

Fig 1. Pilot power output. The tests were carried out on a competitive cyclist (not a peak fitness) and the results show good correlation with Wilkie's 1.

From existing data on the power available from an athletic pilot, it became apparent that any design would only work within ground effect so effort was concentrated on designing a pure ground effect machine. Equally important was weight saving and it was decided that the problems associated with adequate control and stability would have to be secondary to obtaining a low weight and hence low power requirement machine. Bicycling has proved to be the most efficient method of both extracting and transmitting power and the design maximum power to achieve lift off was set at 300 W and the peak maximum limit set at 740 W for 20 seconds. The pedal crank speed would be less than 90 rpm for lift power and between 90 rpm and 120 rpm for the peak value (Fig 1). The effect of the ground becomes significant, at a height (Z) of less than one rotor diameter (D). In ground-effect more weight can be lifted for the same power (thrust) than out of ground effect (Fig 2). Most helicopters, due to the position of the fuselage and landing gear, have a minimum Z/D value of 0.3 and at this height, at least a 30% increase in thrust can be expected. Z/D values below 0.3 are predicted as having a significant effect on reducing the induced power requirements (Fig 2). A test programme to investigate values in the 0.1 to 0.3 range was a failure as there were unquantifiable scale effects and variables, which made reliable measurement extremely difficult. However, it was decided to continue design work on the basis of the existing, but unsubstantiated, data. Hence in order

\* Vertigo project leader and formerly product assessment engineer at Westland Helicopters Limited. He is an EITB fellow in manufacturing management and is now a production and inventory control consultant. CMCL, The Hall, North Cheriton, Templecombe, Somerset BA8 OAE. Wincanton Tel: (0963) 32817

The American Helicopter Society's Igor I Sikorsky Human Powered Helicopter competition (prize \$15000) is for the first man-powered helicopter (MPH) to hover for one minute, whilst reaching a momentary height of three metres. The other main stipulations are that the crew(s) must not rotate and the aircraft must remain within a 10 metre horizontal square. The competition provided the impetus for the design and construction of an MPH to be undertaken as a graduate trainee project within Westland Helicopters Limited. Designing a practical aircraft was started in September 1980 and this article, based on a recent comprehensive paper, gives a broad outline of how the task was carried out. The team did not achieve sustained hover but the project gave rise to a cautious sense of optimism that flight by MPH may well be possible.

## Pedalling towards a vertical take-off

by A D Cranfield\* BSc

to get the rotors as close as possible to the ground, it was decided to position the pilot and transmission above the blades.

### Basic aerodynamics

Since all man powered aircraft operate at Reynolds Numbers of less than  $1 \times 10^6$ , special aerofoil sections have been developed in recent years. The aerofoil best suited to the MPH was specially developed by Aeroenvironment Inc for the Gossamer aircraft. With an 11% chord thickness ratio, the actual blade chord was, for this MPH, primarily governed by structural aspects. Typically, profile power is 25-35% of the total power requirement and hence a low rotational speed is required. The induced power is dependent on the all up weight (AUW) of the helicopter. This means that any design has to trade off the low thrust

requirement and the need for high aspect ratio blades with large radius (for high lift/drag ratios) whilst keeping in mind the low disc loading criteria (for low disc loading criteria (for low down-wash velocities)). A conventional tail rotor would not only have consumed 10% of the total available power, but generated no additional lift whilst incurring an associated weight penalty. With a coaxial contra rotating twin rotor (CCTR), the pilot support structure is minimised, the transmission is compact and the overall size reduced to manageable dimensions. The preliminary stressing of the blades showed the optimum rotor radius to be less than 12 m in terms of acceptable stiffness and strength for weight. Historically a CCTR design is considered to have 1.5 effective disc areas only but initial calculations established that 150W was sufficient to

