THE ORNICOPTER: A SINGLE ROTOR WITHOUT REACTION TORQUE, BASIC PRINCIPLES

Theo van Holten, Monique Heiligers, Gerard-Jan van de Waal
Delft University of Technology, Faculty of Aerospace Engineering

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Abstract

The Ornicopter is a single rotor helicopter without a reaction torque. The principle of the Ornicopter is based on forced flapping of the blades. A flapping rotor blade can generate both the required propulsive force to maintain a steady rotation of the rotor, as well as the required lift to keep the helicopter flying and *a means to control the aircraft. The principles of this forced flapping will be explained in this paper. The feasibility of the Ornicopter concept with respect to power required, means of yaw control and possible forced flapping mechanisms will be ascertained. To conclude the theoretical principles of the Ornicopter will be compared to the results of windtunnel tests.*

1 Notations

Restricted to those not defined in text or figures:

c_{l_α}	Derivative of the lift coefficient for a blade element w.r.t. the angle of attack
C_{l_α}	Derivative of the lift coefficient w.r.t. the angle of attack
dD_p	Profile drag on a blade element
I	Moment of inertia of the blade w.r.t. the flapping hinge
dL	Lift on a blade element
R	Rotor radius
α	Angle of attack
β	Flapping angle
θ	Pitch angle
ψ	Azimuth angle
ρ	Air density
Ω	Angular speed of the rotor

2 Introduction

The tail rotor of helicopters, necessary to counteract the reaction torque of the engine and to control the helicopter in yaw, has always been considered a necessary evil. It is expensive, consumes power, has only marginal control authority under unfavorable wind conditions, and is on top of that noisy, vulnerable and dangerous. The ideal solution to all these problems would be to design a rotor that eliminates the need for a tail rotor. The Ornicopter is such a revolutionary design.

The mechanism of the Ornicopter is derived from bird flight. When birds flap their wings they are able to derive both a lifting force and a propelling force out of it. Instead of propelling a helicopter blade by spinning it around and deriving lift from this rotating movement, as is done in conventional helicopter configurations, the Ornicopter flaps its blades like a bird and derives both lift and a propulsive force from this movement. In this case the blades propel (i.e. rotate) themselves and there is no longer a need for a direct torque supplied by the engine to rotate the blades. The fact that the engine torque is no longer directly transferred from the fuselage to the rotor is the key feature of the Ornicopter, and it is this feature that makes the anti torque device redundant.

3 The forced flapping motion explained

The following paragraphs will explain how the Ornicopter exactly should flap its 'wings' and how this forced flapping motion can be achieved. Additionally it will be shown that the resulting Ornicopter rotor indeed does not produce a reaction torque.

3.1 Orientation of the blades

As stated before, the Ornicopter should flap its blades like bird wings in order to obtain both a propulsive force that will rotate the blades and a lift force that will keep the Ornicopter airborne. The movement of a bird wing however is extremely complicated and it is impossible to mimick this movement exactly with an Ornicopter blade. But a very useful and simple approximation can be obtained by applying a constant pitch angle to the Ornicopter blade.

The movement of an Ornicopter blade during one revolution is pictured in figure 1. During one revolution of the blade, the blade will be forced to flap both up and down once, resulting in the shown undulating path. If a constant pitch angle is applied the lift forces during one revolution will (averaged over one revolution) result in an upward force and an average propulsive force. This average propulsive force is achieved because the forward horizontal component of the lift force that occurs when the blade is flapping downwards is much larger than the backward horizontal component of the lift force that occurs when the blade is flapping upwards. Thus by setting all the Ornicopter blades at a constant pitch angle and flapping them upwards and downwards a propulsive force is created that will rotate the blades around the rotor hub and an upward force is created that will counteract gravity.

