WEIGHT ANALYSIS OF THE DAEDALUS HUMAN POWERED AIRCRAFT

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Abstract

Daedalus is a long range and endurance human powered aircraft (HPA). Through careful design, and the use of advanced materials, it has maintained the low weight of previous HPA's, while significantly improving its aerodynamic cleanliness. These factors have allowed Daedalus to attain lower power levels, and thus increase its range and endurance as compared to previous HPA's. During its construction, careful weight measurements were made of every part and component. A condensed version of the weights log is presented, together with a description of the aircraft and how it is constructed. Based on these data, several formulas for weight prediction of HPA's are proposed. These formulas should be useful for preliminary HPA sizing and optimization.

Introduction

Weight is extremely important to the performance of human powered aircraft (HPA's). The power required to maintain flight varies as $(\text{weight})^{3/2}$. Because of the limited power available from its human engine, low weight is one of the major design goals for an HPA.

Being capable of accurately predicting the weight of an HPA is a requirement throughout the design process. By knowing the weight of components, and how they vary with aircraft size, the engineer can optimize the design and assess its performance.

During the construction of the Daedalus HPA, the weight of all components was measured and recorded. The weights log eventually encompassed over 200 entries. This paper describes the major construction details of the Daedalus HPA, presents a summary of component weights, and proposes several formulas for HPA weight prediction.

Description of the aircraft

Daedalus is a single place, high wing, tractor monoplane of conventional configuration as shown in figure 1. The aircraft is powered by its pilot/engine. With a wingspan of 34.1 m (112 ft.), Daedalus is one of the largest all-composite aircraft ever built. It has a wing area of 30.9 m^2 (332.5 ft.^{2}) and an aspect ratio of 37.7. The aircraft is very short coupled, having a total length of 8.77 m (28.8 ft.). Daedalus has an empty weight of 31.1 kg (68.5 lbs.), carries 6 liters (6 kg or 13.23 lbs.) of drinking fluid, and accepts pilots weighing between 54 and 73 kg (120 to 160 lbs.).

The aircraft is stressed to an ultimate load factor of 1.75 g's, and has a maneuvering speed of 7.88 m/s (17.6 mph). A single lift wire reduces the bending moment on the inner half of the wing, otherwise, the aircraft structure is fully cantilevered.

The primary structure is fabricated of high modulus graphite/epoxy composite and Kevlar roving. All the graphite/epoxy used on Daedalus is Thornel T-40, T-50 and T-650-42 unidirectional prepreg. These prepregs have higher moduli than standard graphite/epoxy materials. Since most of the primary structure on Daedalus is stiffness dominated, the use of these graphite/epoxy materials yielded significant weight savings. Aluminum and steel are used in the gearboxes and landing gear. Most of the secondary structure consists of polystyrene foam with basswood and balsa reinforcements. The aircraft is covered with 0.0127 and 0.00847 mm (0.0005 and 0.0003 inch) thick tensilized Mylar.

Daedalus can be easily disassembled for transportation. The wing consists of 5 independent panels, none longer than 8.8 m (29 ft.). Without disconnecting the control system, the rudder and elevator can be removed. The disassembled aircraft fits in a 12 m trailer. It takes approximately two hours to assemble or disassemble the aircraft.

The design goal of the aircraft is to require a power level of less than 3 watts per kilogram of pilot body weight to maintain level flight at 6.71 m/s (15 mph). By achieving these goals, Daedalus was able to cover the 116 km (72 statute miles) between the islands of Crete and Santorini on 4/23/88, duplicating the mythical escape of Daedalus, and setting new world records for distance and endurance.

Construction details and weights

A weight breakdown by component is shown in Table 1. In this section, some construction details are explained, following the format of Table 1. The information in figure 1 will be of great assistance in clarifying how the aircraft is built.

Wing

The primary structure of the wing consists of a main spar, a rear spar, several struts between these, and a system of Kevlar 49 roving X-bracing. The main spar is a graphite/epoxy tube of varying diameter. Its main role on the wing's primary structure is to take the out-of-plane bending, shear, compression and torsion loads generated by the wing. It is made of two to four layers of T-40 prepreg at ±40 degrees, and one to eight layers of T-50 prepreg at 0 degrees. Each layer is 0.14 mm (0.0055 inch) thick. The ±40 degree layers provide torsional stiffness and strength, while the 0 degree layers, placed only on the top and bottom 90 degree arcs of the tube, provide the required bending stiffness and strength. In-plane bending strength and stiffness is provided by the main and rear spars. The Kevlar 49 roving X-bracing provides the wing with in-plane shear stiffness.

