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Empirical Propeller Mass Sizing for Small-Scale Aircraft

Amy Chang,[*] Eugene Pik,[†] Robert W. Deters [‡]
Embry-Riddle Aeronautical University - Worldwide, Daytona Beach, FL 32114

Or D. Dantsker[§]
Indiana University, Bloomington, IN 47408

The weight of propellers significantly impacts the performance of small unmanned aircraft, influencing factors such as flight duration, maneuverability, and energy efficiency. While typically still a small part of the total weight, propellers play an important in the weight and balance especially if the propeller is at an extreme location on the aircraft. In the context of distributed electric propulsion systems, where numerous propellers are used, the precise estimation of propeller mass becomes critical for ensuring performance. Using a large database of over 1,200 propeller masses, multiple empirical models were created for different propeller series from seven manufacturers. These models range from propeller diameters of 4 inches to 27 inches. In addition to the empirical models, a comparison between measured mass values and those provided by manufacturers is performed. Finally, an equation used to estimate the weight of full-scale propellers is applied to the small-scale propellers of this study.

I. Introduction

Weight is an important factor for all aircraft, but minute differences in weight for a small unmanned aircraft can have a large impact on its performance success. For instance, variations in weight can affect flight time, maneuverability, and energy consumption. Compared to larger aircraft, the propeller mass for small aircraft is a more significant portion of the overall aircraft mass. For example, AIAA Design-Build-Fly competition aircraft had nose- or leading edge-located motor and propeller setups, where the propellers made up 7 to 33% of the overall mass.[1,2] For fixed-wing aircraft, the propeller is often the most forward extent of the aircraft, and therefore can highly affect the center of gravity. A forward-shifting center of gravity can lead to instability and require design modifications to maintain balance. Similarly, lighter-than-air (LTA) vehicles (i.e., autonomous blimps), are very sensitive to component mass and center of gravity changes in their flight stability and control.[3] For multi-rotors, the propellers must carry their own weight along with the rest of the aircraft weight. The efficiency and thrust-to-weight ratio are critical metrics that are directly influenced by the propeller mass in such configurations. With distributed electric propulsion (DEP) vehicles, there could be a dozen or more propellers. This increases the complexity of weight distributions and necessitates precise mass estimation to ensure optimal performance and safety. Large-wingspan, flexible aircraft (e.g., HAPS configuration aircraft) with many propellers are especially sensitive to propeller mass differences.[4,5]

Equations to estimate the mass/weight of propellers for full-scale aircraft are available,[6,7] though their application to much small propellers is not clear. A few previous studies have provided mass estimates for small-scale propellers,[8–10] but the equations were created from a limited number and types of propellers. The model from Bershadsky[10] does account for three material types (carbon fiber, nylon, plastic, and wood) but is based on only 30 propellers. From

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[*] Graduate Student, Department of Graduate Studies. AIAA Student Member. changa8@my.erau.edu

[†] Graduate Student, Department of Graduate Studies. AIAA Student Member. eugene.pik@mevocopter.com

[‡] Associate Professor, School of Engineering, AIAA Senior Member. detersr1@erau.edu

[§] Assistant Professor, Department of Intelligent Systems Engineering, AIAA Member. odantske@iu.edu previous testing for propeller performance[11–15] and from manufacturer provided information, the authors have currently gathered mass data for over 1,200 small-scale propellers. These propellers range in diameter from 2 in. to over 30 in., have different chord and twist distributions, and are constructed from different material. This data is presented in this paper and available on the Unmanned Aerial Vehicle Database.[16] Using this database, new mass relationships can be created. The purpose of creating new mass relationships is to provide designers better equations to estimate the initial mass of the propellers. The results are not meant to be the exact final mass for a new design, but these new relationships should provide a reasonable initial value and a method to bracket the possible range in mass.

This paper analyzes the mass of off-the-shelf small-scale propellers in four different manners. First, the mass of off-the-shelf propellers in which the authors have access are compared to the listed mass values provided by their manufacturers. For many of the propellers, the authors were able to measure the mass of multiple specimens of the same propeller series. In the second analysis, this variation is provided. In the third analysis, the propeller masses are used to create empirical models based on the propeller series. Finally, an initial weight equation for full-scale propellers is applied to small-scale propellers.

II. Comparison between Measured and Manufacturer-Provided Mass Values

From the propellers available to the authors, only manufacturer-provided masses for the propellers from APC and Master Airscrew could be found. Propellers from five Advanced Precision Composites (APC)[17] series and six Master Airscrew[18] series were available to the authors for comparison. Table 1 lists the 11 total propeller series compared.

Table 1: Propeller Series for Measured-Listed Comparison

APC	**Master Airscrew**
Carbon	3 Blade
Electric	BN FPV Bullnose
MR	Electric
Slow Flyer	GF
Sport	MR
	Scimitar

The comparison for each propeller series is provided in two figures. In the first figure, the Measured mass divided by the Listed mass from the manufacturer is plotted against the propeller diameter. Each propeller model from that series is shown as a point on the plot; for example, 9×4 and 9×5 are separate points. If there were multiple specimens of a specific propeller model, the average measured mass was used. The measured-to-listed value of 1 is also highlighted in the first figure to more easily show whether the measured value was greater or less than the manufacturer's value.

The second figure provides the average percent difference and average absolute difference for all propellers at each diameter. While every measured propeller model is shown in the first figure, only two points are provided at each diameter in the second figure: one for percent difference and one for absolute difference. This second figure provides the general error between the mass listed by the manufacturer and the true mass.

The APC propeller comparison plots are provided first with Figs. 1–2 for the Carbon, Figs. 3–6 for the Electric, Figs. 7–8 for the MR, Figs. 9–10 for the Slow Flyer, and Figs. 11–12 for the Sport. The Master Airscrew propellers are then provided with Figs. 13–14 for the 3 Blade, Figs. 15–16 for the BN FPV Bullnose, Figs. 17–18 for the Electric, Figs. 19–20 for the GF, Figs. 21–22 for the MR, and Figs. 23–24 for the Scimitar.

Only three propellers were available for the APC Carbon comparison (Figs. 1–2), so general trends cannot be formed. From the samples available, the propellers are about within 10% of the listed mass with an averaged difference of less than 1 g.

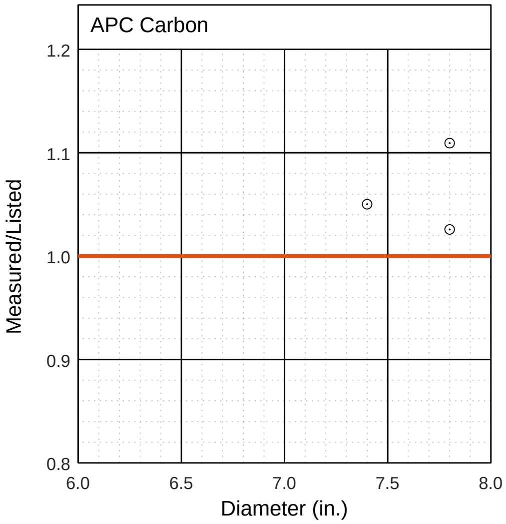

Figure 1: Variation in measured to listed mass for the APC Carbon propellers.

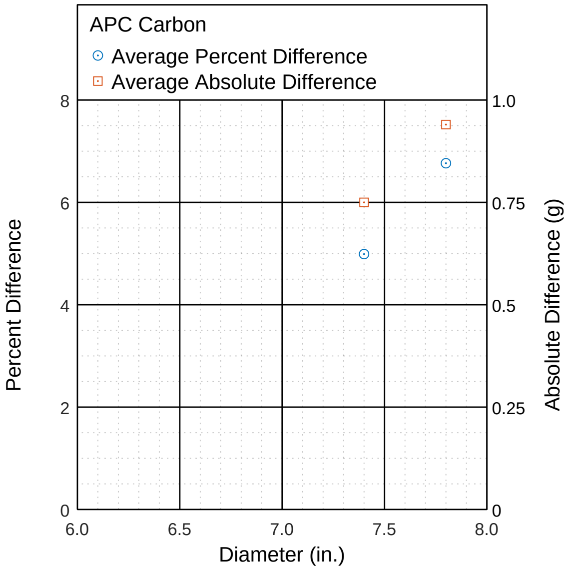

Figure 2: Average percent difference and absolute difference for the APC Carbon propellers.

For the APC Electric propellers, two sets of comparisons were performed. There was a change with APC Electric propellers (date unknown to the authors) where Electric propellers used for testing in the early 2000s are noticeably lighter than propellers from the late 2010s and early 2020s. The older Electric propellers were included in this paper since these propellers can still be found in hobby shops. Both sets of propellers were compared to the currently listed mass from the manufacturer. Figures 3–4 provides the comparison for the current Electric propellers, and Figs. 5–6 provides the comparison for the older Electric propellers. A total of 46 propellers were available for comparison of the current Electric propellers, and 27 were available for the older Electric propellers. With the current Electric propellers, a majority of those measured had a larger mass than listed from the manufacturer with most propellers within 10% of the listed value. For each diameter, a variation is seen corresponding to the different pitch values. For many of the diameters, the listed mass for similar pitch angles were the same, while the measured value was different for each pitch value. For most diameters, the average difference from the listed weight was within a few grams. The largest differences were with the 18 and 21-in. propellers with the 21-in. having a difference of 20 g. More larger diameter propellers (over 20 in.) need to be measured to determine if the large difference with the 21-in. is uncommon. For the older Electric propellers, all but one model had a mass less than the currently listed value with a majority being more than 10% lighter than the currently listed values. As sees with the absolute difference, the amount of difference generally increases as the diameter increased.

Twenty APC MR (Figs. 7–8) models were measured, and for each model, both the tractor and pusher varieties were included. All but one of the models were within 5% of the listed value, and the average differences were within 1 g. For the APC Slow Flyer (Figs. 9–10), 15 models were tested with all but one measuring less than the listed value. Generally, the average difference from the listed increased with diameter but was less than 1 g.

For the APC Sport series (Figs. 7–8), 60 propellers were measured. As with the APC Electric, a variety of pitch values were available for the same diameter, and a difference was measured for each pitch while similar pitches had the same listed mass. Most models from the Sport series were within 10% of the listed value, which corresponded to average differences of less than 2 g for most diameters.

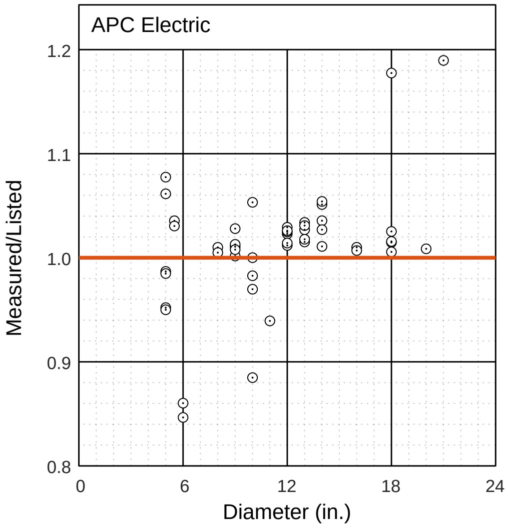

Figure 3: Variation in measured to listed mass for the APC Electric propellers.

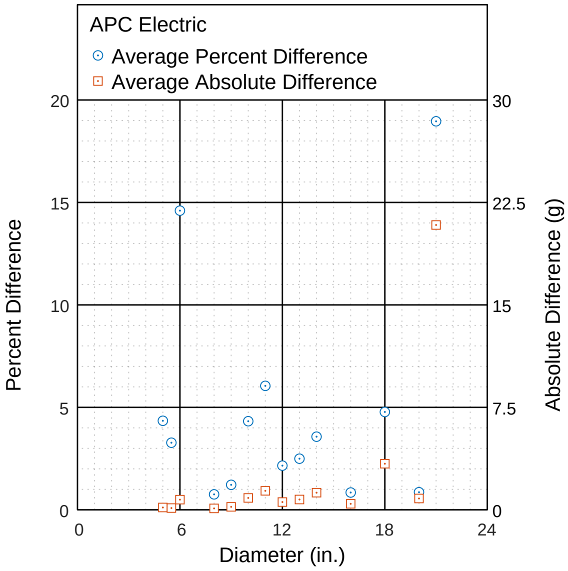

Figure 4: Average percent difference and absolute difference for the APC Electric propellers.

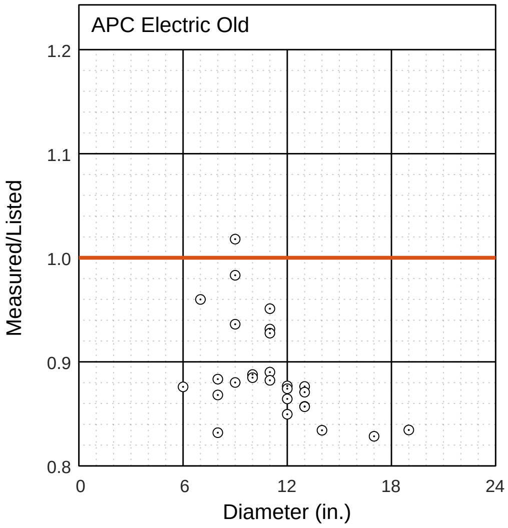

Figure 5: Variation in measured to listed mass for older APC Electric propellers.

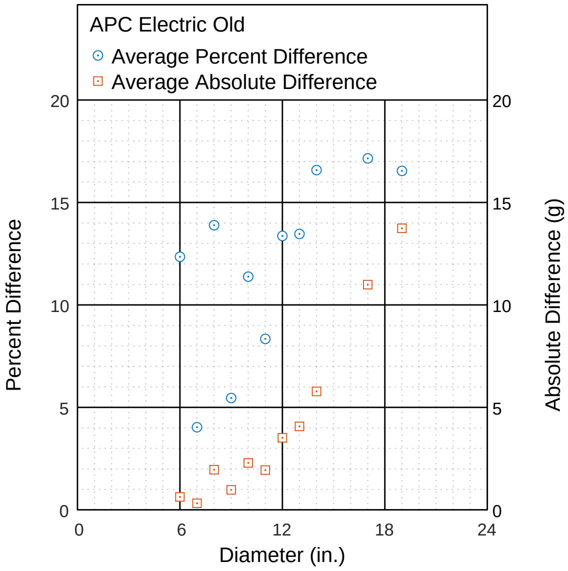

Figure 6: Average percent difference and absolute difference for older APC Electric propellers.

Ten Master Airscrew 3-blade (Figs. 13–14) models were measured, and like the APC MR, both the tractor and pusher varieties were included for each model. All models were within 5% of the listed value with the average differences within 1 g of the listed. For the Master Airscrew Bullnose (Figs. 15–16), two models were measured, but they were the tractor and pusher variety of the same model. This model varies significantly in terms of percentage (over 20%), which corresponds to a difference of about 1.6 g.

For both the Master Airscrew Electric (Figs. 17–18) and Master Airscrew GF (Figs. 19–20), 14 models were measured. For the Electric, 5 sets of those propellers were the tractor and pusher varieties of the model. Most Electric were within 10% of the listed value with most average differences being less than 1 g. Similar results are seen with the GF propellers with most measured values being within 10% of listed. Differences of more than 1 g are larger with

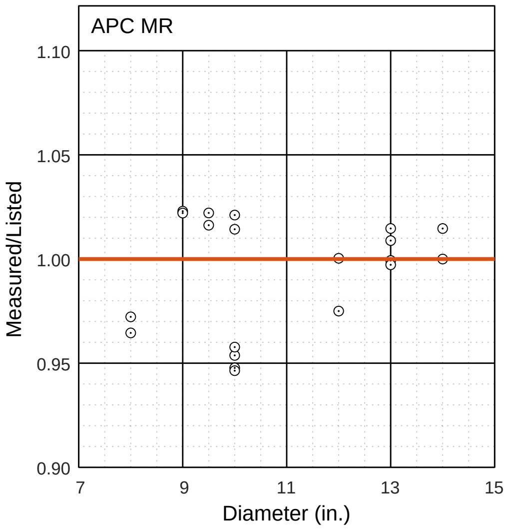

Figure 7: Variation in measured to listed mass for the APC MR propellers.

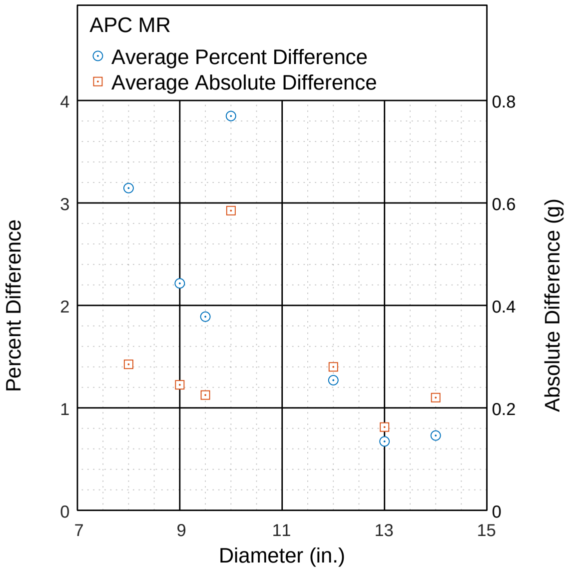

Figure 8: Average percent difference and absolute difference for the APC MR propellers.