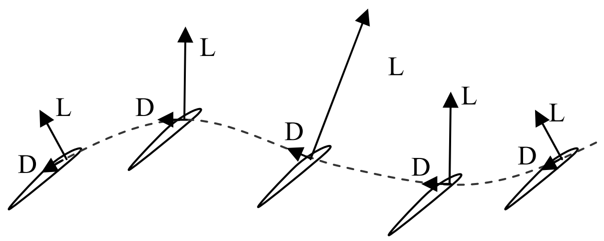

Fig. 1: Lift and drag forces acting on an Ornicopter blade during one revolution when a constant pitch angle is applied

3.2 The forced flapping mechanism

The flap forcing mechanism in some way has to push and pull the Ornicopter blades upwards and downwards. The flapping of the blades will have to be synchronized with the rotational speed of the rotor in order to keep the forced flapping frequency close to the eigenfrequency of the blade (which is favorable for the loads in the blade) and to obtain a flat tip path plane for each rotorblade (which is necessary for cyclic control). Further the forced flapping mechanism needs to contain springs with a low stiffness to enable a superposition of the forced flapping motion and the conventional flapping motion necessary for cyclic control and forward flight.

This flap forcing mechanism can be designed in many different ways, two of the possibilities are: by using an eccentric mechanism (see paragraph 4.4) or by using a push-pull rod with swash plate. To clarify the principles of a flap forcing mechanism the latter possibility will be described in this section. It should be noted that the exact flap forcing mechanism as explained in this section has not been used in practice, however it serves very well to explain the basic principles.

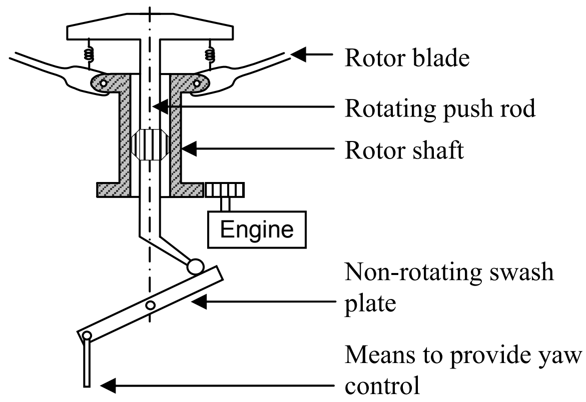

Fig. 2: Principle of a flap forcing mechanism using a push-pull rod and swash plate.

The principle of this flap forcing mechanism for a two-bladed helicopter rotor is shown in figure 2. *It is noted that the conventional swash plate mechanism is also present, although for clarity it is not drawn.* The flap forcing mechanism consists of a push-pull rod through the center of the hollow shaft, the rod co-rotating with the shaft and the rotor. The once-per-rev push-pull motion is converted to a flapping moment on both the blades. Note that there is an essential difference between the flap forcing and the application of cyclic pitch by a swash plate: both are periodical with a 1-P frequency, but cyclic pitch is asymmetrically applied (the magnitude is equal but the direction is different for the two blades), whereas the flap forcing is symmetrical.

The once-per-rev push-pull motion is derived from a mechanism analogous to hydraulic pumps: a radial extension of the push-pull rod is forced to rotate in an inclined, stationary plane. The driving power is derived from the main engine, via the main rotor shaft.

3.3 The absence of a reaction torque

In a conventional helicopter the drag that is acting on the rotor blades is counteracted by the torque that is exerted on the rotor. The rotor is thus rotating because of the torque that is transferred from the fuselage to the rotor. As a result there will also be a reaction torque from the rotor on the fuselage, and this reaction torque will have to be counteracted by an anti-torque device.

For the Ornicopter configuration the drag that is acting on the rotor blades is counteracted by the propulsive force produced by the forced flapping motion of the wing. There is thus no torque transferred from the fuselage to the rotor to rotate the blades. As a consequence there will neither be a reaction torque from the rotor on the fuselage.

In the case of the example flap forcing mechanism (figure 2) the *rotor shaft* is driven by the engine, which might make it difficult to believe that there is no torque transmitted to the rotor and no reaction torque acting on the fuselage. However if the *rotor* is still entirely driven by the flapping of the blades, this means that there is no reaction torque. What actually happens is that the rotational energy of the engine that is transmitted to the rotor shaft is transformed into translation energy by the swash plate and this translation energy is transmitted to the rotor.

