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2C05 A Study on the Combination of Rubber Torque and Propellers in Rubber-Powered Model Airplanes

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Key Words: Rubber Powered Model Plane, Propeller, Section Area of Rubber Motor

Abstract

Propeller/rubber motor combination is important for performance of rubber powered model planes. Modelers usually find optimum combination based on their experience. This paper presents a method to find propeller/rubber combination using dimensionless parameters.

1. Introduction

Despite model airplanes being an excellent subject for study in flight dynamics, they have not been studied much until now, and there are still many things that remain unexplored theoretically. The author, as an enthusiast of free-flight model airplanes, has been conducting research on gliders and rubber-powered aircraft.

In this report, I analyze the combination of rubber torque and propeller (diameter, pitch ratio, etc.) of rubber-powered model airplanes, which has been determined based on experience, and find a quantitative method for determining them. I compare these results with conventional empirical rules.

2. Formulas for Powered Flight

2.1 Equilibrium Equations in Powered Flight

Assuming that a rubber-powered airplane is in steady-state powered flight, consider the airplane ascending at a constant path angle θ and a constant velocity V. Figure 1 shows the forces acting on the rubber-powered airplane. The equilibrium equations with respect to a ground-fixed coordinate system are expressed as follows.

$$T\cos\theta - L\sin\theta - D\cos\theta = 0$$

$$mg - T\sin\theta - L\cos\theta + D\sin\theta = 0$$

$$M - Td = 0$$

where, L is the lift of the aircraft, D is the drag of the aircraft, M is the moment around the center of gravity due to aerodynamic forces, θ is the path angle, m is the total mass of the aircraft, g is the acceleration due to gravity, T is the thrust of the propeller, and d is the distance between the propeller thrust line and the center of gravity (when the thrust line passes above the center of gravity, i.e., in the case of downthrust, d assuming this is positive).

We approximate that the direction of thrust T is the same as the direction of the airflow, i.e., the direction of drag D.

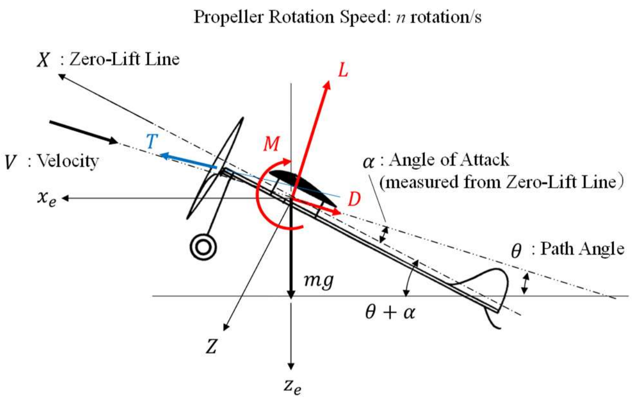

Figure 1. Equilibrium of Rubber-Powered Airplane in Powered Flight

2.2 Aerodynamic Forces

The aerodynamic characteristics of the aircraft are shown in Figure 2. Lift and drag are given by:

$$L = \frac{1}{2}\rho V^2 C_L S_w$$

$$D = \frac{1}{2}\rho V^2 C_D S_w$$

$$M = \frac{1}{2}\rho V^2 C_m \bar{c} S_w$$

where, ρ is the density of the air, C_L is the total lift coefficient, C_D is the total drag coefficient, C_m is the total moment coefficient, S is the wing area, and $\bar{c}$ is the mean aerodynamic chord of the wing.

The total lift coefficient is expressed by the following equation.

$$C_L = C_{L_\alpha}\alpha$$

where, α is the angle of attack measured from the zero-lift line of the aircraft, C_{L_α} is the total lift curve slope.

The total drag coefficient is expressed by the following equation (Reference [1]):

$$C_D = C_{DP} + \frac{{C_L}^2}{\pi e A}$$

where, C_{DP} is the total parasite drag coefficient, e is the Oswald's efficiency factor, and A is Aspect Ratio of the wing.

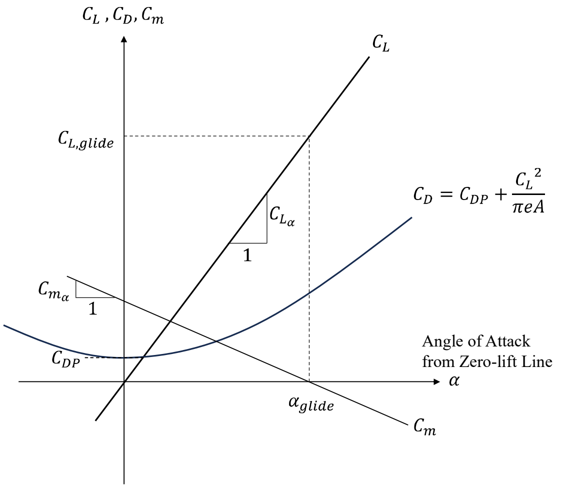

Figure 2. Relationships between Angle of Attack and Lift Coefficient, Drag Coefficient and Moment Coefficient

The relationship between the total lift coefficient and the angle of attack during glide is given by:

$$C_{L,glide} = C_{L_\alpha}\alpha_{glide}$$

where, $C_{L,glide}$ is the total lift coefficient during glide, α_{glide} is the angle of attack during glide measured from the zero-lift line.

The elevator angle is fixed after glide adjustment, and the angle of attack and the lift coefficient in the glide are determined. Then, the relationship between the angle of attack during powered flight and the moment coefficient is determined by the following equation (Figure 2).

$$C_m = C_{m_\alpha}(\alpha - \alpha_{glide})$$

2.3 Propeller Characteristics

The thrust T and torque Q of a propeller are expressed as follows:

$$T = C_T \rho n^2 {D_p}^4$$

$$Q = C_Q \rho n^2 {D_p}^5$$

Where, n is the propeller rotation speed, D_p is the propeller diameter, C_T is the thrust coefficient, and C_Q is the torque coefficient.

The thrust coefficient and torque coefficient are functions of the advance ratio $J = V/(nD_p)$, and are represented by propeller performance curves with J on the horizontal axis.

