity is equal to the sum of the drag and lift forces,[6,11,12]

$$F_g = \frac{1}{2} A_w \rho C_L v_w{}^2 + \frac{1}{2} A_B \rho C_D v_t{}^2 \qquad (1)$$

where A_w is the effective cross-sectional area of the wing, A_B is the cross-sectional area of the entire seed as it falls, ρ is air density, C_L is coefficient of lift, C_D is the coefficient of drag, v_w is the effective wing velocity, and v_t is the terminal velocity.

As seen in Figure 2, the *D. Alatus* seed has a symmetric shape, with two wings, while the *P. tinctorium* seed is asymmetric, with only one wing. Hence the seed ‘wobbles’ while falling, as shown in Figure 4. A stable leading-edge vortex is generated as the wing rotates, which slows the descent by creating lift.[13] However, due to the balance of the seed and its weight, its axis of rotation changes as it falls, which changes the angle of attack of the wing and, therefore, the lift force. However, it is still expected to behave similarly to *D. Alatus*, because of similar wing curvature and helical motion.

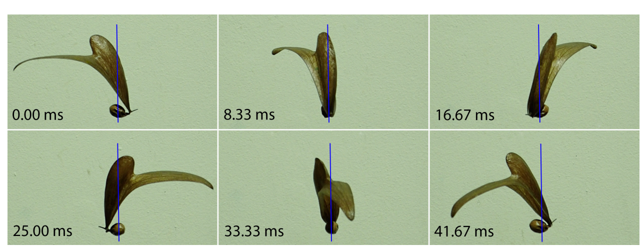


Figure 4. *P. tinctorium* seed sample 9 ‘wobbling’ while falling.

It is expected that as weight increases, terminal velocity, spin frequency, and the lift force will increase, with an accompanying increase in the coefficient of lift.

II. METHODS

Seed Selection

To determine the variability in the population, a representative sample was selected as follows. Firstly, all the 50 seeds, which had been collected from a single tree, were massed. The seeds were grouped by mass into five groups of 10 seeds each. The mass of the seeds ranged from 0.157g to 0.241 g. From each group of 10 seeds, two seeds were selected with similar mass, but with different wing area, determined visually. The 10 samples, shown in Figure 5, were also chosen to represent a wide range of wing curvature, size of the central mast, and wing angle, again determined by inspection.

Mass Variability

For the second part of the investigation, studying the effect of the mass of the seed on aerodynamic parameters, sample 5 (see Appendix) was chosen as it was in the middle of the range of both weight and wing areas of the population sample. A small hole was drilled at the top of the seed and the inner material was removed, leaving the outer shell of the seed unchanged. In this way, the mass of the seed could be changed with a minimal effect on the aerodynamic profile of the seed. Fragments of lead were put into the hollowed-out seed to vary the mass from 0.1065 to 0.4568 g.

Figure 5. The ten sample seeds used in the study.

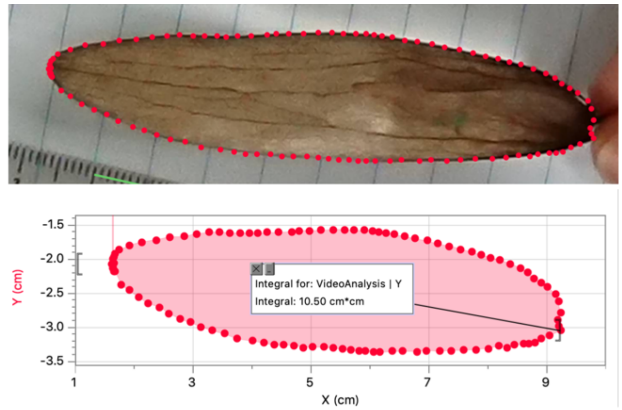


Figure 6. The picture from the top with LoggerPro analysis of the photo for Sample 5.

Seed Measurements

The total cross-sectional area of the seed, A_B, which determines the drag force, was measured using a photograph of each sample taken from above, with the seed held at the approximate average angle as when it falls. The area was measured by analyzing the image using LoggerPro, as shown in Figure 6.
The effective cross-sectional area of the wing, which affects the lift, is the flat part of the wing. To measure this, a photograph was taken from the side as shown in Figure 7. The distance from estimated center of rotation to the edge of the mast, r_1, and the distance from the center of rotation to the tip, r_2, were measured with LoggerPro analysis. The effective wing length, $r_2 - r_1$, was defined as the horizontal distance from the edge of central mast to the endpoint of the wing.