So, then what happens to the engine torque that is driving the rotor shaft if it is not transmitted to the rotor? It can be calculated [1] that the forces that are exerted by the ball-bearing on the swash plate exactly counteract the torque that is produced by the engine. This corresponds to the statement made earlier that the rotational energy is transformed into translational energy by the swash plate: the ball-bearing on the swash plate counteracts the engine torque and produces a vertical fluctuating force that moves the Ornicopter blades upwards and downwards. The reaction torque is thus counteracted within the fuselage.

In general for any Ornicopter flap-forcing mechanism it can be stated that if the rotor is entirely driven by the flapping of the blades, this implies that no shaft torque is directly transmitted to the rotor and that there will thus be no reaction torque acting on the fuselage. Since no torque is transferred from the fuselage to the rotor, this means that the engine torque must in some way be counteracted inside the fuselage.

4. Feasibility

The Ornicopter might be a nice theoretical idea, but its feasibility depends on a couple of practical aspects. The power required to drive the rotor of the Ornicopter should not drastically exceed the power needed to drive the rotor of a conventional helicopter. Additionally a means of yaw control needs to be developed, since the tail rotor that is conventionally used for this purpose is no longer present. Furthermore with this new means of yaw control there must be no cross-coupling between yaw control and cyclic control or yaw control and collective control. And finally a flapping mechanism that can be used in practice must be designed that will enable the forced flapping of the blades. Each of these four practical aspects will be addressed in the following paragraphs and their feasibility will be ascertained. Another feasibility aspect is that the vibrations due to the flapping of the blades must be controllable, this aspect is addressed extensively in the accompanying paper [2].

4.1 Power required

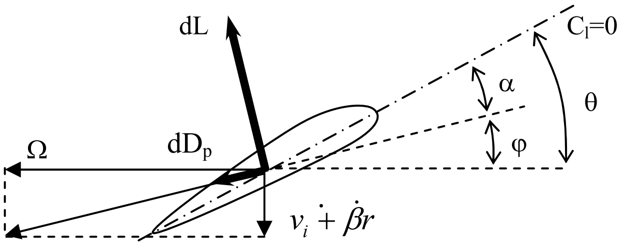

Fig. 3: Aerodynamic forces and velocities on a blade element at distance *r* from the rotor hub

To calculate the power that is needed to drive the Ornicopter rotor, we will start with calculating the average shaft power (P_{sh}) that is necessary to drive a conventional rotor. In order to do so, the power needed to drive the blade element in figure 3 is calculated, and integrated over the entire rotor blade. To find the average power during one revolution, the power is integrated over one revolution and divided by the factor 2π. This yields, assuming small angles:

$$P_{sh} = \frac{1}{2\pi}\int_0^{2\pi} d\psi \int_0^R \left(dL\varphi + dD_p\right)\Omega r \qquad (1)$$

with the inflow angle φ given by:

$$\varphi = \frac{v_i + \dot{\beta} r}{\Omega r} \qquad (2)$$

Substitution of equation (2) into equation (1) gives:

$$P_{sh} = \frac{1}{2\pi}\int_0^{2\pi} d\psi \int_0^R dL\left(v_i + \dot{\beta} r\right) + \frac{1}{2\pi}\int_0^{2\pi} d\psi \int_0^R dD_p \Omega r \qquad (3)$$

$$P_{sh} = P_i + P_p + \frac{1}{2\pi}\int_0^{2\pi} M_a \dot{\beta} d\psi \qquad (4)$$

in which P_i is the power required to overcome the induced drag, P_p the power required to overcome the profile drag, and M_a the aerodynamic flapping moment:

