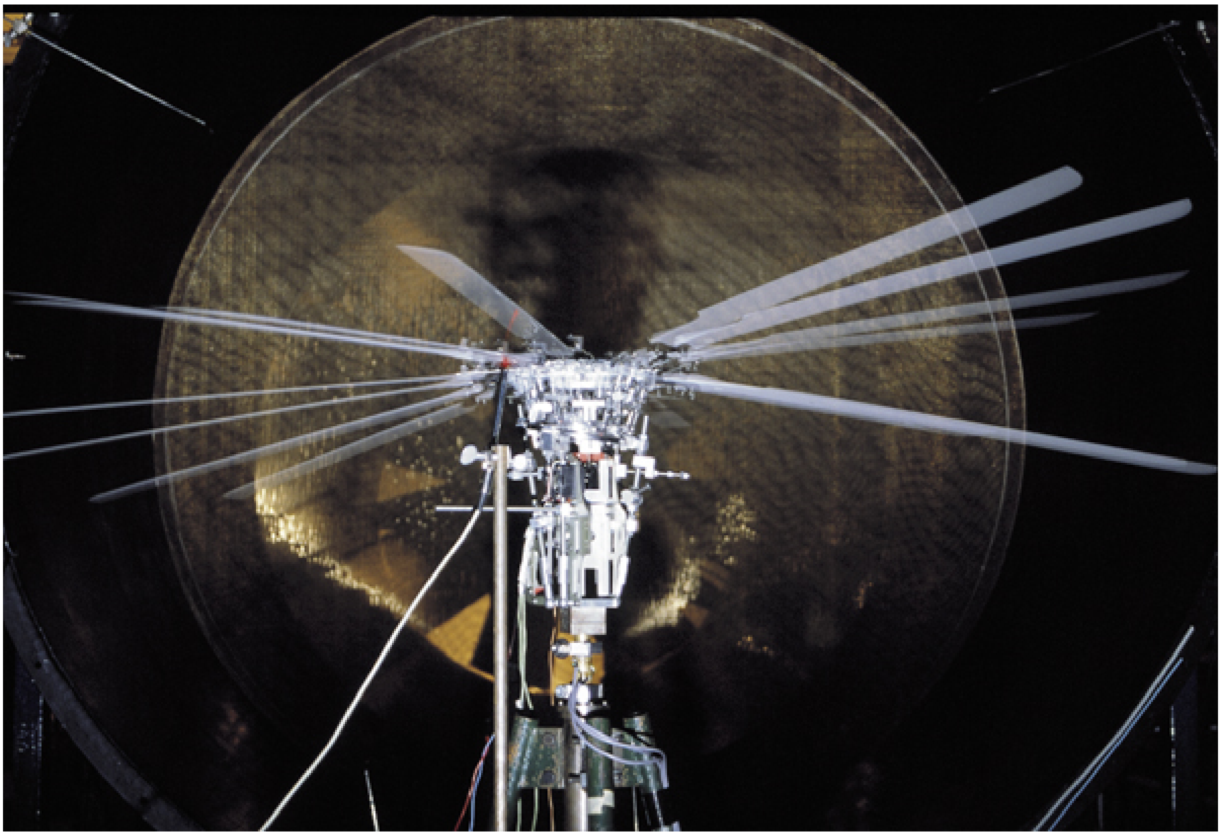
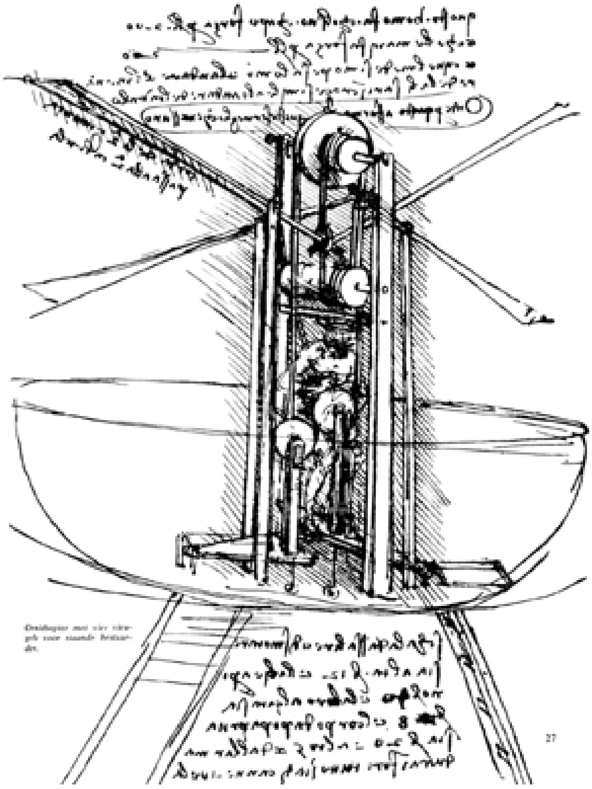
A helicopter that flaps its wings

The Ornicopter flaps its wings like a bird to get into the air





by Bennie Mols

No other type of aircraft is as manoeuvrable as a helicopter. Reverse in full flight, rotate in the air, hover at a standstill, the helicopter can do it all. The police, fire services, medical services, military and civil aviation all use the helicopter for the freedom of flight it offers. However, the helicopter's tail rotor remains a hazardous, energy-consuming, and noisy contraption. Although the NOTAR system offers an alternative by replacing the tail rotor with an adjustable air jet, it too is far from perfect. Aeronautical engineers at Delft University of Technology think that by flapping a helicopter's main rotor blades like the wings of a bird they can dispense with the tail rotor and avoid the drawbacks of the NOTAR system. Increased freedom of movement by flapping like a bird. They have dubbed their new brainchild the ornicopter.