The propeller efficiency η_p is expressed as follows:

$$\eta_p = \frac{TV}{2\pi n Q} = \frac{C_T V}{2\pi C_Q n D_p} = \frac{C_T J}{2\pi C_Q}$$

2.4 Derivation of Dimensionless Parameters Representing Powered Flight

Propeller rotation speed is expressed in terms of torque as follows:

$$n^2 = \frac{Q}{C_Q \rho {D_p}^5}$$

Substituting this equation into the thrust equation yields the relationship between torque and thrust.

$$T = C_T \rho n^2 {D_p}^4 = C_T \rho \frac{Q}{C_Q \rho {D_p}^5} {D_p}^4 = \frac{C_T}{C_Q}\frac{Q}{D_p}$$

Substituting this equation into the equilibrium equation and eliminating the thrust, we get:

$$\frac{C_T}{C_Q}\frac{Q}{D_p}\cos\theta - \frac{1}{2}\rho V^2 C_L S_w \sin\theta - \frac{1}{2}\rho V^2 C_D S_w \cos\theta = 0$$

$$mg - \frac{C_T}{C_Q}\frac{Q}{D_p}\sin\theta - \frac{1}{2}\rho V^2 C_L S_w \cos\theta + \frac{1}{2}\rho V^2 C_D S_w \sin\theta = 0$$

$$\frac{1}{2}\rho V^2 C_m \bar{c} S_w - \frac{C_T}{C_Q}\frac{Q}{D_p} d = 0$$

These equations are divided by mg and we get the following dimensionless equations:

$$\frac{Q}{mgD_p}\frac{C_T}{C_Q}\cos\theta - \frac{\frac{1}{2}\rho V^2 S_w}{mg} C_L \sin\theta - \frac{\frac{1}{2}\rho V^2 S_w}{mg} C_D \cos\theta = 0$$

$$1 - \frac{Q}{mgD_p}\frac{C_T}{C_Q}\sin\theta - \frac{\frac{1}{2}\rho V^2 S_w}{mg} C_L \cos\theta + \frac{\frac{1}{2}\rho V^2 S_w}{mg} C_D \sin\theta = 0$$

$$\frac{\frac{1}{2}\rho V^2 S_w}{mg} C_m \bar{c} - \frac{Q}{mgD_p}\frac{C_T}{C_Q} d = 0$$

From the three equations above, it can be found that the torque of the rubber can be expressed using the dimensionless quantity, $Q/(mgD_p)$. Since it is dimensionless due to the propeller diameter, we will call it non-dimensional propeller torque.

Transforming the equation for advance ratio, we get:

$$n = \frac{V}{JD_p}$$

Substituting this equation into the thrust equation and eliminating the propeller rotation speed, we get:

$$T = C_T \rho \frac{V^2}{J^2} {D_p}^2$$

Substituting this equation into the equilibrium equations and rearranging, we get:

$$C_T \frac{1}{J^2} \frac{{D_p}^2}{S_w} \cos\theta - \frac{1}{2} C_L \sin\theta - \frac{1}{2} C_D \cos\theta = 0$$

$$1 - \frac{\rho V^2 S_w}{mg}\left(C_T \frac{1}{J^2} \frac{{D_p}^2}{S_w} \sin\theta - \frac{1}{2} C_L \cos\theta + \frac{1}{2} C_D \sin\theta\right) = 0$$

$$c_m - \frac{2C_T d}{J\bar{c}} \frac{{D_p}^2}{S_w} = 0$$

From these equations, it can be found that $D_p/\sqrt{S_w}$ can be used as a dimensionless quantity representing the propeller dimensions, and call this the non-dimensional propeller diameter.

To make the propeller rotation speed n dimensionless, we can rearrange Torque equation and get:

$$n^2 = \frac{Q}{C_Q \rho {D_p}^5}$$

$$n = \sqrt{\frac{Q}{C_Q \rho {D_p}^5}} = \sqrt{\frac{1}{C_Q}} \sqrt{\frac{Q}{\rho {D_p}^5}}$$

For another expression:

$$\frac{n}{\sqrt{\frac{Q}{\rho {D_p}^5}}} = \sqrt{\frac{1}{C_Q}}$$

$n/\sqrt{Q/\rho {D_p}^5}$ can be used as a dimensionless quantity to represent the propeller rotation speed, so we will call this the non-dimensional propeller rotation speed.

The distance climbed per propeller rotation divided by $\sqrt{S_w}$ is the dimensionless quantity of the climb speed, the non-dimensional climb speed.

$$\frac{V_z}{n\sqrt{S_w}}$$

where, V_z is the climb speed.

The increase of the aircraft's potential energy divided by the torque energy of the rubber is the climbing energy efficiency.

$$\frac{mgV_z}{2\pi n Q}$$

The following value can be used as a dimensionless quantity to represent the torque.

$$\frac{Q}{mg\sqrt{S_w}}$$

This value is independent of the propeller type and dimensions, and is determined by the aircraft and torque, so we will call it non-dimensional aircraft torque.

2.4 Summary of Dimensionless Parameters Representing Powered Flight

Summarizing the dimensionless parameters derived in the previous section:

- Non-dimensional propeller diameter: $D_p/\sqrt{S_w}$
- Non-dimensional propeller rotation speed: $n/\sqrt{Q/\rho {D_p}^5}$
- Non-dimensional propeller torque: $Q/(mgD_p)$
- Non-dimensional aircraft torque: $Q/(mg\sqrt{S_w})$
- Climbing energy efficiency: $mgV_z/(2\pi nQ)$
- Non-dimensional climb speed: $V_z/(n\sqrt{S_w})$

3. Aircraft Aerodynamic Characteristics

The aerodynamic characteristics of the aircraft, such as the total lift curve slope and the total pitching moment differential, can be calculated using the formulas in reference [1].

4. Calculation Method for Powered Flight

Assume that the specifications of a rubber-powered aircraft, namely the aircraft dimensions, aircraft mass, center of gravity, propeller diameter, propeller performance curves, and rubber torque, are given.

By giving a rubber torque Q_r, and using the angle of attack α, velocity V, path angle θ, and propeller rotation speed n as unknowns, the equilibrium equations are solved using the MS-Excel solver, and dimensionless parameters are calculated.

5. Dimensionless Graphs

5.1 Rubber Powered Model Plane for Analysis

A small stick plane with foam poly-styrene wings shown in Figure 3 is the subject of analysis. The specifications of this aircraft are shown in Table 1.