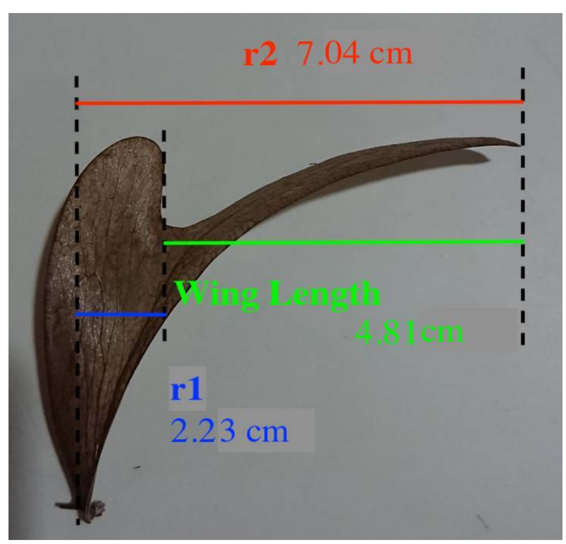


Figure 7. How wing length is measured, shown with sample 5.

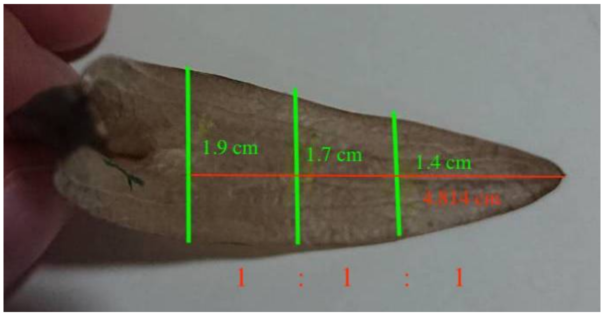


Figure 8. How cross-sectional wing area is measured, shown with sample 5.

The effective cross-sectional wing area was estimated using wing length and width of the wing. As seen in Figure 8, the wing area was divided into three parts and the area of each part was summed to determine the effective cross-sectional area of the wing. The effective surface area of the wing of Sample 5 was estimated to be 6.50 cm^2.

The wing velocity was calculated with the following equation,[6]

$$v_w^2 = \frac{\int_{r_1}^{r_2} 4\pi^2 r^2 f^2}{r_2 - r_1} dr \qquad (2)$$

where r_2 is 7.04 cm, and r_1 is 2.23 cm for Sample 5.

Video Analysis

The seed was dropped from a height of approximately 1.7 m, and its fall was recorded at 300 fps. A target area of about 10cm x 10cm was placed on the floor and only trials in which the seed landed on the target area were analyzed. A reference frame of known length was positioned next to the target, as shown in Figure 9.

The videos were analyzed using Logger Pro to determine the terminal velocity and spin frequency. The terminal velocity was determined by measuring the constant velocity over the last 30 cm before hitting the floor.

III. RESULTS AND DISCUSSION

1. Population Variability

All of the measured data from the 10 seeds used in the population variability study are shown in Table 1 in the Appendix, arranged in order of increasing