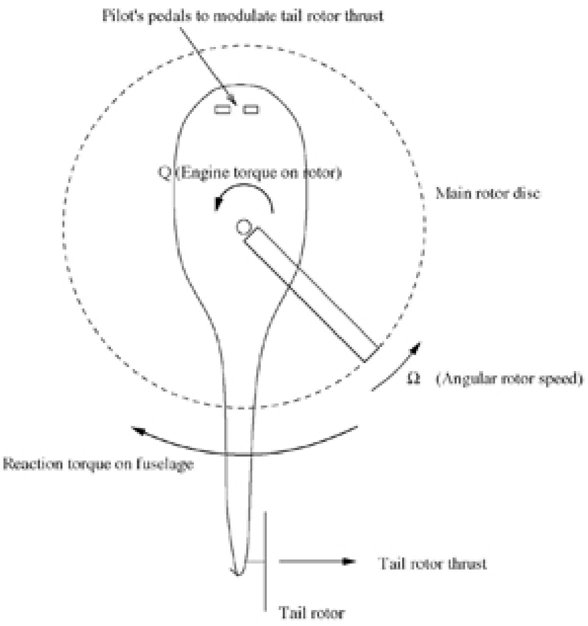
In 1939, Russian-born engineer Igor Sikorsky, who had emigrated to the United States, developed the first useful helicopter with a tail rotor. The operating principle of a helicopter is that the aircraft generates lift by means of its rotating, wing-like rotor blades. Unlike fixed-wing aircraft, the helicopter does not have to move forward through the air to create its lift, which allows it to take off and land vertically, hover, and even fly backwards like a hummingbird. Changing the pitch of all the rotor blades by the same amount allows the helicopter pilot to increase or decrease lift in order to climb or descend. By asymmetrically changing the pitch of the rotor blades as they rotate, the aircraft can be moved in different directions. However, as the main rotor moves round and round, it also creates a fundamental mechanical problem. The rotation results in a counteracting torque affecting the aircraft itself. According to Newton’s third law, any force results in an opposing reactive force. If the rotor blades turn anticlockwise, the helicopter fuselage, as soon as it lifts off the ground, will start to spin in a clockwise direction. The tail rotor was developed to counteract this effect. A set of smaller rotor blades mounted at the end of a tail boom and rotating in a vertical plane pull the helicopter tail sideways — anticlockwise in our example — to cancel the torque effect. Varying the thrust of the tail rotor allows the pilot to rotate the entire aircraft around its vertical axis. Flying a helicopter requires the use of both hands and both feet, the hands being used to control the actions of the main rotor, and the feet to control the tail rotor.

Tackling the problem at the source ¶

Tail rotors are hopelessly inefficient things. They guzzle up five to ten percent of the engine power, produce lots of noise (the typical high-pitched whine), are susceptible to damage, and pose a hazard to bystanders. Added to all that, the tail rotor offers less than satisfactory levels of control in unfavourable wind conditions. Numerous solutions have been proposed to put an end to the tail rotor. The most successful so far is the NOTAR, or NO TAil Rotor-system. It uses a powerful fan to force air into the hollow helicopter tail boom. Slots in the side of the tail allow some of the air to escape sideways, resulting in a force on the tail, counteracting the inconvenient torque effect. The pilot can rotate the helicopter clockwise or anticlockwise by varying the amount of air escaping through the tail duct.

‘Ingenious as it may be, this system still has the drawbacks of requiring extra power as well as a complex set of mechanics,’ says Dr. Ir. Theo van Holten, Professor of Aircraft Performance & Propulsion at the Aerospace Faculty of Delft University of Technology, ‘which is why we decided to tackle the tail rotor problem at the source. We were wondering whether we might be able to make a rotor that would not create the torque problem and so would be able to do without a tail rotor for compensation. Of course, all around us people said it couldn’t be done, since Newton tells us that action equals reaction. We maintain that such a rotor can be created, without violating Newton’s third law of course, since that would be impossible.’ Together with a group of assistants and students, Van Holten is working on the development of the ornicopter, a helicopter without a tail rotor, but with wings that flap like a bird’s. The name, «ornicopter» is a contraction of the words «helicopter» and «ornithopter». Ornithopters

As far as we know, Leonardo da Vinci (1452-1519) was the first to record his thoughts on flying machines. Da Vinci attempted to imitate bird flight using so-called ornithopters (literally bird like winged vehicle). Although this type of aircraft is still being used in experiments, the imitation of bird flight has so far proved elusive.



Even as the Wright brothers were pioneering powered flight just a century ago, inventors elsewhere in the western world were already experimenting with helicopters. One of the problems that had to be overcome by these pioneers was how to counteract the reaction torque induced by the engine as it pushes the rotor in one direction and the fuselage in the other, sending it spinning hopelessly out of control.

