Ornithopter Wing Optimization

Sandra Mau
Institute for Aerospace Studies,
University of Toronto
Downsview, Ontario, Canada
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Abstract

A new ornithopter wing was designed using analytical software to theoretically produce enough lift and thrust to propel an engine-powered piloted aircraft into steady flight.

Nomenclature

GJ_{total}	Total torsional stiffness of segment
GJ_{spar}	Torsional stiffness of segment spar
GJ_{f+r}	Torsional stiffness of segment fabric and ribs
X_{ea}	Distance from leading edge to elastic axis
X_s	Distance from leading edge to spar mass centre
m_{spar}	Mass of segment spar
m_{f+r}	Mass of segment fabric and ribs
I_{spar}	Moment of inertia of segment spar
I_{f+r}	Moment of inertia of segment fabric and ribs
EI	Bending stiffness at elastic axis
α	Inboard sweep (inner crank angle)
β	Crank angle (outer)
AR	Aspect ratio

Introduction

After centuries of dreaming to fly with the birds, the Wright brothers gave flight to those dreams in 1903 when they built and flew the first successful powered and piloted aircraft. However, the dream of flying *like* the birds still eludes us to this day.

Ornithopters are what innovators like Leonardo DaVinci have imagined since before the 1500s; before rigid-wing aircrafts like that of the Wrights. They are mechanical, powered, flapping-wing aircrafts – to imitate the flapping wings of a bird. This type of flight has continually been pursued throughout the ages. Some notable developments in flapping-wing flight included Alphonse Penaud's rubber-powered model ornithopter in 1984, the gliding human-powered ornithopter of Alexander Lippisch in 1929, and Percival Spencer's series of engine-powered, free-flight models in the 1960s.

Fig 1: Orinthopter 2002

The most recent major advancement in flapping wing flight was spawn from the ambitions of Jeremy Harris and James DeLaurier. In 1991, they launched the first successful engine-powered, remotely piloted ornithopter. This craft, dubbed Mr. Bill, became the quarter-scale model upon which a full-scale piloted ornithopter was developed. In 1999, the Harris/ DeLaurier engine-powered piloted aircraft was able to self-accelerate, by flapping wings alone, to lift-off speeds. However, it has yet to maintain steady flight.

One of the major problems was that the wing on the full-scale ornithopter, through providing enough thrust to self-propel the craft, could barely provide enough lift. The wing was originally designed to accommodate around 600 lbs of weight from the aircraft, whereas the actual plane came closer to 700 lbs.

The details of this paper outline the process in which the ornithopter wing was analyzed and modified to theoretically provide the optimum lift and thrust to achieve flapping-wing flight. The analysis was done through two programs, FullWing and Rambod Larijani's Newmark, which predict the performance of the flapping wing craft given various parameters. Based on available data, a new optimized planform for the ornithopter wing was designed.

Description of Ornithopter Wing

The current Harris/DeLaurier model full-scale ornithopter has a very unique wing design. The wing itself consists of three hinged panels – a center panel with constant chord, and symmetrical outer panels that are double tapered. The outer panels can be subdivided further. The innermost section of the outer panel, dubbed "rigid section", lies between the center panel and the hinged pivot attached to the outboard vertical links, which provide support and a pivot point for the flapping panel. Beyond this hinge, the panel chord continues at the same tapered angle as the rigid section, and then tapers again further out along the wing.

