UNKNOWN PROBLEMS IN HUMAN-POWERED HELICOPTER

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Abstract

Many have taken up the challenge of achieving flight in a human powered helicopter (HPH) and have not succeeded. The writer led a team that made four HPHs between 1985 and 1991 and made one HPH by himself between 1992 and 1993. The last one flew for the first time on December 5th 1993. Several valuable lessons were learned during the development of these helicopters. The past failures have been due to lack of knowledge of the fundamentals of human powered hovering flight and to poor mechanical design. The Sikorsky HPH Prize has encouraged a great deal of design activity, but, unfortunately, little actual research, especially concerning the aerodynamics of rotors very close to the ground. The purpose of this paper is to report some basic discoveries that we have made and to pass along some of our experiences to help newcomers to the HPH field.

Introduction

The dream to fly like a bird by purely human-power gave birth to human-powered aircraft (HPA). The first HPA "SUMPAC" to take off under human power was made in by students at Southampton university in England during 1961 and in the same year the first paper on HPH was presented by R. Graves showed that an HPH was just feasible.

HPA technology and achievements have been growing year by year. The MIT Daedalus HPA set the world distance record of 119 km in 1988. A successful HPH flight was not achieved until November 12th 1989, however, when the student team at Cal Poly, San Luis Obispo, took Da Vinci I into the air. On December 10th 1989 a flight of 7.1 seconds was demonstrated to an official witness. Although this was far less than required to win the Sikorsky Prize, it was a notable achievement.

Why is the success so difficult? What factors prevent so many HPHs from hovering? The writer hopes to shed some light on these problems in this paper.

Power for Hovering

The power P (watts) that a HPH requires for hovering flight was given by K. Sherwin in "Man Powered Flight" (with his equation converted to SI units):

$$P = 1.3\,K\,W\sqrt{\frac{W}{2\pi R^2 \rho}} + 0.78\,W\,V\,\frac{C_d}{C_l}$$

where the factor 1.3 is the hovering efficiency factor, W the all up weight in N, R the rotor radius in m, and V is the rotor tip velocity in m/s. Other symbols will be defined below.

The first term is the power lost in induced drag, and the second term is the power required to overcome airfoil drag.

Ground effect is a function of the ratio of the rotor radius to the mean height, h, of the rotor above the ground. K. Sherwin showed that K varied with h/R as line (1) of figure 1.

While this simple equation is basically correct there are considerable uncertainties regarding the ground-effect factor K and airfoil coefficients C_l and C_d. The most optimistic assumption for K is obtained by modelling the rotor as a thin disk that produces an instantaneous change in momentum of the flow (actuator-disk theory). Such models lead to lines 1, 2 and 4 in figure 1, and give very favourable (low) values for K. Another is to consider the ground as the line between the rotor and mirror image of the rotor in which case K becomes high, line 3 in figure 1. (Lines 2 and 3 are from S. Mouritsen.)

Until recently no one has succeeded in measuring K experimentally. Using models presents difficulties because of the very low Reynolds numbers and the relative inaccuracies in the configuration. Measuring from full-scale HPH is difficult because of the fragility of the whole structure.

We have been collaborating with Akira Azuma (emeritus professor at Tokyo University) in research into air foil characteristics at ultra-low Reynolds numbers, producing the data shown in figure 2. With these data and the lift coefficient C_l, we have been able to calculate the second term of the above power equation.

In 1990 we successfully measured the hovering power of small rotorcraft models, enabling us to calculate the first term of the power equation and to produce an empirical value of K line 5 in figure 1. This shows disappointingly, that the rotor blades have to operate extremely close to the ground to realize any worthwhile reduction of the induced drag.

In the same year we begun to make 1/20 scale models of Da Vinci III (USA), Vertigo (UK), A Day Fly and Papillon A and C (Japan). The hover power P (w) and the lift T (N) were measured to produce the efficiency represented by T/P (N/w) and are shown in figure 3. While these values from models should not be extrapolated directly to full-scale HPH, the relative values are instructive. In particular, the value for the machine that has actually hovered, Da Vinci III, is seen to be the highest, and must be taken to be the starting point for all future efforts.

Figure 3 also shows that a single-rotor HPH has a higher T/P ratio than a counter-rotating rotor HPH. But a single rotor HPH must have a reverse-torque system such as a tail rotor or a rotor-tip propeller which can result in a 15-20% percent loss to balance against the major advantage of the lower weight of a single-rotor system.