German aircraft engineers started developing rotating-wing aircraft as early as 1912. Experiments were resumed in 1927 by Anton Flettner having been interrupted by the First World War. In Spain in 1923 Juan de la Cierva covered a distance of 17 kilometres in his Autogiro. De la Cierva continued his work in England, producing his model C-19. Professor Heinrich Focke took out a licence to build De la Cierva’s C-19. In Nazi Germany, the Focke-Wulf company developed several types of helicopter derived from the C-19, culminating in 1938 in the Fw-61, seen here with the famous test pilot, Hanna Reitsch. According to Prof. Ir. Th. van Holten this was the first practical true helicopter. The reaction torque problem was solved by using two contra-rotating rotors that cancelled each other out. The purpose of the propeller at the front of the aircraft was to cool the engine; it was not used for propulsion.

were the first aircraft designs featuring flapping wings on either side of the machine, all of which failed. Leonardo da Vinci was probably the first to design such a flapping-wing aircraft. At Delft University, the design team intends to rejuvenate the flapping-wing principle, this time using a helicopter instead of a symmetrically winged aircraft.

Although in a normal helicopter the rotor blades have the same freedom of movement as bird wings, the only aspect actively controlled by the pilot is the pitch of each blade. The rest of the system moves in a purely passive fashion under the influence of the airstreams around it. Under normal conditions, rotor blades will always flap a little as they move through the air, but they will do so without any measure of control, whereas a bird actively controls every movement for its wings manoeuvrability.

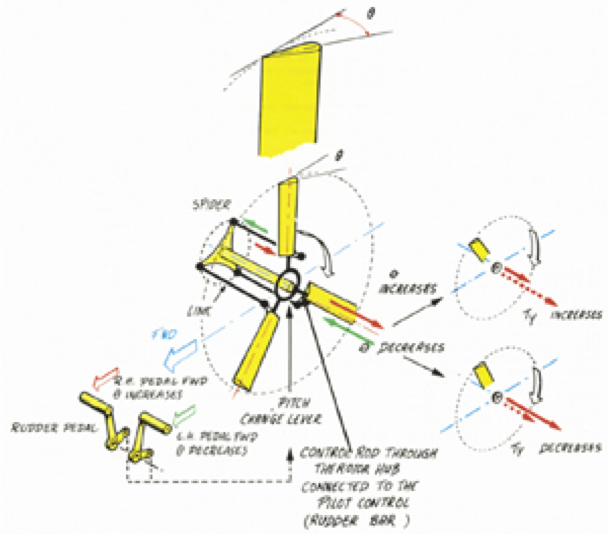
'Birds are very good at this', Van Holten explains. 'They use their wing muscles both to create lift and to provide propulsive power. They can dynamically alter the configuration of their wings in any direction during flight, with an extremely high degree of coordination.'

Auto rotating blades ¶

Van Holten's idea is to actively make a helicopter's rotor blades flap. 'If this is done correctly, this will enable the blades to provide both lift and propulsion, just like a bird does with its wings. The blades will rotate of their own accord, without the need to drive them by a shaft. Dispense with the drive shaft, and you will remove the torque problem. The engine's power is no longer spent on rotating the shaft, but in flapping the rotor blades.' A push-pull rod that rotates with the rotor provides the blades with their flapping motion, which is synchronised with the rotation speed. For each rotation, the flapping motion of each rotor blade reaches a maximum, and on the opposite side, it reaches a minimum. In fact the rotor plane becomes slightly tilted. The synchronisation is tuned to the natural frequency of the blade, just like the little push you use to keep a swing going is synchronised with the swing frequency. To maintain the rotor's natural flapping ability, the rotor blades are attached through a soft spring. The natural flapping motion is what a rotor blade does of its own accord as it moves through the air. The blades of any normal helicopter also flex up and down as they rotate. The ornicopter's blades must be allowed to follow these natural movements. The trick is to find the optimum combination of pitch and flapping motion that will provide constant lift and sufficient propulsion. Birds can often be seen to bob as the lift they generate fluctuates with the flapping of their wings. It goes without saying that this has to be avoided in a helicopter, where the lift should be kept steady, or the pilot and passengers would be constantly moving up in down during a flight, which would be uncomfortable, to put it mildly. Using basic theoretical calculations for power, controllability, flap deflection, and vertical vibration, Prof. Van Holten investigated the ornicopter's feasibility. 'The calculations look promising. We think that we can solve most of the problems.' As it turns out, the power

Le KOLIBRIE sur sa plate-forme

The first Dutch helicopter, the Kolibrie, was built circa 1960 by the Nederlandse Helicopter Industrie N.V. based at Zestienhoven Airport (also known as Rotterdam Airport). The model shown here avoided the reaction torque problem by using a small, simple type of jet engine known as a ram-jet at the tip of each rotor blade to drive the rotor around. The function of the small tail rotor was not to counteract any reaction torque, but to provide directional control for the helicopter.