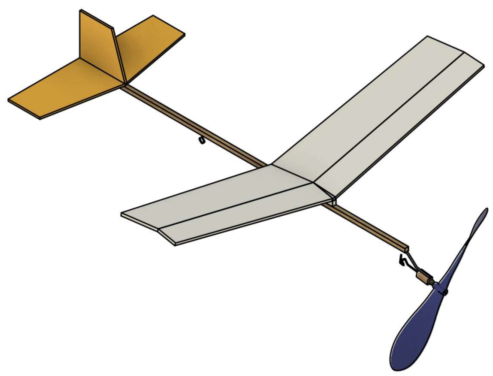

Figure 3. Model Plane Under Study

Table 1. Specification of the Stick Plane

Main Wing

- Wingspan: 338 mm
- Chord Length at Root: 70 mm
- Chord Length at Tip: 61.8 mm
- Wingtip Sweep: 0 mm
- Dihedral angle: 13 degrees
- Taper Ratio: 0.883
- Aspect Ratio: 5.13
- Wing Area: 22274 mm^2
- Mean Aerodynamic Chord: 66 mm
- Center of Gravity: 56%MAC

Horizontal Stabilizer

- Wingspan: 160 mm
- Chord Length at Root: 50 mm
- Chord Length at Tip: 35 mm
- Wingtip Sweep: 15 mm
- Taper Ratio: 0.70
- Aspect Ratio: 3.76
- Wing Area: 6800 mm^2
- Horizontal Tail Volume Ratio: 1.07

Overall Aerodynamic Characteristics

- Lift Curve Slope C_{L_α} : 4.918
- Pitching Moment Derivative: C_{m_α} : -1.02
- Parasite Drag C_{DP} : 0.08
- Oswald's Efficiency Factor e : 0.70
- Lift Coefficient during Glide: 0.80

Gross Mass: 14.0 g

5.2 Propeller

The propellers to be equipped on the aircraft described in the previous section are three types (Table 2) with different pitch ratios and blade chord length distributions.

- Commercially available propeller (Union Model)
- Larrabee Propeller A
- Larrabee Propeller K

The pitch ratio distribution, chord length ratio distribution, and performance curves of these propellers are shown in Figures 4 to 6. For propeller performance calculations, two dimensional wing aerodynamic data of a thin, arc-shaped airfoil (5% camber) with a Reynolds number of 20,000 was used.

Table 2. Comparison of Propeller Characteristics

Type	Pitch Ratio	Max. Chord Length Ratio	Max. Efficiency				J for Zero Thrust	Solidity
	P/D	cmax/R	η p	J	CQ	CT	J_CT=0	σ
Union Model	約1.1	0.34	0.69	0.90	0.021	0.10	1.20	0.146
Larrabee A	約1.3	0.25	0.75	1.07	0.019	0.085	1.42	0.109
Larrabee K	約1.1	0.21	0.74	0.9	0.013	0.07	1.21	0.094

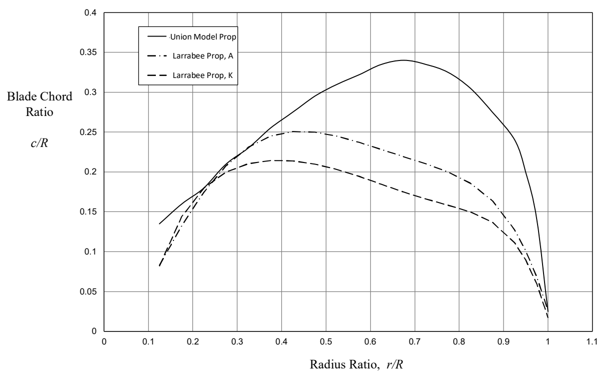

Figure 4. Comparison of Brade Chord Length Distribution

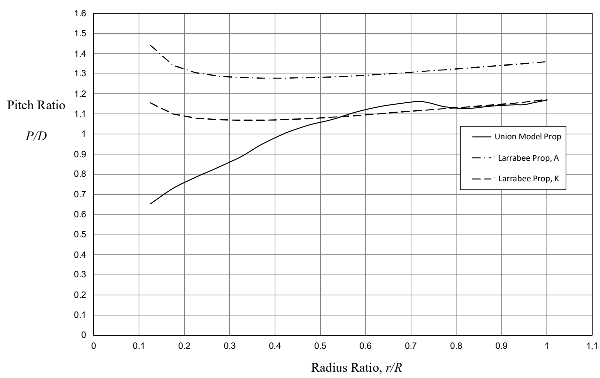

Figure 5. Comparison of Pitch Ratio Distribution

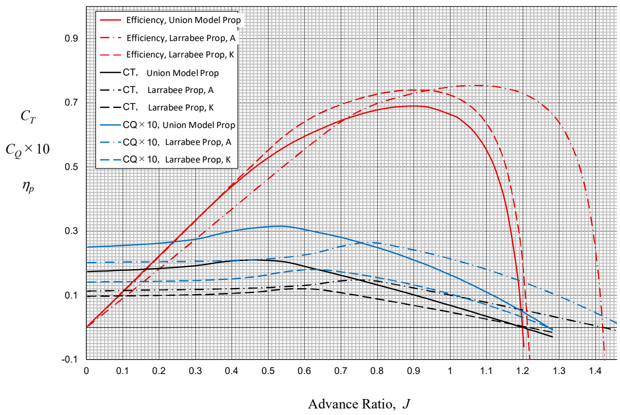

Figure 6. Comparison of Propeller Performance

5.3 Calculation Results

The aircraft's flight state was calculated by performing equilibrium calculations while varying the propeller type, propeller diameter, and rubber torque. The results were represented in contour plots of climbing energy efficiency, non-dimensional propeller rotation speed, and path angle, with the horizontal axis representing non-dimensional propeller torque and the vertical axis representing non-dimensional propeller diameter (Figures 7-9).

6. How to Use Dimensionless Graphs

6.1 Rubber Torque Data

Figure 10 shows measurement data for the number of turns and unwinding torque of FAI TAN Super Sport rubber. The torque is high at the start of unwinding, but decreases rapidly as unwinding progresses, becoming almost constant in the intermediate region. This intermediate region torque is called cruise torque. Two strands (one loop) of 1/8 inch (3.2 mm) wide rubber are used for the aircraft shown in Figure 3 and Table 1.

6.2 Aircraft Under Consideration

The aircraft shown in Figure 3 and Table 1 will use a Larrabee propeller A.

6.3 Determining Propeller Diameter

Using Figure 8, determine the appropriate propeller diameter for the rubber band to be used. The cruise torque of this rubber band is approximately 2.2 N-mm, and powered flight will be designed with this torque value. First, calculating the non-dimensional aircraft torque, we get:

$$Q/\left(mg\sqrt{S_w}\right) = \frac{2.2\mathrm{N}\cdot\mathrm{mm}}{14\mathrm{g}\times 9.80665\,\mathrm{m/s^2}\times\sqrt{22274\mathrm{mm}^2}} = 0.107$$

Draw this non-dimensional aircraft torque line in Figure 8, plot the points where the non-dimensional propeller diameters are 0.8, 0.9, 1.0, 1.1, and 1.2, and read the dimensionless parameters (Figure 11). As shown in Table 3, the propeller diameter, propeller rotation speed, and climb rate can be calculated from the dimensionless parameters. It can be seen that the propeller diameter that maximizes the climb energy efficiency is 150 mm, and the path angle is 26 degrees.

6.4 Influence of Propeller Type and Aircraft Gross Mass

Similar to above, Figure 12 shows the calculation results for aircraft with gross masses of 12g and 14g, using the three types of propellers in Table 2.

