HOW A HIGH-SCHOOL STUDENT BUILT THE FIRST DUTCH HUMAN POWERED AIRCRAFT

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Abstract

In 2009 the first successful Dutch human powered aircraft (HPA) flew in the Netherlands, with a longest flight of 80 m in 2010. This HPA was designed, built and flown by a high-school student.
The document discusses the design process, test flights and why human powered flight is very difficult.

1 Introduction

On August 9th, 2009, the first successful Dutch human powered aircraft (HPA) took off at Kempen Airport, Netherlands. On July 18th, 2010, the longest Dutch HPA flight to date of about 80m-long was made. Remarkably, this HPA (named 'Abhilasha') was designed, built and flown by a high-school student. This document describes the background, design, construction, test flights and conclusions.

2 Project Origins

Around the age of 12 I became interested in flying. I read a lot about the development of the first aircraft including the Wright brothers' aircraft, because these aircraft look deceivingly simple to build. Most books about aviation also include a chapter on unusual and special aircraft, and a picture of a HPA as well. A huge aircraft being propelled and flown under sunny skies by a single human being seemed to be the holy grail of flight. I decided to experience this adventure too. It seemed great fun to board such a large aircraft, and then just pedal off into the sky. Famous and inspiring examples of HPAs are the Gossamer Condor (first to fly figure-of-eight) [1,7], Gossamer Albatross (flew from England to France) [1,7] and Daedalus 88 (flew from Crete to Santorini) [2].

Then, in 2004 I was about 14 years old. I started designing my own HPA since there were not any HPAs around nearby where I might get the experience of flying by muscle power alone. Human powered flight (HPF) is not common in the Netherlands. After two years of literature study and many design iterations I finally arrived at a design which would be relatively easy to build and fly. As a next step, I started 'Project Vliegfiets' ('vliegfiets' means 'flying bicycle' in Dutch) in 2006 with the goal to build and fly my own HPA, and began searching for a workplace and sponsors. The construction period took three years, because I also had to finish high-school and started my first year of my study in Aerospace Engineering at the Delft University of Technology (TU Delft). Test flying is described below.

3 The Challenge of Human Powered Flight

A human being has a very small power output, which is also heavily dependent on the duration of the output. Wilkie [3] has shown that for cyclists the average constant power output for more than a few minutes lies between 200 to 300 Watt, decreasing with increasing duration (Figure 1). The Daedalus Project team [5] have performed a study for cycling duration of 4 to 6 hours, which are essentially an addition to the data collected by Wilkie. It is important to note that for the HPA, the absolute power output is a design parameter, but for the pilot the specific power is a better choice. The specific power is a well-known parameter from the cycling world, and equals the pilot power divided by the pilot body weight in W/kg. This means that a lightweight or heavy pilot might not necessarily be the best choice for a given HPA design, and that there is an optimum.

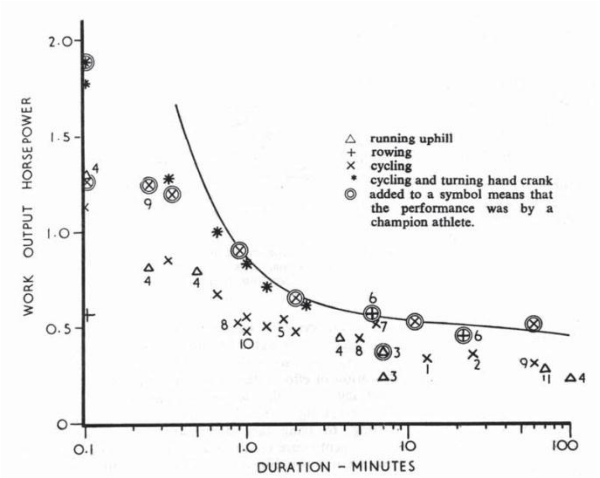

Fig. 1. Constant cycling power (*hp*) versus time (*min*). 'X' marks the 'average fit man' performance. Wilkie, 1960.