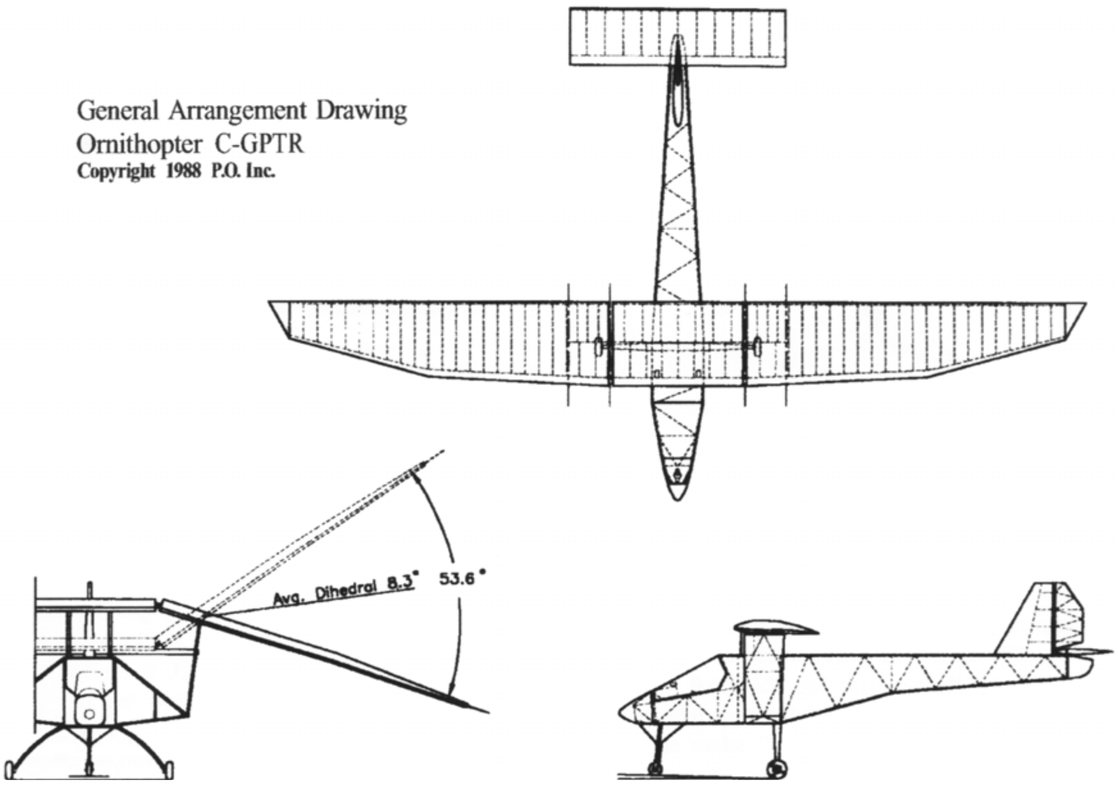

Fig 2: General arrangement drawing of full-scale ornithopter

The center panel is driven in a sinusoidal vertical motion by a Scotch-yoke mechanism, used to produce vertical oscillatory motion by converting the radial motion of the motor, a Konig 3-cylinder, 2-cycle, radial engine that produces 24 hp at 4000 rpm. The up-and-down motion of the center panel pulls and pushes the outer panels' hinged inner edge up and down with it. Since the outer panel is hinged at the end of the rigid section by the outboard vertical links, the entire outer panel flaps in response to the center panel's oscillations.

