The Aerodynamics of a Falling *Hopea Odorata* Seed

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Abstract

The double-winged seeds of the *Hopea odorata* tree generate an auto-rotating motion from their elongated sepals as they fall. The flight dynamics of the seed were analyzed using high-speed video. Terminal velocity and spin frequency were measured as a function of changing seed mass. Both were shown to increase with increasing seed mass. It was also shown that lift force provided 60-85% of the retarding force generated during descent and that the coefficient of lift for the seed decreased from approximately 0.7 to 0.3 as spin frequency increased.

Keywords: *Hopea odorata*, winged seed, mass, terminal velocity, spin frequency, coefficient of lift

I. INTRODUCTION

In many dipterocarp species, seeds possess a pair of elongated sepals extending to opposing sides, which act as wings, to enhance their dispersal by wind.[1] In windy conditions, these seeds travel far from their parent plant as they spiral downwards, slowed by the aerodynamic lift force generated by their spinning wings.[2]

An example of a dipterocarp species is *Hopea odorata* (Thai: ตะเคียน). It is a tree growing up to 25 – 45 meters tall found in Thailand and throughout Southeast Asia.[3] The *H. odorata* seed, shown in Figure 1, is attached to two asymmetric wings extending to opposing sides. This structure allows the seed to generate an auto-rotating motion, resembling the primary rotor of a helicopter.

During the seed's descent at terminal velocity, the forces of lift[4] (F_L) and drag[5] (F_D) balance with the force of gravity. The rotating wings experience both drag and lift forces which combine to oppose the force of gravity. This can be modeled by the equation,[6]

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

where A_W is effective cross-sectional area of the wing, A_B is total cross-sectional area of the seed, ρ is air density, C_L is coefficient of lift, C_D is coefficient of drag, v_w is effective wing velocity, and v_t is terminal velocity. Here the effect of the weight of a *H. odorata* seed on the terminal velocity, spin frequency, and lift generated was studied.

Song conducted a similar investigation into the aerodynamics of *Dipterocarpus alatus*, also a two-winged seed that is part of the dipterocarp family,

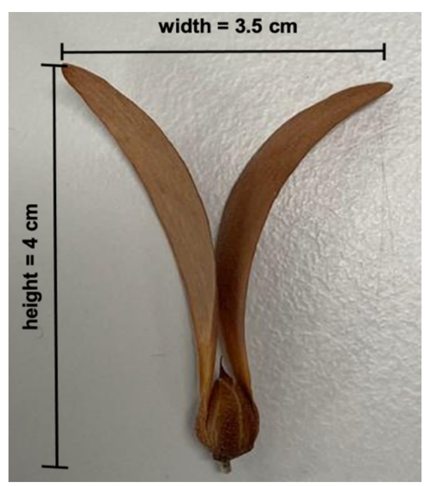

Figure 1. *Hopea odorata* seed selected for this investigation.

Figure 2. A *Dipterocarpus alatus* seed[6] (left) and a *Pterocymbium tinctorium* seed[7] (right).

shown in Figure 2 on the left. Song found that terminal velocity, spin frequency and lift generated all increase as the mass of the seed increased. He concluded that the main component of the retarding force is the lift force, which generates 80-95% of the force. The coefficient of lift, which was estimated to be between 1.3 and 1.6, increased as wing velocity increased. This was attributed to the increased wing velocities, which increased lift generated by the wings.[6]

Ikegami et al's study on the kinematics of a falling *Pterocymbium tinctorium* seed, shown on the right in Figure 2, also found that the weight of the falling seed was directly related to terminal velocity and spin frequency. The coefficient of lift of *P. tinctorium* found to stay constant as the effective wing velocity increased.[7]

It is expected that the weight of the *Hopea odorata* seed studied will be directly related to terminal velocity, spin frequency, and lift force, following the findings of Song and Ikegama et al.

II. METHODS

Seed Measurements

The seed cross-sectional area was measured using a photograph of the selected seed placed on a 1 cm square grid, taken from directly overhead. The photograph was then analyzed to determine the total cross-sectional area of the seed using LoggerPro, shown in Figure 3.

The effective cross-sectional area of the wings was estimated by measuring the horizontal distance from the center of rotation to the point where the wing begins to curve significantly, r_1, and then to the tip of the wing, r_2, as shown in Figure 4.