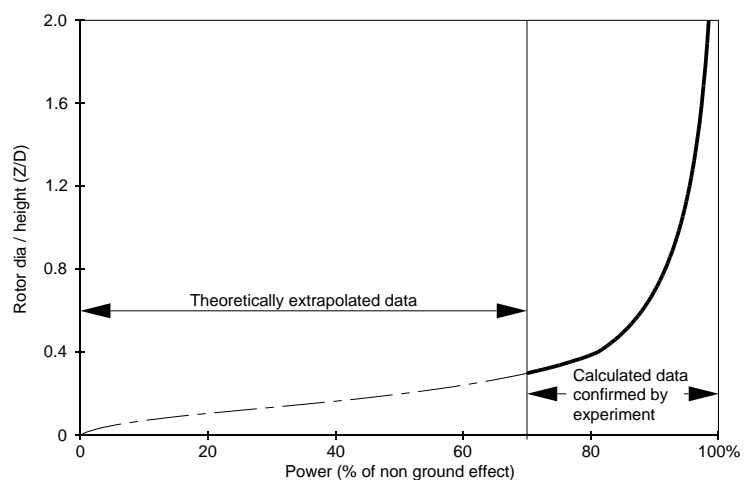


Fig 2. Ground effect on induced power requirement in the hover. The power is expressed as a percentage of the power required to hover out of ground effect. The Y axis is the ratio of rotor diameter to height above the ground.

hover at a height of -0.3 m. At 3 m the power requirement had increased to 300 W. We were fortunate in having access to a computer model developed for the accurate prediction of the hover performance of a CCTR 2 and experimental results compared well with the model. Modifying the program to take into account ground effect, the hover performance was computed (Fig 3). It can be seen that from a purely aerodynamic standpoint the AHS competition height and endurance requirements are theoretically achievable. A hingeless rotor hub was a necessity as the low centrifugal loads meant that if the blades were allowed to flap freely they would assume a coning angle of 80°. It was also possible to dispense with dampers in the lag and flap planes since the aircraft was designed to

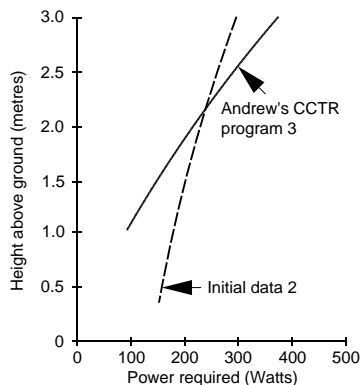


Fig 3. Calculated hover performances for an initial design of 90.7 kg. Andrew's program 2 also showed that the CCTR induced power requirement is reduced by about 5% when compared to a single rotor.

operate in the hover mode only. It was decided to adopt fixed rotor hubs, rotor speed being the only means of varying thrust. For primary control, it was decided to adopt a simple form of pilot weight shift, identical to that used on hang gliders.

### Design description

The four rotor blades (Fig 4) are identical in construction and planform with a 1.5 m chord and a radius of 12 m, the upper rotor coning angle being taken at 9° and the lower rotor being set at 6°. The square box load-bearing spar (Fig 5) is located at the centre of lift and has a depth of 0.163 m. The spar caps consists of a Aramide Nomex honeycomb bonded by an adhesive film to the carbon fibre skins. The side walls are of foam bonded to the skins. The ribs are also foam capped with carbon strips. The leading edge is formed by expanded polystyrene supported by the ribs and a length of 5 mm wide carbon/Nomex sandwich strip running spanwise

at the nose. The skin is Du Pont Mylar film, heated to shrink fit. The blades are one-piece construction and attached to the hubs by 16 x 3 mm bolts. In plan view, the top rotor rotates clockwise and the lower anti-clockwise. The two carbon fibre drive shafts are driven by bevel gears which are in turn powered by a chain driven pinion gear (Fig 6). The alloy hubs are riveted to the drive shafts and lightweight ball and roller bearings are used to locate and support the drive shafts. The bevel gears have straight cut teeth and are riveted to the shafts and tube. The pedal spindles are of titanium and lightened alloy bicycle cranks are used. The pilot's support structure is similar to a racing bicycle with the centre of gravity directly over the centre line of the transmission. The undercarriage is a quadrapod with foam feet at the leg ends.