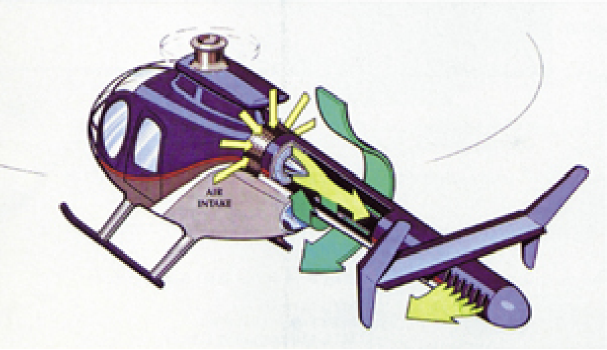
required for rotating the blades is identical to the power it takes to flap them. With the ornicopter in full flapping blade mode, the power requirement is equal to that of a normal helicopter for driving the rotor blades. ‘This means that the ability to control the direction of flight is also present’, Van Holten adds. ‘The rotor blades rotate in a plane inclined at a certain angle. If we assume a situation in which the rotor plane has exactly the right angle, the flapping blades will rotate of their own accord. Now if the pilot decreases the tilt of the plane of rotation, the flapping motions alone will no longer suffice, so the pilot will have to provide additional power input through the drive shaft. This will result in some reaction torque which the pilot can use for directional control.’ In other words, by tilting the rotor plane of the ornicopter, the pilot can vary the power required for flapping and exchange it by direct shaft power, and so control the direction of flight. The ornicopter can do without the power for the tail rotor required by a conventional helicopter. The pilot must be given the means to control the ornicopter just like a normal helicopter, without noticing the difference. Van Holten: ‘Before take-off, the pilot uses the engine to turn the rotor directly by the shaft, and once the blades have reached the required speed, he will switch to flapping mode. If the flapping mode is set correctly, the blades will keep themselves moving around. In our mechanical concept, the full engine power is then spent in the mechanism causing the flapping of the rotor blades, without driving the main rotor shaft at all. No special action by the pilot will be required. Internal material stresses will automatically distribute the energy to either of the two mechanisms. This principle can be used to solve all control problems.’

Small flapping angle ¶

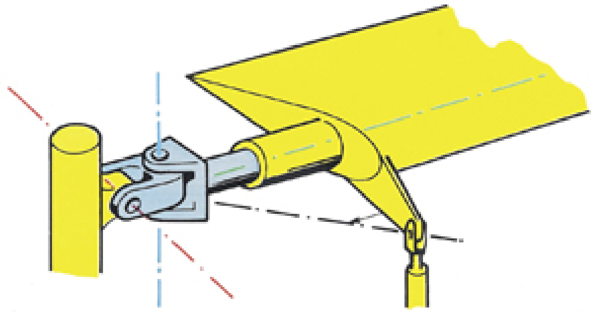
Traditional ornithopters attempted to gain flight by using large deflections of their flapping wings. It did not work at the time, but it might lead one to suppose that the ornicopter’s flapping angle will also be substantial. This is not the case. According to the calculations, the flapping angle required at a high rotational speed of the rotor blades is only five to six degrees. Although flying ornithopters do exist today, the application of the principle is limited to small, unmanned aircraft.

It would seem that a new problem presents itself in the form of the extra vibration caused by the flapping mechanism, which also results in reactive forces. However, the vertical vibrations of the flapping mechanism return as reactive forces through the rotor shaft and straight to the fuselage, just like the reactive forces in a bird’s wing muscles. The result is that the flapping mechanism does not result in additional vertical vibration problems. The only sources of vertical fuselage movement result from the fluctuating lifting forces generated by the flapping blades and from the vertical shifting of the centres of gravity of the blades. To resolve these two problems, Van Holten came up with the double teetering rotor. This mechanism comprises two long rotor wings, each consisting of a pair of blades and positioned at right angles to each other. The assembly results in a four-bladed rotor

Until recently, practically any single-rotor helicopter produced used a tail rotor for the purpose of compensating the reaction torque and providing directional control. The tail rotor system is cumbersome, adding weight and complexity with its system of shafts and gear boxes to provide drive power and vary the pitch of the blades for directional control. Other rotor problems include its susceptibility to damage, the hazard it poses to bystanders, its power saw whine, and the fact that it tends to lose much of its effectiveness in a tailwind. In addition, the tail consumes 5 to 10 percent of the overall engine power.



In a recent attempt to get rid of the tail rotor, the NOTAR (No Tail Rotor) system was introduced. The operating principle of the NOTAR system involves ejecting a jet of air from the tail boom to counteract the rotor’s reaction couple and provide directional control, just like a tail rotor does. The system has proved very successful since it solves the problems of mechanical vulnerability, danger to bystanders, and noise. Researchers at Delft University are currently looking into a much more radical solution by providing a zero-reaction torque main rotor. At first glance this may appear to be at odds with Newton’s third law (action equals reaction), but tests have shown that it can be done by adding a new mechanism to the main rotor’s usual drive layout.



A helicopter rotor blade has roughly the same freedom of movement as a bird’s wings. It can move up and down (the flapping motion), it can sway a bit within the rotor disc plane (lead-lag motion), and it can be rotated along its longitudinal axis. The latter is referred to as changing the blade’s pitch.

system. Whenever the tip of one rotor blade moves upwards, the tip of the opposite blade moves down, like a seesaw. In addition, the two rotor wings move out of phase with each other: the planes in which they rotate are mirrored.