Record-setting HPAs will therefore be designed for athletes, which means that average humans can fly such HPAs for very short times only. Additionally, the pilot/engine cannot fully concentrate on producing power since the HPA also has to be controlled. This is an additional challenge. For long duration flights the pilot has to drink water (plus additives, if necessary) to prevent dehydration and maintain electrolyte balance. The weight of drinks can easily be 5-10% of the HPA empty operating weight (EOW), which increases the power needed considerably.

Using standard and simple equations for lift, drag and power as found in Tennekes [4], the problem becomes obvious. If we assume a pilot to have a mass of 70 kg and the HPA to have a mass of 40 kg, the total mass equals 110 kg (example). A HPA needs a huge wing, as one cannot fly very fast: power is proportional to the cube of the airspeed, while lift is proportional to airspeed squared only. With an maximum take-off weight (MTOW) of 110 kg, and assuming a reasonable lift coefficient equal to unity, typical flight speeds are 4 to 10 m/s. The wing areas range from 20 to 50 m^2 and wing spans of 20 to 35 m – all of this with an EOW of < 40 kg(!)

4 Design Goals

The design goals for my HPA are stated below. Actually, they are very common for almost all HPAs:

- capable of being flown by an average adult human
- capable of flying a few hundred *m* distance
- controllable in pitch and yaw
- able to start and land from hard surface (airport runway)
- easy to build; easy techniques and ubiquitous materials
- easy to repair

Most of the aforementioned goals have been met. A distance of a few hundred *m* is not achieved, although a trained cyclist could undoubtedly fly further than myself.

The 'easy to repair' goal was certainly valuable. Careful construction and ground handling resulted in virtually no damage for 3 years.

The aircraft was also relatively cheap. Material costs were a few thousand Euro. More expensive materials were not an option at that age. Undoubtedly, this meant a weight penalty and hence power penalty.

Still, the choice to use simple materials and construction techniques paid off here, because damage to a complicated composite structure would certainly have meant long repair times.

5 Design Issues

HPAs are very peculiar aircraft. For instance, wing spans of small airliner aircraft, but with EOWs less than the pilot's weight. As a result, they are very wind-sensitive, fragile and still experimental.

The trend in aircraft design over the last decades consists of making larger aircraft which need more power to fly, made possible by building more powerful engines. The power output of the human body can be regarded as constant, apart for individual improvements due to training. Improvement in HPA design through weight reduction has to come mainly from clever structures and new materials, together with a good aerodynamic design.

Although an estimated several hundred HPAs have been built and flown around the world, there are no plans or standardised design methodologies available. Consequently, I had to design my HPA from scratch. I immediately realised that it would be (too) difficult to design for maximum efficiency considering the knowledge, tools and budget I had. Of course, at the age of 15 you have not learned much mathematics yet. I tried then to learn as much of aerodynamics and structural engineering as I could understand.

Therefore, my HPA design became a good trade-off between efficiency, ease-of-construction and budget. Because of the highly iterative nature of the (aircraft) design process, a non-chronological, non-exhaustive list of design issues is given below, with an explanation of my HPA design method.

Material choice. An example is the choice of material for the main structure: composites are a good choice over aluminium or wood because of its specific strength but they are also more difficult to work with and more expensive. Of the three materials listed, aluminium proved to be the most promising.

Manufacturing. From a manufacturing point of view, HPAs can be thought of as being very large model airplanes (the radio-controlled type). The materials, especially the secondary structure, are the same lightweight materials as used in model airplanes. The primary structure might use more advanced methods using CNC machines, lathes for wood and metal parts, and autoclaves, mandrels and lay-up molds for composite parts. The wing ribs (Depron foam) were cut with high accuracy with a home-built CNC machine of an aquintance. Composites are quite expensive, and I did not have any experience working with such materials. Welding aluminium was also beyond my experience, so the HPA structure and especially its joints were designed such that they could be made using standard tooling. The design was also influenced by the dimensions of commonly available parts and ease of manufacturing. This is most obvious in the cockpit design, where I used the 'front triangle' of a standard bicycle frame to support the pilot. This frame included the bottom bracket with pedals as well and was attached as to the main cockpit frame. (Figure 3).