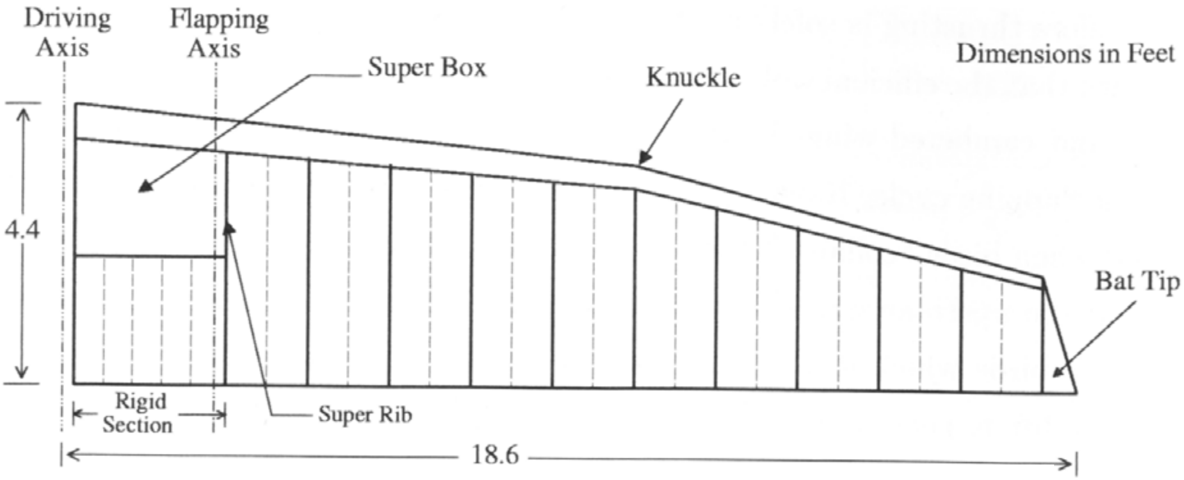

Fig 3: Ornithopter wing outer panel

On the current ornithopter, the wingspan is 41.2 ft. The center panel is in the middle, attached to both outer panels. The outer panel consists of the rigid section, and beyond that it is subdivided by ribs into 11 segments. The chord length of the center panel is 4.4 ft. The outer panel is tapered at the innermost edge at an angle of 2.7°, and tapered even further between segments 5 and 6 by an angle of 15.40°. The last segment, number 11 – dubbed the "bat tip", has a smaller width compared to other segments, and the chord tapers again to form a triangular tip.

The wing also uses patented Shearflexing technology to allow for lateral flexibility. The details of Shearflexing and the composition of the wing itself are specified in [3].

Method of Analysis

The objective of these tests was to gain a better idea of how each different parameter affects flight dynamics such as lift and thrust. This was achieved by altering parameters of the current ornithopter wing and running those numbers through two different programs: FullWing and Rambod's Newmark.

The primary analysis was done mostly through FullWing. FullWing is a program that predicts flight performance of a flapping wing in steady flight. This program was originally designed by Dr. James DeLaurier and later modified by S.J. Fowler. One of the most significant assumptions made by this program is that the flow is fully attached in order to simplify the calculations. According to Rambod, "this gives inaccurate results as stalling dominates in the low forward speed, high flapping-frequency regime" [7].

Another weakness in this program is the assumption of a simple harmonic motion response from the wing, preventing the presence of non-harmonic motion to be predicted. Furthermore, it uses structural influence coefficients in its calculations, whereas Newmark implements a stiffness formulation that can calculate the coefficients for different geometries.

Rambod's program resolves the issues stated above by implementing an "implicit unconditionally-stable time-marching method" known as the Newmark method, and hence is named the Newmark program. The details of formulations, analysis and code used in these programs can be found in reference [7].

After a suitable design was determined through FullWing, further experimentation was done using both FullWing and Newmark to compare the outputs. An Excel spreadsheet was used to facilitate scaling calculations.

Before any wing parameters were altered, baseline output values were recorded for both programs with Mr. Bill (quarter-scale model), Expothopter (another scale model with double tapered wings), and the current Full-Scale piloted ornithopter. From those numbers, some criteria were set out for the new wing to achieve. The criteria included:

- Average thrust must be greater than or equal to current thrust (31.5 lbs predicted by FullWing at flapping frequency of 1.05 Hz)
- Average lift must be greater than or equal to 800 lbs (the main objective of experiment)
- Tip twist must be less than 20° (this is a limitation imposed by Shearflexing technology)
- Maximum of 400 lbs was imposed on lift variation (the higher the variation, the more bouncy the ride will be)
- Maximum limitation of 3000 ft-lbs was imposed on maximum moment value
- Keep stalling to a minimum, ideally none at all
- Ideally, have a twisting phase angle close to –90°
- Chord length at bat tip must be greater than or equal to half the chord at crank

The original derivation and scaling laws used upon the numbers were relearned from Dr. DeLaurier's ornithopter binder. In these papers, an attempt was made to scale Mr. Bill and Expothopter up to a full size piloted version. Similar methods and scaling laws were used to change certain parameters such as torsional stiffness (GJ) and chord lengths. The major relationships used included:

- $(\text{Dynamic twisting ratio})_i = GJ_i / GJ_1$
- $GJ_{total} \times \text{dynamic twisting ratio} = GJ_{spar} + GJ_{f+r}$
- $GJ_{f+r}^{new} = (C^{new} / C^{old})^4 \times GJ_{f+r}^{old}$
- $X_{ea}^{new} = (X_s^{new} / X_s^{old}) \times X_{ea}^{old}$
- $X_s^{new} = (C^{new} / C^{old}) \times X_s^{old}$
- $m_{spar}^{new} = (X_s^{new} / X_s^{old})^3 \times m_{spar}^{old}$
- $m_{f+r}^{new} = (X_s^{new} / X_s^{old})^3 \times m_{f+r}^{old}$