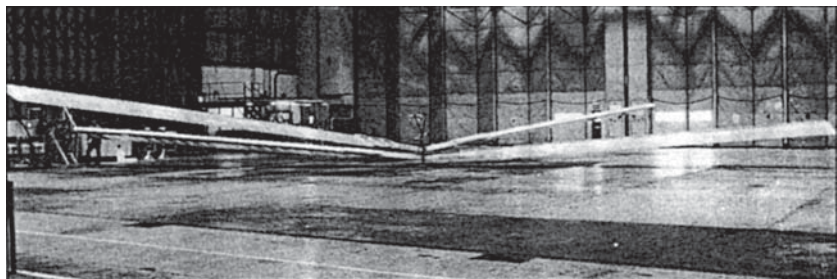


Fig 4. Vertigo fully assembled. The coning angles of the blades were set so that they did not strike each other and to give good ground clearance for the bottom rotor

### Constructional aspects

Carbon fibre was used as the primary structural material for the rotors because no other material can offer the same strength to weight ratio. They were made using a dry lay-up technique, in which the carbon fibres are obtained in resin pre-impregnated sheets. For the spars a honeycomb material of 48 kg/m<sup>3</sup> density, used in conjunction with a lightweight film adhesive, gave the required cap strength. Further tests showed that two full width plies of carbon fibre per side were required for the caps at the root end to help distribute the hub/blade retaining bolt loads. The honeycomb, with its 3 mm hexagonal core, was susceptible to being crushed inadvertently during curing unless very careful control was exercised over the press consolidation pressure. The first stage of the cap manufacture was the bonding of the sized honeycomb core with a cold cure epoxy resin system with a lightweight phenolic microballoon filler. The first spar was load tested and failed below proof load; the prime cause was due to poor bonding between the foam side-walls and the skins. A change of adhesive and revision of surface

preparation procedures of the skins and foam cured the problem.

### Blade assembly

The ribs were cut out, bonded to the spar sidewalls and a single ply of carbon was bonded on as a capping strip. Mylar shrinks more in one direction than another and it was applied so that it shrank predominantly in the spanwise direction giving a smooth surface with the minimum of sag between ribs. The undercarriage legs were constructed by laying up alternate plies of 0° and 45° carbon fibre, tapering the wall thickness down from 1.66 mm at the root end to 1 mm at the tip. The feet were made in moulds out of high density foam and then bonded into position. Each leg was subject to a 90.7 kg proof loading to simulate a worst case landing on one leg.

### Testing and development

The first assembly showed that the most time-consuming part was fitting the blades to the hubs. This operation also showed up the vulnerability of the foam sidewalls at the root end. It proved almost impossible to avoid damaging the foam during assembly.

### The First trial

On turning the blades by hand it was seen that the trailing edge of one of the top blades was just touching one of the lower rotors at 1/3 chord. However, the possibility of blade damage was not considered great. Design faults and material failure in the transmission limited the power the pilot could produce since he was unable to pedal smoothly. Maximum rotor speed was 3.5 rpm, highlighting the need for a transmission rebuild and the incorporation of a chain tensioner. The major problem was that as the blades approached on crossover, an aerodynamic interference caused the top rotor blades to pitch down and then flap down onto the lower blade. Despite this pulsing, the pilot felt the aircraft was perfectly stable at 3.5 rpm and he found he could effectively control the rotor disc tilt very easily by weight

shift. It was not possible to determine how much lift, if any, was being produced.

### The second trial

The main object was to investigate the aerodynamics further. Only the lower two rotor blades were fitted, both being wool tufted so that a better idea of flow visualisation could be gained. Rotor speeds of up to 5 rpm were achieved and the tufts indicated that the flow appeared to be behaving in the classically predicted

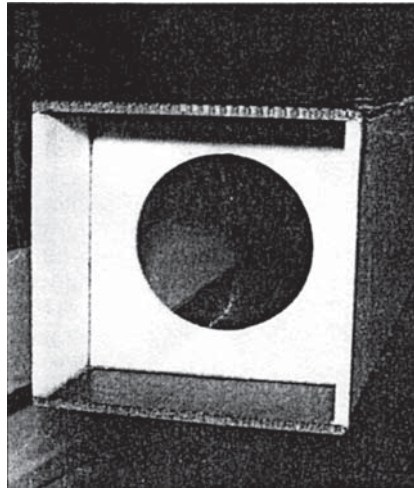


Fig 5. Details of the spar. The final version used Araldite resin AY 105 and Versamid 140 hardener with Aerosil micro balloon filler for the foam/carbon fibre interface for satisfactory peel strength.

fashion. It was now apparent that the main operational constraint, apart from the aircraft problems, was the size of the hangar. The blade tips were at places less than 2.5 m from the hangar walls and as a result wake recirculation was occurring. This had the same effect as if the aircraft was flying in sinking air therefore requiring greater sinking air therefore requiring greater power output.