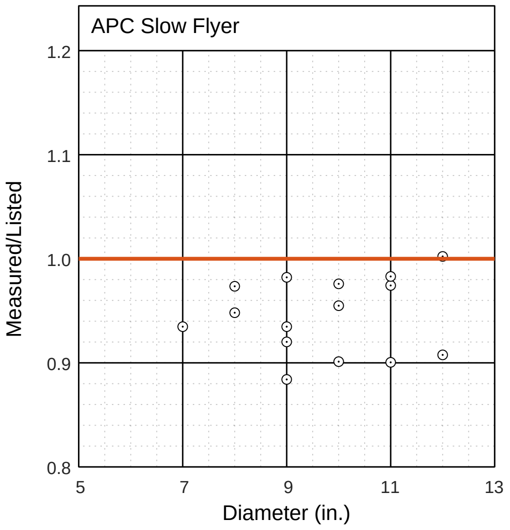

Figure 9: Variation in measured to listed mass for the APC Slow Flyer propellers.

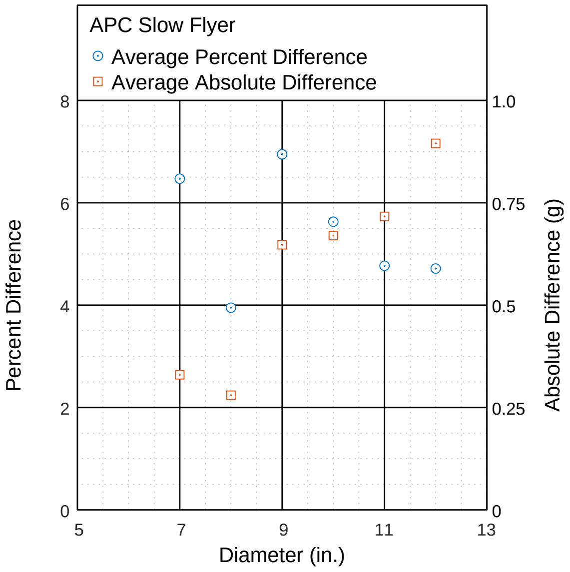

Figure 10: Average percent difference and absolute difference for the APC Slow Flyer propellers.

the GF propellers, though these propellers are heavier than the Electric propellers with the same diameter, so similar percent differences will correspond to larger absolute differences with the GF propellers.

Ten models were measured for both the Master Airscrew MR (Figs. 21–22) and Master Airscrew Scimitar (Figs. 23–24) series. As with the APC MR series, the Master Airscrew MR series included both the tractor and pusher varieties of the same model. Only the 9.4 in. MR model had a percent difference greater 10% and an absolute difference greater than 1 g. It should be noted that 9.4 in. model is a special design meant as replacement propellers for the DJI Phantom drone and not a standard MR model. The 10-in. model with the larger difference from the listed mass was also a special design meant as replacement propellers for the Solo drone. For the Scimitar propellers, only the 10 in. propellers had a percent difference over 10%.

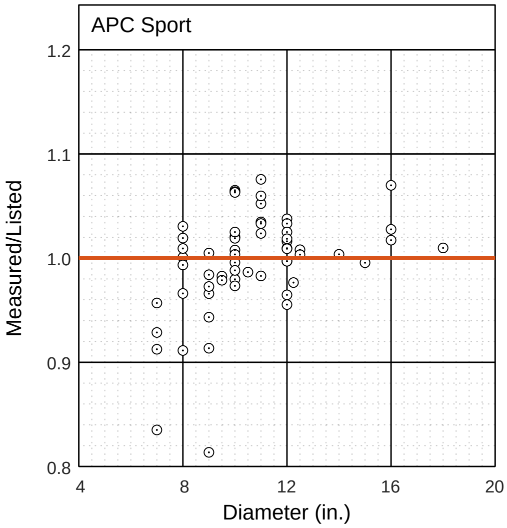

Figure 11: Variation in measured to listed mass for the APC Sport propellers.

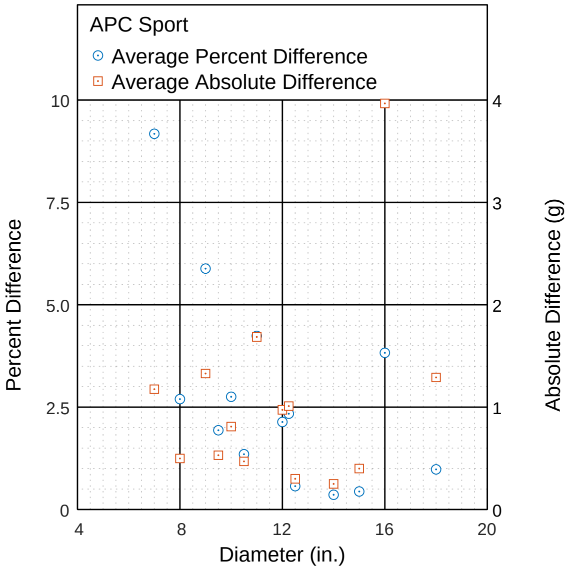

Figure 12: Average percent difference and absolute difference for the APC Sport propellers.

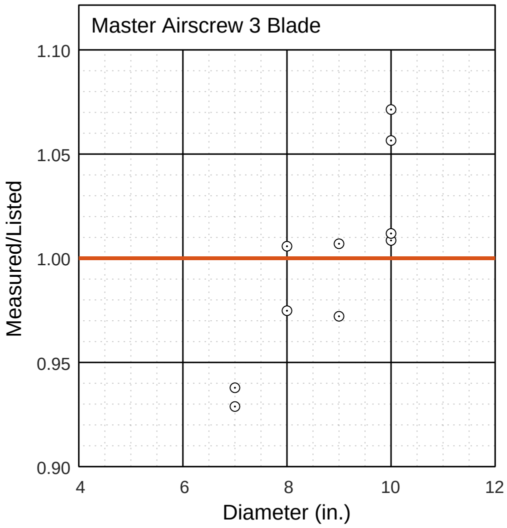

Figure 13: Variation in measured to listed mass for the Master Airscrew 3 blade propellers.

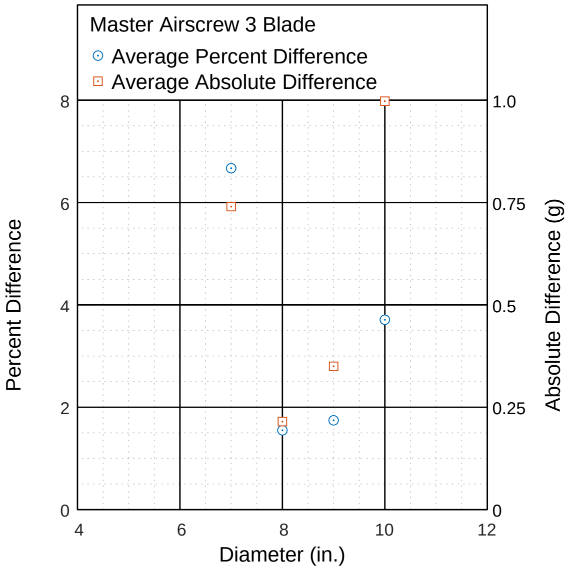

Figure 14: Average percent difference and absolute difference for the Master Airscrew 3 blade propellers.

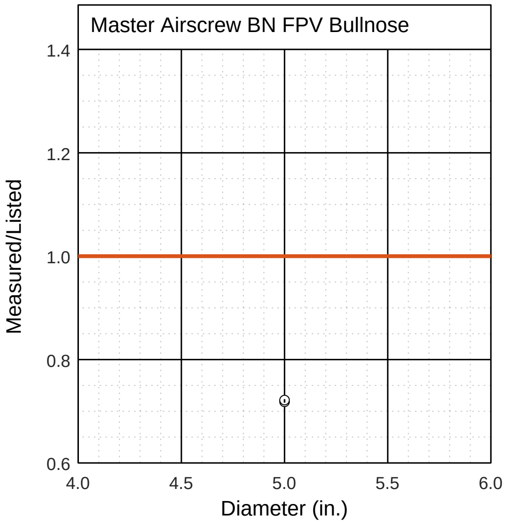

Figure 15: Variation in measured to listed mass for the Master Airscrew BN FPV Bullnose propellers.

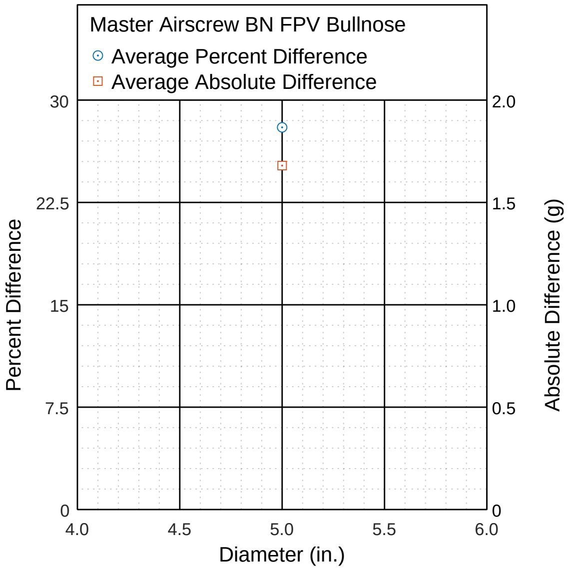

Figure 16: Average percent difference and absolute difference for the Master Airscrew BN FPV Bullnose propellers.

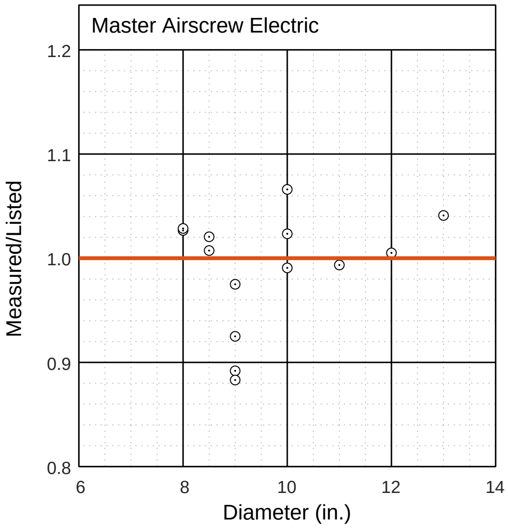

Figure 17: Variation in measured to listed mass for the Master Airscrew Electric propellers.

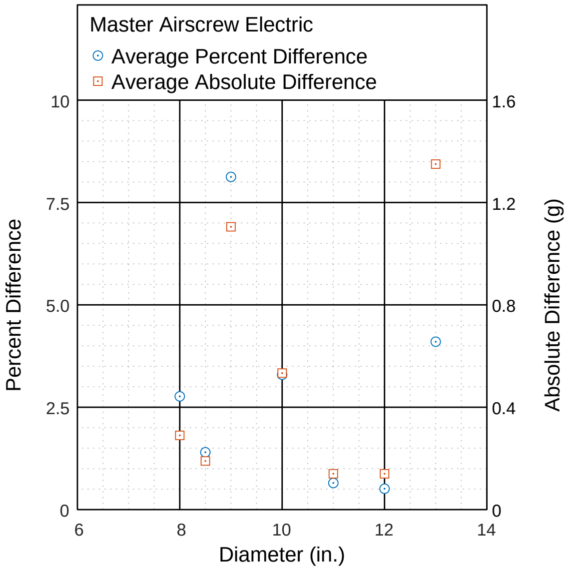

Figure 18: Average percent difference and absolute difference for the Master Airscrew Electric propellers.

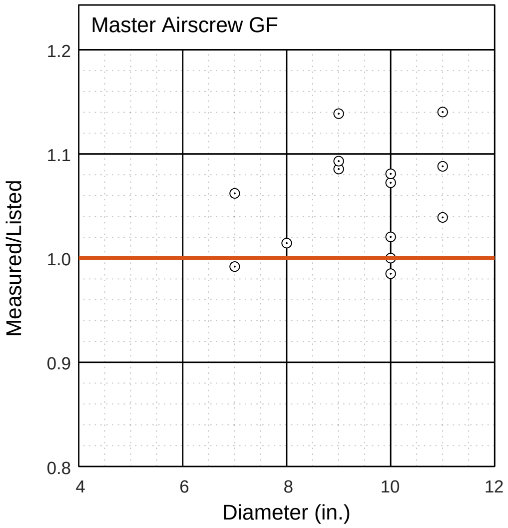

Figure 19: Variation in measured to listed mass for the Master Airscrew GF propellers.

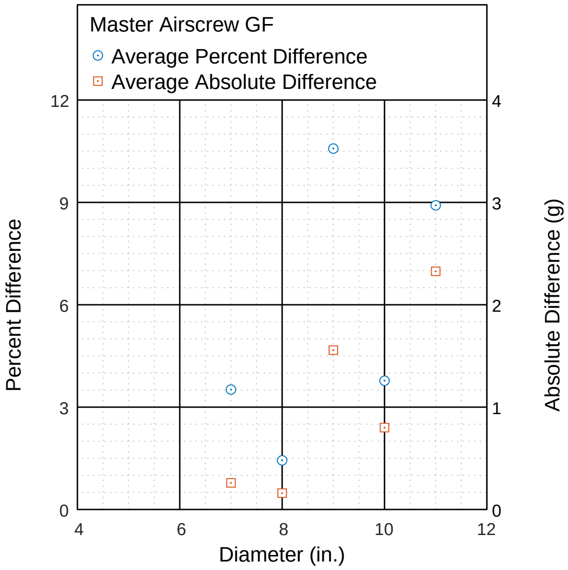

Figure 20: Average percent difference and absolute difference for the Master Airscrew GF propellers.

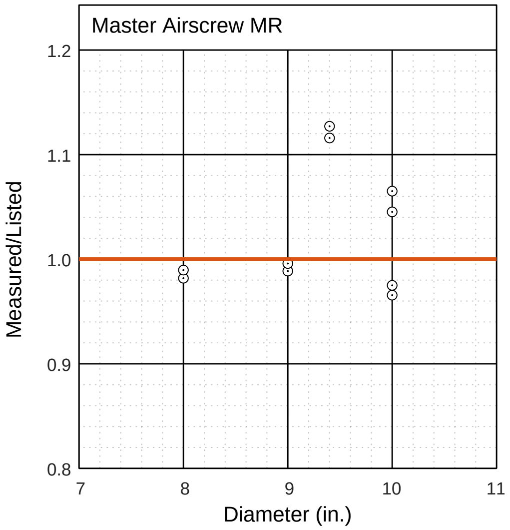

Figure 21: Variation in measured to listed mass for the Master Airscrew MR propellers.

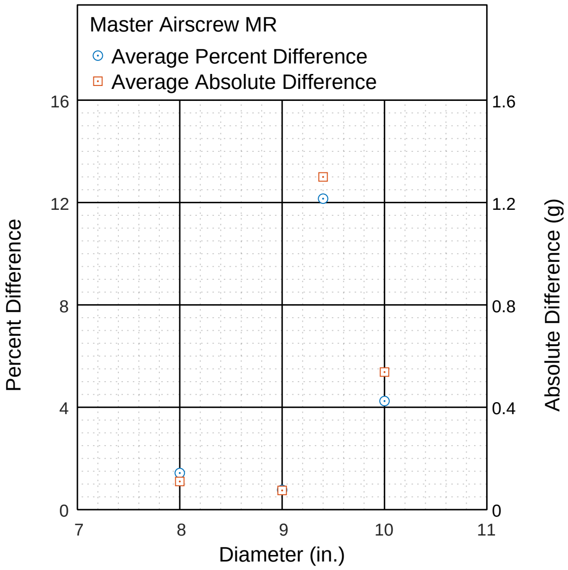

Figure 22: Average percent difference and absolute difference for the Master Airscrew MR propellers.

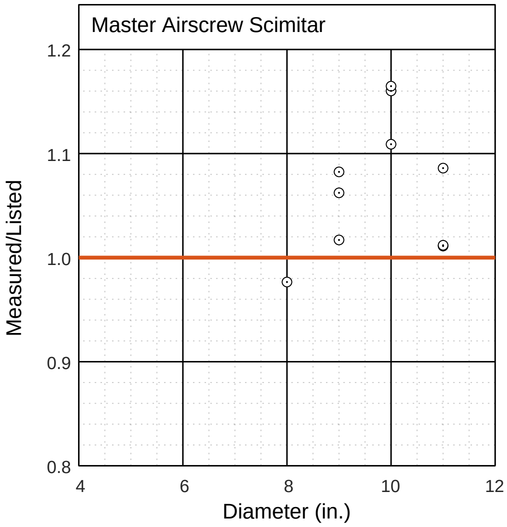

Figure 23: Variation in measured to listed mass for the Master Airscrew Scimitar propellers.

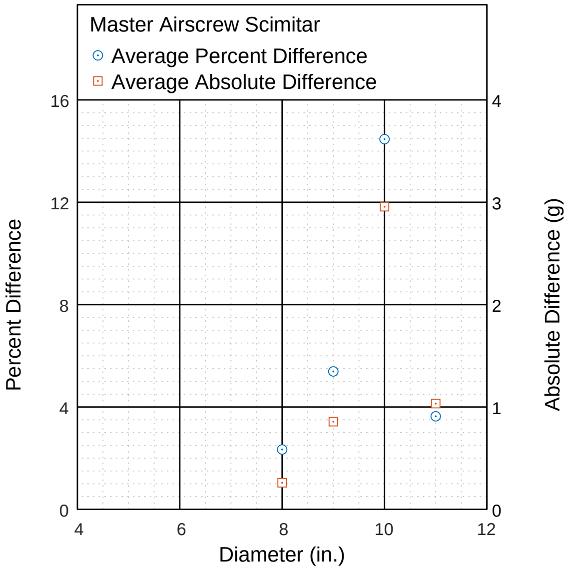

Figure 24: Average percent difference and absolute difference for the Master Airscrew Scimitar propellers.