$$P_i = \frac{1}{2\pi}\int_0^{2\pi} d\psi \int_0^R dL v_i \qquad (5)$$

$$P_p = \frac{1}{2\pi}\int_0^{2\pi} d\psi \int_0^R dD_p \Omega r \qquad (6)$$

$$M_a(\psi) = \int_0^R dL r \qquad (7)$$

Equation (4) is a power equation that can be used for conventional helicopters, but note that $\dot{\beta}$ will be zero for a conventional helicopter during hover. To be able to add the mechanical flapping power to equation (4), consider the equation of motion for a centrally hinged rotor blade in Ornicopter configuration, i.e. with a mechanical flapping moment (M_{fl}) applied to the blade. The equation of motion can be expressed as (see figure 4):

$$\ddot{\beta} + \Omega^2 \beta = \frac{M_a}{I} + \frac{M_{fl}}{I} \qquad (8)$$

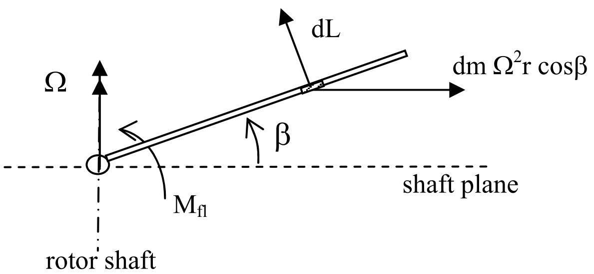

Fig. 4: Moments and forces on an Ornicopter blade with mechanical flapping moment applied to the blade

If the forced flapping frequency is chosen equal to the 1-P frequency of the blade, then the flapping angle will in response also have a 1-P frequency and will be given by:

$$\beta = \beta_0 + C\cos\psi + S\sin\psi \qquad (9)$$

β_0 is the cone angle. Equation (8) now yields:

$$M_a = -M_{fl} + I\Omega^2 \beta_0 \qquad (10)$$

When combining equations (10) and (4):

$$P_{sh} = P_i + P_p - \frac{1}{2\pi}\int_0^{2\pi} \left(M_{fl} - I\Omega^2\beta_0\right)\dot{\beta} d\psi \qquad (11)$$

$$P_{sh} = P_i + P_p - P_{fl} \qquad (12)$$

$$P_{fl} = \frac{1}{2\pi}\int_0^{2\pi}\left(M_{fl} - I\Omega^2\beta_0\right)\dot{\beta}\,d\psi \qquad (13)$$

In which P_{fl} denotes the flapping power: the average power per revolution exerted by the flap forcing mechanism on the blade. Equation (12) shows that if the flapping power (P_{fl}) is chosen sufficiently large, the shaft power can be reduced to zero. This means that if the rotor is driven by the flap forcing mechanism, there will be no need for any additional shaft power (engine power however will still be needed for the flapping of the blades). So, for the Ornicopter situation, equation (11) transforms into:

$$0 = P_i + P_p - \frac{1}{2\pi}\int_0^{2\pi}\left(M_{fl} - I\Omega^2\beta_0\right)\dot{\beta}\,d\psi \qquad (14)$$

$$0 = P_i + P_p - P_{fl} \qquad (15)$$

It can thus be seen that the flapping power has to replace the shaft power, and that the flapping power will thus not be larger than the power that is transferred to the rotor in conventional helicopters. As a matter of fact the total power that is needed will be less for an Ornicopter since the tail rotor, which normally consumes 5-10% of the total power, is no longer present.

4.2 Yaw control

Yaw control is conventionally realized by the tail rotor, by over-counteracting or under-counteracting the reaction torque. Since the Ornicopter obviously does not have a tail rotor a different means for yaw control needs to be developed. Yaw control for an Ornicopter can be achieved by deliberately introducing a small amount of reaction torque, depending on the direction of this reaction torque the fuselage will yaw in one direction or the other. How this reaction torque can be introduced will be explained below.

If no yaw movement is desired, the blades of the Ornicopter will entirely be propelled by flapping of the blades, and there will thus be no reaction torque acting on the fuselage. This situation is schematically depicted in figure 5a for the example flapping mechanism of figure 2. To realize this reactionless situation a certain inclination (δ) of the swash plate will be necessary; and all the engine power will be converted into the flapping of the blades.