HPH with four rotors give the highest T/P. In the experiment with 1/20 models, the solidity is changed. As the solidity is increased the T/P increases. At the highest point of T/P, a deflector is put above the centre of 4 rotors. It is effective in further increasing the T/P ratio. Figure 4 shows these relations. These considerations were used in the fifth HPH “YURI I”.

Human Power Available

The power requirement discussed above is for smooth input power. The power required will be larger if the input torque fluctuates. There is also the possibility that a varying torque will set up vibrational instabilities in

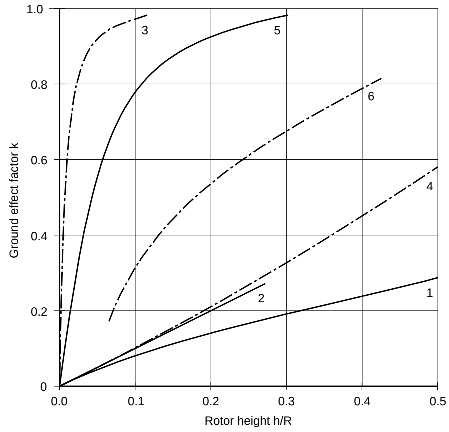

Figure 1. Comparison of k

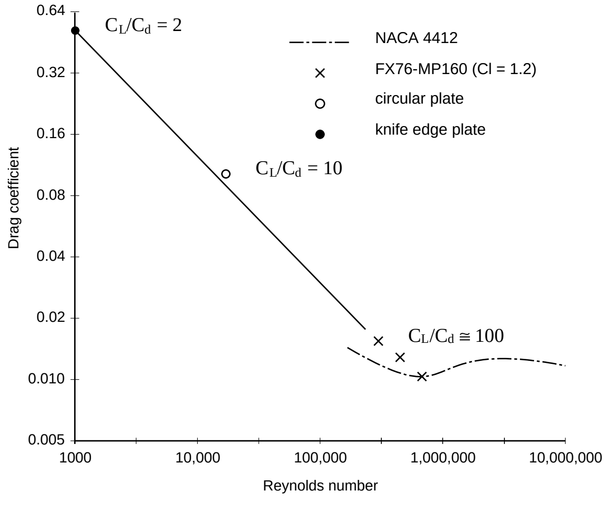

Figure 2. drag coefficient in ultra low Reynolds number flow

the rotor blades. But human power delivered by legs does fluctuate approximately as shown in figure 5.

We used four countermeasures. One was the use of an oval gear (figure 6) tailored to each individual pilot. The high-torque parts of a pilot's peddling cycle could thereby be smoothed. However, the oval gear could not produce output power where there was no input power the dead points could not be cancelled.

The second countermeasure was to use a 'cam spring' system of energy storage. The stored energy could then be released at the dead points. After lengthy tests on a bicycle we employed this system on Papillon A. It was effective in reducing the superimposed oscillations of the rotor blades.

The third measure was to use two pairs of one-way clutches. The pilot pushes the crank bars with the feet alternately instead of rotating the cranks. There are therefore, no dead points in this system, and it was applied to Papillon B and C. This system did not fit in pilot.

The fourth measure is to use a flywheel and oval roll. This system is applied to 4 rotors HPH YURI 1. These rotors turn by light cables that are winched in the oval roll by the pilot's pedalling. The flywheel is used to even the power input. This system works very well and YURI I succeeded to fly. We learned the effect of flywheel from Da Vinci

Other HPH Problems

There are other unsolved problems with HPH. Here we will discuss what we believe are the most important.

Slipstream near the ground

The flow around the rotating blades is entirely unknown. The stream is too complex to solve by the momentum theory and to model as an actuator disk. This In counter-rotating HPH is the case for a single rotor: for counter-rotating rotors we have even less insight.

Change of airfoil characteristics near the ground

An airfoil moving near the ground plane suffers considerable modification of its free-air pressure distribution. The negative pressure decreases on the upper surface and the positive pressure increases on the lower surface. The flexibility of HPH rotor blades makes the proximity to the ground uncertain even for a known pilot position.