Concept, Structural design. The wing of a HPA is by far the most important part, since it constitutes a large part of the total mass and performance of a HPA. When looking at the wing, there are generally 3 concepts: cantilevered wing (Jupiter [1]), cantilevered with a single lift wire (Daedalus 88 [2,5]), and fully wire-braced (Gossamer Condor [1]). A study by the Daedalus Project [5] shows that for low speeds (<5 m/s), a fully wire-braced wing needs the least power. For increasing cruise speeds a single lift wire is the optimum, while at high speeds (>8.5 m/s) a fully cantilevered wing is the optimum configuration. For my design I did not consider cruise speed a limiting parameter. When selecting an aluminium primary structure, a fully wire-braced single-spar wing structure is the most lightweight solution of the three, and it meant automatically a low cruise speed. The wing structure (Figure 2) and the position of the wires make it a statically indeterminate structure. Calculating such a design was beyond my capabilities. By calculating parts of the structure as if they were statically determinate (force equilibrium and moment equations) and 'stitching' them together, I was able to obtain a good estimate of the forces.

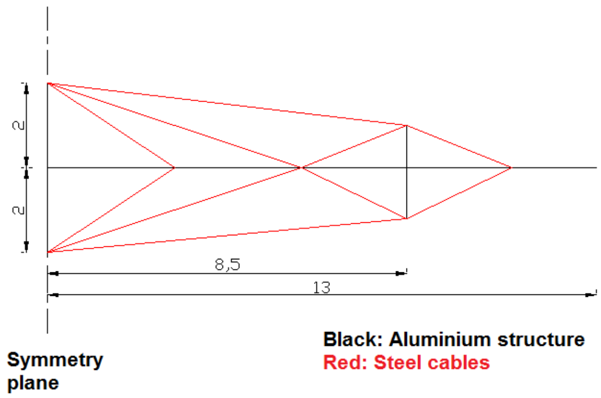

Fig. 2. 'Abhilasha' primary wing structure. Front view of left wing. Dimensions in *m*.

Computer analysis later showed that the largest discrepancies were up to 10% of the actual forces found in the structure.

The wing spar sections were checked for Euler buckling using the conservative assumption of pinned ends, while they were more or less rigidly joined by short pieces of aluminium tubing.

Transportability. It is very important, but not so obvious. The construction site was not located at an airfield. Therefore, one of the design criteria was that no parts could be longer than 6 m, so all parts could fit in the hold of a single small truck. Obviously this constraint adds weight to the aircraft in the form of extra joints and local reinforcements. Estimations by the Gossamer team [7] indicate that including transport joints and subsequent reinforcements the HPA EOW mass increases by 1-2 kg, i.e. by 4-6%.

Pilot position. There are generally two pilot positions found in HPAs: upright and recumbent. Which of the two is the optimum is still heavily debated. There is little difference in power output and it might also vary per pilot. Using a well-designed aerodynamic fairing, there is little difference in power needed between a upright or recumbent cycling position.

Originally the design incorporated a fairing around the pilot to reduce aerodynamic drag. The fully wire-braced wing called for a minimum cockpit height to reduce the stresses in the wires and buckling loads of the wing spar. This provided space for an upright seated pilot. Since I always ride standard (upright) bicycles and visibility is less when flying in a recumbent position, there was little question about the pilot position.

Aerodynamics. The low flight speeds and relatively small aerodynamic surface chords pose a challenge because the Reynolds numbers (Re) are small. Typical values are $5\cdot10^5<Re<1\cdot10^6$ for the wing and cockpit, $2\cdot10^5<Re<6\cdot10^5$ for the tail surfaces, and $Re\approx2\cdot10^5$ for the propeller.