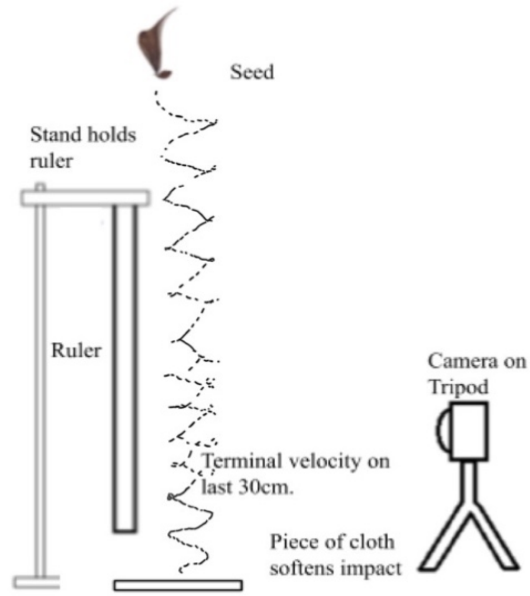
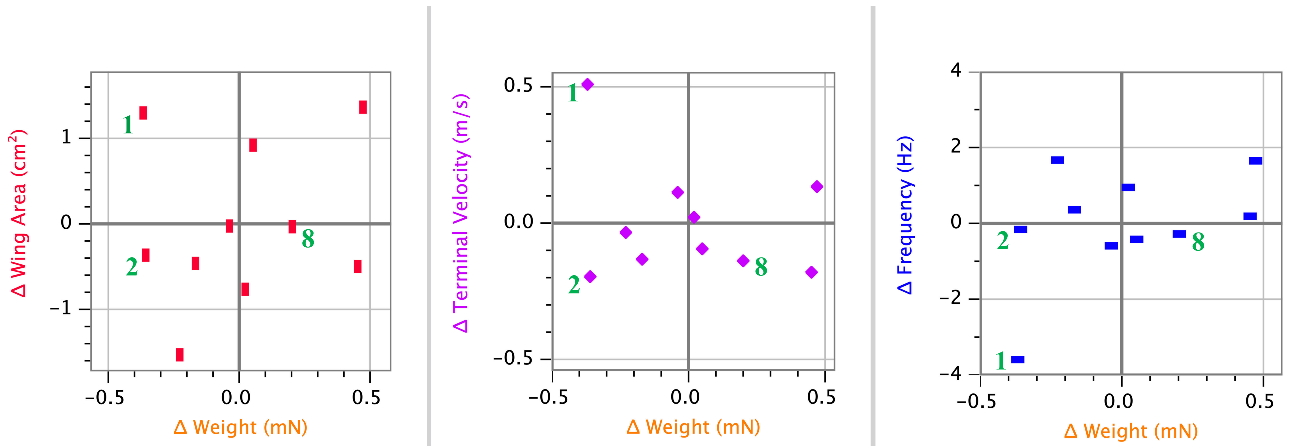


Figure 9. Experimental set up.

mass. In order to more easily analyze the results, the data for each seed has been graphed as the difference from the mean value for each parameter for all the seeds (noted by Δ) in Figures 10 and 11.

Looking at Figure 10, several interesting things can be noted. First, there is no correlation ($p = 0.57$) between the weight and wing area of the seeds in the population sample (Figure 10a). The size of the wing is independent of the weight of the seed. Looking at Figures 10b and 10c, it can be seen that there is not a strong correlation between the weight of the seeds and their terminal velocity ($p = 0.49$) or spin frequency ($p = 0.20$). This result is contrary to the positive correlation between weight and terminal velocity found in *P. sylvestris*.[8] It is likely that this is due to the fact that *P. sylvestris* is a flat-winged seed, while *P. tinctorium* has a curved wing. Looking at the population variability in terminal velocity and frequency, there is about 30% variability in terminal velocity and 20% variability in frequency, which is similar to the population variability found in the species studied by Green.[10]

While most of the seeds spun clockwise (as viewed from above) while falling, seeds 1, 2, and 8 (indicated on the graphs) spun counterclockwise. It is clear that the direction of spin is not a major factor in the aerodynamics of the seed as it falls. While seed 1 has a significantly higher terminal velocity

