

Design process of a Human Powered Helicopter

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Abstract

The paper outlines the 9 year design and development process that led to the first documented human powered helicopter flight.

Nomenclature

P	power
R	rotor radius
c	rotor chord
n	number of blades
wt	weight
ρ	air density
C_{d0}	drag coefficient
W	angular velocity
I_{xx}	moment of inertia about the x axis

rotation about the 'x' axis will be ϕ and the rate is $d\phi/dt$

rotation about the 'y' axis will be θ and the rate is $d\theta/dt$

rotation about the 'z' axis will be ψ and the rate is $d\psi/dt$

Design Process

A design team has two distinct and very different tasks. The first and most difficult is to determine the layout and configuration of the artifact being constructed. In the case of a totally new object, no human powered helicopter was currently flying, the task is indeed formidable. The conceptual design, or invention, was carried out in 1981-82 and has been the basis for all further development. One of the jobs of the manager/advisor is to keep new members of the team focused on the original concept and not have the team fall victim to the "not invented here syndrome".

The second task is to design the components that will be used to allow the artifact to achieve its goals. This task is, component design or simply engineering. It is the kind of design taught in engineering schools. The only problem occurs when the needed components are not like anything seen before. Then we are back to step one on a smaller scale. We are then asking our design engineer to be an inventor.

Conceptual Design

The Human Powered Helicopter project at Cal Poly began during the winter quarter of 1981. AHS offered a prize to be given for the first hover under human power. How was such a

machine to be configured? Torqueless drive is the obvious system of choice, the power plant is limited and the losses generated by a tail rotor could not be tolerated. Later, it became obvious that the side ward thrust of the tail would also demand a sophisticated control system.

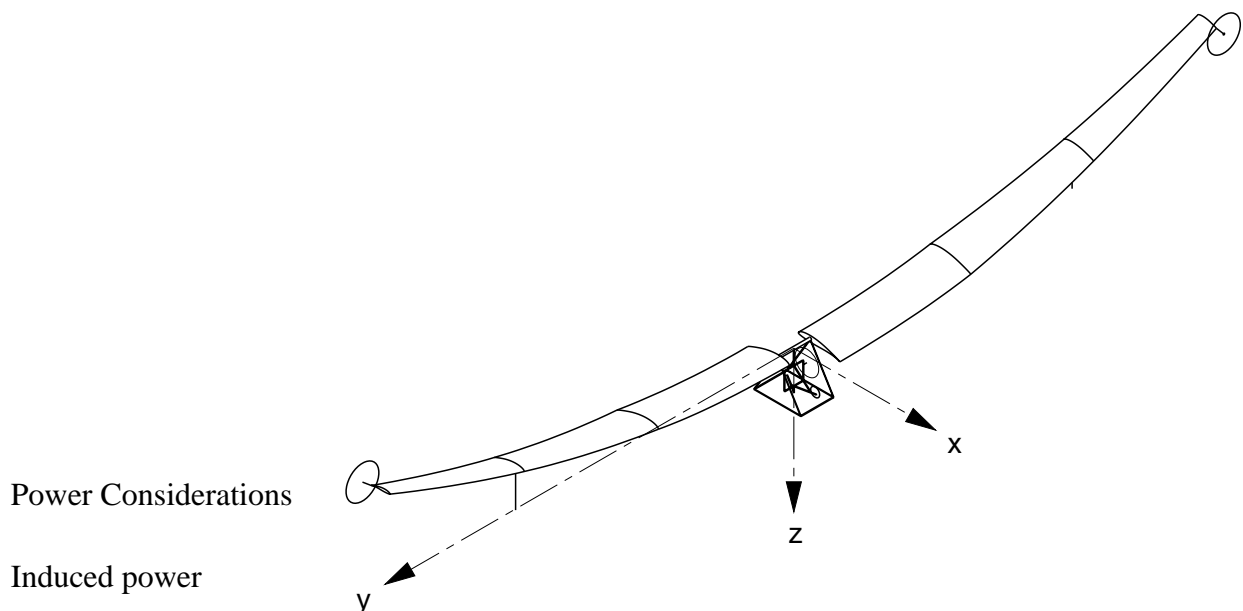
Three systems were considered:

- single rotor, tip driven
- dual rotor (either tandem or coaxial)
- multiple rotor

The current configuration of the successful Japanese entry was not considered. We all felt that multiple rotor heads would decrease efficiency. The number of rotor blades was always a consideration. A large number of rotor blades would impose a weight penalty and would increase profile drag. The minimum number of blades was considered to be beneficial. Again, this may not be as important as we had anticipated. Our successful competitors have 8 blades and have suffered no loss in performance.