III. Variation in Measured Propellers

An analysis of the variation in the mass of a propeller model is important for aircraft sizing and weight and balance. Little to no variation in the mass of a specific propeller model is desired. Also of importance is any variation in mass of propeller models that have tractor and pusher varieties. Tractor and pusher configurations are necessary for multirotor designs and are also used with distributed electric propulsion designs. Only one series of folding propellers is provided in this report, but the mass of single blades with folding propellers should match to minimize the need for balancing.

This section summarizes the variation in the measured propellers for those models that had more than one specimen available. Each table included in this section is for a different propeller series, and each table includes the model, the mean mass, the standard deviation, the minimum mass, the maximum mass, and the number of specimens. Propellers from 21 series are represented, and Table 2 lists the included series. The measured masses were gathered using different scales over a period of multiple years. The average error from these scales can be considered ±0.05 g.

Table 2: Propeller Series for Measured Variation

Aeronaut CAM Carbon Folding	Graupner CAM Prop	Master Airscrew 3 Blade
APC Carbon	Graupner CAM Slim	Master Airscrew Bullnose
APC Electric	Graupner C-Prop	Master Airscrew Electric
APC Electric Old	Graupner Sport	Master Airscrew GF
APC MR	Graupner Super Nylon	Master Airscrew MR
APC Slow Flyer	Kavan FK	Master Airscrew Scimitar
APC Sport	Kyosho	Zingali

Results from the measured variations are provided in Tables 3–23. For most propellers models in all series, the variation between specimens was very small and within the measurement error. At least one propeller from the following series had a variation of at least 0.5 g: APC Electric old (Table 6), APC Slow Flyer (Table 8), APC Sport (Table 9), Graupner CAM Prop (Table 10), Kavan (Table 15), Kyosho (Table 16), Master Airscrew Electric (Table 19), Master Airscrew GF (Table 20), Master Airscrew MR (Table 21), Master Airscrew Scimitar (Table 22). Only three series had propellers with a variation of at least 1 g: Master Airscrew Electric, Master Airscrew MR, and Master Airscrew Scimitar. When comparing tractor and pusher configurations, the following had models with significant differences: APC Electric (Table 5), APC MR (Table 7), APC Sport (Table 9), Graupner C-Prop (Table 12), Graupner Sport (Table 13), Master Airscrew 3 Blade (Table 19), Master Airscrew Electric (Table 19), and Master Airscrew MR (Table 21).

Table 3: Aeronaut CAM Carbon Folding — Single Blade

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
9×4	4.13	0.0	4.12	4.13	2
9×5	3.65	0.0	3.65	3.65	2
9×6	4.00	0.0	4.00	4.00	2
9×7	3.71	0.01	3.70	3.72	2
10×4	4.99	0.01	4.98	5.00	2
10×5	4.59	0.0	4.59	4.59	2
10×6	4.84	0.0	4.84	4.84	2
10×7	4.65	0.01	4.64	4.66	2
10×8	4.77	0.0	4.77	4.77	2
10×12	4.61	0.0	4.61	4.61	2
11×4	5.25	0.0	5.24	5.25	2
11×6	5.53	0.01	5.52	5.53	2
11×7	5.25	0.0	5.24	5.25	2
11×8	5.82	0.0	5.82	5.82	2
11×10	5.76	0.0	5.76	5.76	2
11×12	5.16	0.0	5.15	5.16	2
12×5	6.28	0.0	6.28	6.28	2
12×6	6.20	0.04	6.16	6.24	2
12×6.5	6.55	0.0	6.54	6.55	2
12×9	8.06	0.06	8.00	8.12	2
12×10	7.40	0.01	7.39	7.40	2
12×11	8.43	0.01	8.42	8.44	2
12×13	5.78	0.01	5.77	5.78	2
12.5×6	7.17	0.0	7.17	7.17	2
12.5×7	7.05	0.0	7.05	7.05	2
12.5×9	6.52	0.0	6.52	6.52	2
13×5	7.45	0.01	7.44	7.46	2
13×6.5	8.20	0.0	8.19	8.20	4
13×8	5.93	0.0	5.92	5.93	2
13×10	6.66	0.0	6.66	6.66	2
13×11	7.88	0.01	7.87	7.89	2
14×6	8.51	0.02	8.49	8.53	2
14×8	9.03	0.0	9.03	9.03	2
14×9	8.91	0.01	8.89	8.92	2
14×12	9.08	0.02	9.05	9.10	2
14×13	9.82	0.0	9.81	9.82	2
15×6	9.71	0.0	9.71	9.71	2
15×8	9.58	0.0	9.58	9.58	2
15×10	10.26	0.0	10.26	10.26	2

Table 4: APC Carbon

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
7.4×8.25C	15.78	0.02	15.76	15.8	2
7.8×6C	14.25	0.08	14.17	14.33	2
7.8×7C	15.41	0.1	15.31	15.51	2

Table 5: APC Electric

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
5×3E	3.36	0.01	3.34	3.38	4
5×3EP	3.31	0.01	3.3	3.32	4
5×4.3E	4.65	0.01	4.63	4.66	4
5×4.3EP	4.64	0.02	4.61	4.65	4
5×4.5E	4.82	0.0	4.82	4.83	4
5×4.5EP	4.81	0.01	4.8	4.82	4
5.5×4.5E	4.11	0.0	4.1	4.11	4
5.5×4.5EP	4.09	0.04	4.05	4.14	4
6×4E	4.39	0.02	4.37	4.41	4
6×4EP	4.32	0.0	4.32	4.33	4
8×6E	14.03	0.03	13.99	14.07	4
8×6EP	13.96	0.01	13.95	13.97	4
9×4.5E	17.89	0.03	17.85	17.92	4
9×4.5EP	18.36	0.02	18.34	18.39	4
9×6E	18.05	0.2	17.64	18.17	5
9×6EP	18.09	0.01	18.07	18.11	4
10×5E	19.78	0.06	19.68	19.86	5
10×5EP	19.52	0.03	19.47	19.55	4
10×7E	20.13	0.03	20.08	20.18	5
10×7EP	21.2	0.01	21.19	21.22	4
14×7E	35.81	0.05	35.76	35.86	2
14×8.5E	38.30	0.16	38.14	38.46	2

Table 6: APC Electric Old

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
7×5E	7.62	0.03	7.58	7.66	4
8×4E	11.52	0.29	11.23	11.82	2
8×6E	12.06	0.26	11.76	12.33	4
11×5.5E	20.44	0.05	20.39	20.5	2
12×8E	22.87	0.09	22.78	22.99	3
12×10E	22.8	0.01	22.79	22.8	2
12×12E	22.16	0.01	22.15	22.16	2
13×4E	25.76	0.2	25.56	25.95	2
17×12E	53.08	0.0	53.08	53.08	2
19×12E	69.32	0.02	69.3	69.35	2

Table 7: APC MR

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
8×4.5MR	8.82	0.07	8.74	8.94	6
8×4.5MRP	8.75	0.04	8.67	8.79	6
9×4.5MR	11.31	0.04	11.21	11.38	8
9×4.5MRP	11.3	0.05	11.17	11.33	8
9.5×5MR-P3	12.17	0.03	12.14	12.23	8
9.5×5MRP-P3	12.1	0.02	12.08	12.13	8
10×4.5MR	14.24	0.02	14.21	14.27	4
10×4.5MRP	14.22	0.02	14.2	14.25	4
10×4.5MR(ST)	16.39	0.05	16.36	16.5	7
10×4.5MRP(ST)	16.5	0.05	16.44	16.55	7
10×5.5MR	14.33	0.01	14.31	14.35	4
10×5.5MRP	14.39	0.01	14.38	14.41	4
12×4.5MR	22.12	0.02	22.1	22.14	3
12×4.5MRP	21.56	0.06	21.48	21.6	3
13×4.5MR	24.45	0.05	24.4	24.52	3
13×4.5MRP	24.31	0.02	24.29	24.34	3
13×5.5MR	24.08	0.03	24.05	24.12	3
13×5.5MRP	24.03	0.0	24.03	24.04	3
14×5.5MR	30.49	0.03	30.45	30.52	3
14×5.5MRP	30.05	0.0	30.05	30.06	3

Table 8: APC Slow Flyer

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
7×4SF	4.77	0.02	4.74	4.79	2
8×3.8SF	6.72	0.36	6.37	7.08	2
8×6SF	6.9	0.03	6.86	6.93	2
9×3.8SF	8.48	0.02	8.46	8.51	2
10×3.8SF	11.37	0.47	11.03	12.04	3
11×3.8SF	14.64	0.01	14.63	14.66	2
11×4.7SF	13.53	0.03	13.5	13.56	2
11×7SF	14.77	0.02	14.75	14.79	2
12×3.8SF	17.9	0.04	17.85	17.94	2
12×6SF	17.24	0.02	17.22	17.25	2

Table 9: APC Sport

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
7×6	11.9	0.08	11.82	11.99	2
7×9	10.89	0.08	10.81	10.97	2
8×4	16.36	0.18	16.17	16.54	2
8×5	19.36	0.01	19.35	19.37	2
8×6	18.35	0.0	18.35	18.35	2
8×8	19.17	0.08	19.09	19.25	2
8×9	18.87	0.04	18.83	18.91	2
9×6	22.22	0.03	22.17	22.26	4
9×6P	21.76	0.03	21.72	21.79	4
9.5×4.5	27.58	0.05	27.53	27.63	2
9.5×6	26.36	0.0	26.36	26.36	2
10×3	26.62	0.01	26.61	26.63	2
10×4	29.44	0.13	29.32	29.68	8
10×4P	31.14	0.03	31.11	31.18	4
10×5	28.6	0.04	28.57	28.64	2
10×6	30.8	0.13	30.68	30.99	6
10×6P	30.76	0.02	30.73	30.78	4
10×7	31.01	0.18	30.74	31.31	7
10×7P	30.77	0.0	30.77	30.78	4
10×8	29.64	0.27	29.42	30.04	6
10×8P	30.74	0.02	30.72	30.76	4
10×9	32.01	0.06	31.95	32.08	4
10×10	35.58	0.27	35.3	35.94	4
10.5×6	34.4	0.01	34.39	34.41	2
11×3	41.17	0.07	41.1	41.24	2
11×5	40.05	0.02	40.03	40.07	2
11×6	42.36	0.0	42.36	42.37	2
11×7	41.36	0.03	41.33	41.38	2
11×8	42.47	0.0	42.47	42.48	2
12×4	41.48	0.02	41.46	41.49	2
12×5	41.77	0.0	41.77	41.77	2
12×6	47.45	0.03	47.42	47.48	2
12×7	44.17	0.05	44.12	44.22	2
12×9	44.36	0.05	44.31	44.41	2
12×10	46.34	0.02	46.33	46.36	2
12×10W	50.05	0.02	50.03	50.07	2
12×11	44.96	0.01	44.95	44.98	2
12×11N	44.94	0.05	44.89	44.99	2
12×12	50.88	0.02	50.86	50.89	2
12.25×3.75	42.08	0.33	41.83	42.55	3
12.5×6	53.44	0.02	53.42	53.46	2
12.5×10	51.2	0.03	51.17	51.23	2
14×13	69.14	0.0	69.14	69.14	2

Table 10: Graupner CAM Prop

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
9×4	13.58	0.01	13.57	13.6	2
9×6	15.82	0.0	15.82	15.82	2
10×4	17.45	0.0	17.45	17.45	2
10×6	19.28	0.0	19.28	19.29	2
10×8	20.22	0.01	20.21	20.23	2
11×6	25.07	0.04	25.03	25.11	2
11×8	25.43	0.43	25.0	25.86	2

Table 11: Graupner CAM Slim

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
9×5	14.79	0.01	14.78	14.8	2
10×6	11.95	0.0	11.95	11.95	2
10×8	11.93	0.0	11.93	11.94	2

Table 12: Graupner C-Prop

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
5×3	2.59	0.0	2.59	2.59	4
5×3P	2.52	0.0	2.51	2.52	4
9×4	9.29	0.04	9.23	9.34	4
9×4P	8.45	0.02	8.43	8.49	4
10×4	9.3	0.03	9.25	9.34	4
10×4P	9.88	0.06	9.82	9.99	4

Table 13: Graupner Sport

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
8×4.5	10.0	0.0	10.0	10.01	2
8×4.5P	9.63	0.02	9.61	9.65	2

Table 14: Graupner Super Nylon

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
9×4	25.42	0.04	25.39	25.46	2
9×5	25.20	0.02	25.18	25.21	2
9×6	25.90	0.04	25.86	25.93	2
9×7	25.84	0.01	25.83	25.84	2
10×4	27.78	0.01	27.77	27.78	2
10×6	27.24	0.11	27.13	27.35	2
10×7	25.94	0.01	25.93	25.94	2
11×6	37.51	0.04	37.47	37.55	2
11×7	37.84	0.06	37.78	37.9	2
11×8	38.68	0.09	38.59	38.77	2

Table 15: Kavan FK

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
9×4	16.76	0.46	16.30	17.22	2
10×4	19.91	0.03	19.88	19.93	2
10×5	20.80	0.01	20.79	20.81	2
11×6	24.01	0.10	23.91	24.11	2
11×7.75	23.00	0.10	22.9	23.09	2

Table 16: Kyosho

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
9×6	21.45	0.32	21.13	21.77	2
10×6	26.81	0.0	26.80	26.81	2
10×7	27.96	0.0	27.96	27.96	2
11×9	39.13	0.17	38.95	39.30	2

Table 17: Master Airscrew 3 Blade

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
7×4-3	10.41	0.01	10.4	10.43	4
7×4-3P	10.31	0.01	10.3	10.32	4
8×6-3	13.98	0.01	13.97	13.99	4
8×6-3P	13.55	0.01	13.54	13.57	4
9×7-3	20.24	0.01	20.21	20.25	4
9×7-3P	19.54	0.0	19.53	19.54	4
10×5-3	27.13	0.01	27.11	27.14	4
10×5-3P	27.22	0.03	27.18	27.25	4
10×7-3	28.42	0.02	28.4	28.45	4
10×7-3P	28.82	0.01	28.81	28.84	4

Table 18: Master Airscrew BN FPV Bullnose

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
5×4.5BN	4.31	0.01	4.3	4.32	4
5×4.5BNP	4.33	0.01	4.31	4.34	4

Table 19: Master Airscrew Electric

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
8×4E	10.78	0.04	10.75	10.85	4
8×4EP	10.8	0.03	10.75	10.81	4
8.5×6E	13.88	0.01	13.87	13.89	4
8.5×6EP	13.7	0.03	13.66	13.75	4
9×4E	12.13	0.09	11.99	12.22	4
9×4EP	12.01	0.01	12.0	12.02	4
9×6E	13.26	0.4	12.93	13.85	6
9×6EP	12.58	0.03	12.55	12.62	4
10×7E	17.27	0.78	16.71	18.45	6
10×7EP	16.05	0.04	16.0	16.11	4
10×8E	16.58	0.0	16.58	16.58	2
11×7E	21.36	0.06	21.3	21.43	2
12×8E	27.34	0.99	26.35	28.34	2
13×8.5E	34.25	0.1	34.15	34.35	2

Table 20: Master Airscrew GF

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
7×3GF	7.34	0.0	7.34	7.35	2
7×4GF	7.86	0.09	7.77	7.94	2
8×4GF	11.26	0.16	11.11	11.42	2
9×4GF	15.74	0.13	15.6	15.87	2
9×5GF	15.85	0.1	15.75	15.95	2
9×7GF	17.08	0.3	16.77	17.38	2
10×4GF	21.0	0.29	20.71	21.29	2
10×6GF	22.52	0.19	22.16	22.71	6
10×6GFP	22.7	0.01	22.69	22.72	4
10×7GF	21.77	0.36	21.05	22.0	5
11×4GF	27.12	0.07	27.05	27.19	2
11×5GF	29.76	0.38	29.38	30.13	2
11×8GF	28.4	0.05	28.34	28.45	2

Table 21: Master Airscrew MR

Model	**Mean Mass (g)**	**Standard Deviation (g)**	**Min Mass (g)**	**Max Mass (g)**	**N**
8×4.5MR	7.56	0.01	7.54	7.58	5
8×4.5MRP	7.62	0.03	7.58	7.66	5
9×4.5MR	9.59	0.04	9.55	9.67	6
9×4.5MRP	9.66	0.09	9.58	9.84	6
9.4×5MR-DJI-PH	12.06	0.7	11.02	12.61	6
9.4×5MRP-DJI-PH	11.94	0.58	11.07	12.35	6
10×4.5MR	12.36	0.04	12.28	12.38	5
10×4.5MRP	12.48	0.1	12.41	12.68	5
10×4.5MRP-Solo	13.42	0.46	12.77	13.76	6
10×4.5MR-Solo	13.17	0.59	12.33	13.6	6

Table 22: Master Airscrew Scimitar

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
8×4S	10.84	0.13	10.63	10.98	4
9×7S	16.89	0.04	16.85	16.92	2
10×5S	22.29	0.03	22.26	22.32	2
10×6S	23.32	0.09	23.24	23.41	2
10×7S	24.46	0.15	24.31	24.6	2
11×6S	27.2	0.54	26.65	27.74	2
11×7S	28.94	0.04	28.9	28.98	2
11×8S	31.06	0.25	30.81	31.3	2

Table 23: Zingali

Model	Mean Mass (g)	Standard Deviation (g)	Min Mass (g)	Max Mass (g)	N
10×6	27.62	0.01	27.61	27.62	2
11×7	36.33	0.0	36.32	36.33	2

IV. Empirical Models

Using the measured and listed mass values, mass models for 28 propeller series were created. From the square-cube law, the volume, and therefore the mass, of a perfectly scaled propeller will be proportional to the cube of the diameter. However, propellers are not usually perfectly scaled. The hub size does not need to scale in the same proportions of the rest of the propeller, and structural concerns may change the overall chord size of the propeller blade. For the off-the-shelf propellers used in this paper, the blade shape (i.e., the chord distribution), does not vary greatly for propellers within a propeller series, so while the propellers in a series are not perfectly scaled, the models developed for these propellers were still based on the cube of the diameter. As seen with the results of the models, the cubed scaling works well. It should be noted that the diameter used for developing the models is the value given in the propeller name. For example, if the propeller is given as 9×6, then a diameter of 9 in. was used. It is known that the actual diameter might not be what is listed, though most will be within 0.1 in. (reference the University of Illinois at Urbana-Champaign (UIUC) Propeller Database for examples[11]).