6.5 Application of Dimensionless Graphs to Other Aircraft

This section demonstrates that the relationship between rubber and propeller can be calculated using the dimensionless graph (Figures 7-9) of the aircraft in Figure 3, even for aircraft with different dimensions, shape, and mass.

The aircraft used is a so-called 203 Light Plane with a gross mass of 23g (rubber 3g) (wing span 480mm, area 36150mm², aspect ratio 6.43, FAI TAN Super Sport rubber 1/8 inch width 4 strands (2 loops) = cruise torque 7.0 N-mm). Figure 13 compares the results of calculating the propeller diameter and powered flight state using Figure 7 (dimensionless aircraft torque 0.163) when using a Union Model propeller with the results of calculating the powered flight state from the aircraft specifications and equilibrium conditions of a 203 Light Plane. As can be seen from this figure, dimensionless graphs can be used in the design even if the aircraft are different.

7. What can be learned from the Dimensionless Graphs

The following can be learned from the graphs shown above.

(1) The shape of the dimensionless graph differs greatly depending on the type of propeller.

(2) When the non-dimensional propeller torque exceeds a certain value, it causes vertical ascent. This value is approximately 0.17 for Union Model propellers and Larrabee A propellers, and approximately 1.6 for Larrabee K propellers. (Figures 7-9)

(3) When the cross-sectional area of the rubber band is kept constant, there is an optimal propeller diameter

that maximizes the climbing energy efficiency. The optimal propeller diameter differs depending on the type of propeller. (Figure 12)

(4) A high ascent speed does not necessarily mean high climbing energy efficiency. (Table 3) The distance climbed per propeller rotation is proportional to the climbing energy efficiency. Reducing the propeller diameter increases the climb speed, but also increases the rotation speed. There is an optimal propeller diameter that maximizes climbing energy efficiency.

(5) The smaller the aircraft's gross mass, the larger the optimal propeller diameter. (Figure 12)

(6) The smaller the aircraft's gross mass, the higher the climbing energy efficiency. (Figure 12)

(7) The larger the propeller diameter, the smaller the path angle and propeller rotation speed. (Figure 12))

8. Comparison with Actual Rubber-Powered Plane Data

Figures 14-16 show the plots of data from actual small rubber-powered aircraft (aircraft mass 8-65g, wingspan 250-760mm) (references [5], [7], [8], [9], [10], etc.) plotted on a dimensionless graph (using cruise torque).

The P30 is a model plane with a maximum wingspan and overall length of 762mm, a commercially available plastic propeller with a diameter of 240mm or less, and a rubber weight of 10g or less. The following can be observed from these figures:

(1) Scale models are in the lower left of the graph, i.e., in the region where non-dimensional propeller torque and non-dimensional propeller diameter are small. Non-dimensional aircraft torque is 0.08 or less. This region corresponds to a small path angle (20 degrees or less). The torque of the rubber is reduced, and the number of turns is increased to increase powered flight duration.

(2) The P30 has a non-dimensional aircraft torque of around 0.062, and a non-dimensional propeller diameter of around 0.8-0.9. The climbing energy efficiency is about 0.4. This result is due to the fixed wingspan and propeller diameter.

(3) Stick planes are distributed over a wide area. A distinctive feature is the existence of aircraft with a non-dimensional propeller torque of 0.17 or higher. These aircraft are designed to perform vertical climbs even with cruise torque, and their climbing energy efficiency is considered low. They aim for vertical climbs by using high-torque rubber on ultra-lightweight airframes.

(4) Excluding the extreme aircraft mentioned in the previous section, most stick planes and other aircraft have a climbing energy efficiency of 0.45 or higher.

(5) The non-dimensional propeller diameter is in the range of 0.7 to 1.4. Rewriting the formula for the non-dimensional propeller diameter,

$$\frac{D_p}{\sqrt{S_w}} = \frac{D_p}{\sqrt{\frac{b^2}{A}}} = \sqrt{A}\frac{D_p}{b}$$

where, A is the aspect ratio, and b is the wingspan.

The aspect ratio of rubber-powered aircraft is approximately 6, therefore,

$$\frac{D_p}{b} \approx \frac{0.7 \sim 1.4}{\sqrt{6}} \approx 0.29 \sim 0.57$$

8. Comparison with Empirical Rules

We will compare the empirical rules regarding the relationship between propellers and rubber found in the literature with the calculation results obtained using the method described in this report.

- "What I've found over the years is that certain props work with certain motors."
  First, the rubber is chosen, and then the propeller that matches the rubber is chosen. (Reference [2])
  There is a rubber of a certain width or thickness that yields the best overall result for a given aircraft and propeller. (Reference [3])

⇒ This is consistent with the results in section 7 (3).

- For plane with high drag, choose a low-pitch propeller, and for aircraft with low drag, choose a high-pitch propeller. (References [2], [4])
  "The less drag on the ship the higher P/D you can safely use, but I never exceed 1.3." (Reference [5])

⇒ Figure 17 shows the results of calculations for the aircraft in Figure 3 and Table 1, where the total parasite drag is 0.05 and 0.10, and the pitch ratios of Union Model propellers are 1.0 and 1.4. Looking at the graph of climbing energy efficiency, in the case of low-drag aircraft, the effect of the pitch ratio is small, so using a propeller with a large pitch ratio, which results in a smaller propeller rotation speed, is advantageous as it extends the powered flight time.

However, in the case of high-drag aircraft, using a propeller with a small pitch ratio results in better climbing energy efficiency.

- "The ancient rule of selecting a prop of 33% to 40% of the wingspan is pretty broad. Models with a high aspect ratio wing certainly do not need a prop this big." (Reference [6])

  ⇒ From equation in 8. (5),

  $$\frac{D_p}{b} = \frac{\text{Non}-\text{Dimensional Propeller Diameter}}{\sqrt{A}}$$

  This indicates that the higher the aspect ratio of the main wing, the smaller the propeller diameter/wingspan ratio can be.

9. Summary

- I derived dimensionless parameters representing the relationship between the rubber torque and propeller of a rubber-powered aircraft, calculated the dimensionless parameters for constant-power flight, and created contour plots (dimensionless graphs) of the dimensionless parameters.
- I proposed a method for determining the optimal rubber and propeller combination for an aircraft using the dimensionless graph.
- I confirmed that the calculation results proposed in this report are consistent with the empirical rules of rubber-powered airplane enthusiasts.