Since the laminar airfoils used on Daedalus requires good contour accuracy and surface smoothness, the secondary structure accounts for a large percentage of the wing weight. There are 98 rib stations on the wing, with an average rib spacing to chord ratio of 0.38. At the end of each of the 5 wing panels, a stronger end rib is placed to withstand the covering loads. These end ribs are of sandwich construction with a foam core 9.5 to 12.7 mm (3/8 to 1/2 inch) thick, and 0.40 mm (1/64 inch) thick birch plywood facesheets. The leading edge is sheeted with Foamular 150 polystyrene foam over 15% of the lower surface, and 65% of the upper surface. This sheeting provides the contour accuracy and smoothness required to maintain laminar flow. A Kevlar/Rohacell foam wedge serves as the trailing edge. The wing is covered with 0.0127 mm thick Mylar film. The loads generated by shrinking the film are significant; most of the secondary structure is sized by the requirement to withstand the covering tension.

The number under "Miscellaneous" is the difference between the measured weight of a completed component, such as the wing, and the sum of all the individual weights. This term is a measure of how carefully the weights of all the pieces was recorded, and the amount of adhesive used to assemble the aircraft. For Daedalus, it varies from 1 to 5% of the total, depending on the component.

Elevator and Rudder

The construction of the tail surfaces is almost identical to that of the wing. Both the elevator and rudder lack the wing's Kevlar X-bracing; the Mylar film, 0.00847 mm thick on these surfaces, provides the needed in-plane shear stiffness. The surfaces are all-moving and hinge around the spar, located at the 1/4 chord. A rudder tab, geared to move with the surface, increases the maximum lift coefficient and provides centering force to the rudder.

Fuselage

The fuselage frame consists of seven graphite/epoxy tubes, three to five plies thick. They are lashed together with graphite rovings, fabric, and a room temperature curing, low viscosity epoxy. Even though this method of joining tubular components may seem crude, it is extremely light, and yields joints stronger than the tubes themselves. The major loads in the cockpit area arise from the pilot pedaling the aircraft, while the tailboom is sized by the tail loads generated at maneuvering speed.

Power is transmitted from the pedals to the propeller through two gearboxes. Although these are heavier than the chain system used on most HPA's, the added reliability and efficiency of the gearboxes more than compensate for the extra weight. The gearbox housings are made of aluminum, while the gears and shafts are steel.

The main landing gear is sprung, but non-castering. It is machined out of aluminum, and uses a rubber block as a shock absorber. The nose landing gear is of similar design, but it is allowed to caster.

Two layers of 120 Kevlar 49 fabric and epoxy form the lower

Table 1
Daedalus HPA Weight Distribution

	Grams	Pounds
Wing		
Primary Structure		
Main Spar	9222.2	20.33
Rear Spar	1313.5	2.90
Struts	76.1	0.17
Fittings	512.0	1.13
Kevlar X-Bracing	211.3	0.47
Wing-Fuselage Mounts	47.2	0.10
Wing Primary Structure Subtotal	11382.3	25.09
Secondary Structure		
Ribs	884.0	1.95
End Ribs	732.9	1.62
Leading Edge Sheeting	3497.7	7.71
Trailing Edge	943.6	2.08
Covering	952.3	2.10
Miscellaneous Secondary Structure	207.2	0.46
Wing Secondary Structure Subtotal	7217.7	15.91
Miscellaneous	385.4	0.85
Wing Total	18985.4 gm	41.85 lb
Elevator		
Primary Structure	272.0	0.60
Ribs	53.8	0.12
Leading Edge Sheeting & Webs	90.6	0.20
Hinges & Attachment Hardware	43.1	0.10
Covering	39.5	0.09
Miscellaneous Secondary Structure	23.7	0.05
Miscellaneous	15.1	0.03
Elevator Total	537.8 gm	1.19 lb
Rudder		
Primary Structure	150.9	0.33
Ribs	90.0	0.20
Leading Edge Sheeting & Webs	87.3	0.19
Hinges & Attachment Hardware	59.3	0.13
Covering	39.5	0.09
Rudder Tab	125.0	0.28
Miscellaneous Secondary Structure	63.2	0.14
Miscellaneous	8.1	0.02
Rudder Total	623.3 gm	1.37 lb