Tables 24 and 25 provide the 28 models developed. In the tables, the series name, the coefficients of the model (*m* and *b*), the number of propellers used to develop the model (N), the minimum diameter, the maximum diameter, the average error between the model and actual mass, and the maximum error are provided. Next to the series name will either be an (L) meaning that manufacturer's listed values were used or an (M) meaning that measured values were used to create the model. An asterisk with the series name means that some propellers were not used for the model within that series and will be explained with that respective model.

To create a model, the mass of all the propellers within a series was plotted against the cube of the diameter. A linear regression was then performed to find the slope (*m*) and intercept (*b*). An example of the mass points plotted against the cube of the diameter and the corresponding linear fit is shown in Fig. 25. Mass models were only created for series where the mass of at least three different propeller diameters were known. For most series, the pusher version of the propellers were not included in the points to create the model in order to not double a given point. For series that include variations to the standard blade shape, such as narrow or wide blades, these also were not included. Any additional considerations about the mass points used to create the models are discussed with their respective models.

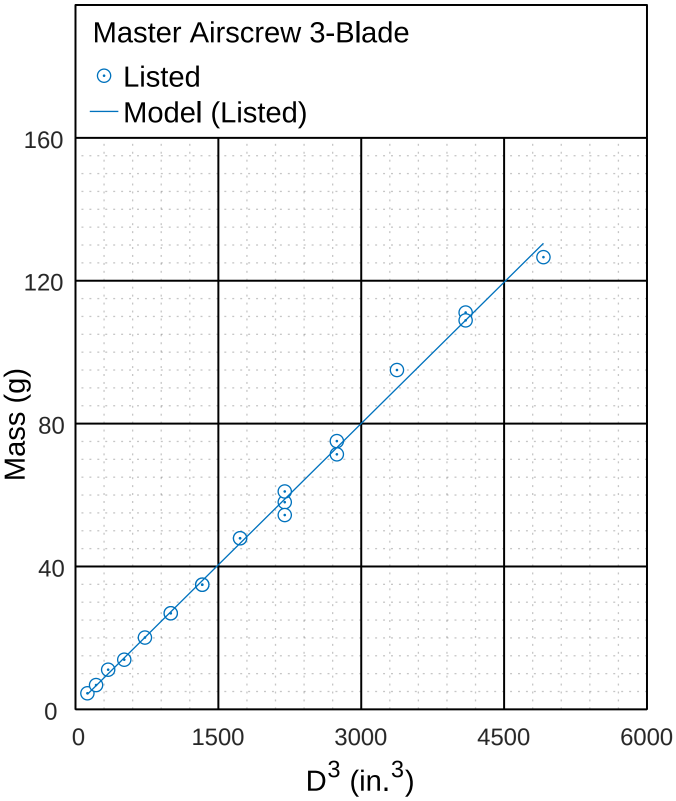

Figure 25: Master Airscrew 3-Blade model. Mass plotted against the cube of the diameter and corresponding linear fit.

Figure 26: Propeller examples for the Aeronaut propellers: CAM Carbon Folding, CAM Carbon Light, and CAM Carbon Power. Pictures are from the Aeronaut website.[19]

As mentioned earlier, propeller series generally have the same blade shape for the propeller within the series. Figures 26–33 show pictures of example propellers within each series. As seen in the pictures, the blade shape can vary greatly. The relative size of the propeller blades is an important factor in the mass of the propeller. Also important is the material used and the airfoil.

Figures 34, 35, and 36 show the mass points and models for the Aeronaut CAM Folding, CAM Light, and CAM Power, respectively. For these three propellers, measured values were used. For the folding propeller, the model is for a single blade and does not include any hub hardware. With the folding propeller, many different pitch values were

Table 24: List of Mass Models: 1 of 2

Series	mD^3+b		**N**	**Min D**	**Max D**	**Average % Error**	**Max % Error**
	m	b					
Aeronaut CAM Carbon Folding (M)	0.002309	2.467	39	10	15	6.35	27.2
Aeronaut CAM Carbon Light (M)	0.009583	1.215	16	10	14	3.72	8.65
Aeronaut CAM Carbon Power* (M)	0.01392	4.431	19	10	18	4.07 (6.92)	9.04 (61.0)
APC 3 Blade Electric (L)	0.02197	2.855	8	4	12	18.6	46.6
APC 4 Blade (L)	0.03150	2.460	5	9	15.5	4.89	11.0
APC Electric (L)	0.01186	4.606	103	4	27	18.6	95.2
APC Electric* (M)	0.01268	3.291	36	5	21	11.4	45.1
APC Electric Old (M)	0.008905	7.958	27	6	19	12.1	121
APC Electric Low (L)	0.01958	1.870	44	4	10	13.7	38.4
APC Electric Low (M)	0.01886	2.106	12	5	10	15.9	40.8
APC Electric Old Low (M)	0.02434	-0.6264	9	6	9	3.83	8.91
APC Electric High (L)	0.01186	4.606	59	11	27	4.18	20.5
APC Electric High (M)	0.01268	3.291	24	11	21	4.97	10.7
APC Electric Old High (M)	0.008790	8.201	18	10	19	4.87	11.1
APC MR (L)	0.009559	4.479	14	8	18	3.57	6.57
APC MR (M)	0.009260	4.591	18	8	14	3.17	6.91
APC SLow Flyer (L)	0.008790	2.792	21	7	14	4.78	13.8
APC Slow Flyer (M)	0.009127	2.018	15	7	12	3.68	8.13
APC Slow Flyer Indoor 3D (L)	0.007149	0.8990	11	5	12	12.5	21.7
APC Sport (L)	0.02394	5.156	161	4.2	22	17.9	122
APC Sport (M)	0.02378	5.950	53	7	18	7.98	33.3
Graupner CAM Prop (M)	0.01601	3.009	8	9	11	5.89	8.97
Graupner C-Prop (M)	0.008445	1.786	6	5	10	9.44	14.5
Graupner Super Nylon (M)	0.02414	6.507	11	9	11	7.64	18.1
Kavan FK (M)	0.01010	10.12	6	9	11	2.70	4.31
Kyosho (M)	0.02783	0.3162	5	9	11	3.42	5.02

Table 25: List Mass Models: 2 of 2

Model	mD^3+b		**N**	**Min D**	**Max D**	**Average % Error**	**Max % Error**
	m	b					
Master Airscrew 3-Blade (L)	0.02637	0.9209	21	5	17	3.34	10.2
Master Airscrew 3-Blade (M)	0.02695	0.7129	5	7	10	2.68	4.32
Master Airscrew 3MR (L)	0.01957	0.2534	8	6	13	1.69	6.65
Master Airscrew 3X (L)	0.02222	3.912	7	9	15	2.51	6.95
Master Airscrew Classic (L)	0.02208	15.3	11	12.5	20	8.35	31.6
Master Airscrew Electric* (L)	0.01374	3.136	21	6	14	4.60 (5.80)	19.7 (29.7)
Master Airscrew Electric (M)	0.01381	3.447	9	8	13	4.19	14.1
Master Airscrew Formula One (L)	0.01661	2.361	5	9	13.5	1.92	2.39
Master Airscrew GF* (L)	0.02008	0.7279	34	5.5	11	3.75 (7.82)	10.7 (40.2)
Master Airscrew GF (M)	0.02108	0.6448	13	7	11	3.02	7.22
Master Airscrew K-Series (L)	0.02154	-2.303	18	12	16	2.76	3.53
Master Airscrew MR (L)	0.01103	1.931	6	8	13	1.76	2.82
Master Airscrew MR (M)	0.009856	2.470	3	8	10	0.495	0.725
Master Airscrew Scimitar (L)	0.02069	0.3904	36	6.5	16	2.83	10.7
Master Airscrew Scimitar (M)	0.02144	1.056	10	8	11	4.67	11.0
Master Airscrew Wood Beech* (L)	0.01624	-1.686	21	9	16	6.95 (10.5)	14.6 (34.5)
Master Airscrew Wood Maple (L)	0.007934	36.92	10	18	24	3.21	6.69
Zingali (M)	0.02704	0.4085	3	9	11	0.420	0.600

Figure 27: Propeller examples for the APC propellers: Sport, Electric, MR, Slow Flyer, Slow Flyer Indoor 3D.[17]

measured for the same diameter, which is the reason for the spread in mass values at some diameters and the larger maximum error shown in Table 24. For the Power propeller, the mass for the 19 in. propeller does not follow the trend of the other propellers and was not included in the creation of the model. In Table 24, the first average error and maximum error values do not include the 19 in. propeller; the values in the parentheses do.

The models for the APC 3 Blade Electric and 4 Blade are provided in Figs. 37 and 38, respectively. Both of these propellers used listed mass values from the manufacturer, and both had a small number of available points. The 4 Blade model fits well, but there is a large error with the 9 in. propeller for the 3 Blade Electric.

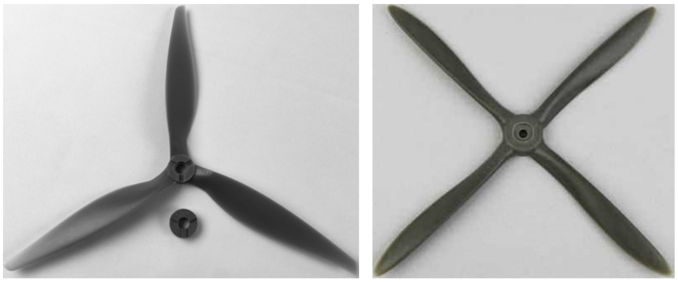

Figure 28: Propeller examples for the APC propellers: 3-bladed and 4-bladed. Pictures are from the APC website.[17]

Figure 29: Propeller examples for the Graupner propellers: CAM Prop,[11] C-Prop, and Super Nylon.

Figure 30: Propeller examples for the Master Airscrew propellers: Classic,[18] Electric, Formula One,[18] and GF.

Figure 31: Propeller examples for the Master Airscrew propellers: K-Series,[18] MR, Scimitar, and Wood.[18]

The APC Electric propellers are covered by 9 models as shown in Table 24. Models were created for the manufacturer's listed values, measured values of current propellers, and measured values of older propellers (see discussion in Section II). Models using the full range of propeller diameters are shown in Figs. 39 and 40. In both of

Figure 32: Propeller examples for the Master Airscrew propellers: 3MR,[18] 3X,[18] and 3-blade.

Figure 33: Propeller examples for the Kavan FK, Kyosho,[11] and Zingali.

these figures, the model from the listed values is shown with the model from the measured values (current propellers in Fig 39 and older propellers in Fig. 40). When developing the model from the listed values, it was noticed that for diameters less than 11 in., the propellers did not follow the same curve as the larger propellers. The model overpredicted the mass of the smaller propellers leading to the large maximum error. The diameters were then divided between those less than 11 in. (Low) and those 11 in. and greater (High). The models just from these diameters better predicted the masses within their respective diameter range.

For the measured values of the current propellers, including all the diameters also led to large errors for the smaller diameters. However, if the model just used the diameters from 11 in. and greater, this model actually predicted the masses at the smaller diameters better. The asterisk in Table 24 is because only diameters starting at 11 in. were used, and this is the reason why the model for the full diameter range is the same as that for the High. With the older propellers, the full model also overpredicted the mass of the smaller diameters, though the division between Low and High diameters was found at 10 in. instead of 11 in. The model results for the lower diameters are shown in Figs. 41 and 42. The model results for the higher diameters are shown in Figs. 43 and 44.

The models for the APC MR series are shown in Fig. 45. For this series, both the tractor and pusher configurations were included as there were an equal number of both. Figure 46 provides the listed and measured models for the APC Slow Flyer. For the Slow Flyer Indoor 3D series, this model is compared to the regular Slow Flyer in Fig. 47.

The final APC models are for the Sport series and are shown in Fig. 48. These series had the most listed values and the most measured values. For the listed values, only propellers listed as “Sport” on the APC website were used, though many also had additional categories such as pattern and free flight. This series also had a large diameter range from 4.2 in. to 22 in. With the larger diameters, there was a greater spread of mass values for a given diameter. The resulting model worked well for diameters starting at 7 in. and greater, with most errors less than 20%; however, the model overpredicted the mass for the smaller diameters leading to the maximum error shown in Table 24. Since there were only a few diameters that did not fit well to the model, a model of just the smaller diameters was not attempted. For the measured values, the resulting model was very similar to the listed model.

The Graupner CAM Prop, C-Prop, and Super Nylon models are shown in Figs. 49, 50, and 51, respectively. Since values for only three diameters were available for each series, the accuracy of the resulting models is limited. Similarly, only three diameters were available for the Kavan FK and Kyosho series, which are provided in Figs. 52 and 53, respectively.

The models for the Master Airscrew 3 bladed series are shown in Figs. 54, 55, and 56 for the 3 Blade, 3MR, and 3X, respectively. These models fit the mass value points very well with small errors. The same is not true for the Master Airscrew Classic series shown in Fig. 57. This series might benefit from measured values since all listed values for a diameter were the same even though the pitch changed greatly — 18×6 to 18×12 as an example.

Figure 58 provides the models for the Master Airscrew Electric series. For the listed values, the mass given for the 14 in. diameter is much larger than expected from the trend seen from the other diameters. The model provided does not use the 14-in. listed mass. The first set of errors provided in Table 24 does not include the 14 in. propeller while the values in the parentheses do. The Formula One model is shown in Fig. 59, and similar to the 3 blade series, the resulting model fits the listed values well.

For the Master GF series (Fig. 60), the listed mass values for 5.5 and 6 in. propellers did not fit the trend with the other diameters, so they were not included when forming the model. The first set of errors provided in Table 24 do not include these diameters while the values in the parentheses do. As seen with the measured values, the models diverge more as the diameter increases as the measured values were larger than the listed.

Similar to Classic series, the K-Series (Fig. 61) had multiple propellers at each diameter, and the listed mass value was the same for each diameter. The fit for this series was better than the Classic, but this series could also benefit from measured values to validate and improve. For the Master Airscrew MR series (Fig. 62), both the tractor and pusher configurations were included in the values for the model just like the APC MR series.

The final Master Airscrew models are for the Scimitar (Fig. 63) and the two Wood series. For the Beech series (Fig. 64), the values for the 16 in. propellers were not included in values used to create the model, but measured values could determine if this was correct. As with other series that did not use some diameters, the first set of errors provided in Table 24 do not include the 16 in. diameter while the values in the parentheses do. The Maple model is provided in Fig. 65. The final model is for the Zingali shown in Fig.66. Only three values were used for this model with a very good fit.

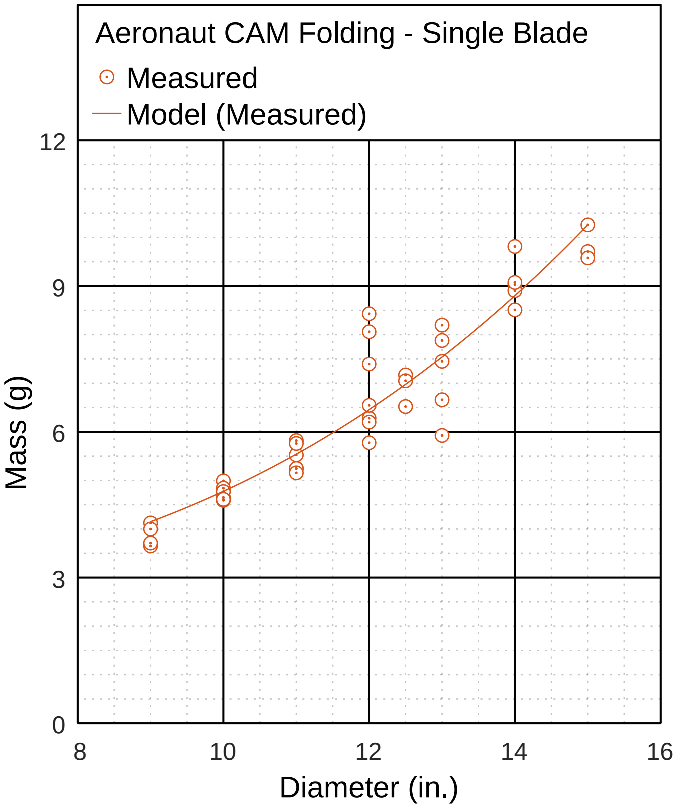

Figure 34: Aeronaut CAM Carbon Folding model.