- $I_{spar}^{new} = (GJ_{spar}^{new} / GJ_{spar}^{old}) \times I_{spar}^{old}$
- $I_{f+r}^{new} = (C^{new} / C^{old})^4 \times I_{f+r}^{old}$
- Other changes to parameters included altering the geometry of the wing such as angles, widths and chord lengths

Discussion of Results

Using the current ornithopter numbers as a basis, certain parameters were altered to determine its effect on an ornithopter's flapping wing performance. Details of the calculation methods can be found in [8]. For the variation of parameters, mainly only one or two were targeted per trial. However, since many parameters are interrelated, the results would not be true to life, and the trials can only give an idea of the change in performance.

Many different methods and parameters were tested based on the current Full-Scale ornithopter planform. The most significant were: changing GJ_{spar}, changing GJ_{f+r}, varying width of panels and segments, changing crank location and angles, plus various methods of increasing chord and GJ_{spar}. In these trials, an assumption was made based on previous experience from Dr. DeLaurier that EI values only have to be over a certain threshold for the wing to be effective. Hence EI numbers were assumed independently variable and present baseline numbers from Full-Scale was used.

From these trials, some interesting results were found. Increasing GJ_{spar} would increase both lift (linearly) and thrust (up to a threshold of around 33 lbs). However, much stalling occurred before the desired lift of over 800 lbs was attained. Increasing GJ_{f+r} had a very similar effect. However, its overall contribution to flight performance was much less dramatic than GJ_{spar}. Hence, it was decided that in subsequent trials changing just GJ_{spar}, rather than both, would be a more effective and efficient method.

The widths of the centre, rigid, and segments 1, 2 and 3 were altered to see their effects. To maintain the same planform, chord lengths were accordingly altered. It was found that by increasing the width of either the centre or rigid panel, lift increased while thrust decreased. The rate of increase in lift for rigid panel was higher than that of centre, however, the rigid panel had a maximum threshold of around 718 lbs of lift. The thrust decreased too much for it to be able to propel the aircraft. Altering the widths of outer segments had much less effect on lift, though thrust increased rather than decreased.

A seemingly effective method was to change the geometry of the wing by increasing chord length while increasing GJ_{spar}. By increasing the chord length by certain constants (1, 2 and 3 ft) while increasing GJ_{spar}, it was found that both lift and thrust increased dramatically to an acceptable range with little stalling. However, the lift variation and moment both exceeded the self-imposed restrictions. By increasing chord length by a certain percentage while changing GJ_{spar} through scaling relationships, the result in performance was somewhat promising. However, stalls occurred before enough lift was attained.