The tip driven configuration had several disadvantages. The driving propellers would be some distance from the power source, so the drive system would be more complicated and would suffer additional losses. The system would also require new propellers to be designed and constructed for any change in tip speed or power requirements as the Da Vinci evolved.

The dual rotor coaxial system would have a more compact drive mechanism but would need a minimum of four rotor blades, two for each rotor head. The tandem rotor system would use four rotor blades and would also require an extensive support structure. The decision was to try to fly with a tip driven system because it could be flown with only two rotor blades. See Figure 1.



Induced power is the power needed to generate lift. It is the predominate power requirement in a hover. Happily, induced power is reduced significantly near the ground. (in ground effect, IGE).

Cursory analysis of the induced flow indicates that a human powered craft with a gross weight of 200 lbs. will need a very large rotor to hover out of ground effect (OGE), see ref. 1.

$$P = [wt^3 / 2\rho\pi]^{1/2} / R$$

for $P = 0.8 \text{ hp} = 440 \text{ ft lbs/s}$, $wt = 230 \text{ lb}$

$$R = 65 \text{ ft}$$

Profile power

The above does not include Profile power, which is the friction and form drag needed to move the rotor through the air. The pilot must also provide the additional power for this purpose.

$$\text{profile power} = C_{d0} n \rho R^4 W^3 c / 8 = 0.1 \text{ hp}$$

Ground effect

The first effort was to determine the effects of ultra low in ground effect (IGE) on induced power. Much effort was spent with electrically driven model rotors showing that as the rotor approaches the ground plane the induced flow and the induced power is indeed sharply reduced.

The test data are difficult to scale up to da Vinci size. Current expectation is that induced power necessary to hover is indeed less than 50 per cent that for OGE.

The Leonardo da Vinci project can be clearly understood by looking at the five major components separately. These components are: the rotors; the propellers; the centre section; the drive system; and the control system.

Rotors

Da Vinci I

The purpose of the rotors is to provide the lift necessary for flight. Originally a tip speed of 35 fps was imposed for safety reasons. This fiat put success back by a period of 3 to 4 years. Using the limitations imposed on them, the students designed a tapered and twisted rotor blade system that was very similar to the successful craft that flew 8 years later. The main structural member of the Da Vinci I was a 4 in. diameter carbon graphite beam with an 8 degree wrap to withstand the 6000 ft-lb. bending moment. The main spar failed its static test. The rotor was then raised to 4 ft. above the ground. This allowed a guy wire to be used to relieve bending moment stresses. The airfoil was a Liebeck design. The chord tapered from 6 ft. at the tip to 8 ft. at the root. The twist was linear -6 degrees.

Da Vinci II

The next generation rotor blades were designed using numerical analysis. The decision was to conquer the performance problem with size. The new blades were built with no taper and no twist. The radius was increased to 70 ft. possibly the largest rotor system ever built. The problem was that the new machine was not stable and crashed upon liftoff.

Da Vinci IIB

The rotor system was a 120 ft rotor with a tapered chord. it was tested a Vandenberg AFB during the spring of 1989.

Da Vinci III

The rotor system was reduced to 100 ft. with smaller chords to use a higher tip speed.

DaVinci IV

The rotor system will be similar to successful craft but with lighter structures.

Propellers

Da Vinci I

The propellers function is to provide the drive to turn the rotors. The initial props were built by hand and were just made to look correct. No analysis or test was attempted. The first props were never used. During the hiatus of 1983 while the drive system was being sorted out, a proper set of props were designed and built using the Larrabee derivations for a minimum induced loss propellers. The props were produced in a mold using expanding foam. They were then covered by fiberglass or kevlar. The design criteria were to use minimum power at 35 fps at 8 lbs. of thrust turning 350 rpm. This allowed the props to absorb approximately 1 HP.

Da Vinci II-IV

The new craft had a much higher tip speed and needed less thrust. Flight attempts with the old props indicated that they were inadequate to operate in the different of a flight regime and were subject to quality control problems. New props, optimized for a higher speed and lower thrust were needed. The decision was made to redesign the props and to test them thoroughly before use. Each new prop is now built according to the same set of equations but is carved by hand out of balsa and covered by mylar. The props were then tested in a NASA Ames wind tunnel. The successful test gave the crew a great deal of confidence in their performance. This propeller design is currently in use and will be applicable for all future machines that fly at a tip speed of approximately 55 fps. A severe stability problem was encountered during actual flight. Very small differences of propeller thrust create a pronounced swirl of the center section. Present plans for future stabilizing systems will not be able to overcome propeller thrust problems. The Da Vinci IV props must be adjusted precisely for a successful record attempt.