If now for this same situation a smaller inclination of the swash plate is chosen (figure 5b), this implies that the flapping of the blades will not be sufficient to keep the rotor at its required rotational speed, and therefore some additional shaft torque will be needed. The same engine power is now used both for flapping of the blades and for applying some additional shaft torque. Since in this case shaft torque is directly transmitted from the fuselage to the rotor there will also be a reaction torque acting on the fuselage. This reaction torque will cause a yaw movement.

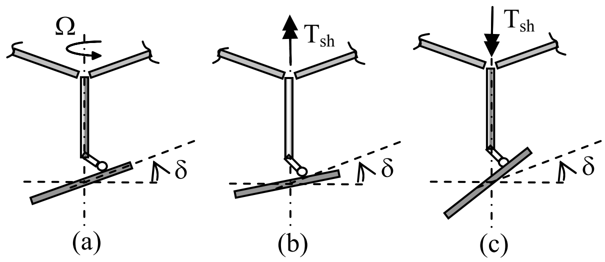

Fig. 5: Schematic representation of yaw control by introducing a reaction torque (the depicted torque is the torque transmitted by the fuselage on the rotor, the reaction torque will thus be directed in the opposite direction).

To create a yaw movement in the opposite direction a larger inclination of the swash plate needs to be applied (figure 5c). As a result of the larger inclination the flapping of the blades will increase and as a result the rotor will tend to speed up. In order to keep the rotor at its desired rotational speed the rotor will have to be slowed down. The rotor will as a matter of fact tend to rotate faster than the shaft (which is driven at a fixed angular velocity by the engine), and as a result the shaft will slow the rotor down. The reaction torque that is caused by this slowing down is acting in the opposite direction as in the situation of figure 5b, and will therefore cause a yaw movement in the opposite direction.

4.3 Cyclic and collective control

As noted before the conventional swash plate mechanism is also present in the Ornicopter and will provide cyclic and collective control. One might wonder whether cyclic control and yaw control, and collective control and yaw control are fully decoupled?

Cyclic control and yaw control are indeed fully decoupled. It might seem as if there is a cross coupling because both yaw control and cyclic control are achieved by using a swash plate. The key difference between these two swash plates however lies in the manner in which these swash plates influence the tip path planes of the blades.

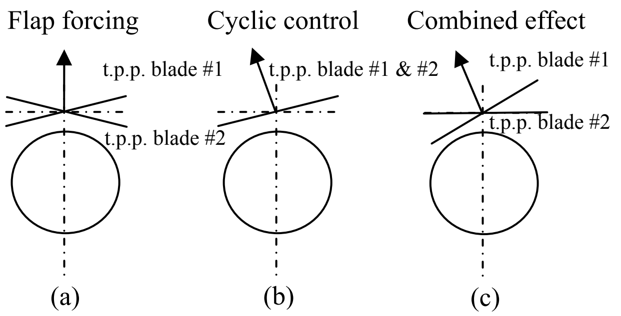

Fig. 6: Different effects of cyclic control and flap forcing on the tip path planes (t.p.p.) of the rotor blades.

As can be seen from figure 2 and 4 tilting of the additional swash plate in the Ornicopter that regulates the forced flapping of the blades will result in both blades moving upwards or downwards at the same moment in time. Both blades move in tip path planes that are anti-symmetrically tilted with respect to the shaft, see figure 6a. Regulating the forced flapping angle will thus not cause a resulting force in the horizontal plane.

Tilting of the conventional swash plate for cyclic control will result in one blade moving upwards and one blade moving downwards at the same moment in time. The blades will thus remain in one tip path plane, but this tip path plane has rotated slightly, see figure 6b.

It can thus be seen that each swash plate has a different effect on the tip path planes of the blades. If these two effects are now combined the result is as depicted in figure 6c. Increasing the forced flapping angle, and applying cyclic control are two effects that can be superimposed. Cyclic control can be achieved on top of the forced flapping motion and independent of the magnitude of this forced flapping motion. The required cyclic control is thus not influenced by the flap forcing and subsequently not influenced by the yaw control. In other words, there is a complete mutual decoupling of the cyclic and yaw control.