Flow condition in the test space

Tests of HPH have been conducted principally indoors usually in athletic facilities because

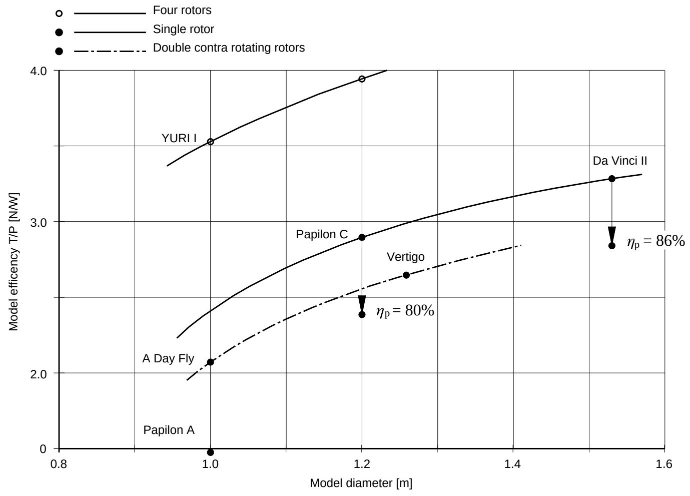

Figure 3. Comparison between 1/20 scale models

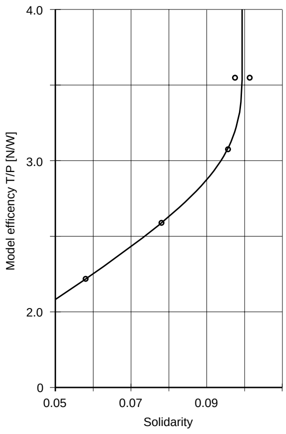

Figure 4. Change of model effiiciency with rotor solidarity

even very low wind would have a strong effect on performance. But as a test run in a large enclosed space proceeds, the rotor reaction can set the whole air mass rotating. Soon a large vortex ring is formed that acts to decrease the HPH lift. The volume of the air in the dome which we are using is 23,000 cu m. It is insufficient to provide relatively undisturbed condition for an HPH flight.

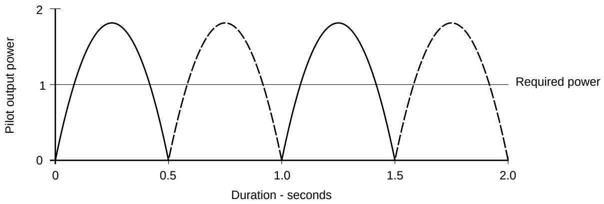

Figure 5. Pattern of pilot power

Structural problems

In contrast to the load on an aircraft wing, the load on a helicopter rotor rises strongly towards the tip. This produces a very high bending moment at the blade root. The pilot's pedal force also produces a high stress at the blade root. Large torsional stresses occur on the blades as they pass each other. All these large but somewhat uncertain loads make the design of the blade spar very difficult.

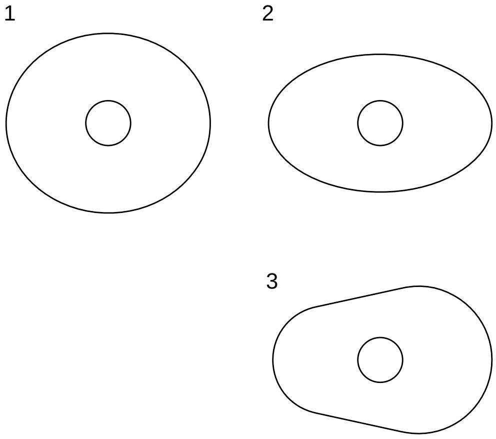

Figure 6. Alteration of the oval gear design
Slipstream near the ground;

Dynamic stability

When Da Vinci III succeeded in hovering the problems of dynamic stability of HPH began. The dynamic stability is affected by the position of the centre of gravity relative to the rotor disk. These problems were discussed fifty years ago in the early days of so-called "flying platforms". The conclusions were that the vehicle is dynamically stable with the CG just above the rotor disk and unstable with the CG just under the disk. However the conditions of "flying platforms" were very different to those for an HPH in which, for instance, the rotor blades rotate extremely slowly.

Da Vinci III was too unstable to be controlled however, YURI I is too stable to be controlled. The problem of the stability and the control has come as a new face in HPH field.

Conclusions

The problems of human-powered hovering flight have been discussed with the aim of giving some guidance to newcomers to the field to avoid some of the problems experienced by the author.

To design a successful HPH demands new approaches in aerodynamics, structures, mechanics, stability & control and physics, all virtually virgin fields in the unusual constraints of this endeavour. There are few reports and no manuals. Learning is largely through trial and error. The only way to shorten the road to success is to learn from the failures of others and to listen to the advice of experts in all the fields just listed. Over enthusiasm to have the dreams of HPH flight come true can lead to repeating past failures. We should learn from experience and avoid repeating mistakes.

Acknowledgments

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