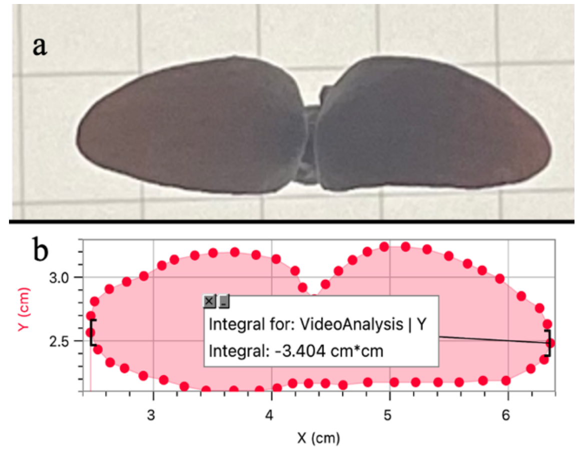

Figure 3: a) Overhead shot of *H. odorata* seed used and b) LoggerPro analysis of the cross sectional area of the seed.

The average wing velocity squared was calculated using the equation,

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

where r_2 is 2.0 cm, and r_1 is 0.5 cm for the seed.[6]

Seed Mass Manipulation

After 4 trials of dropping the seed at its original mass, the weight of the seed was manipulated by drilling a small hole on the side of the seed and filling it with varied amounts of white glue. Creating a small hole resulted in a small change to the seed's aerodynamic profile. Trials were conducted with 5 different masses of the seed ranging from 0.065 – 0.197 g.

Experimental Setup

The experimental setup is shown in Figure 5. The seed was dropped from a height of approximately 1.0 m onto a soft cloth landing zone to reduce damage to

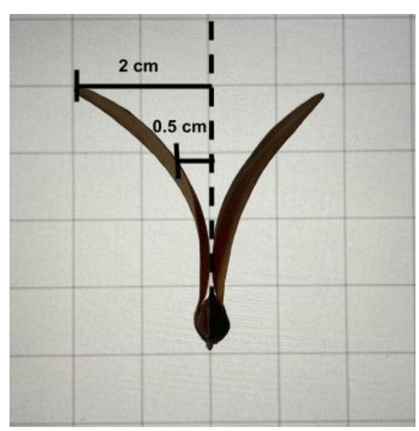

Figure 4. Radial length measurements for lift generating section of wings.

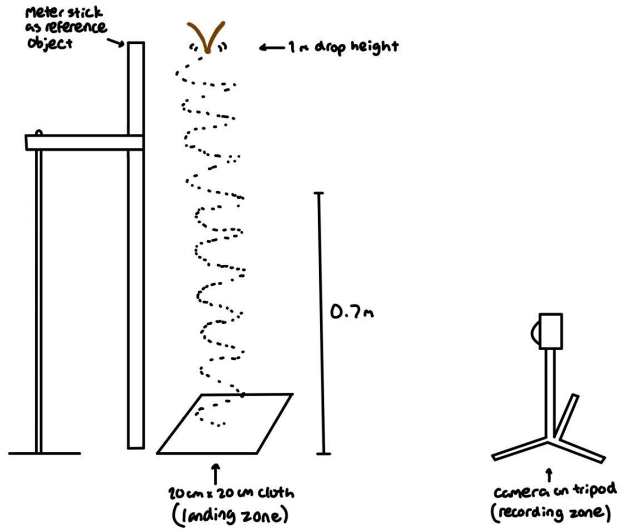

Figure 5. Experimental setup.

the seed. The camera was aligned horizontally to record the last 70 cm of the fall, with a meterstick placed next to the landing zone as a reference. The falling seed was recorded at 1000 frames per second. The videos were analyzed using LoggerPro to determine the seed's terminal velocity and spin frequency. The terminal velocity was determined for the last 50 cm of the seed's descent, and spin frequency was determined by taking the average time to perform three full revolutions during the last 50 cm of the descent.

III. RESULTS AND DISCUSSION

The dynamics of a falling *Hopea odorata* seed were studied and compared to the findings reported by Song and Ikegami in their studies of *Dipterocarpus alatus* and *Pterocymbium tinctorium* seeds, respectively.

As the weight of the *H. oderata* seed increased, the square of the terminal velocity was found to increase proportionally with weight, as shown in Figure 6, with a proportionality constant of 1310 ± 40 $Nm^{-2}s^{-2}$. This trend is similar to the effect of weight on the terminal velocity of falling *D. alatus* and *P. tinctorium* seeds found by Song and Ikegama et al. Interestingly, the proportionality constants were much smaller, with *P. tinctorium* at 376 ± 10 $Nm^{-2}s^{-2}$ and *D. alatus* at 74 ± 2 $Nm^{-2}s^{-2}$. More detailed study of the seeds is needed to explain this difference.