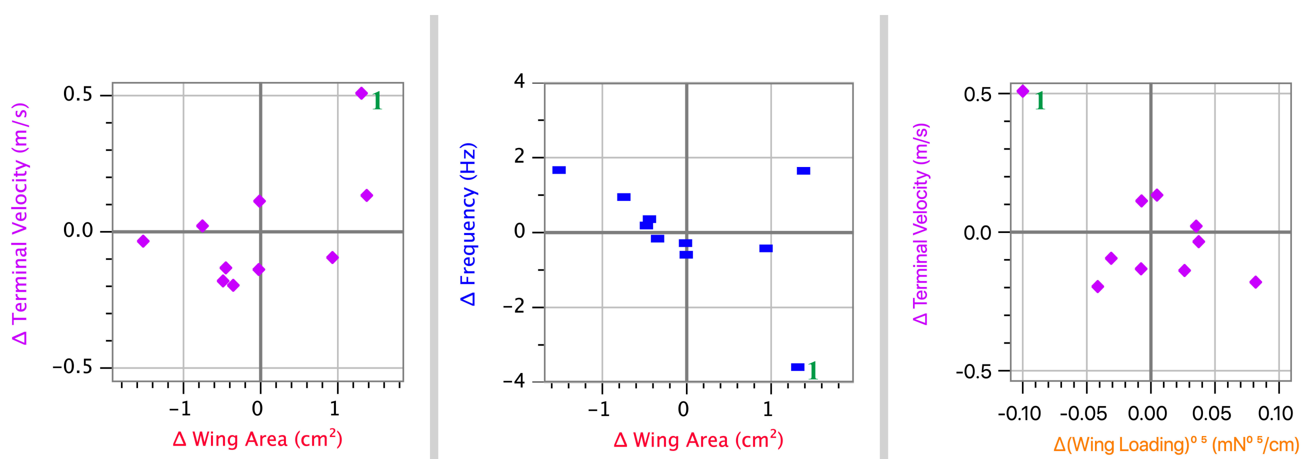


10a **10b** **10c**

Figure 10. Data for the 10 seeds in the population sample. Difference from the mean of the Weight compared to: **10a**. Wing Area, **10b.** Terminal Velocity, and **10c**. Frequency.

and lower spin frequency than the others, this is not due to its spin direction, as seeds 2 and 8 behaved similarly to those that spin clockwise. By carefully observing the shapes of the wings (Figure 5), it was found that sample 1 has a unique angle of wing and curvature that was significantly different from all the other seeds in the sample, while sample 2 and 8 are not distinctly different from other samples in those features. Therefore, these features cannot be considered as the cause of difference in direction of rotation. While the seed factors that determine direction of rotation, terminal velocity, and frequency could not be determined given the parameters measured in this study, it is likely that wing curvature and attack angle, which were not controlled or measured, are the factors that determine the seeds' spin frequency and terminal velocity.

As seen in Figure 11a and 11b, discounting seed 1 (indicated on graphs), there is not a significant correlation between wing area and spin frequency (11b) (p = *0.15*) while there is a weak positive correlation with terminal velocity ($p = 0.09$). While this correlation is interesting, it is unlikely to be causal, as a negative correlation is expected.[6,10] Turning to Figure 11c, Green found a proportional relationship between the square root of the wing loading and terminal velocity[10], and the same was expected for the *P. tinctorium*. However, in the sample population studied, the square root of wing loading and terminal velocity showed a weak



11a **11b** **11c**

Figure 10. Difference from the mean of the Wing Area compared to: **11a**. Terminal Velocity, and **11b**. Frequency, and **11c**. Square Root of Wing Loading and Terminal Velocity.

negative correlation, (p = 0.07). It is likely that, unlike the samaras studied elsewhere, the angle of attack and wing curvature are the dominant factors determining terminal velocity for *P. tinctorium*, thus clear correlations between the measured variables were not observed in the sample studied.

2. Varying Mass

In the second part of this study, the mass of the selected seed, Sample 5, was varied from 0.1065g to 0.4568g, and its resulting aerodynamic behavior investigated. Firstly, the relationship between terminal velocity and frequency was investigated. Looking at Figure 12, they are shown to have a strong proportional relationship.

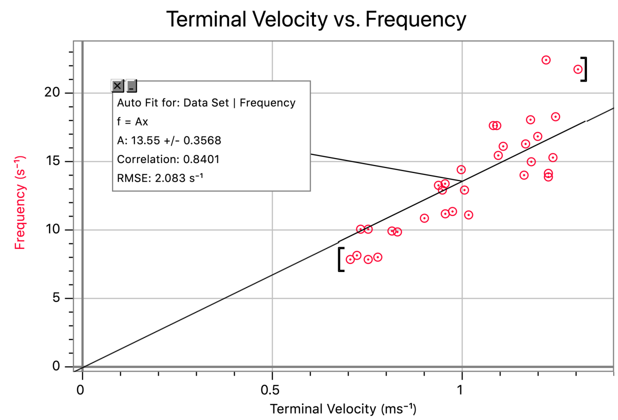


Figure 12. The relationship between Terminal velocity and frequency.

Given a proportional relationship between terminal velocity and frequency, Equation 1 predicts that weight would have a proportional relationship with terminal velocity squared. This is shown to be true in Figure 13.