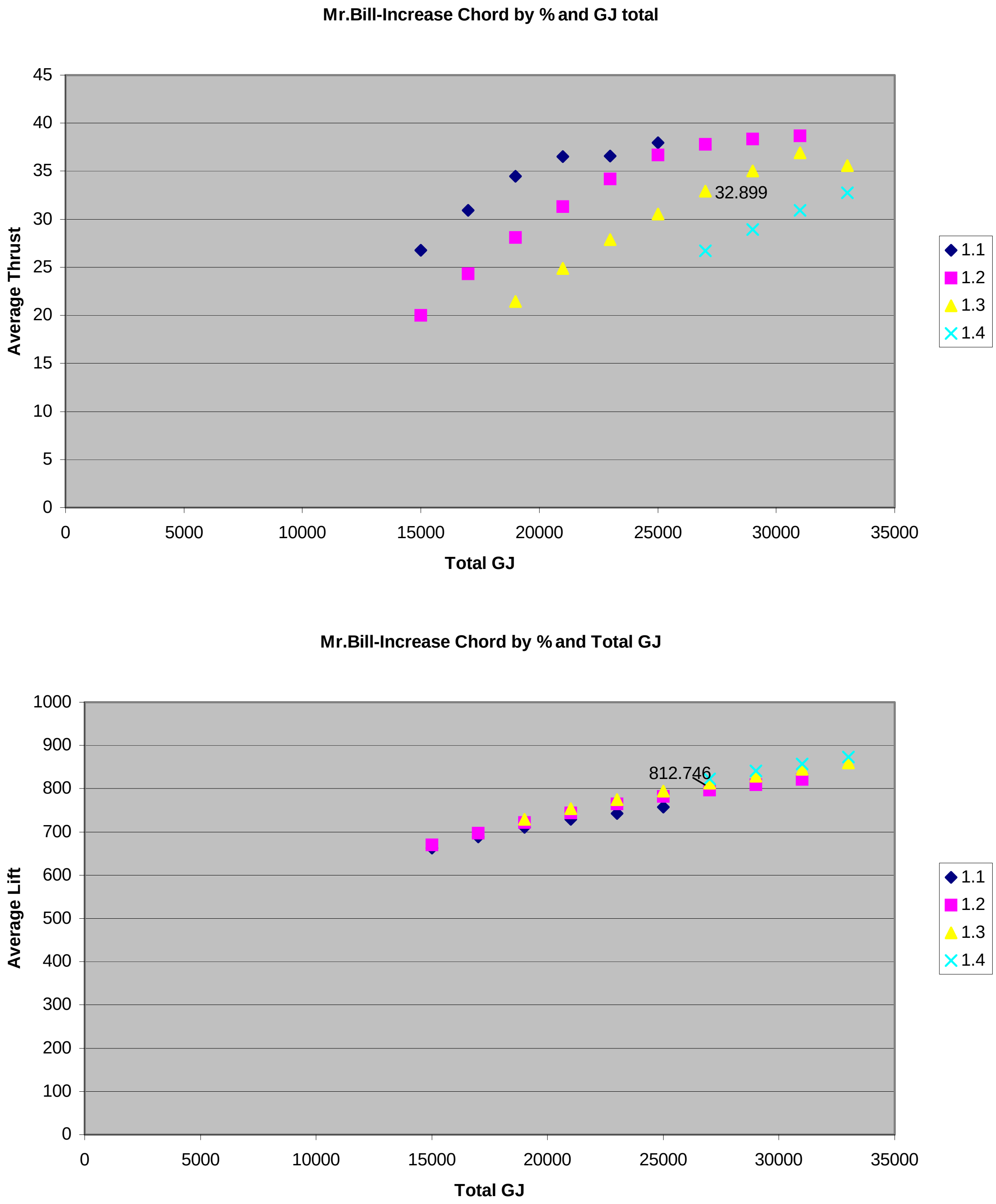

***Fig 4:** Results from increasing chord length by a percentage of former length and increasing GJ_{spar} on a Mr. Bill planform. Labelled is NEW1.*

After modifying various parameters on the current Full-Scale/Expothopter double-tapered planform, a Mr. Bill planform was attempted. Mr. Bill's planform consists of only one crank between segments 5 and 6, with segments 1 to 5 and rigid panel chords the same length as the centre panel. Scaling relationships outlined in equations summarized in Methods of Analysis were used to scale current Full-Scale numbers to fit a Mr. Bill planform. Some of the previous promising trials were applied to this new planform.

The crank angle was varied within certain limits, such that the chord at the bat tip would be greater than half the chord length at the crank. It was found that the current angle of 15.6° was close to the maximum allowable 17.1°. As crank angle increased, thrust decreased and lift increased. However, the change was not significant enough to dramatically affect flight performance.

The same trial of increasing both chord length and GJ_{spar} was attempted once again. Similar results occurred, where appropriate numbers for lift and thrust were found but moment and lift variation exceeded limitations. Again, similar results when increasing GJ_{spar} by a percentage of its previous chord length. However, some results were promising in that only the moment exceeded the prescribed limit.

Since both planforms had similar results, it was decided to choose the most promising modification ideas, apply them to both planforms and determine which was better for flapping wings. Two comparisons were done; both the constant and proportional increase in chord and GJ_{spar} was compared. Based on previous results, the chords were increased by 1 and 1.5 ft for both Mr. Bill and Full-Scale/Expothopter planforms while increasing GJ_{spar}. From those results, none of the tests met all imposed limitations. Again based on previous results, the chords were increased proportionally by 30% while increasing GJ_{spar}. From these trials [Table 1 in Appendix], there was only one candidate that met all criteria. This one trial was based on a Mr. Bill planform, dubbed NEW1.