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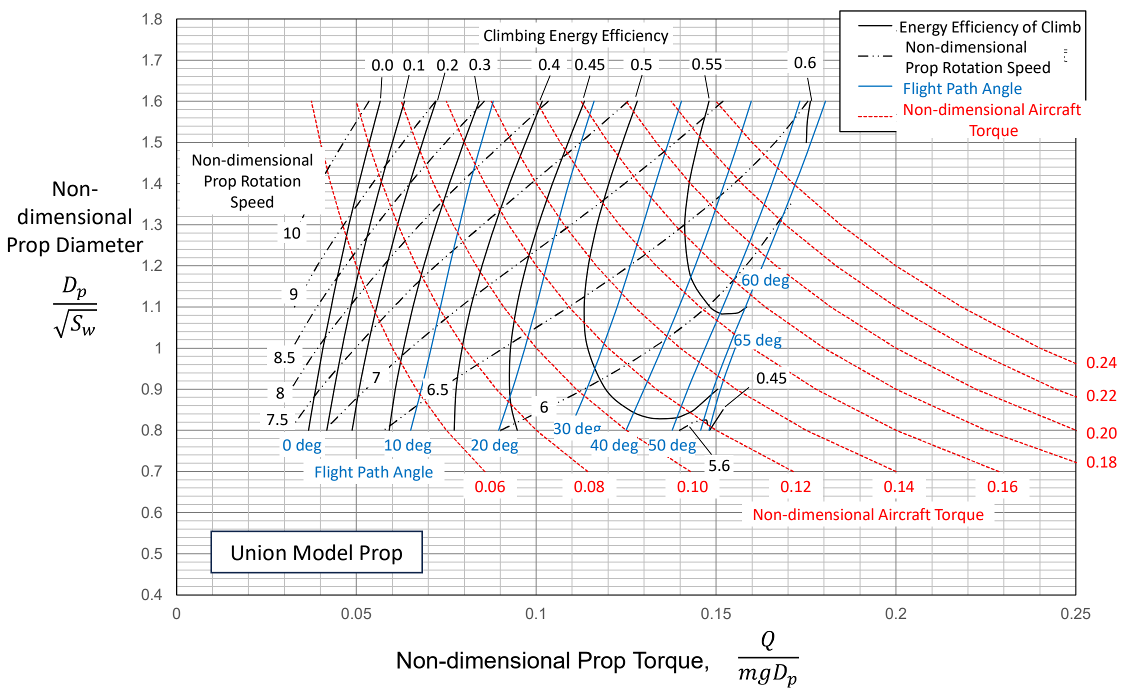

Figure 7. Relationship between Torque and Propeller Diameter – Union Model Propeller

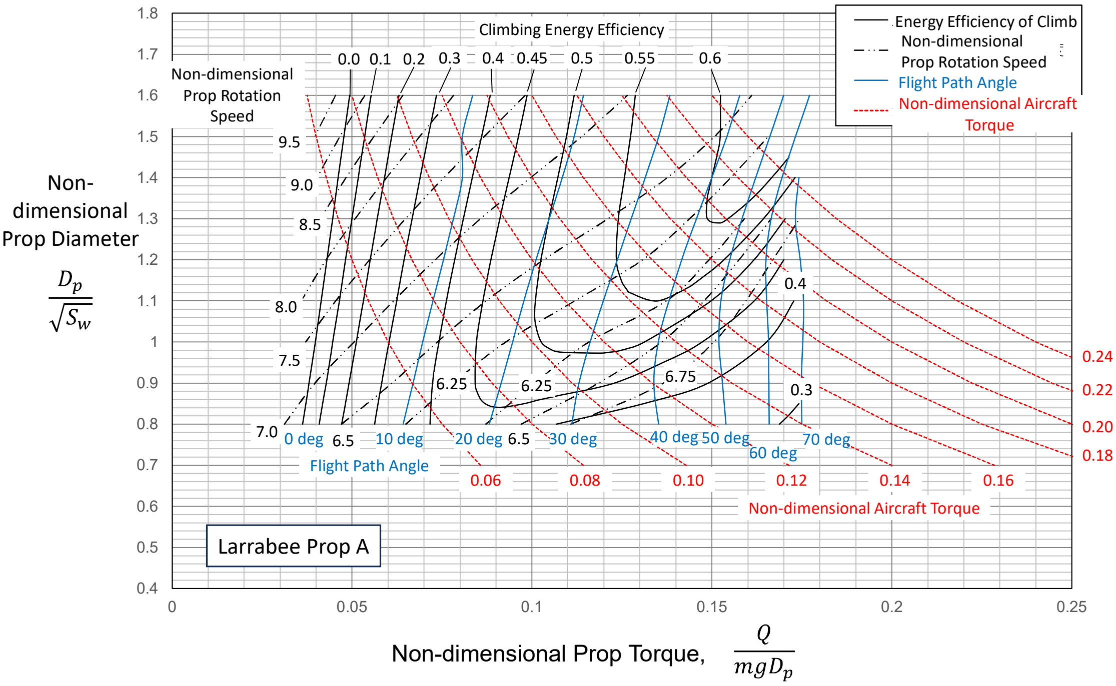

Figure 8. Relationship between Torque and Propeller Diameter – Larrabee Propeller A

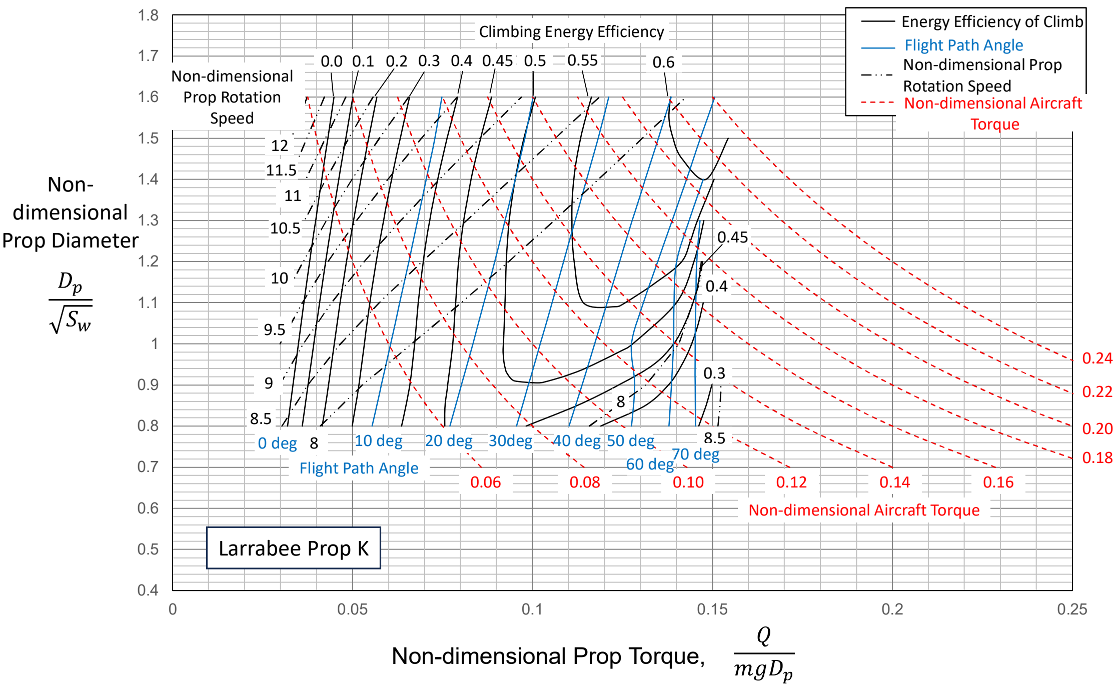

Figure 9. Relationship between Torque and Propeller Diameter – Larrabee Propeller K