Equation 1 also predicts a proportional relationship between weight and wing velocity squared, which is proportional to frequency squared, as in Equation 2. This is clearly shown in Figure 14. Since weight has a positive linear relationship both with terminal velocity squared and frequency squared, it is predicted that terminal velocity and frequency also have a positive relationship. It must be noted that there are two trials (circled in red) for the heaviest weight which were significantly above the trend line, indicating that the seed behaved very differently here. A possible cause for this is a shifting of the center of mass or instability during rotation due to the very high weight.

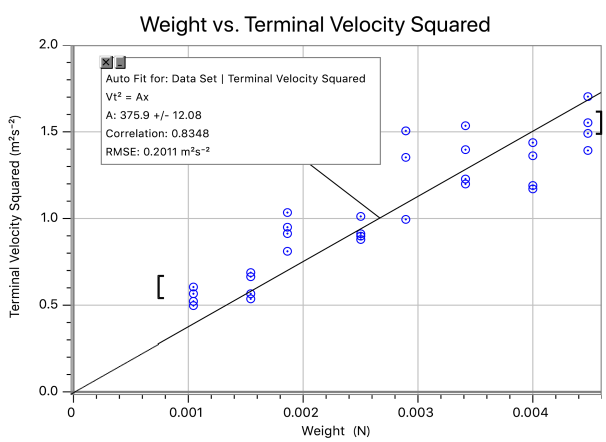


Figure 13. The relationship between weight and terminal velocity squared.

Because the drag due to air resistance can only be calculated given the coefficient of drag, a minimum and maximum coefficient of drag was assumed to be between 0.5 and 1 respectively, following Song's example. As in Equation 1, given the estimated values of coefficient of drag, the estimated force of drag can be calculated. Then, since the lift force is equal to the difference between the weight and the drag force, the lift force can be estimated.

Figure 15 shows the estimated maximum and minimum lift force with the estimated drag force and the weight. The graph clearly shows that the lift due to rotation provides most of the retarding force and

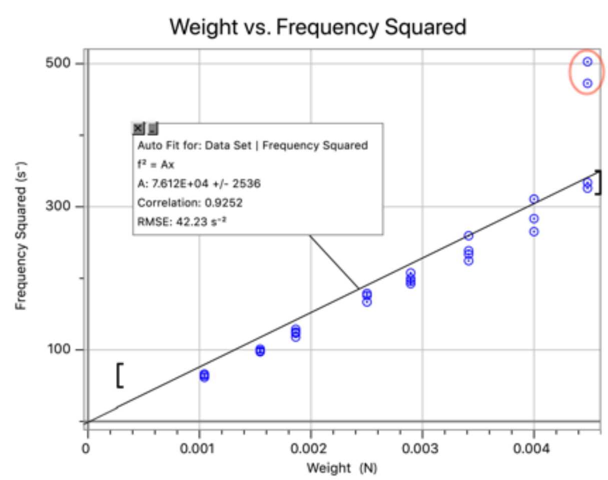


Figure 14. The relationship between weight and frequency squared.

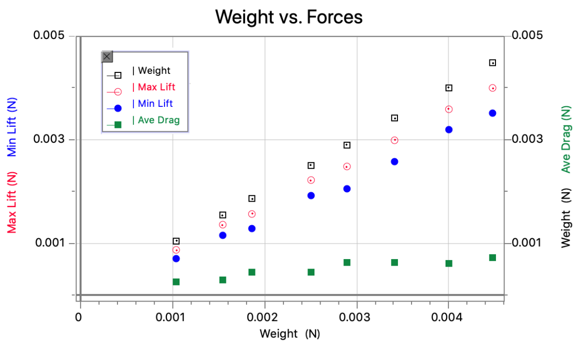


Figure 15. The relevant forces at terminal velocity.