'Of course, the whole system follows Newton's laws to the letter', Van Holten explains. 'We have a closed mechanical loop, and a closed aerodynamic loop. In the closed mechanical loop, the reactive torque exerted by the engine on the fuselage is counteracted by a torque on the disc of the new drive system. In the closed aerodynamic loop, propulsion is produced by slightly tilting the lift force. The resulting reactive force can be retraced to an increased rotation of the air in the rotor's wake.' Even so, some problems still remain to be solved, as for example the behaviour of the fuselage around its longitudinal axis. This is affected by the higher harmonic vibrations exerted on the fuselage by the rotor. Van Holten intends to eliminate these harmonics by means of special dampers. 'This is hardly surprising,' the professor says, 'since you also find lots of vibration dampers in any of today's helicopters.'After the initial calculations, the next research step involved experiments with a wind tunnel model. The team has completed a scale model that has been used to test the various calculations in the Delft wind tunnel. The model is one-fifth the size of the real thing, so whereas the rotor would normally be some 7.5 metres in diameter, the wind tunnel model carries a rotor of about a metre and a half. The results of the wind tunnel experiments proved to be close to Van Holten's theory, which can now be used with confidence for designing further full-scale experiments.

Construction kit ¶

When Van Holten applied for a patent on the ornicopter concept, he discovered that he had been pipped at the post by a Bulgarian, Vladimir Savov.

'We were certain we had invented a new system. It was quite a shock to discover that somebody else had got there just ahead of us.'

As it is, Savov has opted for quite a different approach with different applications in mind, including unmanned reconnaissance aircraft and toys. In his opinion, the ornicopter concept introduces too many new problems that cannot be resolved.

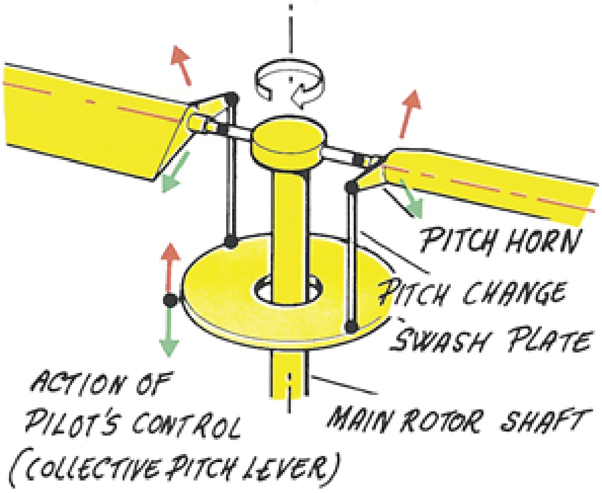
'We on the other hand think we can solve the new problems,' Van Holten says, 'and our initial calculations and experiments support our view.'

Although the flapping rotor principle could no longer be patented, last year Van Holten did file for a patent on practical helicopter applications and the specific design of his own flapping mechanism. The patent covers many new aspects, including the configuration of spring stiffnesses and phase shifts that provides directional control. Now that the patent has been filed, he can at last go public.

Balancing the books ¶

Aerospace engineer Kathleen Boonen has taken on the management of the project. Now that the concept has been published, the primary concern will be to raise

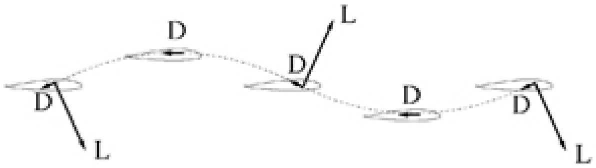
The blade's flapping motion, lead-lag motion, and change of pitch are all made possible by hinges built into the rotor head, or in more recent types of helicopter, by flexible structural elements.



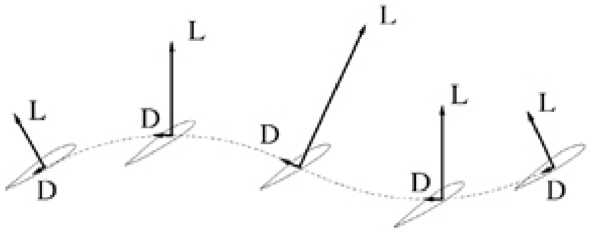
A bird actively flaps its wings; current types of helicopter do not. Researchers at Delft University are working on a method to add active flapping. This will generate lift and propulsion, causing rotation in the case of helicopters. In normal helicopters, only the pitch of the blades is actively controlled by means of the swash plate. Moving the swash plate up or down changes the pitch of all the rotor blades in equal measure so the rotor will produce more or less lift. Tilting the swash plate ensures that the pitch of each rotor blade will change periodically as it revolves, causing the rotor as a whole to tilt and so provide the helicopter pilot with speed control. Any other movement by the rotor blades is purely passive as they move up and down or to and fro to reduce internal stresses, just like a length of rope being spun around in the air. The new concept proposed by the Delft researchers involves active excitation of the flapping motion, the way a bird does using its flapping muscles. By coordinating the flapping and pitching motions, a bird can use its wings to generate both lift and propulsion. The same should be possible using a rotor blade when actively controlling both its pitch and its flapping motion. This will cause the blade to provide lift as well as its own propulsion, so it will no longer be necessary to add rotational power through the drive shaft. By eliminating the engine torque through the drive shaft, the reaction torque of the rotor will also be nil.