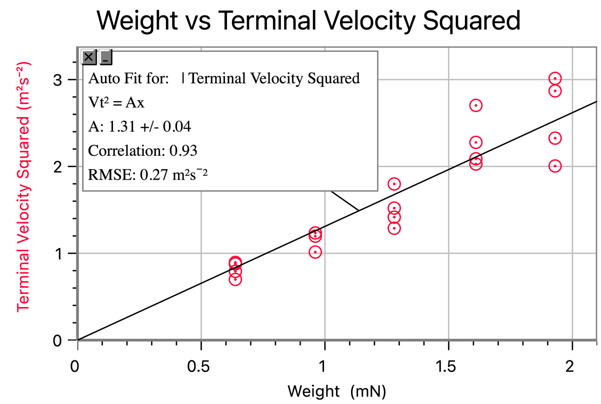

Figure 6. The proportional relationship between weight and terminal velocity squared.

An increase in seed weight led to higher variability in terminal velocity, as indicated by the increased scatter of data points for the heavier seeds. It is possible that drilling the seed and adding white glue may have shifted the weight distribution of the seed and its aerodynamic profile, leading to increased instability and changing aerodynamics as it falls.

The relationship between weight and spin frequency of the falling *H. oderata* seed is shown in Figure 7. The weight of the seed is proportional to the square of the spin frequency, with a proportionality constant of 4.5 ± 0.1 x 10^5 $N^{-2}s^{-2}$. Figure 8 shows the terminal velocity vs the spin frequency of the seed. As expected, given Figures 6 and 7, they are proportional. The proportionality constant of terminal velocity and spin frequency for the falling *H. oderata* seed is 450 ± 10 s^{-1}/ms^{-1}, while the proportionality

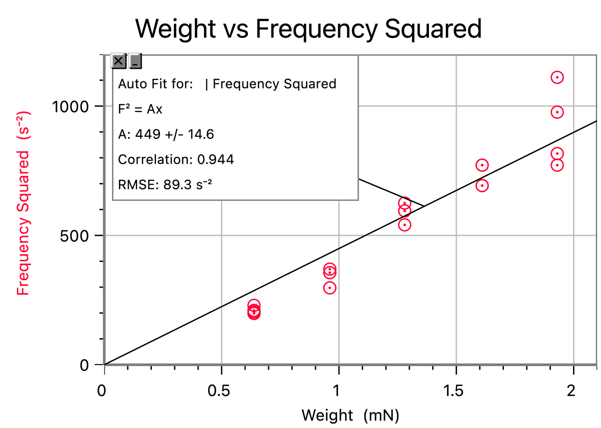

Figure 7. The proportional relationship between weight and frequency squared with line of best fit.

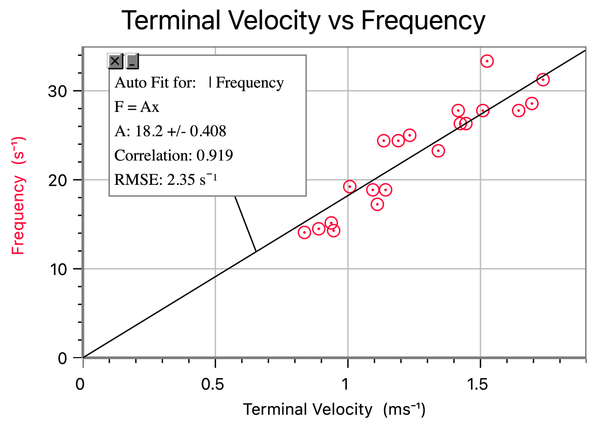

Figure 8. The proportional relationship between terminal velocity and frequency with line of best fit.

constant for *P. tinctorium* was 13.6 s^{-1}/ms^{-1} and *D. alatus* was 9.3 s^{-1}/ms^{-1}. The ratio of spinning to velocity of the *H. oderata* was much greater than the other two seeds. While no measurements were made, it is possible that this is due to the *H. oderata* wings being at a sharper attack angle than the other seeds, leading to greater torque on the seed as it falls through the air. Further research is needed to confirm this.