### The third trial

The object of this trial was to gain an idea of the flow over the top rotor blades as well as both rotor blades as well as both rotors together and assimilate the results of transmission and assimilate the results of transmission rebuild and gearing change, which allowed the rotors to turn at approximately 5.5 rpm. While the wool tufts on the top blades showed a very similar pattern to the lower rotor, at the exact point of crossover, reverse flow was seen to take place momentarily on the lower rotor. At this speed, however, the severity of the pulses was such that after running for a few minutes the top blade foam sidewalls fractured at the root end. The pilot felt at this stage that only

continuing transmission problems had prevented him from increasing his power output. In order to investigate the transmission problems further the top blades were removed and the lower rotor spun up. At 6 rpm the blades started to show signs of generating significant lift; this was confirmed as the aircraft began to skip around the floor. Higher speeds were not investigated so as to avoid over stressing the blades. The pilot considered he was producing less than half his potential power. Close examination of the transmission, in particular the pattern of wear exhibited by the gear teeth, indicated that the pinion gear bracket was bending outwards under load thus allowing the teeth to jam momentarily at peak loads, as had appeared to have happened during the trials. The problem was further compounded by suspected flexing of the drive shafts, bending of the stem tube and lack of rigidity at the crank/stem interface. It was thought that a quick and relatively easy solution to the aerodynamic problems would be to increase both hub separation and blade root cut out. In the area of the transmission, the pinion gear bracket was redesigned as the original was suspected of bending outward due to high thrust loading. The carbon fibre frame crank/spigot assembly was replaced by a similar aluminium alloy assembly incorporating reinforcing webs in order to avoid chain misalignment. Other modifications were also made to strengthen certain components. Further extensive trials showed that the main problems still existed to a degree which limited the power input. In addition there were indications that stability and control were adversely affected. To what extent wake recirculation was attributable to these problems was not clear, but it is certainly an area requiring further investigation.

### Conclusions

The results of the trials were encouraging but the dynamic pulsing requires a redesign of the hubs, possibly to incorporate either teetering or restricted flapping hinges. Further development is being carried out on Vertigo with encouraging results. However, a great deal of further work has to be done if flight by MPH is to be achieved and the competition won. It is interesting to note that a group at Nihon University in Japan has built a rigid rotor hub machine virtually identical in configuration to Vertigo. It is known that very similar dynamic problems are being encountered by the group.

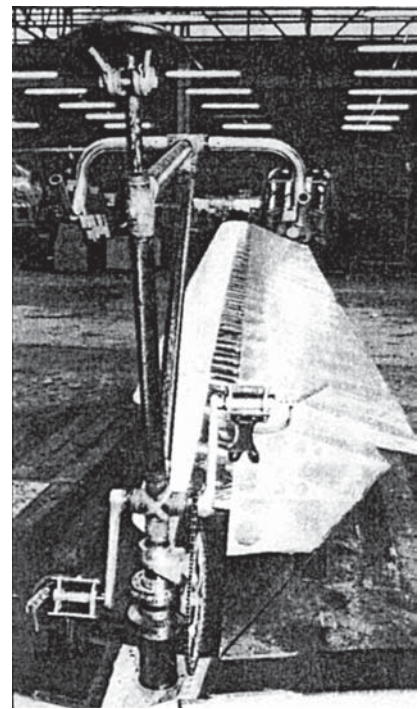


Fig 6. The frame and transmission. The pilot frame tubes were first lightly bonded into position and checked for alignment then woven carbon matting and tows were used to reinforce the joint. Glass fibre tape was then tightly wound around the joints to force out surplus cold cure resin and provide additional local reinforcing. When comparing identical components, a composite item gave a weight saving of between 30% and 40% over the aluminium alloy item it replaced. The termo setting prepreg used has a UTS three times greater than aluminium alloy for approximately half the density.

### References

1. Wilkie D R, 'Theoretical and practical considerations in harnessing manpower', Proceedings, RAGS Manpowered Aircraft Group symposium, February 1977.
- 2 Andrew M J, 'Co-axial rotor aerodynamics in hover', Vertica Vol 5, 1981.