funds to enable a full-scale ornicopter to be built.
‘You can spend as long as you like on calculations, but there comes a time when you simply have to go out and build a full-scale design to see if the practical application matches the theory’, Boonen says. ‘The easiest approach probably is to buy a helicopter kit which we will then adapt to fit our ornicopter design. We intend to incorporate the flapping mechanism in the existing rotor drive mechanism.’
In the near future, the two scientists will be looking for commercial interest in the project. Boonen is a fixed-wing aircraft pilot-engineer and hopes to soon gain her helicopter wings in order to be able to supervise the flight tests.
‘Kathleen will soon be risking her life in our first ornicopter,’ Van Holten laughs, ‘so the design theory better be good.’ n

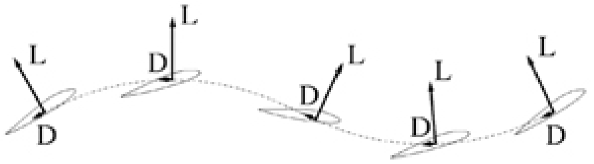
For more information, please contact Prof. Dr. Ir. Theo van Holten,
phone +31 15 278 5301, e-mail [http://www.delftoutlook.tudelft.nl/info/ mailto_Th.vanholten_lr.tudelft.html](http://www.delftoutlook.tudelft.nl/info/mailto_Th.vanholten_lr.tudelft.html)



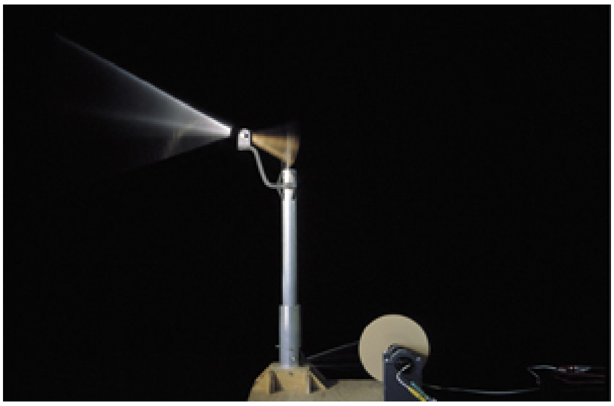
The propulsion of a rotor blade or wing that moves up and down can be explained as follows. In the diagram, the (symmetrical) wing moves from left to right while moving up and down. During the upward stroke, air strikes the wing at an angle from above. Therefore, the direction of lift, which is always at right angles to the relative airflow angle, points down and forward. During the downward stroke, the lift points up, but again forward. In between the two situations, there are moments at which the lift is nil and the wing generates nothing but drag in the direction opposite to the direction of flight. If the shape of the wing section is efficient enough, the drag forces will be much less than the lift forces, and so the average result will be a force acting in the forward direction. We still have no lift, however.

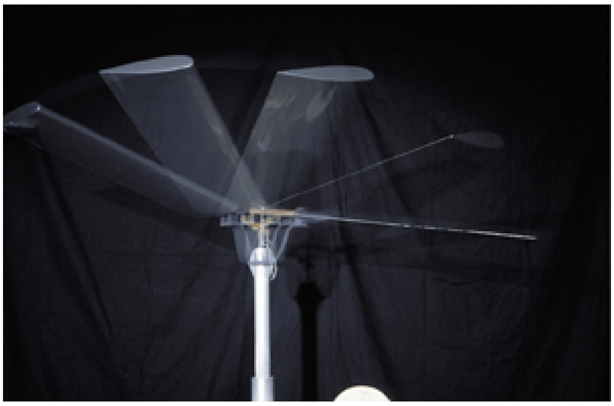


If, in addition to the flapping motion, the wing also assumes a positive angle of attack, a constant, positive lift will be superimposed on the lift forces from the previous diagram. The resulting lift will fluctuate as the wing moves up and down, and will be directed forward at the precise moments that the lift is at its greatest. The average result will be to generate lift as well as propulsion. This is the situation that the Delft researchers hope to achieve using a reaction less rotor. They have dubbed this the ‘Ornicopter principle’ since it combines the operating principles of the helicopter and the ornithopter.