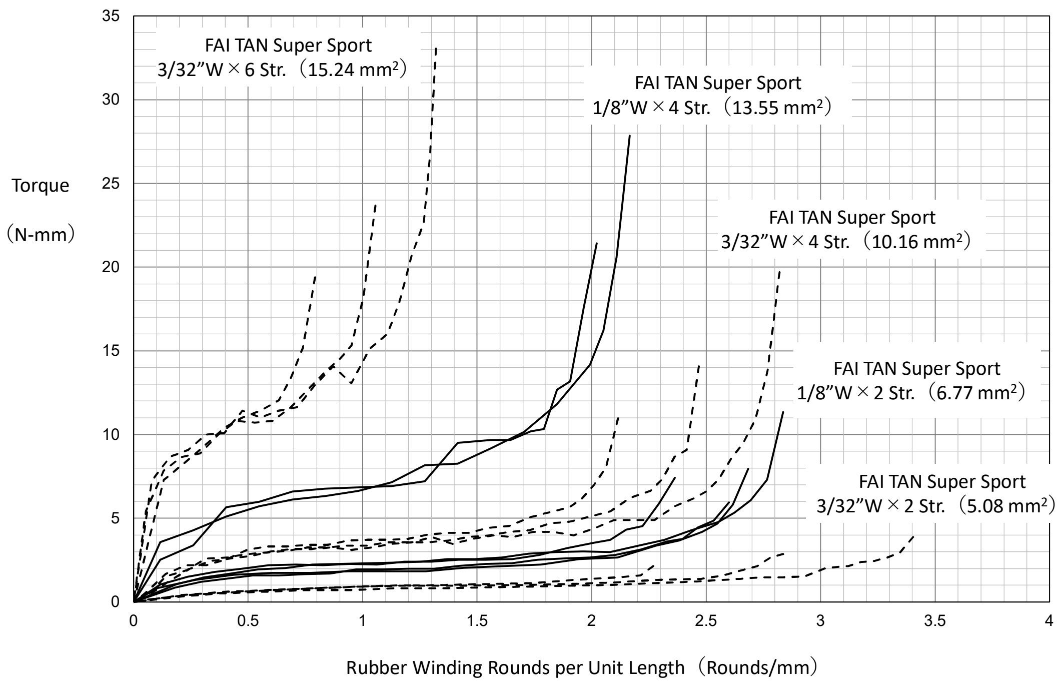

Figure 10. Examples of Rubber Torque Data

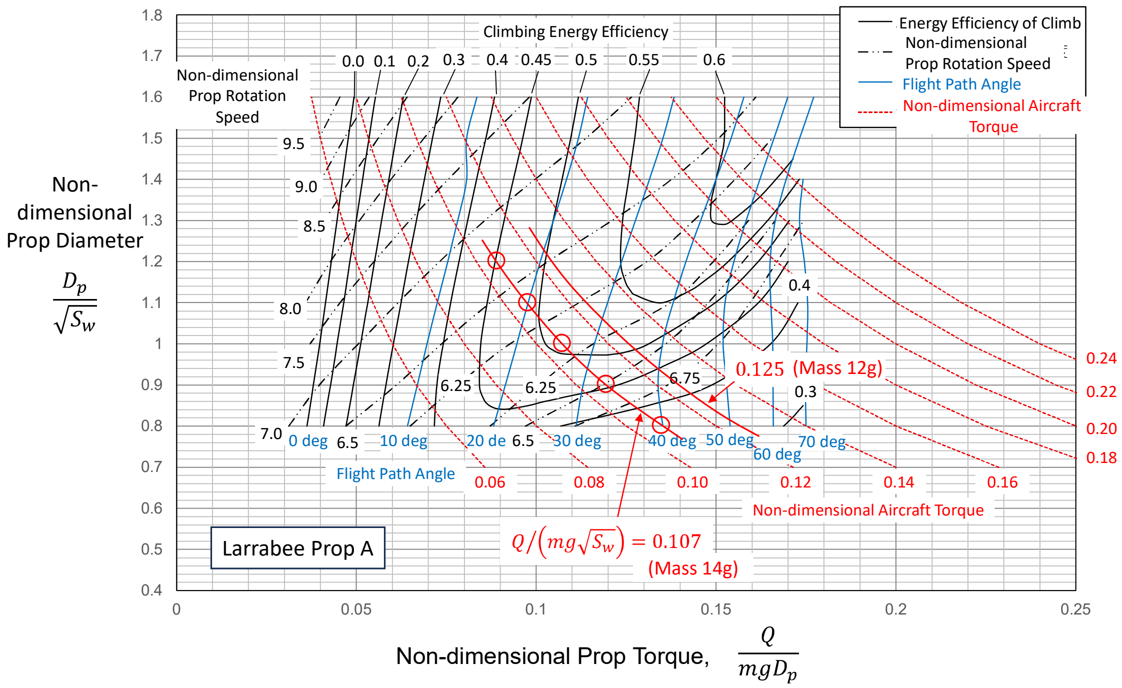

Figure 11.