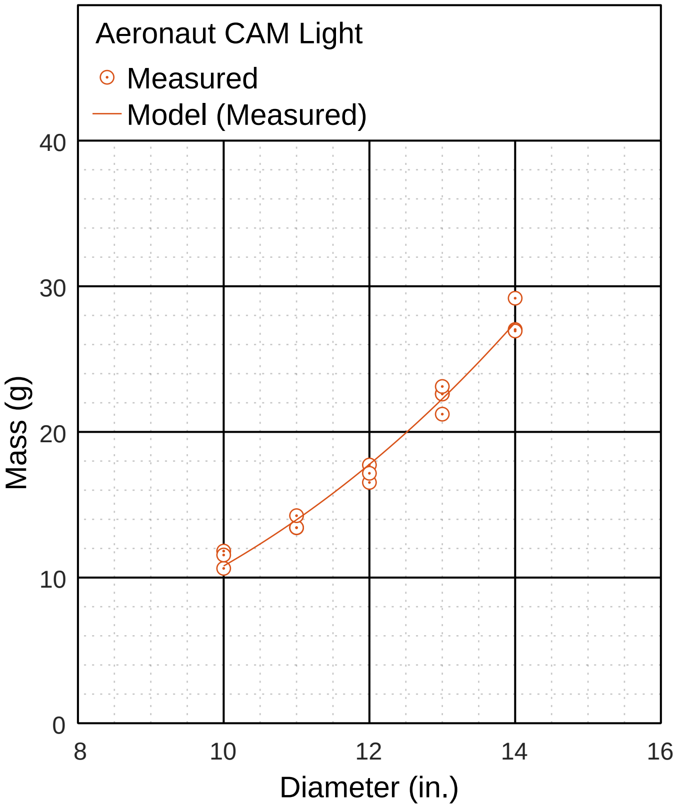

Figure 35: Aeronaut CAM Carbon Light model.

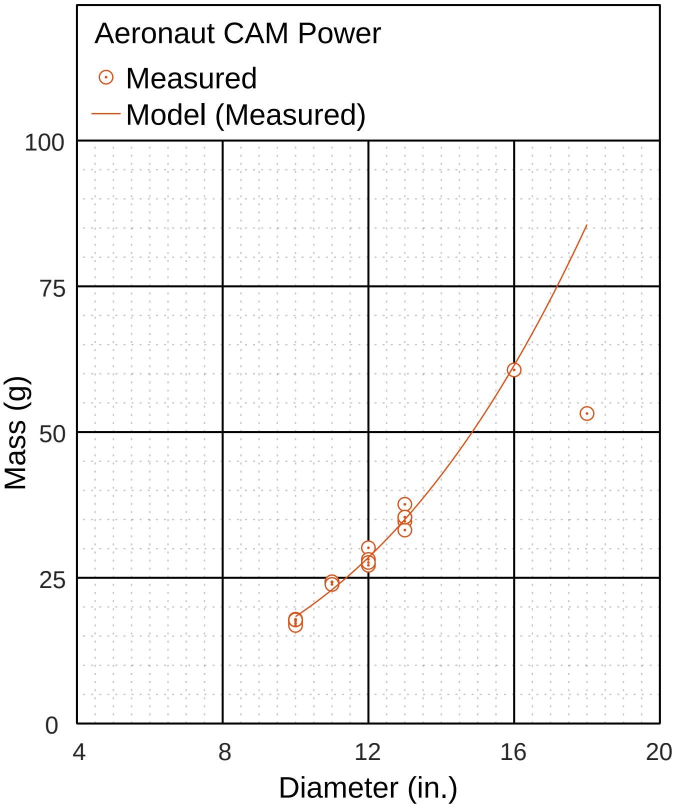

Figure 36: Aeronaut CAM Carbon Power model.

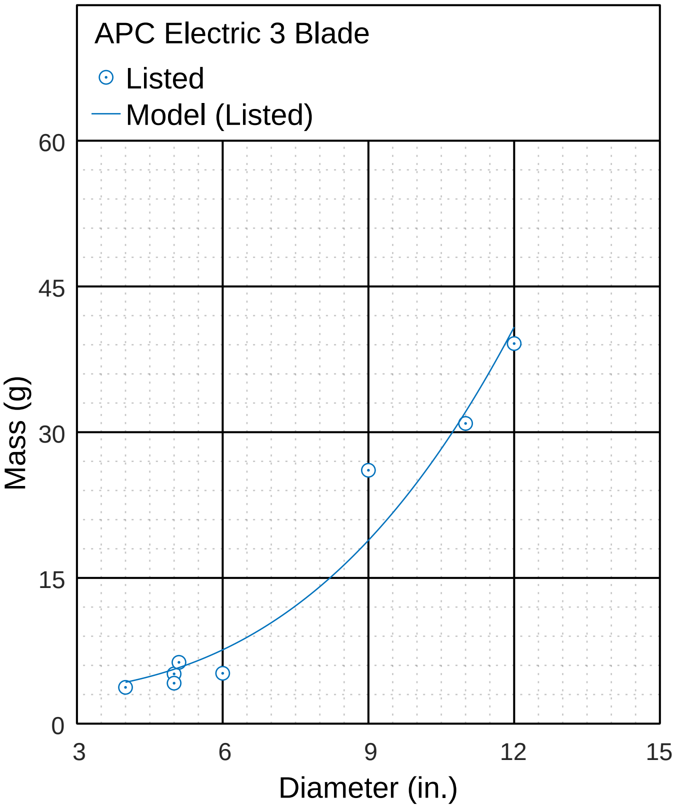

Figure 37: APC 3 Blade Electric model.

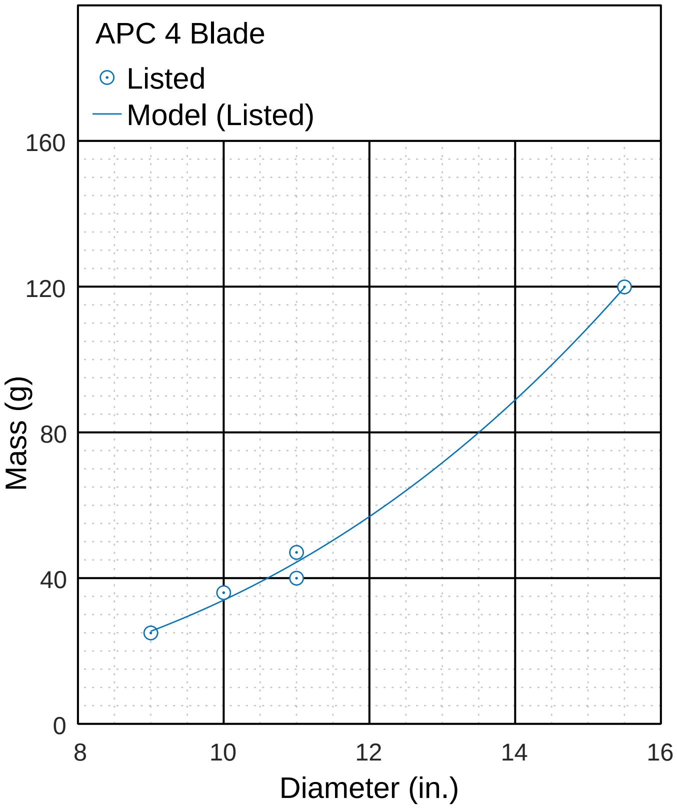

Figure 38: APC 4 Blade model.

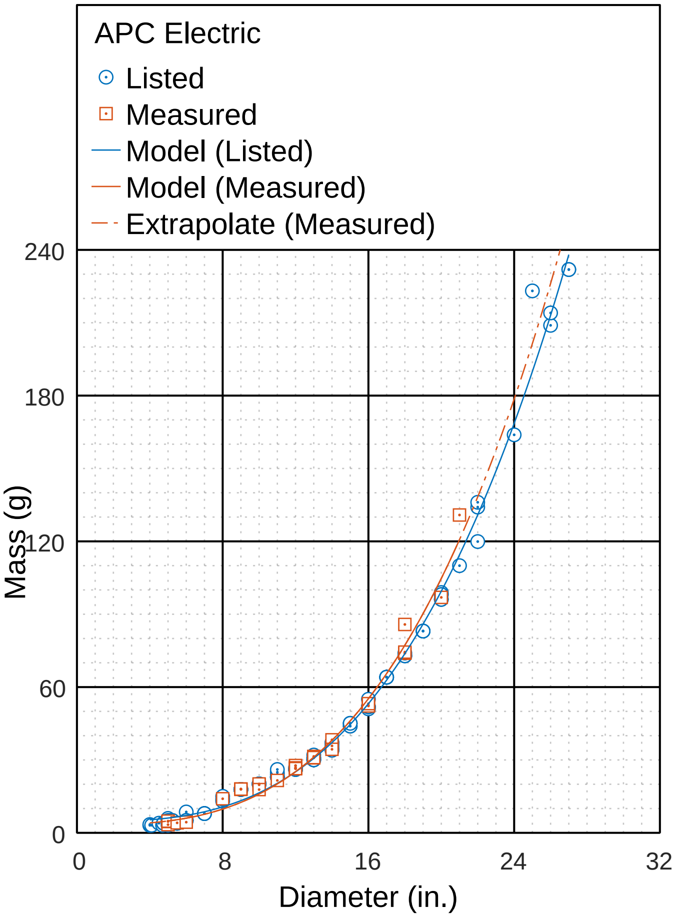

Figure 39: APC Electric model for all diameters.

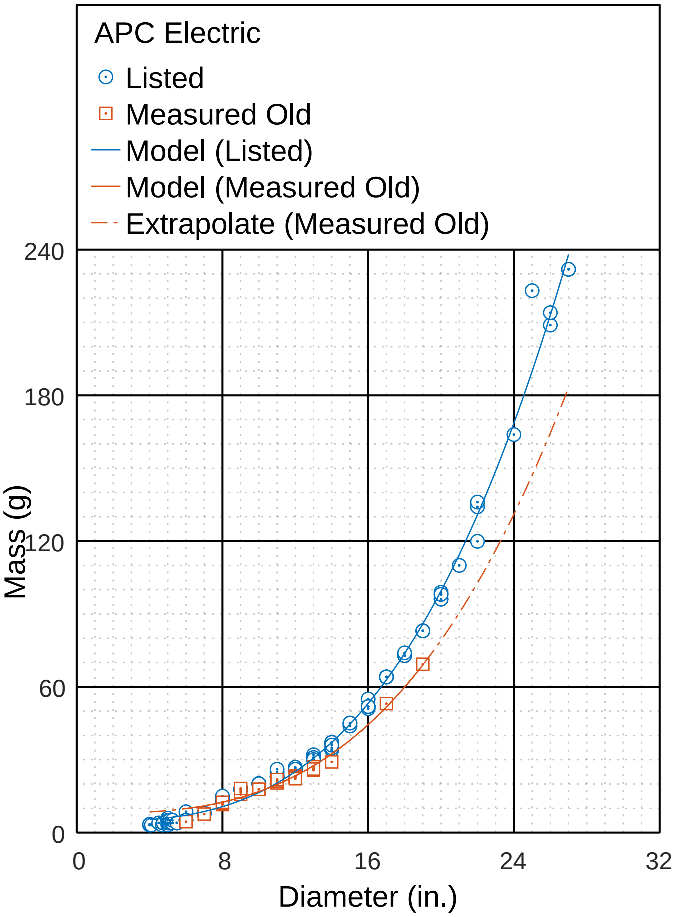

Figure 40: APC Electric model of older propellers for all diameters.

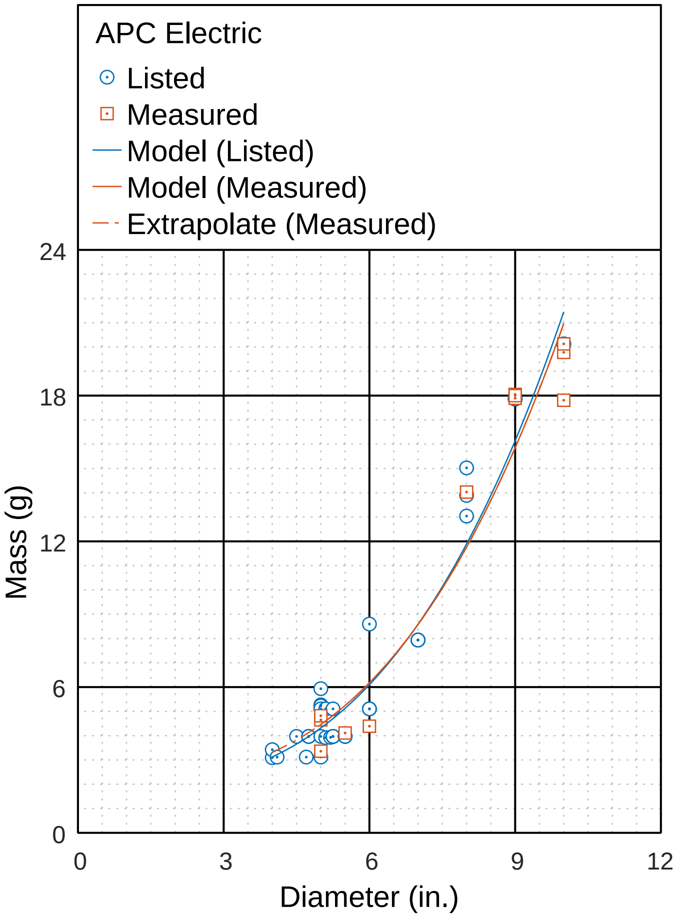

Figure 41: APC Electric model for diameters up to 10 in.

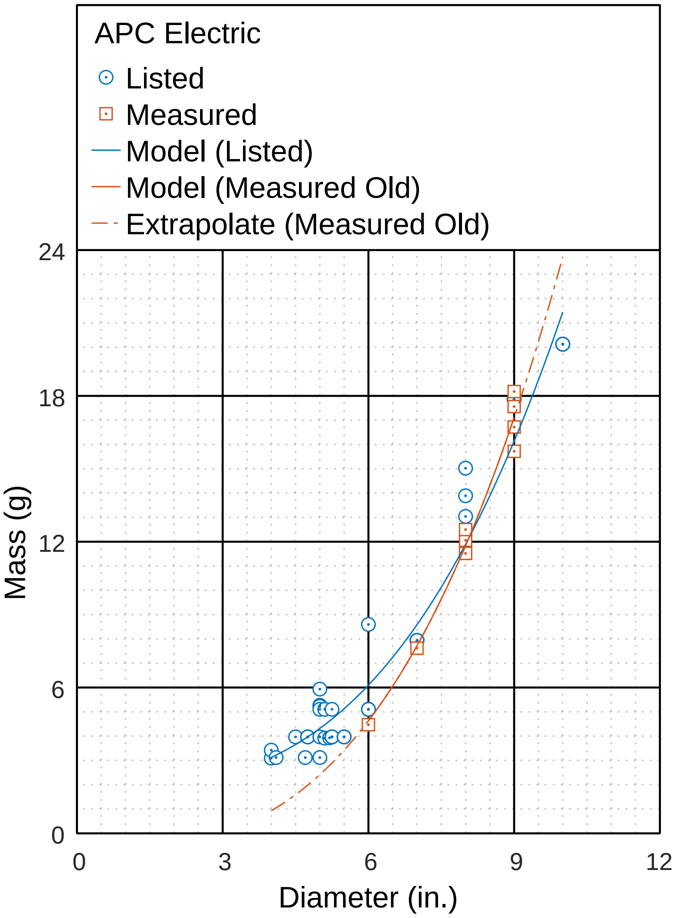

Figure 42: APC Electric model of older propellers for diameters up to 10 in. for the listed values and up to 9 in. for the older propellers.

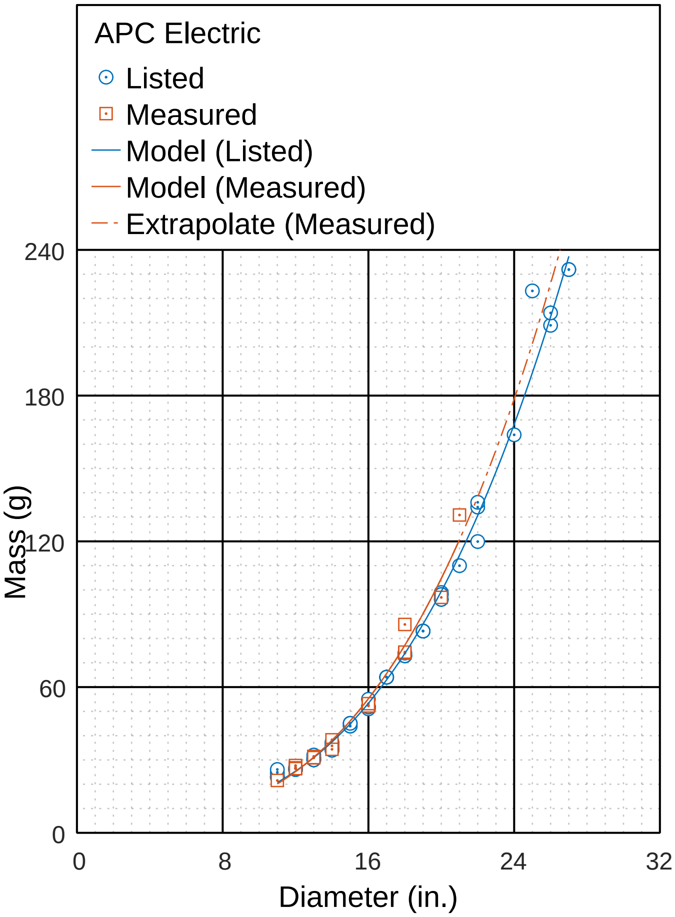

Figure 43: APC Electric model for diameters starting at 11 in.