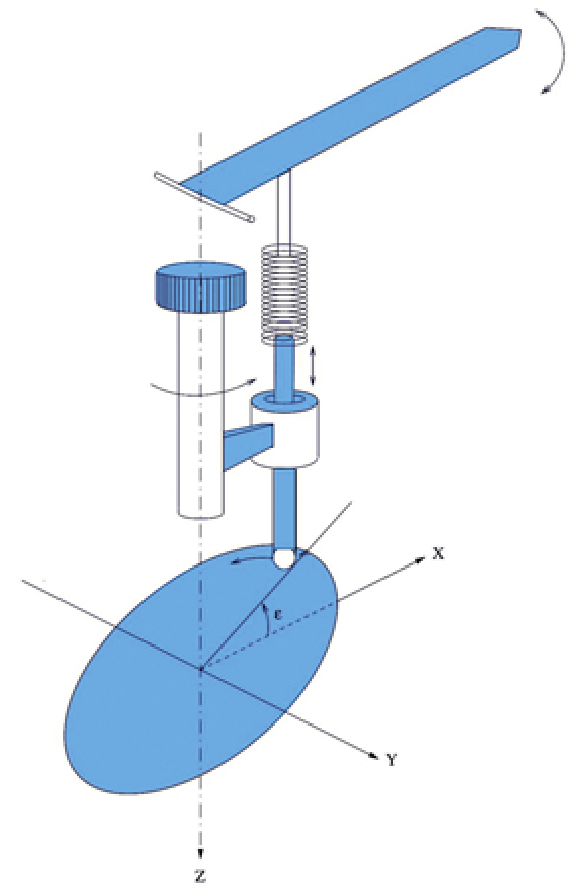


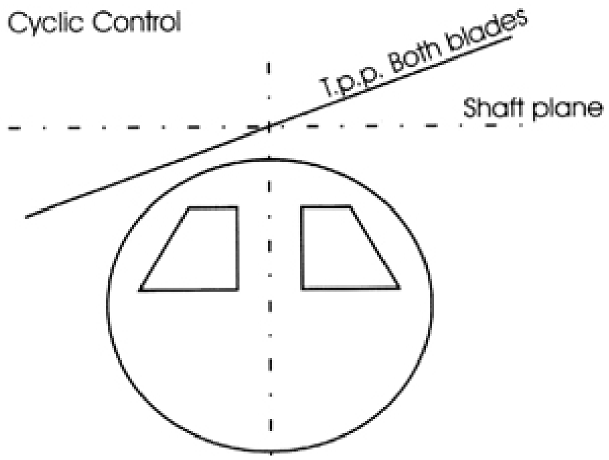
Birds manage to optimise the process by constantly changing the angle of attack of their wings. This diagram shows the limit situation in which the periodical wing rotation is such that the angle at which it strikes the airflow remains constant. The resulting lift will be constant, but the average propulsion will be nil. In reality, birds flap their wings in a way that is somewhere between diagrams B and C, depending on whether the bird is flying at a constant speed or accelerating.



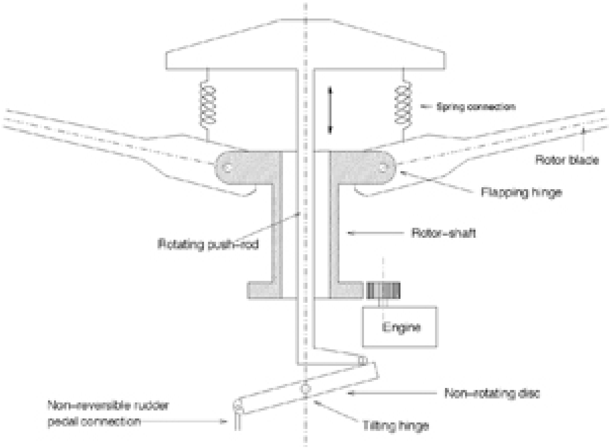


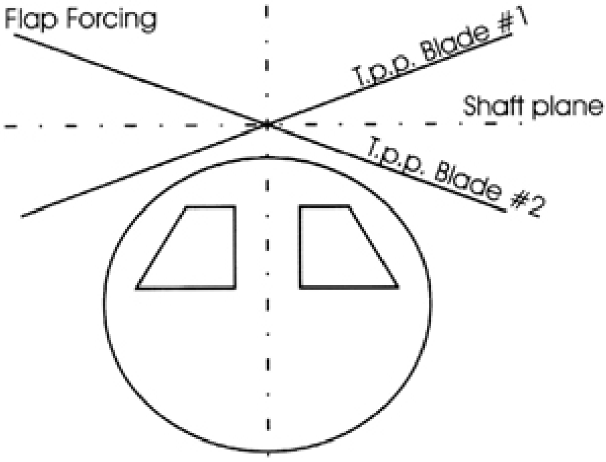
The Delft researchers constructed a simple model to demonstrate the ornicopter principle. Its single blade is moved up and down by pulling a string. The resulting flapping motion causes the assembly to rotate. The model is then placed on a turntable together with a drive system for the string to show that the result is a true zero-torque helicopter rotor. Even so, the Delft researchers are well aware that there is still a long way to go before an actual helicopter can be built. The rotor blade simply wobbles around and there is nothing even remotely resembling a rotor disc plane, something absolutely essential to achieve control over an ornicopter.



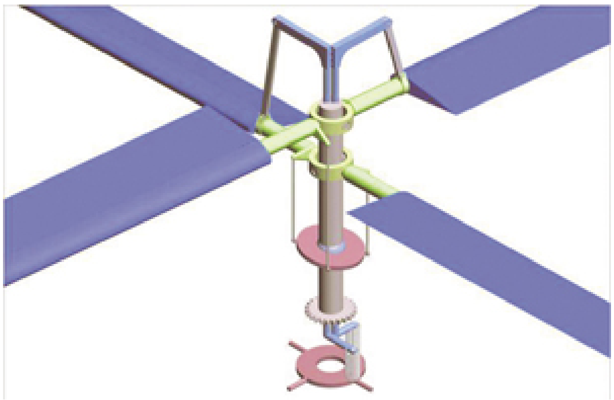


In the practical execution of the ornicopter principle, the flapping motion of the blade is synchronised with the rotation. The blade is moved up and down by means of a push-pull rod the lower end of which is forced to move through an inclined plane as it revolves. Once every revolution, the blade reaches a high and a low point, so that it moves in fact in a flat plane at a slight angle to the vertical shaft [bottom]. The mechanism includes a soft spring, so the normal flapping movements needed to control the ornicopter can be superimposed on the flapping motion of the drive. The spring stiffness is selected so as to make the natural frequency of the rotor blade coincide with the drive frequency of the push-pull rod. Like a swing, at each rotation the blade receives a push at just the right moment, which is the most efficient way of transferring the drive power to the blade.