Since most of the parameters of the flapping wing are interrelated, all the other variables had to be scaled accordingly to give a more realistic idea of performance. So, based on a GJ_{total} of 27000 lb-ft^2/rad and new chord lengths, parameters such as X_s, X_{ea}, I_{spar}, I_{f+r}, m_{spar}, m_{f+r} were all scaled. EI was assumed independent and individually customized. The updated NEW1 was renamed NEW2. Unfortunately, after all these changes, the twist, lift variation, and maximum moment all exceeded limitations [Table 2].

The same method was retried on the Full-Scale/Expothopter planform equivalent (GJ_{total} = 27000 lb-ft^2/rad, 30% increase, $\alpha = 3.70°$, $\beta = 19.59°$, aspect ratio = 8.16). After all parameters were scaled, the output was rather favourable. All performances met limitations except for twist-in-tip which was 20.0819° instead of the imposed maximum of 20°. However, the error involved was much greater than the difference, rendering the difference negligible. This new wing with all its modified parameters was dubbed NEW3 [Table 3].

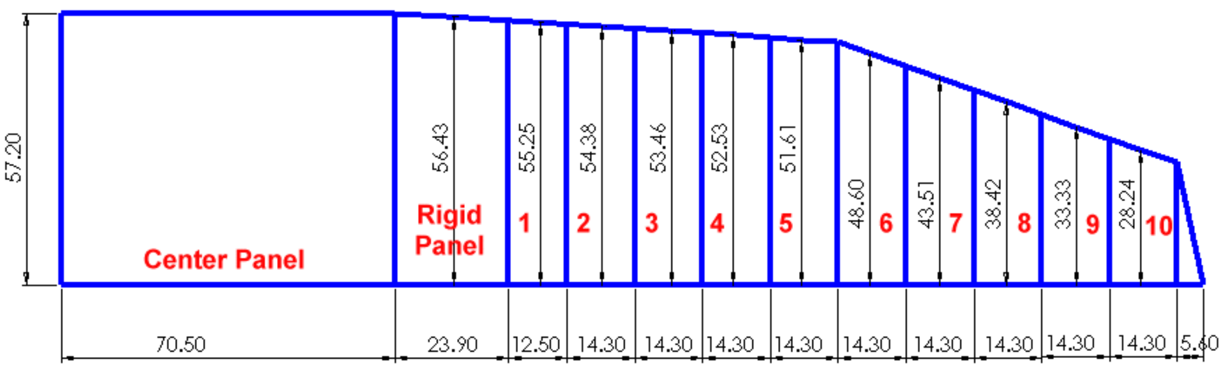

Fig 5: NEW3 dimensions in ft x 10^1

Based on this NEW3 planform, various changes in parameters were retried to see if there was another more optimal solution. The span was allowed to increase from 41.2 ft to 43.2 ft maximum. The new tests included increasing the width of each segment by a constant value, by a certain percentage, width changes on only certain segments (i.e. before or after knuckle), all the while varying GJ_{spar}. After various measures for increasing wing span, it was observed that the increase resulted in the lift variation and maximum moment values exceeding the prescribed limitations. Although the lift and thrust both seemed to improve, the violation of the set criteria seemed to outweigh the performance benefits.

Rambod's Newmark program was then used to compare flight performance of NEW3 with results given in FullWing. This data is shown in [Tables 4 and 5], contrasted with the outputs for current Full-Scale ornithopter. Based on Rambod's Newmark, the NEW3 wing will produce less thrust than predicted by FullWing (28.8 lbs as opposed to 33.0 lbs). All other values are approximately the same between the two programs, with no other criteria violations.

Since the thrust was less than anticipated in Newmark, the GJ_{spar} and I_{spar} (which has a dependent relationship with GJ_{spar}) was increased to search for better results. As before, in FullWing, beyond a GJ_{total} of 27000 lbs-ft^2/rad, the maximum moment and lift variation increases beyond limits, and stalling occurs. However, according to Newmark, no stalling occurs and GJ_{total} can go up to 28000 lbs-ft^2/rad before exceeding the maximum moment [Table 6]. To err on the safe side, NEW3 configuration with GJ_{total} of 27000 lbs-ft^2/rad was decided to be the optimal wing at a flapping frequency of 1.05 Hz.

Conclusion

The main objective of these trials was to develop a flapping wing that can produce enough lift and thrust to propel a piloted ornithopter into steady flight. To accomplish this feat, the targeted wing was desired to lift around 800 lbs and provide at least 33 lbs of thrust. It must also meet other desired criteria such as having moments below 3000 ft-lbs, tip twist lower than 20°, and lift variation lower than 400 lbs.