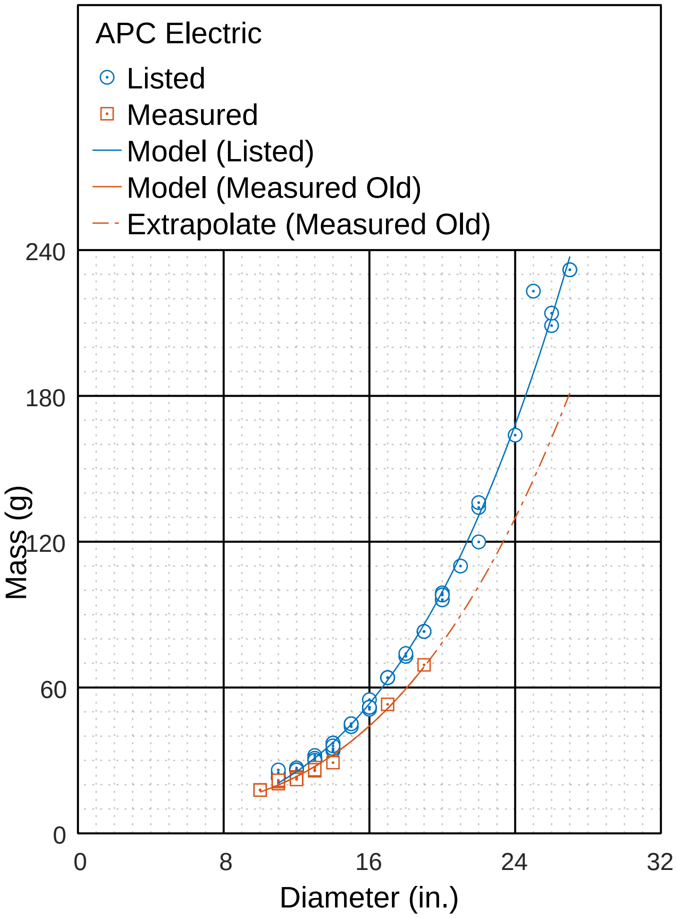

Figure 44: APC Electric model of older propellers for diameters starting at 11 in. for the listed values and starting at 10 in. for the older propellers.

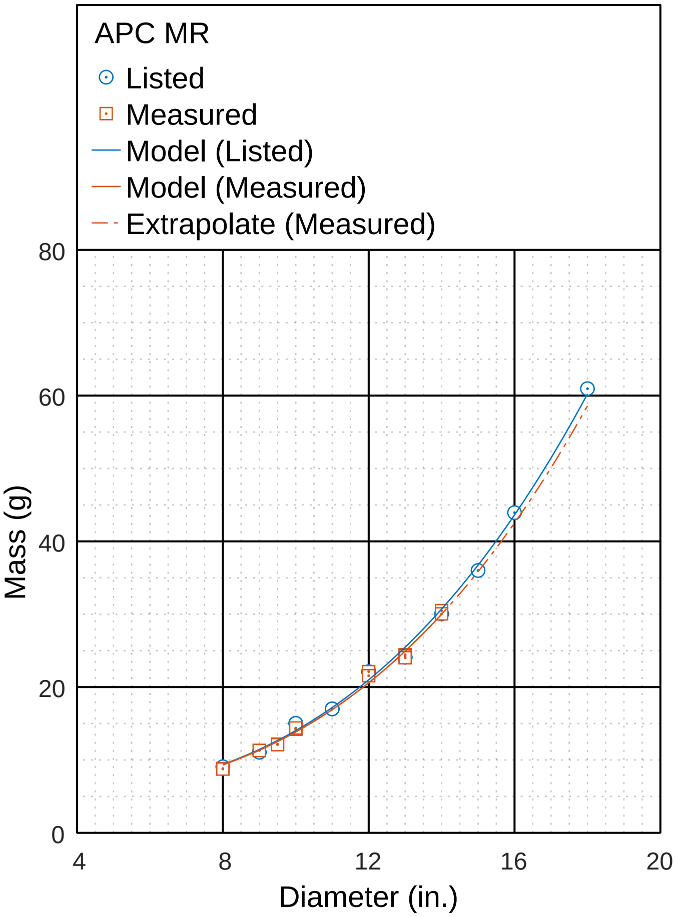

Figure 45: APC MR model.

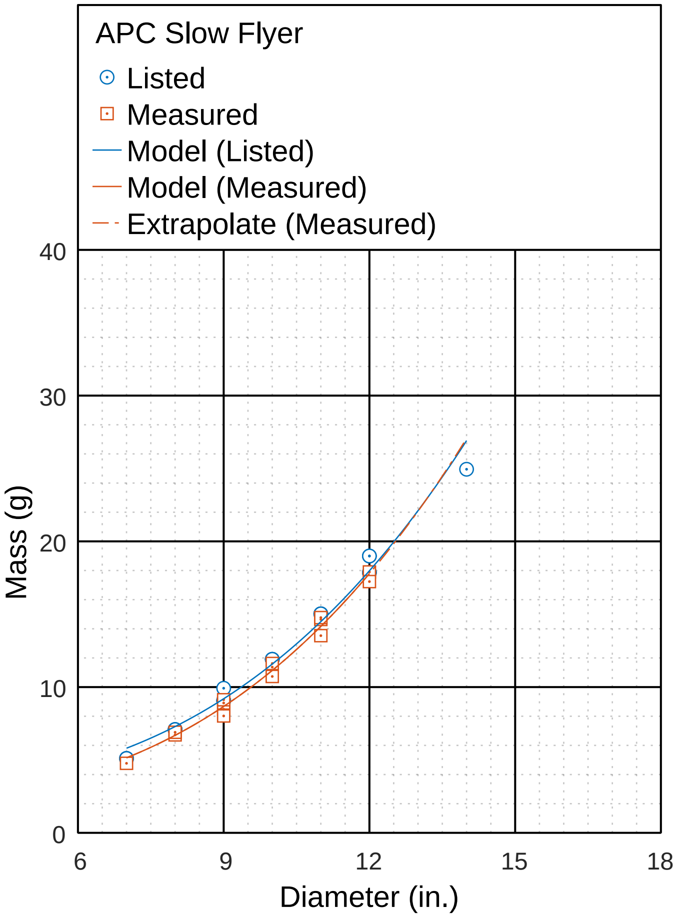

Figure 46: APC Slow Flyer model.

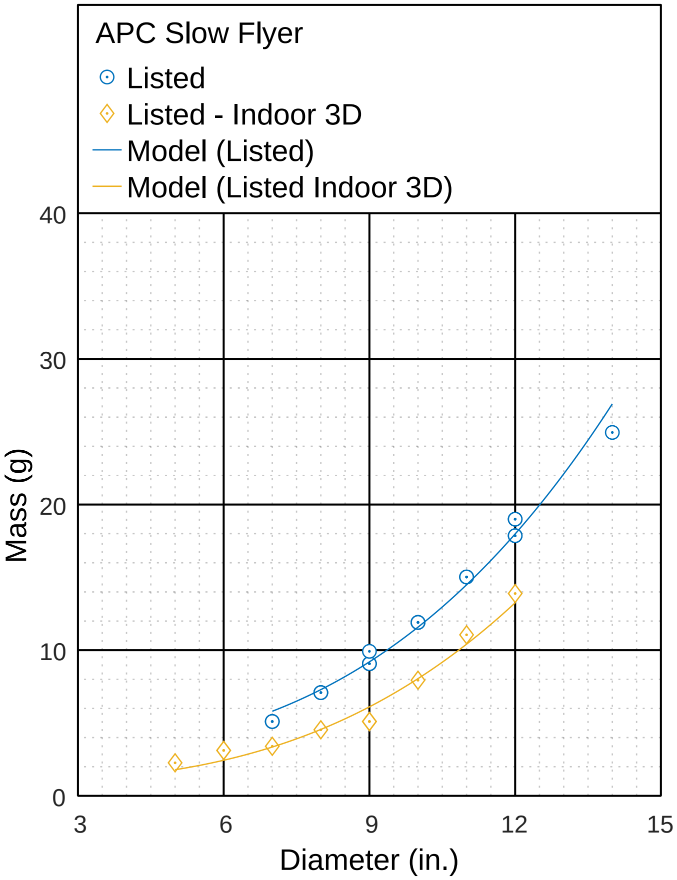

Figure 47: Comparison between APC Slow Flyer and Lighter Slow Flyer models.

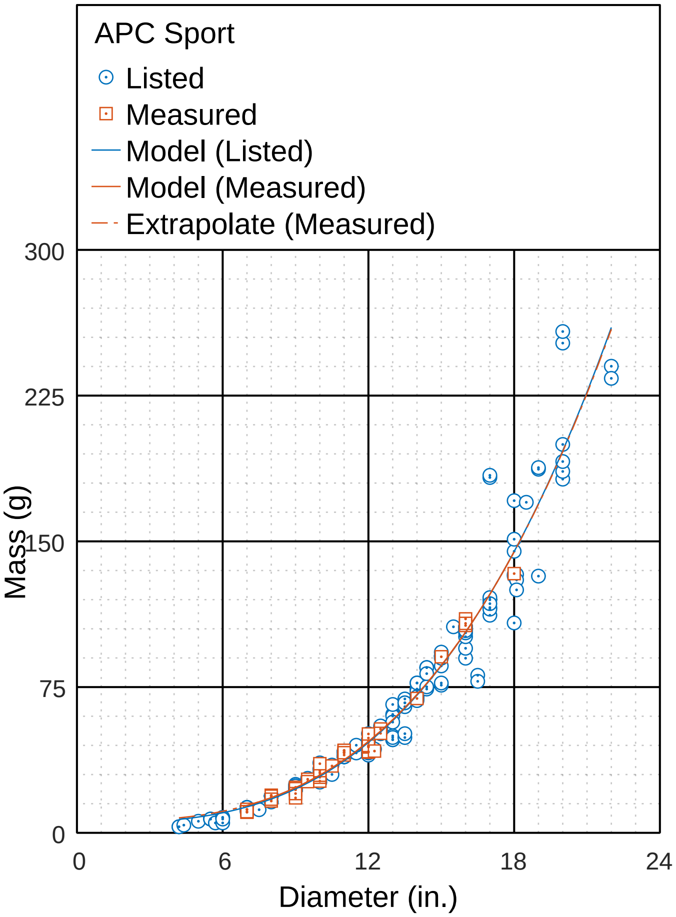

Figure 48: APC Sport model.

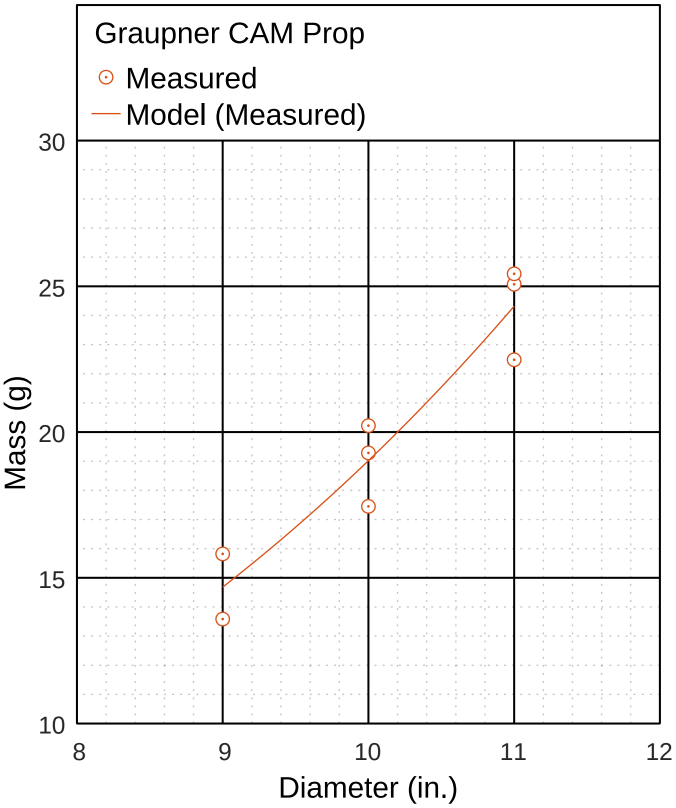

Figure 49: Graupner CAM Prop model.

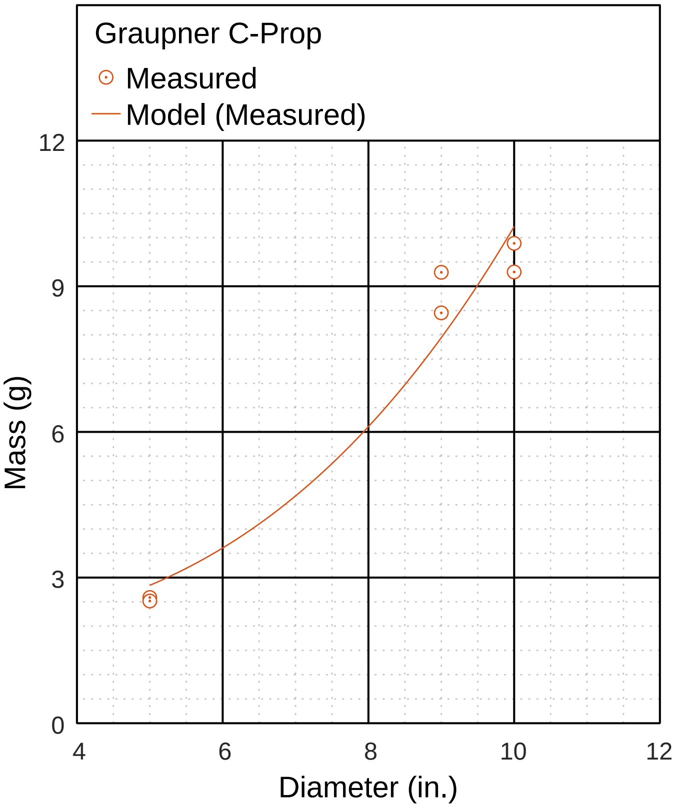

Figure 50: Graupner C-Prop model.

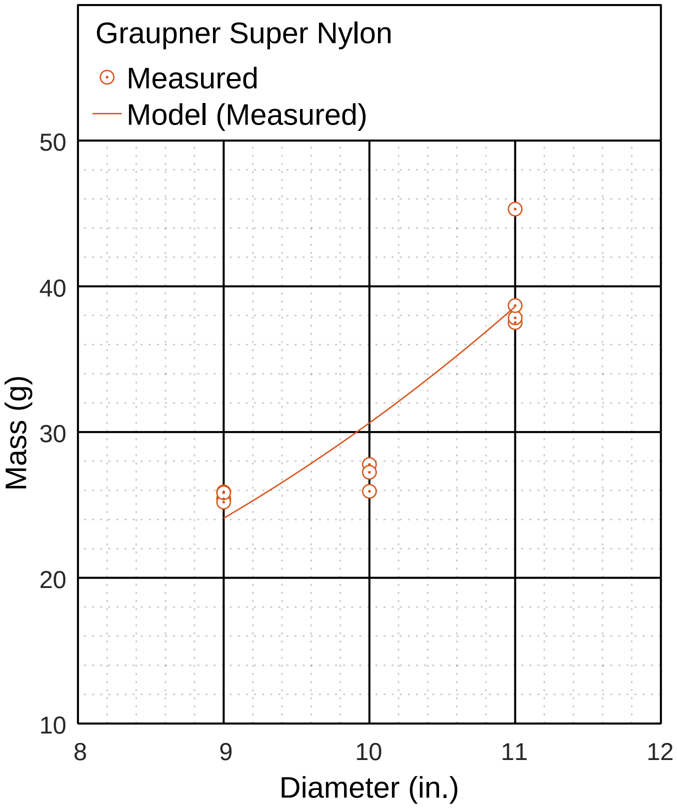

Figure 51: Graupner Super Nylon model.

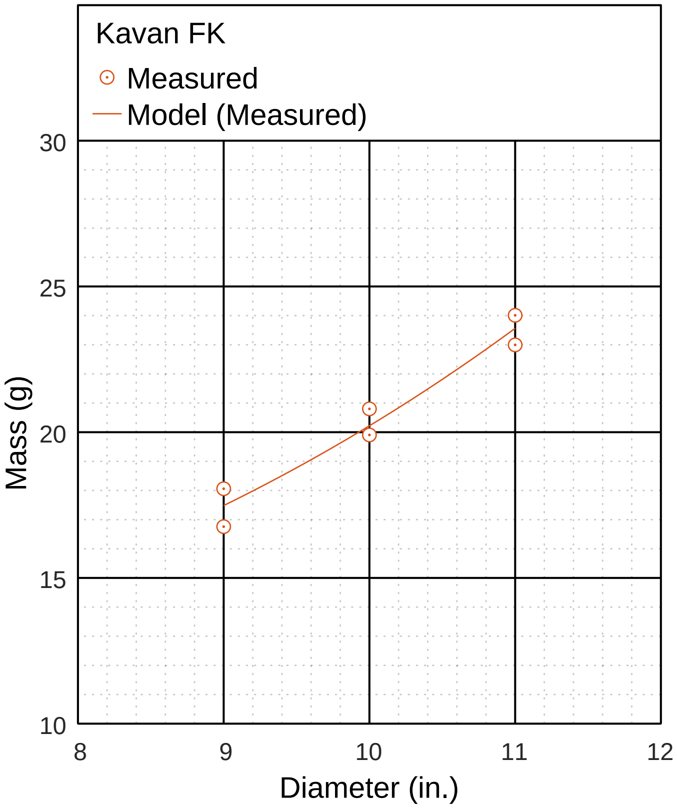

Figure 52: Kavan FK model.