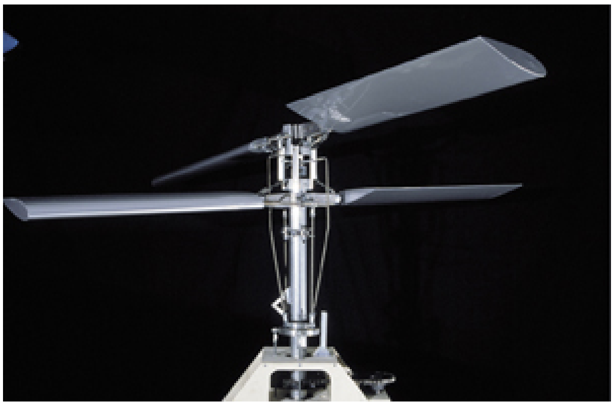




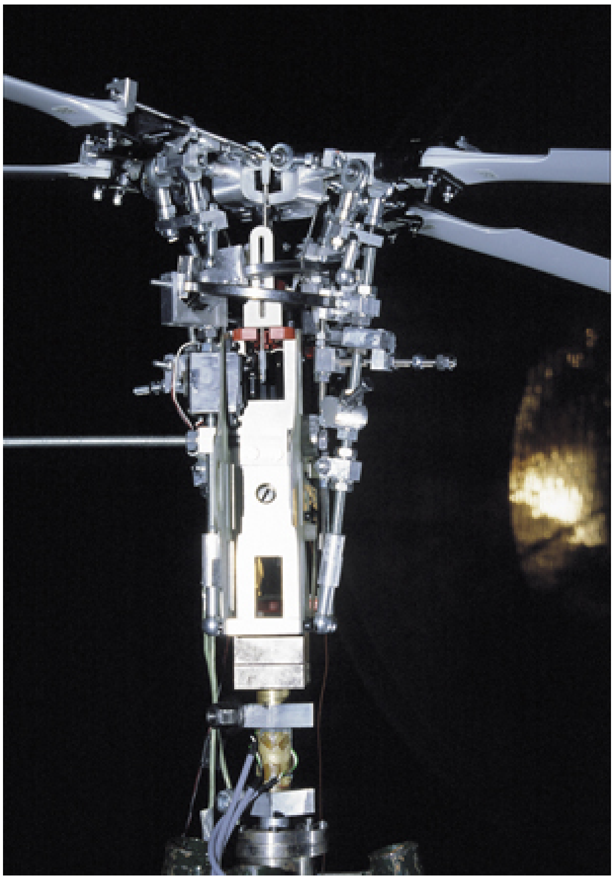
A helicopter with a single rotor blade is impractical due to the high vibration levels. By using a double-bladed rotor, the blades can be moved so that the induced flapping motion will cause them to rotate in different planes mirrored about the plane of symmetry of the fuselage [bottom]. In this way, any transverse forces on the fuselage will cancel each other, except when the pilot induces them intentionally through the normal swash plate control. The inclined plane below the push-pull rods has been made adjustable to enable the flapping motion to be reduced or increased so a little torque needs to be added through the shaft to maintain rotor speed. The resulting reaction torque (either positive or negative) can then be used for directional control.



A bird’s body in flight will always move up and down slightly as a result of the varying lift created by the flapping wings. In a practical ornicopter this kind of motion must be avoided. The solution is to use a four-bladed rotor in which each of the two pairs of blades has been attached in seesaw fashion. As one blade moves up, the opposing blade moves down at the same speed to cancel any lift fluctuations. Flapping the two sets of blades in the correct relative phase [see also figure B above] will again result in the blade tips moving in two mirrored planes, a prerequisite for the machine’s equilibrium.



This mock-up used to demonstrate the principles outlined above uses a highly simplified version of the mechanism, based on an eccentric that induces the flapping motion. The four-bladed rotor appears to be similar to a conventional rotor, with the visible control rods being the same as the normal swash plate control rods. The rotor shaft drive is also conventional. The secret is on the inside, with the hollow rotor shaft containing a static shaft that transfers the torque on the eccentric of the fuselage. Since this torque is exactly equal and opposite to the reaction torque the engine exerts on the fuselage, the reaction torque is neutralised.



A wind tunnel model of the Delft ornicopter. The first tests took place in early 2003 to provide quantitative checks of the theoretical predictions such as the required engine power, vibration levels, equilibrium of forces and control movements. The theory was fully confirmed. It appeared possible to achieve an exact reaction less operation, but also to induce either negative or positive reaction torque for directional control. A free-flying model is now being built to test controllability in dynamic manoeuvres during field tests. In addition a preliminary design study is being carried out for a full-scale manned demonstrator, the hardware of which will be based on a commercially available kit for a twin-seat helicopter. The flight hardware will be tested on a static whirl tower, which at present is on the drawing board. The tower is to be erected on the university wind turbine test field.