	Grams	Pounds
Fuselage		
Primary Structure		
Fuselage Frame	2775.0	6.12
Tail Surfaces Attachments	90.3	0.20
Wing Mounts	50.7	0.11
Fittings	24.1	0.05
Lift Wire	366.4	0.81
Fuselage Primary Structure Subtotal	3306.5	7.29
Power System		
Gearboxes	1073.1	2.37
Propshaft & Driveshaft	384.2	0.85
Propeller	800.0	1.76
Propeller Pitch Mechanism	216.8	0.48
Cranks & Pedals	286.0	0.63
Miscellaneous Hardware	38.3	0.08
Power System Subtotal	2798.4	6.17
Landing Gear		
Main Landing Gear	286.6	0.63
Main Wheel & Axle	267.0	0.59
Nose Landing Gear	113.8	0.25
Nosewheel	60.1	0.13
Landing Gear Subtotal	727.5	1.60
Cockpit & Pylon Fairings		
Lower Fairing	1028.0	2.27
Upper Fairing & Ventilation Duct	350.0	0.77
Miscellaneous Structure	365.7	0.81
Windshield	171.0	0.38
Covering	47.6	0.10
Front Pylon Fairing	105.0	0.23
Cockpit & Pylon Fairings Subtotal	2067.3	4.56
Control System	236.3	0.52
Seat & Attachments	565.2	1.25
Water System (6 liter capacity)	212.0	0.47
Emergency Tow System	29.0	0.06
Instruments	120.0	0.26
Radio	300.0	0.66
Miscellaneous	564.6	1.24
Fuselage Total	10926.8 gm	24.09 lb
Aircraft Empty Weight	**31073.3 gm**	**68.50 lb**

cockpit fairing, and the forward section of the upper fairing. The lower fairing is reinforced with graphite/Rohacell foam stringers, while the upper fairing is stiffened by the built in, polystyrene foam ventilation duct. Most of the secondary structure on the cockpit fairing consists of graphite/balsa ribs and small diameter graphite/epoxy tubes. The cockpit area is covered with 0.0127 mm thick Mylar.

The control system consists of a single side stick, on the right hand side, for both rudder and elevator. A system of braided Kevlar lines and pulleys transmit the inputs to the control surfaces.

Because of the variation in pilot sizes, the seat can be moved over a 150 mm range to accommodate different individuals. The seat frame is made of 0.51 and 0.71 mm (0.020 and 0.028 inch) thick wall aluminum tubing and covered with a stretched nylon mesh. It attaches directly to the landing gear to reduce the loads on the fuselage frame.

Weight prediction formulas for HPA's

Based on the information in Table 1, and the analysis done to design Daedalus, several weight prediction formulas can be derived for components whose weight depend on the aircraft's size and configuration. These formulas, shown in Table 2, are useful during preliminary sizing and optimization of an HPA design. It should be noted that these formulas were derived for aircraft similar to Daedalus in configuration, dimensions, and construction. As a new design moves away from the Daedalus baseline in these three areas, the accuracy of these formulas diminishes. Thus, the equations should be modified accordingly as more accurate information on the particular design becomes available.

The weight of most other components cannot be expressed as functions of the aircraft size. These components are either a constant, independent of the aircraft size, or so dependent on the particular aircraft configuration that no attempt is made here to quantify them. Perhaps, with the assistance of the information in Table 1, the designer will be able to make estimates of these weights.

Acknowledgement

The author wishes to thank the MIT undergraduate students and other team members who built the Daedalus HPA, and recorded most of the data presented in this paper. Their attention to every construction detail made Daedalus an exception, rather than the rule, among aircraft; Daedalus is 0.68 kg lighter than its design goal.

Thanks are also due to Amoco Performance Products, Inc., for the donation of the high modulus graphite/epoxy materials used in Daedalus. Without these materials, the weight design goals of the aircraft would have been impossible to meet.