Center Section

Da Vinci I

The center section supports the pilot and the main rotor blades. Originally the pilot was above the blades and the rotor head was very near the ground. The rotor blades were cantilevered in order to keep the blades as deep in ground effect as possible. Failure of the main spar during tests demanded the use of guy wire system so the rotor head was elevated 3.5 feet. Later the

sprocket and chain to be added. The slight increase in weight was offset by the ease of changing gears on the new craft.

Da Vinci IV

Current design is under review, see ref. 2.

Control System

The system as flown during 1989 was unstable. The control system will consist of a weight shift of the pilot in the rotating system. Only instabilities due to rotations will be addressed. A rotating axis system must be defined.

'x' axis is perpendicular to the rotor axis in the horizontal plane.

'y' axis out the rotor axis.

'z' axis points down to form a right handed system.

The rotors are contemplated to weigh 65 lbs. or to have a mass of two slugs. They can be modeled as a slender rod 100 ft. long. Common practice includes the mass of air contained in the wing cylinder (1 slug) when finding I_{xx}

$$I_{xx} = 1/12 \times 3 \times 100^2$$

$$I_{xx} = 2500 \text{ slug ft}^2$$

$$I_{zz} = 1/12 \times 2 \times 100^2$$

$$I_{zz} = 1700 \text{ slug ft}^2$$

The moment of inertia about the wing axis is very low. We assume the pilot is a point mass of 4 slugs at 3.5 ft. The system is chosen for convenience not at the mass center, and does not include coning of the rotor system.

$$I_{yy} = 50 \text{ slug ft}^2$$

The major instability seems to be produced by a rotation about the wing axis ' ϕ '. This rotation changes the lift on the rotors and produces a very large moment along the negative 'x' axis.

Each rotary wing produces 150 lb. of lift at a pitch of approximately .15 radian above zero lift. So the force generated on the right wing of a pitch ' θ ' is $+1000\phi$ and the lift on the left wing is -1700ϕ . The lift vector occurs at $3/4$ radius which produces a moment about the 'x' axis of $-125,000\phi$ ft. lbs.

Remember that we are in a rotating frame, so the moment equations must include coriolis accelerations. Hz is -1700 because $\frac{d\psi}{dt}$ equals -1 rad/sec. The moment equation about the 'x' axis is as follows.

$$M_x = I_{xx} \frac{d^2\phi}{dt^2} + (I_{zz} - I_{yy}) \frac{d\psi}{dt} \frac{d\theta}{dt}$$

$$-150000 \theta = 2500 \frac{d^2\phi}{dt^2} + 1650 \frac{d\theta}{dt}$$

The weight of the pilot provides a small restoring moment about the 'y' axis.

$$M_y = I_{yy} \frac{d^2\theta}{dt^2} + (I_{xx} - I_{zz}) \frac{d\phi}{dt} \frac{d\psi}{dt}$$

$$-500 \phi = 50 \frac{d\theta}{dt} - 800 \frac{d\phi}{dt}$$

We can use a step function movement of the pilot as a control, or add aerodynamic surfaces to stabilize the system. Figure 2 is a plot of roll versus time.

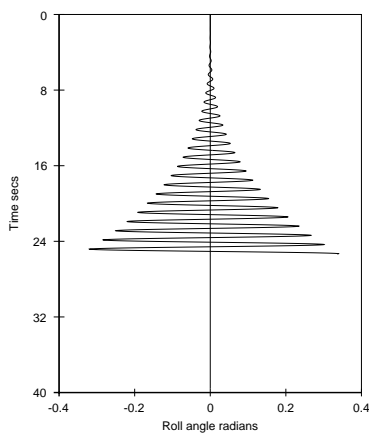


Figure 2

We will attempt to fly with an open loop controller. The rules are somewhat vague on the subject. For a more complete analysis see reference #3.

Wish us luck!

Reference

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2. Human Powered Helicopter: The Next Sam, Wm. B. Patterson, Fourth International Human Powered Vehicle Scientific Symposium. 1994.
3. Control of a Human Powered Helicopter in Hover, Joseph Totah and William Patterson, NASA Tech Memo 101029 1988.