Figure 11. How to Use Dimensionless Graph – Larrabee Propeller A

Table 3. Calculation from Readout Data of Figure 11

Gravitational Acceleration	m/s^2	9.80665	9.80665	9.80665	9.80665	9.80665
Density of Air	kg/m^3	1.225	1.225	1.225	1.225	1.225
Model Gross Mass	g	14	14	14	14	14
	kg	0.014	0.014	0.014	0.014	0.014
Wing Area	mm^2	22274	22274	22274	22274	22274
	m^2	0.022274	0.022274	0.022274	0.022274	0.022274
Cruise Torque of Rubber	N-mm	2.2	2.2	2.2	2.2	2.2
	N-m	0.0022	0.0022	0.0022	0.0022	0.0022
Non-dimensional Aircraft Torque		0.107	0.107	0.107	0.107	0.107
Non-dimensional Prop Diameter		0.8	0.9	1	1.1	1.2
Climbing Energy Efficiency		0.37	0.455	0.505	0.49	0.45
Flight Path Angle	deg	40	33	26	20	15
Non-dimensional Prop Rotation Speed		7.3	6.5	6.2	6.35	6.75
Prop Diameter	m	0.119	0.134	0.149	0.164	0.179
	mm	119	134	149	164	179
Prop Rotation Speed	回/s	62.8	41.7	30.5	24.6	21.1
Climbing Speed	m/s	2.34	1.91	1.55	1.22	0.95