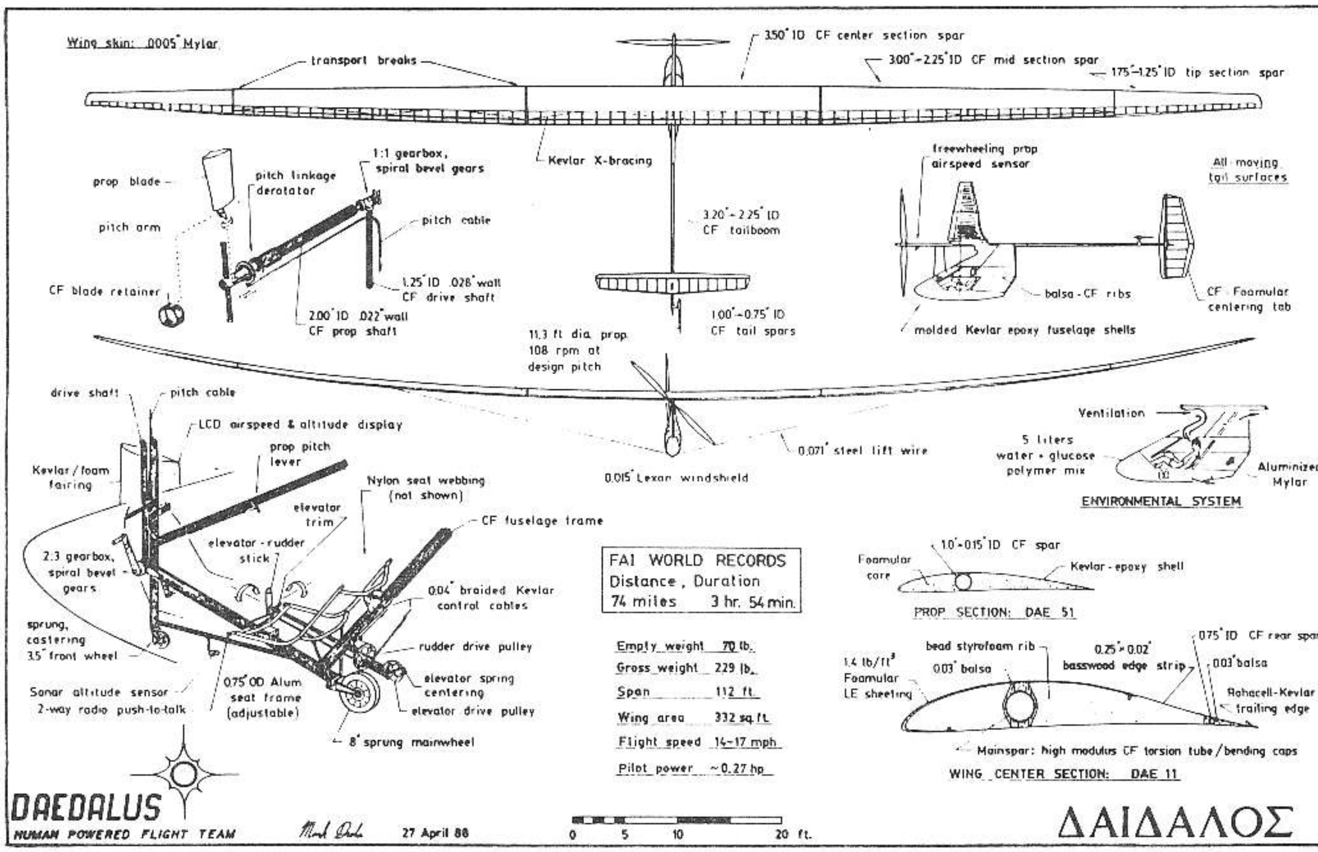

FIGURE 1

DAEDALUS HUMAN POWERED AIRCRAFT

Table 2
Weight Prediction Formulas for HPAs

Symbols

Wing or Tail Surfaces (Rudder or Elevator)