Both turbulent and laminar airfoils have been used on HPAs. Laminar airfoils give a considerable improvement in 2D lift-to-drag ratio, but are sensitive to disturbances due to the low Re and the lightweight structure deformations (sagging of skin between wing ribs, for example).

The wing uses a non-laminar airfoil specifically designed for the HPA flight regime: Lissaman7769 (L7769). It was used with great success on the Gossamer HPAs [7] and several other HPAs. The tail sections have a symmetrical, low drag airfoil: NACA0009.

The propeller uses the Eppler 193 airfoil (E193) because of its good performance on model airplanes (same Re range) and was designed using simplified blade-element theory, much like the Wright brothers' propellers.

Control. The HPA was controllable in pitch and yaw through an all-flying elevator and rudder. Ailerons were not present since only minor course corrections for straight flight were anticipated. However, provisions for rotating wing tips for roll control were incorporated into the design. In any case, other HPAs show that rolling an HPA is difficult due to the 'apparent mass effect'. Most course corrections are therefore made by using roll-yaw coupling [6].

The wing would carry all lift loads, such that the tail would be unloaded during steady symmetrical flight. This is the reason for using symmetrical airfoils on the tail surfaces. On normal aircraft the center of gravity location is chosen such that the stabilizer needs to provide a small downward force to keep the aircraft stable. For HPAs, which have no power to spare, the downward force of the stabilizer and subsequent larger lift of the wing are unwelcome. Therefore longitudinal stability is traded for better aerodynamics, which is no problem with the large pitch damping found in HPAs [6**]**.

Fig. 3. Jesse van Kuijk flying his HPA at Kempen Airport (NL) in 2010.

6 Flight Tests

In spring 2009 the aircraft was fully assembled indoors to check the assembly. No flaws were found. For safety reasons the propeller spar got reinforced as the tip deflection was substantial during hard pedaling on the ground.

On August 9th, the wind died down completely in the evening, and runway access was granted after 8pm: the attempt to fly was GO. Assembly took almost three hours with six people. At 8.30 pm the HPA was ready at the end of the runway, clear skies and no wind at all. I rode some warming-up rounds on a normal bicycle, and boarded my HPA. The first few take-off runs did not succeed, as the aircraft was a little tail heavy. Subsequent slight down elevator during take-off solved the problem. Finally, the HPA got airborne two times that evening. Chain tensioner problems prevented longer flights as the chain would randomly jump off due to a faulty chain tensioner. After modifying the chain tensioner construction the aircraft was ready for new flights in summer 2010 (Figure 3). Unfortunately, I did not have time for major improvements.

On July 18th, 2010, the weather was good enough to try again. During one of the take-off trials, the left wing vertical post suffered damage and was repaired on the runway with a sawed-off broom handle and tape. Because flying should continue! That same day I managed to fly about 70-80 *m* distance using my own power, the longest HPA flight to date in the Netherlands.

7 Flight Results

- The structural design of the HPA was sound. There were no in-flight failures.
- Pitch response was very sensitive and effective because there is much damping around the pitch axis.
- Yaw response is unknown. The weather conditions where so calm that no directional corrective actions where needed to stay above the runway. By pointing the aircraft a few *deg* off the runway axis before takeoff, the aircraft was pointed into the wind direction (the wind was barely noticeable, but the large wing reacted to it).
- The fixed-pitch propeller proved acceptably effective at design speed, but was semi-stalled during the take-off run, as expected. See below.
- Stall characteristics were quite gentle. The drag increase of the wing close to C_{Lmax} is such that the aircraft will already start to slowly descent before full stall has developed. With a flying altitude of a few *m* maximum this means that there is no time or altitude for stall recovery, but the vertical velocity at impact is not of any concern. This is primarily due to the large wing surface which slows the vertical descent during stall.
- The largest distance flown was 70-80 *m*, at an altitude of 1 to 1.5 *m*. Distances of about 30-40 *m* have been flown a couple of times.
- The empennage was heavier than expected. As a result the center of gravity (CG) of the aircraft itself was more rearwards than expected. This posed no major issue, except that during flight the elevator was trimmed to provide an upward force to stay horizontal. This suggests that the CG was located very slightly aft of the wing spar, while it was designed to coincide with the wing spar location in longitudinal direction.
- Runway coarseness together with small wheels increases take-off power considerably, and much more than expected. Together with the off-design propeller conditions, it was decided to have a push-start. This prevented me from wasting a substantial amount of energy pedaling the propeller in stalled condition during the first few *m*. Take-off was then achieved by pedaling alone to qualify for true human powered flight.
- The forcing from the pilot pedaling made the structure shake a little, although this was not a big issue. Except for the chain tensioner, which could get