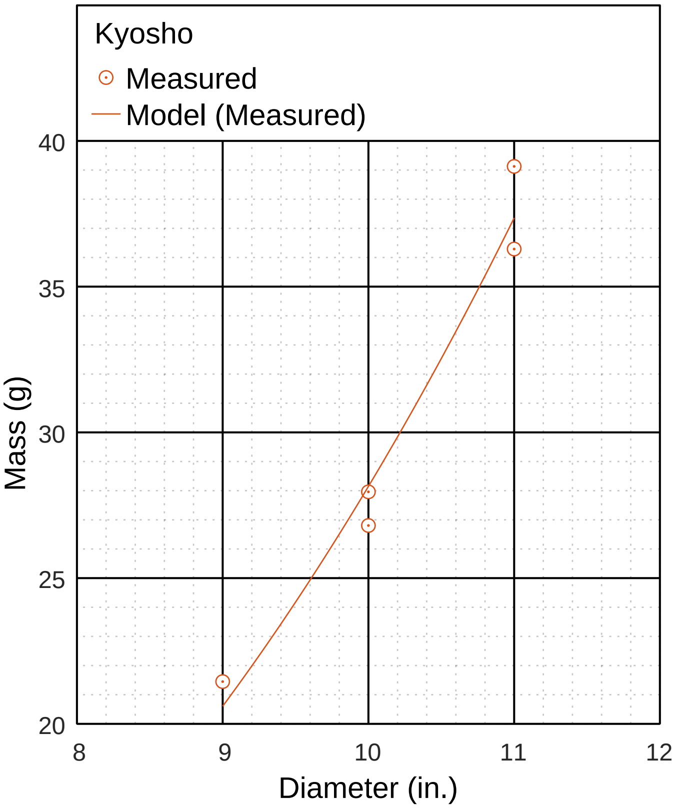

Figure 53: Kyosho model.

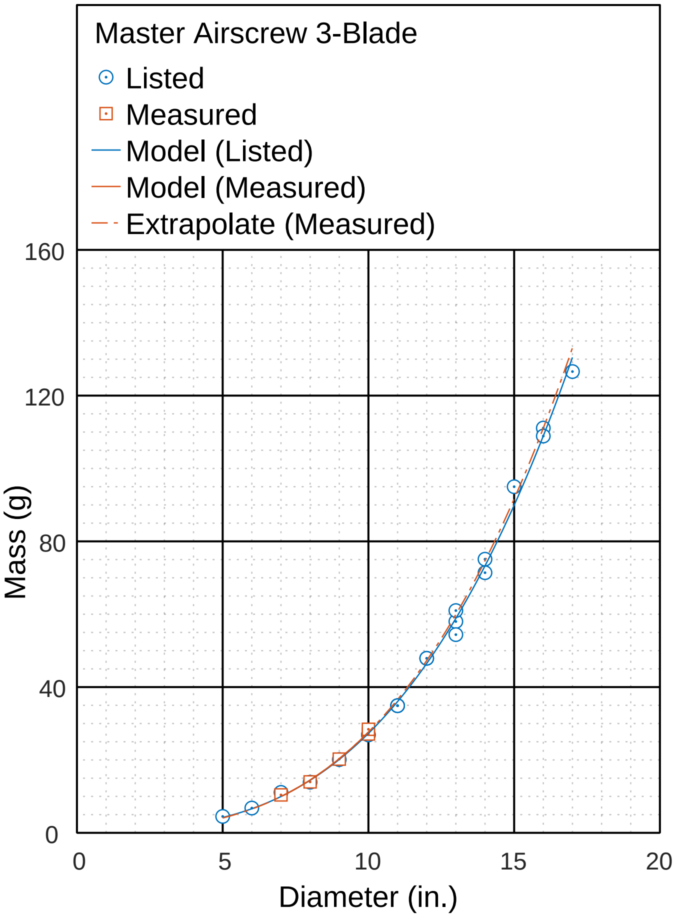

Figure 54: Master Airscrew 3-Blade model.

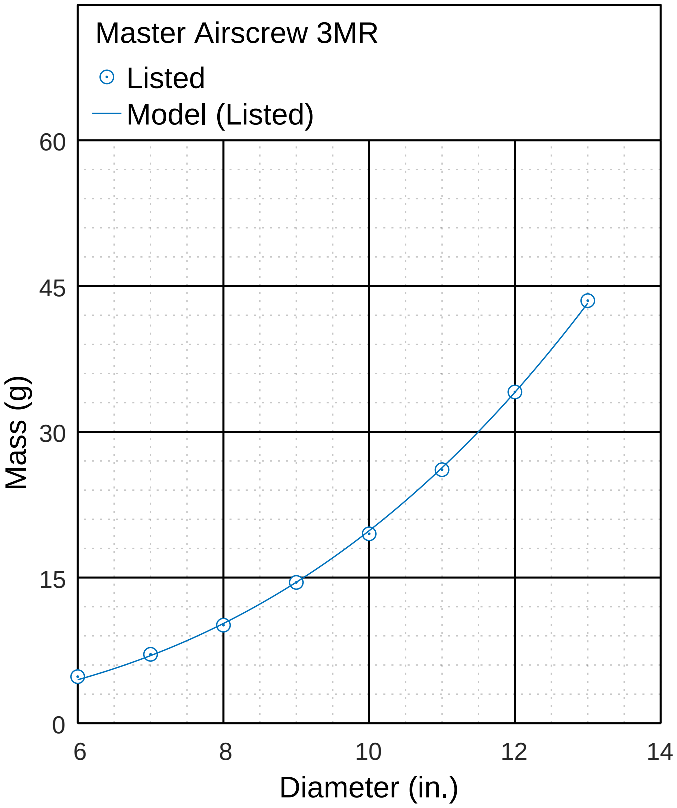

Figure 55: Master Airscrew 3MR model.

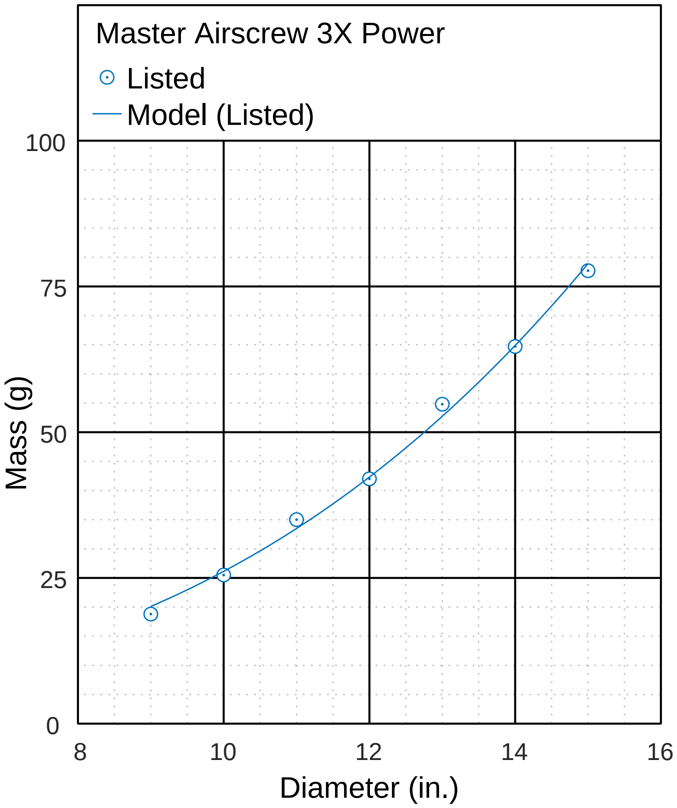

Figure 56: Master Airscrew 3X model.

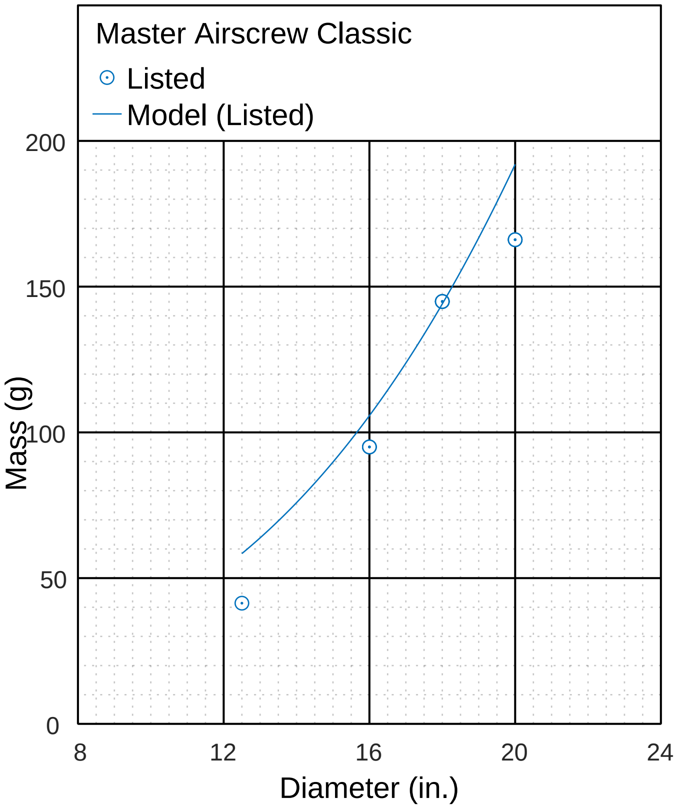

Figure 57: Master Airscrew Classic model.

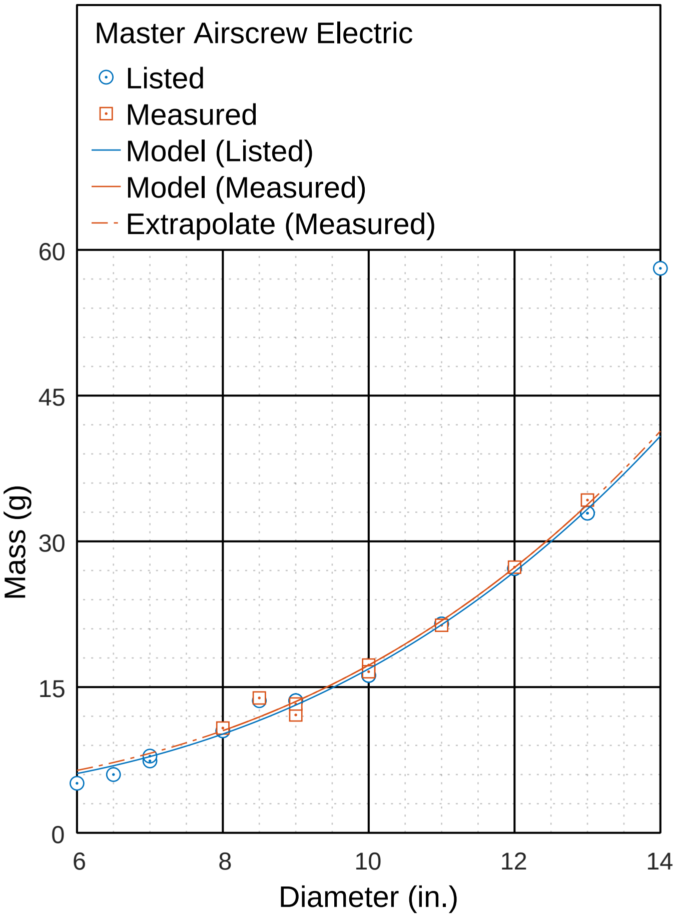

Figure 58: Master Airscrew Electric model.

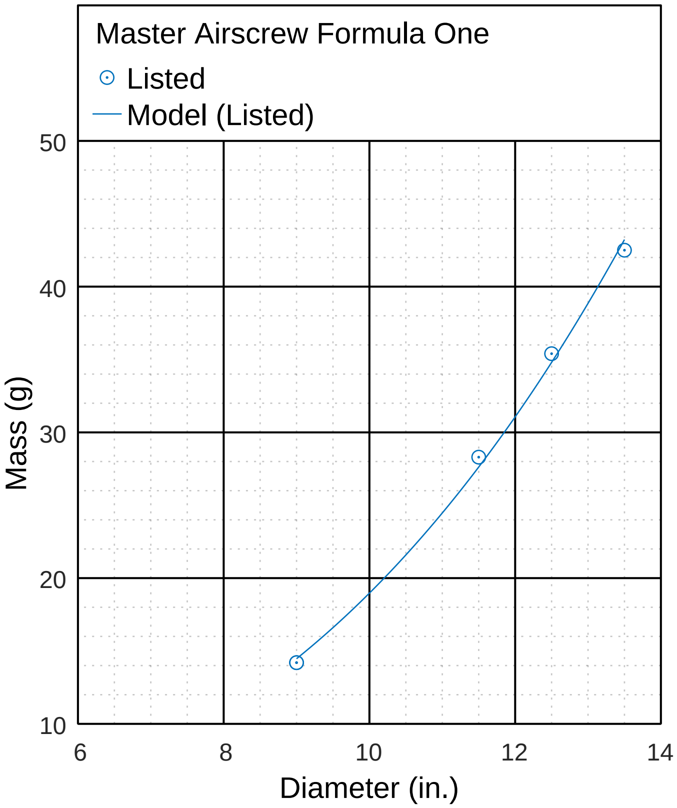

Figure 59: Master Airscrew Formula One model.

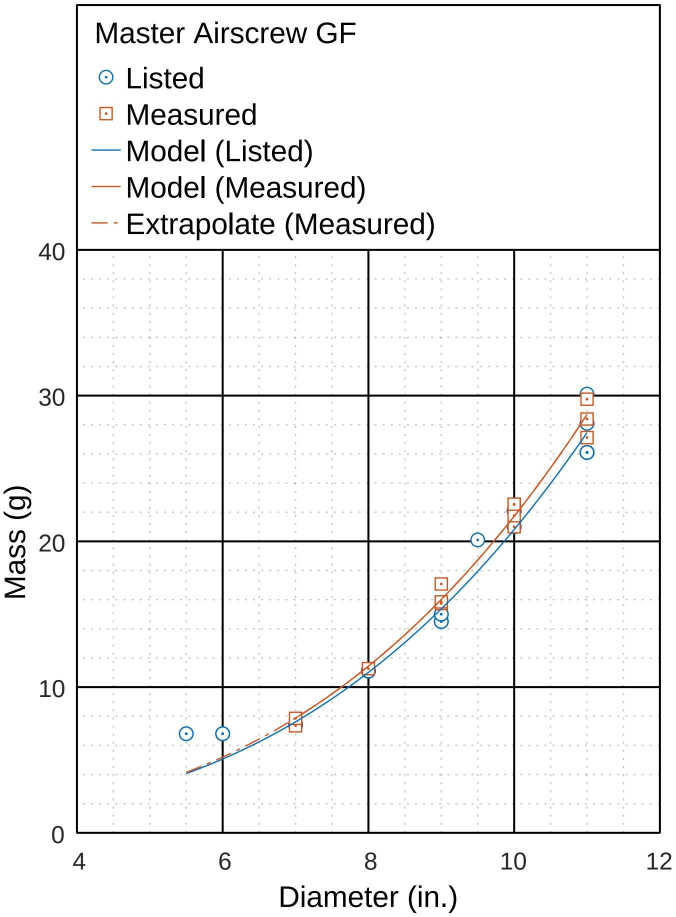

Figure 60: Master Airscrew GF model.

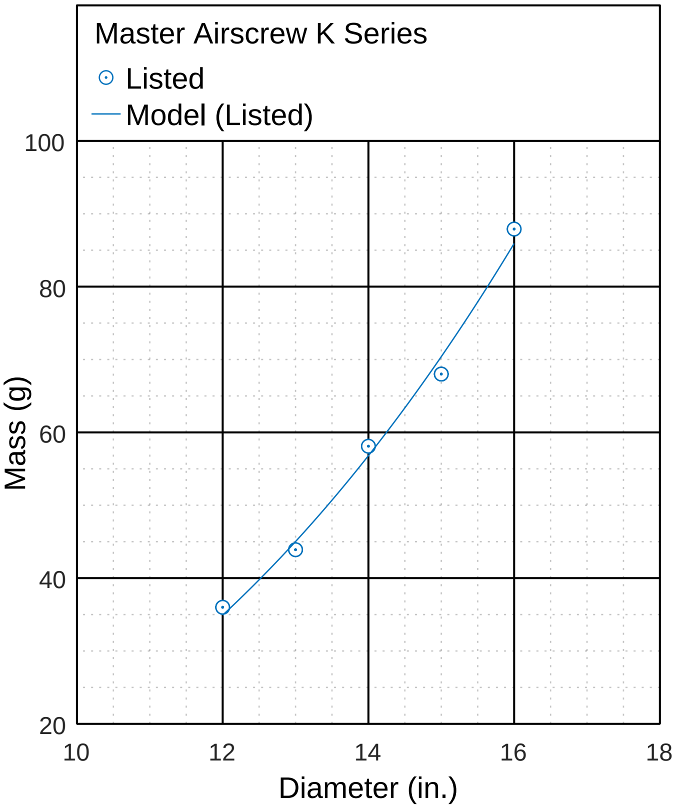

Figure 61: Master Airscrew K-Series model.