As in conventional helicopters, a coupling does exist between collective control and yaw movement. If collective control is exerted the pitch angles of all the blades will increase, thereby providing more lift but also more drag. This increase in drag causes a reaction torque which will cause the fuselage of the Ornicopter to yaw. This problem can be solved in exactly the same way as in conventional helicopters, but instead of requiring a change in pitch angle of the tail rotor blades when the collective is used, in the Ornicopter configuration a change in the forced flapping angle is required. As a result the rotor will remain reactionless.

4.4 Eccentric flapping mechanism

The eccentric mechanism is a means to provide a flapping moment to the Ornicopter blades in an uncomplicated way. As the name already leads one to suspect, the mechanism is placed at a certain distance from the rotor axis (the eccentricity *e*), see also figure 7. The mechanism exists of a cross and four linear springs, which are at one side connected to the cross and at the other side connected to the blades. The midpoint of the cross is attached to the fixed shaft, and will therefore remain at the same position, and will not rotate around the rotor axis. The cross however can rotate around its own center.

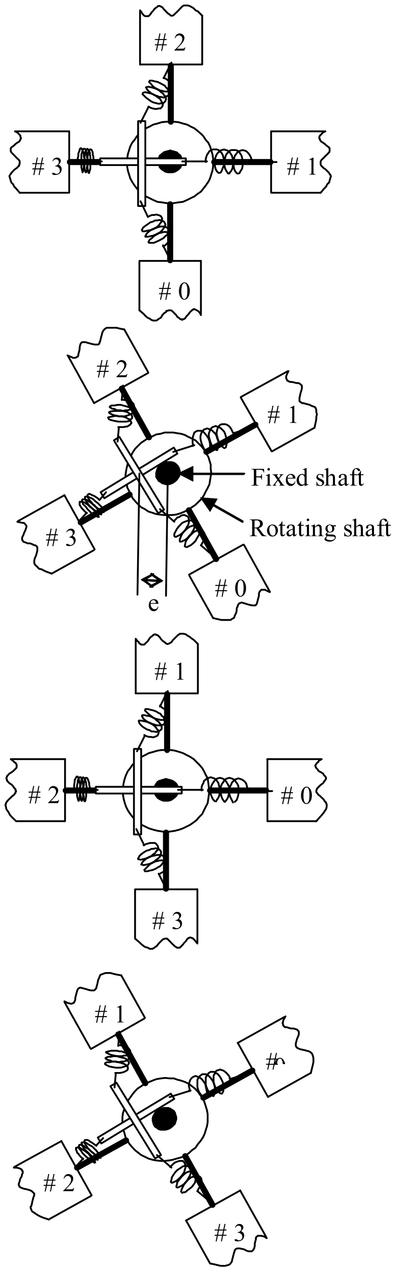

Fig. 7: Principle of the eccentric mechanism, top-view

Contrary to the flapping mechanism in figure 2, which flaps two opposite blades in the same direction, this eccentric flapping mechanism consists of two teeters, meaning that two opposite blades will flap in the opposite direction. (See for a more elaborate explanation of the double teeter configuration the accompanying paper [2]).

The blades are attached to the rotating shaft (a hollow shaft since there is a fixed shaft inside). For clarity, in figure 7, all blades are drawn as if they were attached separately to the rotating axis. Bear in mind however, that in reality this is not the case. The rotor consists of two teeters which means that blades #0 and #2 are connected (and attached to the rotating shaft) and that blades #1 and #3 are connected (and attached to the rotating shaft).

If the eccentricity is chosen to be equal to zero, the midpoint of the cross will coincide with the midpoint of the fixed axis. As a result the length of the linear spring will stay constant during a revolution since the distance between the attaching point at the cross and the attaching point at the blade will remain constant. In this case the blades are not forced to flap and will remain in their neutral position.