To determine this optimal wing, the parameters of the current Full-Scale ornithopter wing were adjusted and scaled, and fed into flapping-wing performance programs FullWing and Newmark. After altering many parameters, most significantly GJspar and chord lengths, a wing was settled on that gave significantly better lift than the current one. This wing was dubbed NEW3.

The NEW3 wing was based on the Full-Scale planform but with longer chords and higher GJspar values. It has a double taper, one crank between the center panel and outer panel, another between segments 5 and 6. The chords were lengthened proportionally by 30% and GJ_{total} was increased to 27000 lb-ft^2/rad.

When ran in FullWing at a frequency of 1.05 Hz, the lift given was over 800 lbs and thrust was just about the same as what the current wing produces. All other criterion were met, hence it seemed an ideal solution. In Newmark however, a lower thrust was predicted, about 4 lbs of force less than necessary. Whether this will be significant will have to be verified experimentally. Based on the Newmark program, the results suggested that increasing GJspar of NEW3 might help make up for the lost thrust. However, FullWing's predictions on that same increase were that some stalling might occur. To be safe, it was decided that NEW3 configuration is the most optimal wing found in these experiments.

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Table 1: Comparing Mr. Bill and Current planform - Increasing Chord proportionally and Gjspar

				Angle									
GJtot	Mult	Planform	AR	Inner	Outer	Twist	Phase	Thrust	Lift	Lift Vari	Max Mom	Max Pow	Stall
25000	1.3	Expo	8.16	3.64	19.98	18.9163	-101.8424	28.464	787.83	316.992	2757.892	30.359	0
		Mr. Bill	7.69	0	21.8	19.6534	-94.722	30.45	794.285	363.965	2787.743	33.433	0
27000	1.3	Expo	8.16	3.64	19.98	18.4958	-102.0321	30.32	803.995	334.917	2916.344	32.052	0
(NEW1)		Mr. Bill	7.69	0	21.8	19.1911	-94.7773	32.824	812.38	382.397	2972.235	35.444	0
29000	1.3	Expo	8.16	3.64	19.98	18.1093	-102.2118	31.963	818.828	351.417	3062.23	33.609	0
		Mr. Bill	7.69	0	21.8	18.7638	-94.8304	34.942	829.054	399.846	3142.959	37.305	0
31000	1.3	Expo	8.16	3.64	19.98	17.7528	-102.3827	33.422	832.492	366.655	3196.992	35.048	0
		Mr. Bill	7.69	0	21.8	18.3675	-94.8818	36.838	844.475	417.664	3301.397	39.033	0
33000	1.3	Expo	8.16	3.64	19.98	17.423	-102.5454	34.724	845.124	380.77	3321.858	36.381	0
		Mr. Bill	7.69	0	21.8	17.999	-94.932	38.543	858.787	434.223	3448.826	40.641	0
35000	1.3	Expo	8.16	3.64	19.98	17.1169	-102.7008	34.637	854.251	393.88	3437.882	37.619	1 (s9)
		Mr. Bill	7.69	0	21.8	17.6554	-94.981	38.931	869.818	449.651	3586.349	42.141	1 (s10)
37000	1.3	Expo	8.16	3.64	19.98	16.8321	-102.8495	34.638	863.125	406.089	3545.971	38.772	2 (s9,10)
		Mr. Bill	7.69	0	21.8	17.3343	-95.0292	38.854	879.246	464.059	3714.932	43.544	2 (s9,10)

Table 2: Performance Analysis of NEW2 by FullWing

Twist at Tip (deg)	21.3660
Phase Angle (deg)	-84.1451
Average Thrust (lbs)	30.246
Average Lift (lbs)	835.295
Lift Variation (lbs)	470.487
Average Power (hp)	14.107
Max Power (hp)	40.625
Max Moment (ft-lbs)	3116.498
Stalls	1 (seg 10)

Table 3: NEW3 Parameters

α = inner sweep angle = 3.70°
β = outer sweep angle = 19.59°
AR = aspect ratio = 8.16