S_w, S_{ts}	= wing or tail surface area (m^2)
b_w, b_{ts}	= wing or tail surface span (m)
c_w, c_{ts}	= average wing or tail surface chord (m) = S_w/b_w or S_{ts}/b_{ts}
δ_w, δ_{ts}	= average rib spacing to average chord ratio wing or tail surface
N_{wr}, N_{tsr}	= number of wing or tail surface ribs = $(b_w)^2/(\delta_w*S_w)$ or $(b_{ts})^2/(\delta_{ts}*S_{ts})$
t/c_w, t/c_{ts}	= wing or tail surface airfoil thickness to chord ratio
N_{wer}	= number of wing end ribs = 2*number of individual wing panels−2
n_{ult}	= ultimate load factor
GW	= aircraft gross weight (kg)
W_{ws}, W_{tss}	= weight of wing or tail surface spar (kg)
W_{wr}, W_{tsr}	= weight of wing or tail surface ribs (kg)
W_{wer}	= weight of wing end ribs (kg)
W_{wLE}, W_{tsLE}	= weight of wing or tail surface leading edge (kg)
W_{wTE}	= weight of wing trailing edge (kg)
W_{wc}, W_{tsc}	= weight of wing or tail surface covering (kg)
q_m	= dynamic pressure at maneuvering speed (N/m^2)

Fuselage

L_{tb}	= tailboom length (m)
W_{tb}	= tailboom weight (kg)

Wing

Primary Structure

Cantilevered Main Spar

$$W_{ws} = (b_w*1.17e\text{-}1 + b_w^2*1.10e\text{-}2)*(1.0 + (n_{ult}*GW/100.0 - 2.0)/4.0)$$

One Wire Main Spar

$$W_{ws} = (b_w*3.10e\text{-}2 + b_w^2*7.56e\text{-}3)*(1.0 + (n_{ult}*GW/100.0 - 2.0)/4.0)$$

Multi Wire Main Spar

$$W_{ws} = (b_w*1.35e\text{-}1 + b_w^2*1.68e\text{-}3)*(1.0 + (n_{ult}*GW/100.0 - 2.0)/4.0)$$

Notes: A One Wire spar uses a single wire to reduce the bending loads on the inner section of the spar. *Daedalus* is an example of this structural configuration. A Multi Wire spar uses two or more sets of wires to reduce the bending and torsion loads on the spar. The *Gossamer Albatross* is an example of this structural configuration. A single tubular spar of high modulus ($E \geq 228$ GPa (33 Msi)) graphite/epoxy prepreg, similar to that on *Daedalus*, is assumed for all three cases. Fittings and other wing primary structure not included in this weight estimate.

Secondary Structure

$$W_{wr} = N_{wr}*(c_w^2*t/c_w*5.50e\text{-}2 + c_w*1.91e\text{-}3)$$

$$W_{wer} = N_{wer}*(c_w^2*t/c_w*6.62e\text{-}1 + c_w*6.57e\text{-}3)$$

$$W_{wLE} = 0.456*(S_w^2*\delta_w^{4/3}/b_w)$$

$$W_{wTE} = b_w*2.77e\text{-}2$$

$$W_{wc} = S_w*3.08e\text{-}2$$

Rudder/Elevator

Note: The same formulas apply for both the rudder and elevator.

Primary Structure

$$W_{tss} = (b_{ts}*4.15e\text{-}2 + b_{ts}^2*3.91e\text{-}3)*(1.0 + ((q_m*S_{ts})/78.5 - 1.0)/2.0)$$

Notes: A single tubular spar of high modulus ($E \geq 228$ GPa (33 Msi)) graphite/epoxy prepreg, similar to that on *Daedalus*, is assumed. Fittings and other primary structure not included in this weight estimate.

Secondary Structure

$$W_{tsr} = N_{tsr}*(c_{ts}^2*t/c_{ts}*1.16e\text{-}1 + c_{ts}*4.01e\text{-}3)$$

$$W_{tsLE} = 0.174*(S_{ts}^2*\delta_{ts}^{4/3}/b_{ts})$$

$$W_{tsc} = S_{ts}*1.93e\text{-}2$$

Fuselage

$$W_{tb} = (L_{tb}*1.14e\text{-}1 + L_{tb}^2*1.96e\text{-}2)*(1.0 + ((q_m*S_{ts})/78.5 - 1.0)/2.0)$$

Notes: A tubular tailboom of high modulus ($E \geq 228$ GPa (33 Msi)) graphite/epoxy prepreg, similar to that on *Daedalus*, is assumed. Tailboom length is calculated as the distance from the wing 1/4 chord to the furthest tail surface. In this formula, S_{ts} is the average area of the tail surfaces.