If the eccentricity is chosen to be as in figure 7, the length of the linear spring will vary during a revolution. If the blade is on the left hand side of the shaft the spring will be compressed, if the blade is on the right hand side of the axis the spring will be stretched. The stretching and compressing of the springs will cause forces in the springs, and thus forces on the Ornicopter blades. This will cause the blades to flap.

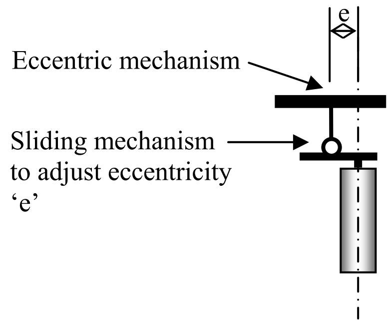

Fig. 8: The eccentric mechanism is attached to the fixed axis, and will therefore not rotate around the axis. The eccentricity can be adjusted by moving the eccentric mechanism along a slide.

The magnitude of the flapping can be controlled by adjusting the eccentricity, see figure 8. Increasing the eccentricity results in larger forced flapping angles, decreasing the eccentricity results in smaller flapping angles.

As can be seen in figure 9, the two teeters are mounted on top of each other, and the eccentric mechanism is added in between. Two of the four springs are therefore directed downwards from the eccentric mechanism, and two springs are directed upwards. This means that if the spring that is directed upward to one of the blades of the top teeter is stretched, it will cause that blade of the teeter to flap downwards. If the spring that is directed downward to one of the blades of the lower teeter is stretched it will cause that blade of the teeter to flap upwards.

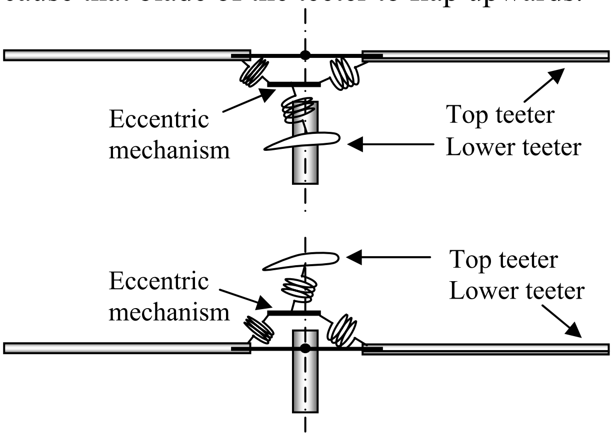

Fig. 9: Principle of the eccentric mechanism, side-views 90° apart.

When returning to figure 7, this means that if a blade of the top teeter arrives at the right hand side of the axis, and the spring is stretched, that blade will flap downwards; if a blade of the lower teeter arrives at the right hand side of the axis and the spring is stretched, that blade will flap upwards.

4.5 Conclusions regarding feasibility

It has been demonstrated (theoretically) that the power required to drive the Ornicopter is equal to the power required to drive a conventional helicopter; that yaw control can be achieved by deliberately introducing a small amount of reaction torque, and yaw control and cyclic control are fully decoupled. Additionally a solution for a forced flapping mechanism has been developed and described. In theory the Ornicopter thus is a feasible concept.

5 Windtunnel tests

To verify the theory that is stated above windtunnel tests have been performed [3] with a windtunnel model as depicted in figure 8. The radio controlled helicopter which was used as a starting point is the Vario Silence (Max RPM: 1032, Rotor diameter: 1.4 m, Number of blades: 2 (teeter), Engine: Graupner ULTRA 2000-7, Engine power (max): 840 Watt). The forced flapping mechanism has been added to this helicopter, and the blades have been replaced by the blades of a four bladed Vario rotor. The resulting modified Ornicopter rotor thus consists of four blades with a rotor diameter equal to 1.648m and a chord length of 53 mm. The windtunnel consists of a flow channel of circular cross section (diameter 2.24 m) with a fan at the inlet, a conical afterbody, a flow straightener and three identical gauzes. The maximum wind velocity is 14.5 m/s and the degree of turbulence is approximately 1%. Since the windtunnel model does not contain vibration absorbers or dampers the rotational speed of the rotor was kept low during the tests (150 rpm with blade tip Mach numbers varying from 0.0397 to 0.1324), to minimize the expected vibrations (see also the accompanying paper [2]). It is noted that the low rpm did not have a large effect on the signal to noise ratio or the reliability of the force measurements.