Segment	Chord	Width	GJ_{spar}	GJ_{f+r}	X_s	X_{ea}	I_{spar}	I_{f+r}	m_{spar}	m_{f+r}
Center	5.72	7.05	–	–	–	–	–	–	1.857585	–
Rigid	5.643	2.39	–	–	–	–	–	–	0.874252	–
1	5.525	1.25	26614	386.00	0.40076	0.422809	0.003545	0.05735	0.103125	0.086333
2	5.438	1.43	25308.45	357.75	0.39552	0.416337	0.0032	0.053638	0.11648	0.078024
3	5.346	1.43	24062.8	334.40	0.387613	0.408424	0.002892	0.050856	0.113429	0.075917
4	5.253	1.43	22845.9	312.00	0.379706	0.401812	0.002614	0.048882	0.111367	0.074545
5	5.161	1.43	21681.6	291.00	0.3744	0.3952	0.002336	0.046394	0.108319	0.073345
6	4.860	1.43	9933.5	229.30	0.30669	0.371667	0.00136	0.039209	0.066379	0.062854
7	4.351	1.43	6777.38	148.12	0.276661	0.332512	0.000884	0.027741	0.054476	0.055839
8	3.842	1.43	4590.35	88.75	0.251372	0.294353	0.00056	0.017499	0.045773	0.048035
9	3.333	1.43	2983.68	51.12	0.224375	0.254205	0.000336	0.012521	0.036156	0.041532
10	2.824	1.43	1880.7	25.50	0.205276	0.215736	0.000182	0.007572	0.029636	0.055594
11	2.47	0.56	801.9	0	0.7631	-0.3523	0.007807	0	0.033621	0

Table 4: Performance Analysis of Current Full-Scale Ornithopter by FullWing and Newmark

	FullWing	Rambod’s Newmark
Twist at Tip (deg)	18.6779	18.094
Phase Angle (deg)	-95.4434	–
Average Thrust (lbs)	31.504	32.965
Average Lift (lbs)	636.568	664.301
Lift Variation (lbs)	264.426	264.944
Average Power (hp)	10.168	9.974
Max Power (hp)	26.018	26.224
Max Moment (ft-lbs)	2276.742	2434.2
Stalls	0	0

Table 5: Performance Analysis of NEW3 by FullWing and Newmark

	FullWing	Rambod's Newmark
Twist at Tip (deg)	20.075	20.748
Phase Angle (deg)	-91.572	–
Average Thrust (lbs)	31.395	28.820
Average Lift (lbs)	825.431	852.753
Lift Variation (lbs)	392.078	328.669
Average Power (hp)	13.246	11.812
Max Power (hp)	35.845	33.243
Max Moment (ft-lbs)	2995.380	2919.065
Stalls	0	0

Table 6: NEW3 – Increase GJspar and Ispar in FullWing and Newmark

FullWing

Gjtot	Tip Twist	Phase Ang	Avg Thrust	Avg Lift	Lift Vari	Avg Power	Max Power	Max Moment	Stalls
25000	20.5388	-91.315	29.159	809.644	378.88	12.709	34.07	2829.703	0
26000	20.3021	-91.4459	30.311	817.715	385.619	12.984	34.976	2914.33	0
27000	20.0754	-91.5724	31.395	825.431	392.078	13.246	35.845	2995.38	0
28000	19.8582	-91.6949	31.299	830.688	398.274	13.35	36.678	3073.073	1
29000	19.6498	-91.8136	31.379	835.611	404.224	13.477	37.478	3147.614	2
30000	19.4498	-91.9586	32.25	842.341	409.94	13.706	38.247	3219.189	2

Newmark

Gjtot	Tip Twist	Phase Ang	Avg Thrust	Avg Lift	Lift Vari	Avg Power	Max Power	Max Moment	Stalls
25000	21.066	–	26.851	838.115	311.7806	11.3199	31.656	2764.229	0
26000	20.9025	–	27.864	845.6023	320.379	11.571	32.465	2843.137	0
27000	20.7476	–	28.8196	852.753	328.669	11.812	33.243	2919.065	0
28000	20.601	–	29.7231	859.5919	336.701	12.045	33.993	2992.07	0
29000	20.4613	–	30.578	866.14	344.462	12.269	34.717	3062.32	0
30000	20.3287	–	31.3888	872.418	351.978	12.486	35.414	3130.138	0