Read from Figure 11

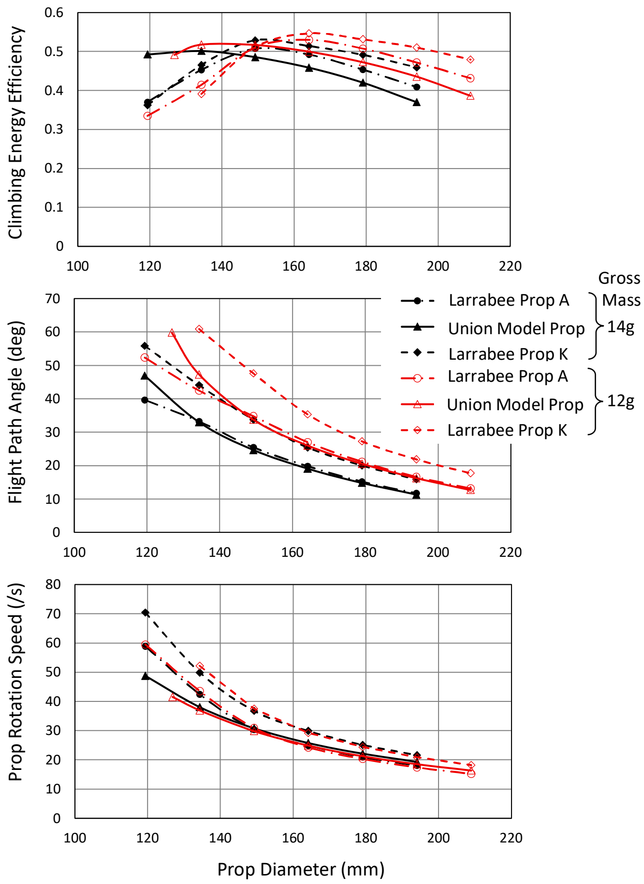

Figure 12. Effect of Propeller Type and Aircraft Mass

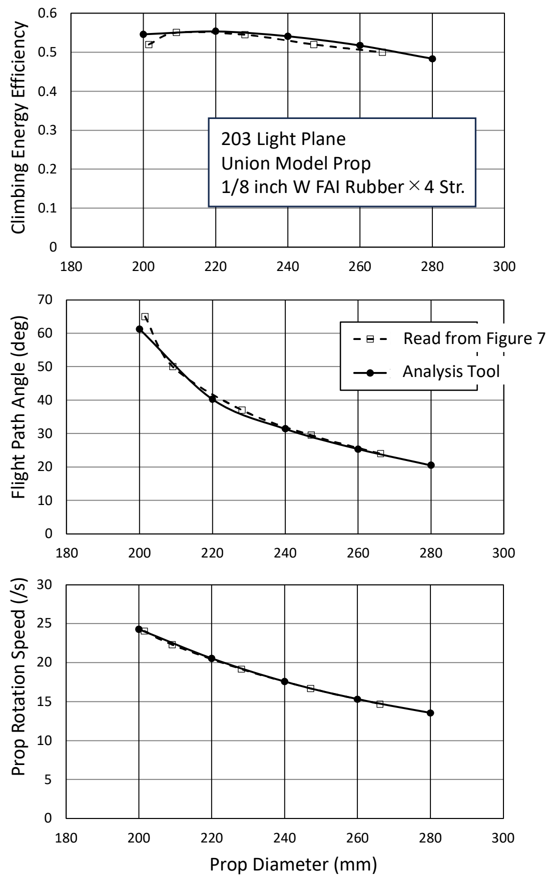

Figure 13. Application of Dimensionless Graph to Other Model Plane

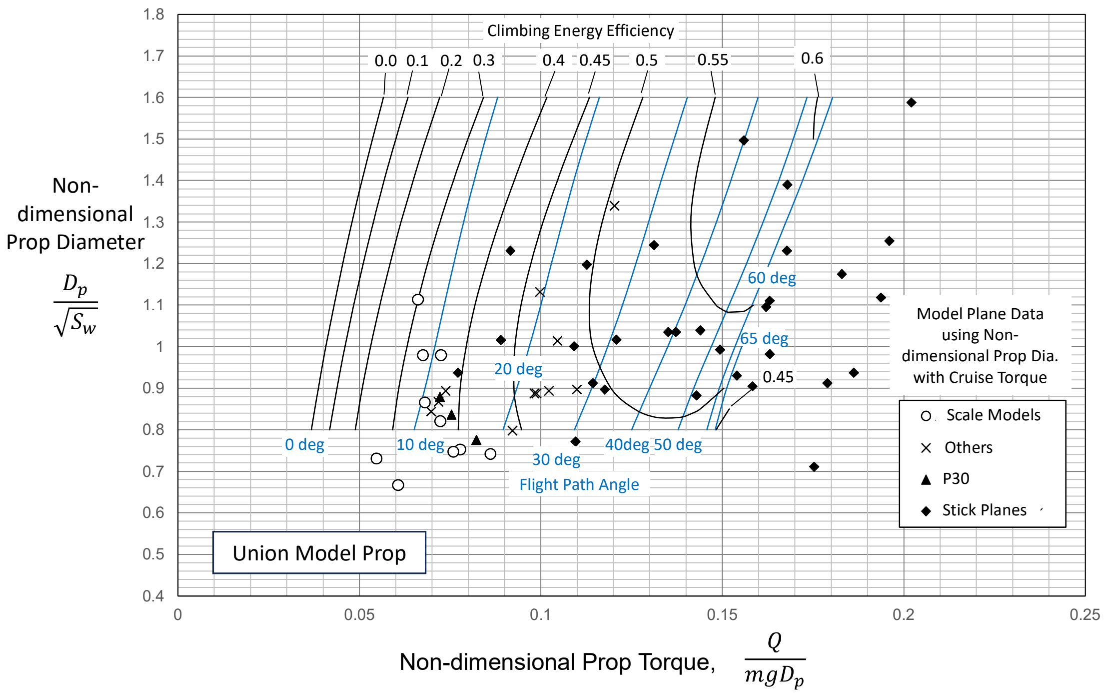

Figure 14. Comparison with Model Plane Data – Union Model Propeller

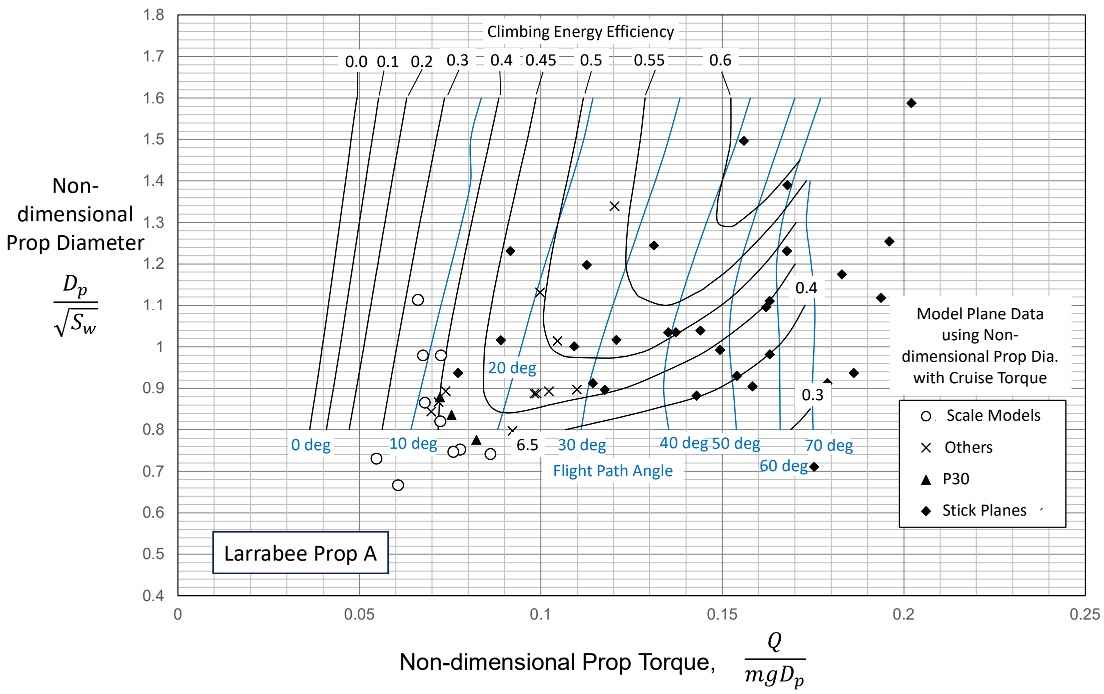

Figure 15. Comparison with Model Plane Data – Larrabee Propeller A

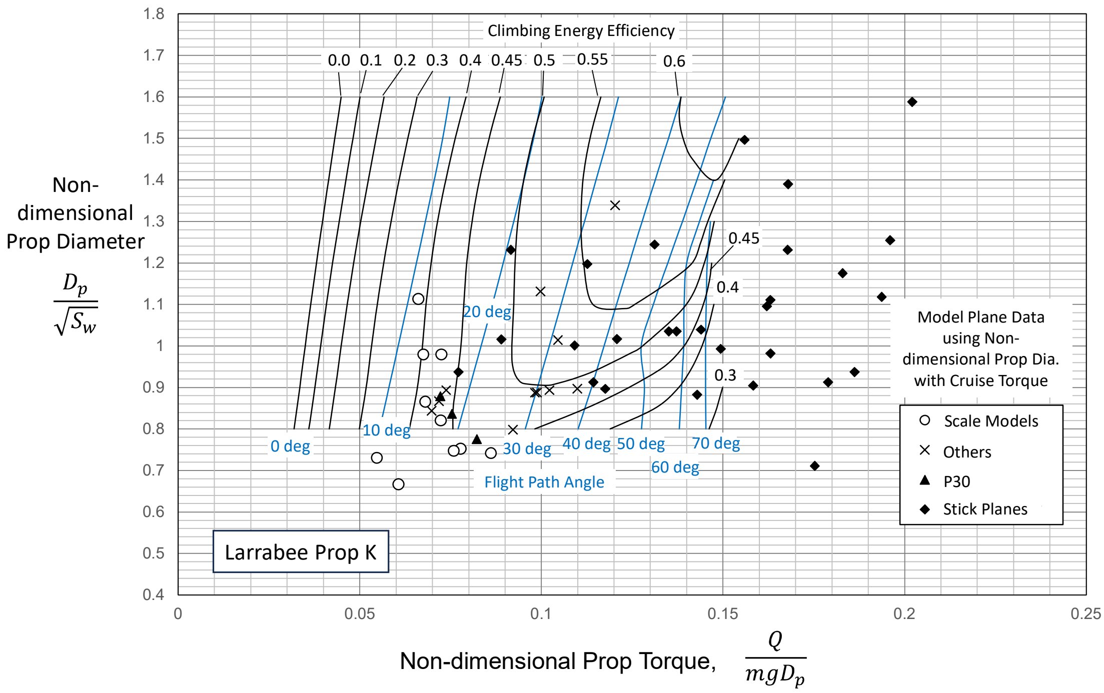

Figure 16. Comparison with Model Plane Data – Larrabee Propeller K

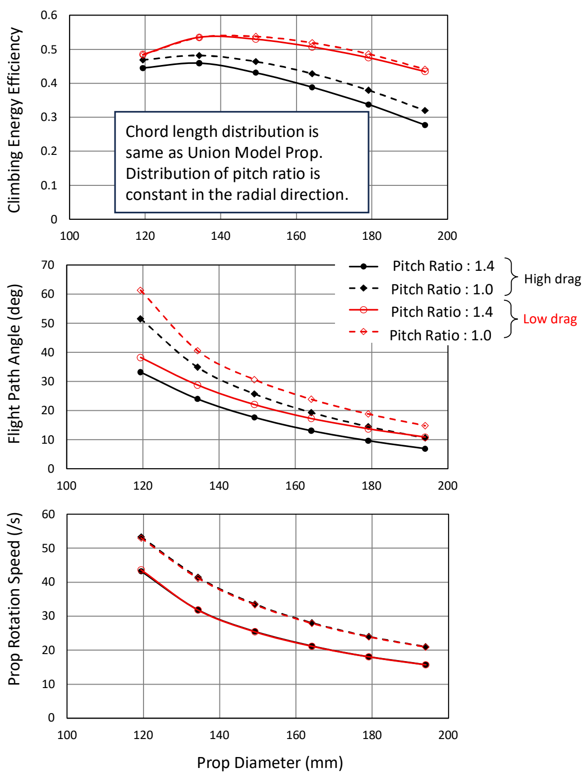

Figure 17. Comparison of Model Plane with High Drag and with Low Drag