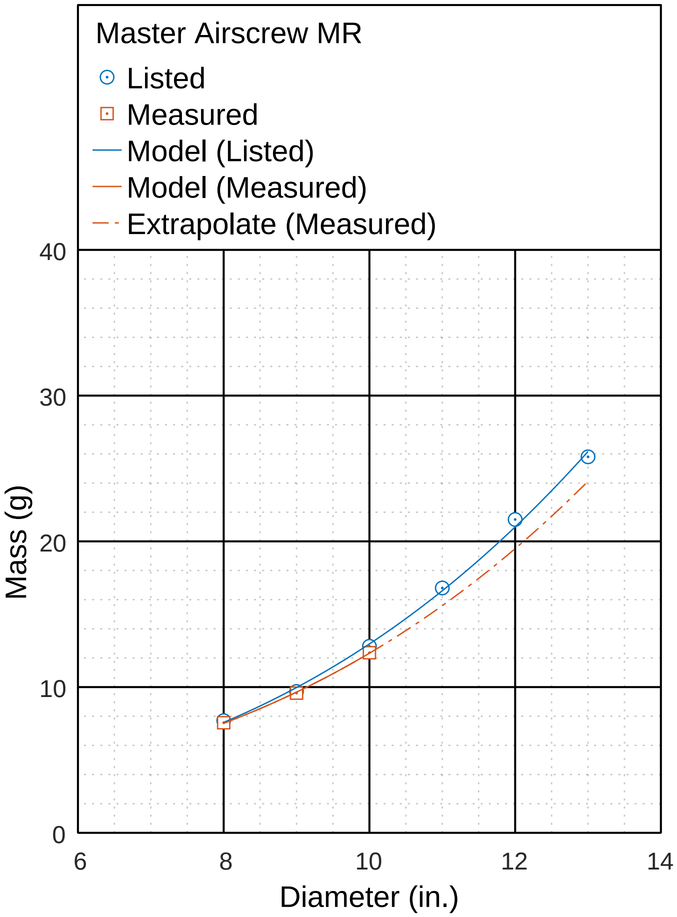

Figure 62: Master Airscrew MR model.

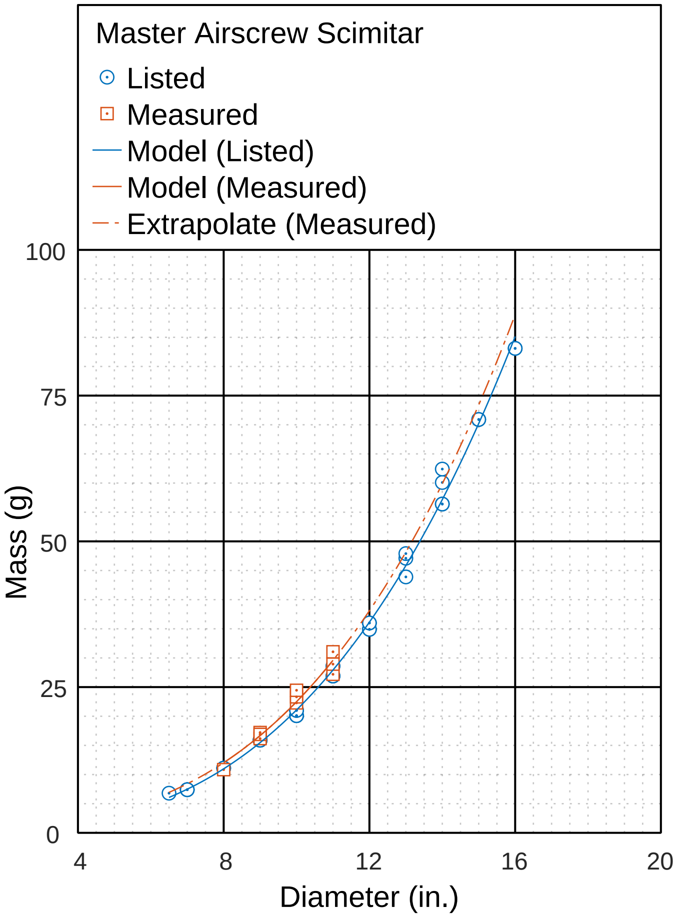

Figure 63: Master Airscrew Scimitar model.

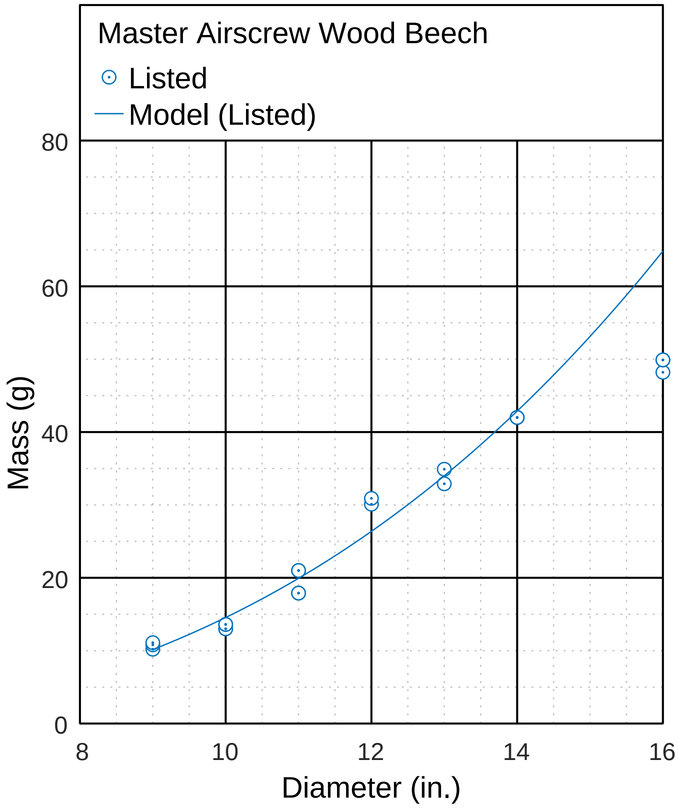

Figure 64: Master Airscrew Wood Beech model.

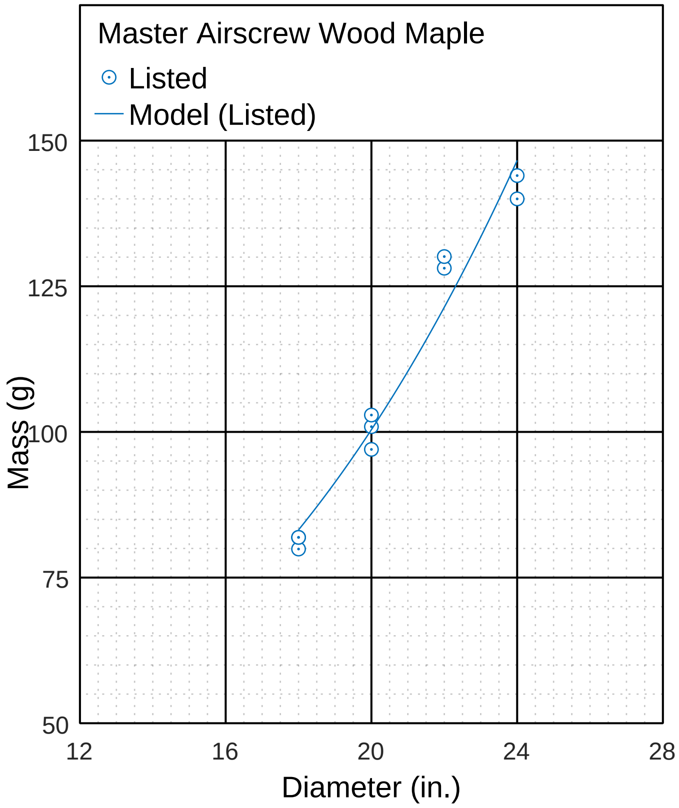

Figure 65: Master Airscrew Wood Maple model.

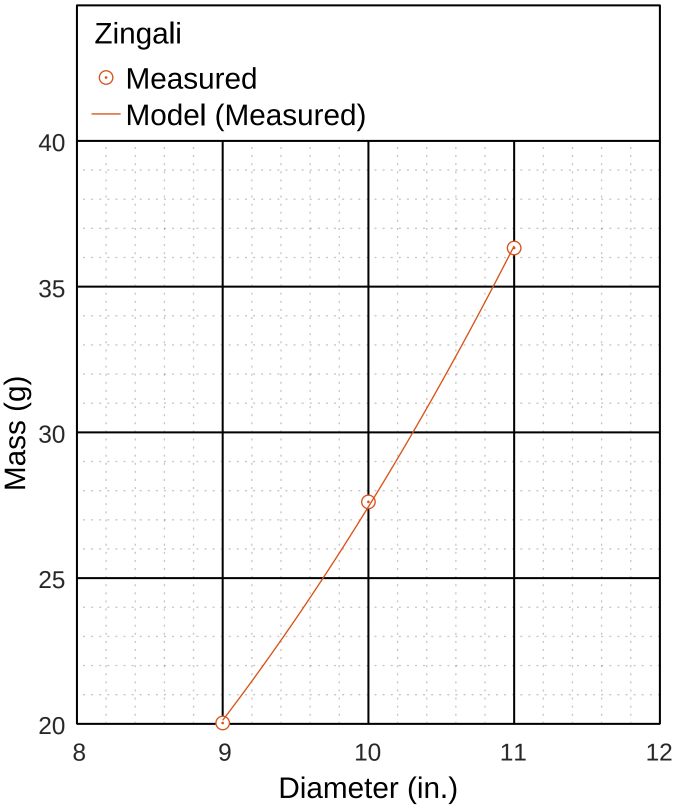

Figure 66: Zingali model.

V. Application of Full-Scale Propeller Weight Equation

In Part V of Roskam's design books,[7] he provides the General Dynamics propeller weight method to provide a weight estimate of full-scale propellers. In Gundlach's UAS design book,[20] he also provides this equation as a way to obtain reasonable results for small-scale propellers as well. The General Dynamics equation is given as

$$W_{Prop} = K_{Prop} \cdot N_{Props} \cdot N_{Blades}^{0.391} \cdot \left(\frac{D \cdot P_{Max}}{1000 \cdot N_{Props}} \right)^{0.782} \tag{1}$$

Where:

W_{Prop}: Weight of the propeller in lb
K_{Prop}: Multiplication factor
N_{Props}: Number of propellers
N_{Blades}: Number of blades per propeller
D: Diameter of the propeller in ft
P_{Max}: Maximum power input to the propeller in horsepower

Gundlach recommends a value of 15 for K_{Prop} for propellers made from plastic or composite and for engines of less than 50 hp.

To test how well the General Dynamics equation predicts the weight of small-scale propellers, three engine types were use: 2-stroke glow engines, 4-stroke gas engines, and brushless electric motors. For each engine type, representative engines were researched to determine engine power and recommended propeller sizes. O.S. Engines[21] were used as the basis for the 2-stroke and 4-stroke engines, and AXI motors[22] were used as the basis for the electric motors. The results from the testing are provided in Tables 26–28. Each table lists the recommended propellers from the engine manufacturer, the propeller diameter, the listed power for the engine, the predicted weight in grams, the listed weight from the propeller manufacturer, and the ratio of the predicted to listed weight.

The results for the 2-stroke engines (Table 26) show that the propeller weight equation generally overpredicts the propeller weight with a few exceptions. For most of the propellers, the overprediction is 20% and higher. For the 4-stroke engines (Table 27), the prediction is much better with most results falling within 10% of the listed value. For the electric motor (Table 28), the results have a large variation. Predictions go from 40% under to 100% over.

From this limited analysis, the General Dynamics equation seems to work best for the 4-stroke engines. Since most predictions for the 2-stroke engines are over the listed values, lowering the K_{Prop} value to around 12 will provide better results. Using this equation for electric motors do not seem to provide consistent predictions.

VI. Summary and Future Work

With access to a large database of mass values, 28 empirical models were created for multiple small-scale propeller series. The mass values came from manufacturer provided values and from measured values. Along with creating models to describe the propeller mass, measured values were compared to manufacturer provided values, and the variation in the mass of difference specimens of the same propeller was analyzed. Finally, a propeller weight estimation equation developed for full-size propellers was applied to these small-scale propellers.

Comparing measured to listed mass values, the measured mass of most propeller models was within 10% of the listed value from the manufacturers (APC or Master Airscrew). With respect to the variation in measured propellers, a

Table 26: 2-Stroke Glow Engines

Propeller	**D (in.)**	**Power (hp)**	**Predicted (g)**	**APC Sport Listed (g)**	**Predicted/Listed**
7×5	7	0.31	10.4	11.1	0.941
10×6	10	1.28	42.4	28.9	1.466
11×6	11	1.28	45.6	40.0	1.141
12×6	12	1.28	48.9	45.9	1.064
10.5×6	10.5	1.63	53.0	34.9	1.519
11×6	11	1.63	55.0	40.0	1.375
11×8	11	1.63	55.0	41.1	1.338
12×6	12	1.63	58.9	45.9	1.282
12×7	12	1.63	58.9	43.1	1.366
12×7	12	1.68	60.3	43.1	1.398
12×8	12	1.68	60.3	47.9	1.258
13×6	13	1.68	64.1	47.9	1.339
12×6	12	1.73	61.6	45.9	1.343
13×6	13	1.73	65.6	47.9	1.370
14×6	14	1.73	69.5	71.2	0.977
13×8	13	2.37	84.0	49.0	1.714
13×10	13	2.37	84.0	60.1	1.398
14×6	14	2.37	89.0	71.2	1.250
14×7	14	2.37	89.0	77.1	1.155
14×8	14	2.37	89.0	70.0	1.272
14×8	14	2.86	103.2	70.0	1.474
15×6	15	2.86	108.9	76.0	1.433
15×7	15	2.86	108.9	77.1	1.413
15×8	15	2.86	108.9	86.0	1.267
16×6	16	2.86	114.6	89.9	1.274
16×7	16	2.86	114.6	95.0	1.206
16×8	16	2.86	114.6	100.9	1.135
15×10	15	3.06	114.8	89.9	1.277
15×11	15	3.06	114.8	91.0	1.261
16×8	16	3.06	120.7	100.9	1.196

Table 27: 4-Stroke Gas Engines

Propeller	D (in.)	Power (hp)	Predicted (g)	APC Electric Listed (g)	Predicted/Listed
12×6	12	1.12	44.1	45.9	0.960
12×7	12	1.12	44.1	43.1	1.023
12×8	12	1.12	44.1	47.9	0.920
13×6	13	1.12	46.9	47.9	0.980
12×7	12	1.18	45.9	43.1	1.065
12×8	12	1.18	45.9	47.9	0.958
13×6	13	1.18	48.9	47.9	1.020
13×7	13	1.18	48.9	47.9	1.020
14×6	14	1.18	51.8	71.2	0.727
14×7	14	1.18	51.8	77.1	0.671
13×7	13	1.68	64.1	47.9	1.339
13×8	13	1.68	64.1	49.0	1.309
13×9	13	1.68	64.1	61.0	1.052
14×6	14	1.68	68.0	71.2	0.955
14×7	14	1.68	68.0	77.1	0.882
14×8	14	1.68	68.0	70.0	0.971
13×11	13	2.07	75.7	57.0	1.328
14×10	14	2.07	80.2	74.0	1.084
14×11	14	2.07	80.2	72.8	1.101
16×8	16	2.56	105.2	100.9	1.043
16×10	16	2.56	105.2	104.9	1.003
16×11	16	2.56	105.2	106.0	0.992
16×12	16	2.56	105.2	102.9	1.022
17×8	17	2.56	110.3	115.9	0.952
17×10	17	2.56	110.3	115.1	0.958
17×12	17	2.56	110.3	119.9	0.920

Table 28: Brushless Motors

Propeller	D (in.)	Power (W)	Power (hp)	Predicted (g)	APC Sport Listed (g)	Predicted/Listed
12×6E	12	245	0.33	16.8	27.0	0.624
10×5E	10	245	0.33	14.6	20.0	0.730
12×6E	12	270	0.36	18.2	18.0	1.010
14×6E	14	300	0.40	22.3	37.0	0.602
9×6E	9	330	0.44	17.0	18.0	0.943
13×8E	13	365	0.49	24.5	31.0	0.790
9×6E	9	400	0.54	19.7	18.0	1.096
7×7E	7	450	0.60	17.8	8.0	2.222
9×7.5E	9	450	0.60	21.6	18.0	1.202
13×6.5E	13	450	0.60	28.8	30.0	0.962
13×6.5E	13	530	0.71	32.8	25.0	1.311
14×7E	14	665	0.89	41.5	34.0	1.220
14×7E	14	675	0.91	42.0	34.0	1.235

majority of models were within the margin of measurement error, but a few had significant differences. The results from the application of the full-scale propeller equation are promising for 4-stroke engines and possibly with 2-stroke engines with a modification to the multiplication factor. The limited analysis using electric motors did not provide good results.

With the empirical models, most propeller series reasonably followed a cubic diameter trend. The largest errors were typically for the smaller diameters or with diameters with a large pitch variety. From the data available, a good correlation of the mass with the pitch-to-diameter (p/D) ratio could not be found. From the manufacturer provided values, the mass many times did not change between similar pitch values at the same diameter. For the Aeronaut CAM Carbon Folding, which had the most variation in p/D of the measured values, the blade shape varied with the same diameter, which has a large effect on the mass.

For future work, more measured values will be gathered to add to and enhance the empirical models. The authors have many other measured propellers that have not been included in the analysis for this paper. Many of these propellers are for specific multirotor aircraft or are from other manufacturers. The majority of the propellers in this paper are made from glass fiber composite (APC and Master Airscrew) or are carbon (Aeronaut). Future work will include other materials such as carbon fiber.

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