slightly out of alignment due to this forcing. This was the cause for the chain derailments in 2009, and a redesign of the chain tensioner solved this problem.

Overall remarks

- Assembly and de-assembly take two to three hours. This is not uncommon for wire-braced HPAs, but they are wind-sensitive. Therefore it is highly desired to reduce the (de-)assembly times, in order to protect the aircraft from rapid weather changes.
- The Mylar skin could have been tightened more by heat-shrinking to obtain a more smooth wing surface. Because it introduces extra stresses (which are difficult to predict) on the flimsy structure, it was avoided for the flight testing (Figure 4). As the last 70% upper surface of the L7769 airfoil is non-laminar, the effects of a non-taut surface are not nearly as large as found on laminar HPA airfoils [2]. Due to time constraints, the wing skin was never made fully taut.
- It is possible, with a proper design, to build such a large aircraft in parts up to a few *m* length, which can be assembled without problems at the first try. However, the aircraft was assembled indoors first to check all structural joints and wire lengths.
- Standard, high-speed bicycle chain is fully capable of handling a 90° twist under heavy bicycling loads. Although this might cause extra wear and fatigue of the chain, the total flight duration of most HPAs is such that this will never be a problem.
- Efficiency could be improved significantly using a better propeller. While the used propeller was good enough for the test flights, a new propeller with a minimum induced loss design might increase power efficiency by 10-20%.
- The small gap between the two center wing panels, where the connection with tailboom, fuselage and mast is made, might have contributed considerably to the required high power. In fact, there are essentially two extra wing tips. Analysis with XFLR5 software suggests that this gap increased power by about 8-10%. Therefore, great attention should be paid in creating a smooth and continuous wing shape in this area on future HPA(s).
- A wire-braced structure of this size is still quite flexible. The wires sag due to their length and the flexible aluminium structure. Accurate initial adjustments of wire lengths are very difficult. Best solution is to adjust wire length after examining photographs of the structure deflection during flight, if needed.

Fig. 4. Detail of the wing, showing wing ribs, main spar, Mylar skin and the author.

8 Conclusions and Future

This attempt proved possible to build a flying HPA with high-school knowledge of mathematics and physics, focusing the design on simplicity and efficiency. With a flight of 70-80 m and no failures, the project is considered successful. The HPA is on permanent display at the Aviodrome aerospace museum in the Netherlands.

With the knowledge gained by studying Aerospace Engineering at TU Delft I have designed a new HPA, which would be able to fly for several *km*. At the time of writing, I'm working with Japanese students to build a HPA based on my new design. We hope to finish in time to compete in the Japan International Birdman Rally 2012 (JIBR). JIBR is a large annual event for HPAs, where well-designed

HPAs compete for annual distance and speed records above Lake Biwa, Japan.

This new HPA has a primary structure consisting of carbon tubes, aluminium fittings and steel wire. The wing has a laminar airfoil and tapered planform. The cockpit will be improved as well, for pilot safety, efficiency and weight saving reasons. The propeller will be a minimum induced loss design, to achieve efficiencies in the range of 85-90%.

Project Vliegfiets:
www.projectvliegfiets.nl

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