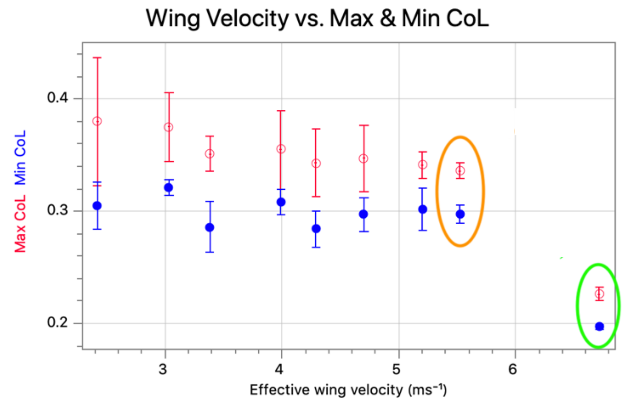


Figure 16. The graph shows the relationship between wing velocity and max and min coefficient of lift. Both circled points come from trials with 0.00448 N mass.

increases as the weight of the seed increases, as found by Song for a weighted *D. Alatus* samara (Figure 3).

Given the wing velocity (Equation 2), the possible maximum and minimum coefficient of lift can be calculated. Figure 16 shows a fairly constant trend of coefficient of lift, independent of wing velocity, ranging between roughly 0.28 and 0.38, compared to *D. Alatus'* estimated coefficient of lift ranging from 1.2 to 1.5.[6] It should be noted that two of the trials for the greatest weight (circled in orange) were consistent with the trend of coefficient of lift for the other weights. However, the data points circled in green are the anomalous trials with very high frequency (circled in red in Figure 14) which results in a low calculated coefficient of lift.

Interestingly, the coefficient of lift remained relatively constant regardless of wing velocity, which is very different from the result of *D. Alatus* which showed that as wing velocity increases, coefficient of lift increases.[6] It is likely that the effect of adding weight to a single wing seed might be different in terms of how it spins, and how it is oriented as spinning, which would affect values that are assumed constant, such as the effective wing area, which provide the lift force. With a seed with two wings, like *D. Alatus*, it is less likely that adding weight would have a significant effect on the orientation, although increasing the frequency of spinning would affect the centrifugal force on the wings, causing it to flatten out more and, therefore, increasing the effective wing area.

Further research into the effect of wing curvature and angle of attack on the aerodynamics of *P. tinctorium* is needed. Research into population variability from a range of different trees of this species is also suggested to verify whether the single tree from which this sample was taken is typical of the species. Further research determining the role of wing curvature and attack angle in its aerodynamic behavior is also needed.

IV. CONCLUSION

No significant correlation was found between *P. tinctorium* seed weight, area, terminal velocity, and frequency for the population sample studied. It is likely that other factors, such as wing curvature and angle of attack, play important roles in the seed's terminal velocity. In addition, the square root of the wing loading and terminal velocity have a weak negative correlation, contrary to the finding by Green. It is interesting to note that seeds rotated in either direction while falling, but this had no significant effect on terminal velocity or spin frequency for the sample studied.

When varying the mass of a single seed, it was shown that terminal velocity and frequency had a proportional relationship, leading to a proportional relationship between weight and terminal velocity squared and between weight and frequency squared. The lift force was shown to increase roughly proportionally with weight and comprised about 80-90 % of the retarding force. The coefficient of lift for *P. tinctorium* was shown to remain fairly constant between 0.28 and 0.38, regardless of weight.

IV. REFERENCES

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APPENDIX

Table 1: Data from Part 1: Mass, wing area, terminal velocity, frequency, and direction of rotation (Clockwise or Counter-clockwise) for all samples.

Seed #	Mass (± 0.001g)	Wing area (± 0.01cm^2)	Terminal velocity (ms^{-1})	Frequency (s^{-1})	Direction of Rotation
Sample 1	0.157	7.82	1.36 ± 0.02	8.1 ± 0.3	CCW
Sample 2	0.158	6.16	0.65 ± 0.04	11.6 ± 0.1	CCW
Sample 3	0.171	4.99	0.81 ± 0.09	13.4 ± 1.4	CW
Sample 4	0.177	6.06	0.72 ± 0.06	12.1 ± 1.4	CW
Sample 5	0.190	6.50	0.96 ± 0.06	11.1 ± 0.3	CW
Sample 6	0.196	5.76	0.87 ± 0.05	12.7 ± 1.2	CW
Sample 7	0.199	7.45	0.75 ± 0.01	11.3 ± 0.2	CW
Sample 8	0.214	6.49	0.71 ± 0.04	11.4 ± 0.2	CCW
Sample 9	0.239	6.03	0.67 ± 0.02	11.9 ± 0.3	CW
Sample 10	0.241	7.89	0.98 ± 0.03	13.4 ± 1.0	CW