Further analysis of the aerodynamics of the seed focused on the drag and lift forces on the seed. Since drag and lift cannot be precisely determined based on data available, an assumed coefficient of drag ranging between 0.5 and 1.0 was used, following Song. Given the estimated range of the coefficient of drag, drag force can be calculated with reference to Equation 1, and lift force can be calculated as the difference between weight of the object and the drag force acting upon it.

Figure 9 displays weight (black), estimated average drag force (purple), and the inferred maximum and minimum possible lift forces, following the analysis of Song and Ikegama et al. The estimated range of the lift force generated was found to be responsible for a significant proportion of the retarding force during its descent, ranging from approximately 60-85%.

Estimates of the coefficient of lift were calculated from the estimated range of the lift force using Equation 1. The relationship between effective wing velocity and maximum and minimum coefficient of lift is shown in Figure 10. The C_L was greatest for the lightest seeds with the slowest spin frequency, ranging from 0.6 to 0.8, and decreased with increasing seed weight, reaching a C_L range of 0.4 to 0.6 for the heaviest seeds.

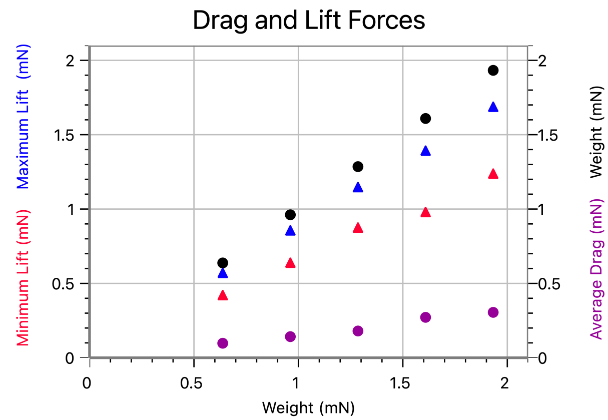

Figure 9. Forces contributing to terminal velocity.

The C_L is influenced by factors such as wing shape, angle of attack, and wing velocity. In general, as the angle of attack of the wings is increased, the amount of lift generated by the wing increases. The decreasing trend in C_L with increasing wing speed observed in the study may be due to a decrease in the attack angle of the wings at higher spin rates. As the heavier seeds spin faster, this may cause the wings to extend and rotate slightly to a flatter attack angle, thus reducing lift. Further research is needed to confirm this.

Comparing *H. oderata* to the other seeds, Song found that the C_L of the *D. alatus* seed was much greater, ranging from 1.2 to 1.5, with the C_L increasing with increasing seed weight. Ikegama et al found that the C_L of the *P. tinctorium* seed was lower than *H. oderata*, ranging from 0.3 to 0.4, and stayed quite constant over the range of speed studied.

Further research for the *Hopea odorata* and other seeds is suggested to investigate the impact of wing

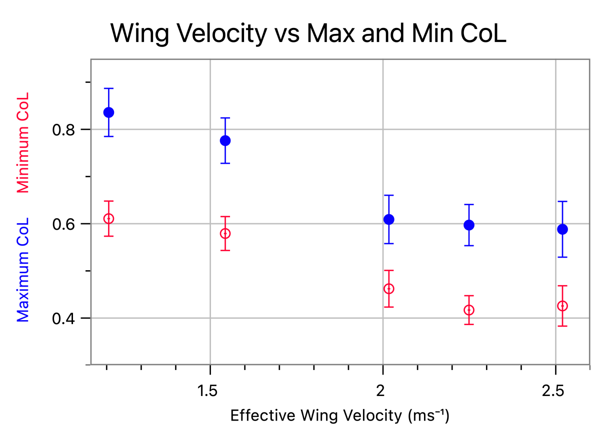

Figure 10. Relationship between effective wing velocity and maximum and minimum coefficient of lift.

curvature and angle on spin frequency and coefficient of lift at different terminal velocities, using high-speed cameras to closely monitor the shape and movement of the wings during descent. Such observations can provide a more detailed understanding of the aerodynamics of each seed and allow development of more accurate models.

IV. CONCLUSION

By varying mass of the seed, a proportional relationship was shown between the weight of a Hopea Odorata seed and its terminal velocity squared as well as its spin frequency squared. As the seed's weight increased, aerodynamic lift force generated by the wings increased. This lift force provided 60-85% of the overall retarding force. The coefficient of lift was estimated to be between 0.41-0.84 and decreased with increasing wing speed.

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