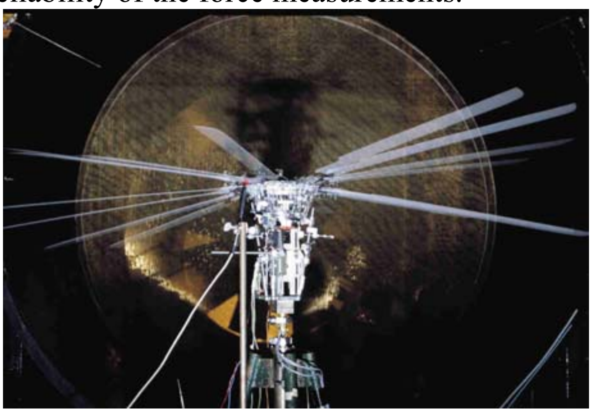

Fig. 8: Ornicopter windtunnel model

Figure 9 shows the relation between the collective pitch input and the torque on the fuselage (M_z) and thrust (T). The flapping angles during this measurement were set at 12 degrees (at the blade root) in hover configuration. It can be seen that the torque increases with absolute pitch, and, most importantly, that the torque on the Ornicopter's fuselage equals zero at -2.7 and 3.5 degrees pitch. This shows that it *is* possible to construct a single rotor without reaction torque, the Ornicopter concept indeed works!

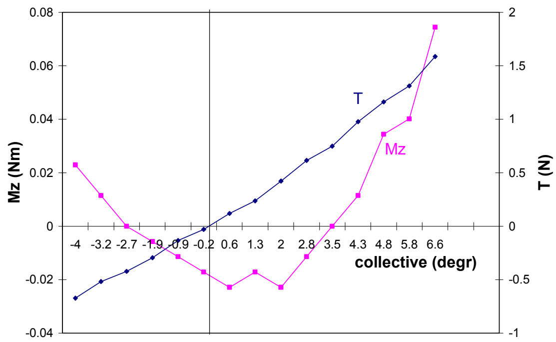

Fig. 9: Rotor torque (M_z) and rotor thrust (T) as a function of collective pitch for a double teeter Ornicopter with twelve degrees flapping

Figure 9 also proves that both a positive and a negative reaction torque on the fuselage can be achieved, which thus verifies the theoretical new means of yaw control in paragraph 4.2: enabling yaw control both in positive and in negative direction.

The thrust as measured during the tests is rather low: for the torqueless condition at 3.5 degrees collective, the thrust is around 0.8 N (figure 9) which corresponds to an average lift coefficient $\overline{C}_L = 0.147$. For this low rotational speed the thrust is not smaller than the thrust of a conventional helicopter, see figure 10.

Calculations show that the test results at the torqueless situation (3.5 degrees collective) can be very well approximated by assuming $C_{D_p} = 0.04$ and k=1.2 yielding $\overline{C}_L = 0.147$ and $C_T = 0.0018$ (using the fact that T =0.8 N). The high value of the profile drag coefficient is to be expected at the low Reynolds number of the test and was confirmed by tests on the conventional helicopter configuration. The test results thus agree very well with the developed theory.

In figure 11 different forced flapping angles (i.e. maximum flapping angles) are compared. The figure clearly shows that an increase in flapping angle decreases the torque on the fuselage. Ten degrees of flapping is the minimum amount of flapping needed to overcome the profile drag, with this flapping amount the rotor is torqueless but at the same time thrustless. It can thus be appreciated that only modest flapping angles are needed, especially when considering the fact that this is the flapping angle at the root of the blade. Due to the flexibility of the blade the flapping angle of the tip of the blade w.r.t. the flapping hinge will only be approximately half the size of the flapping angle of the root of the blade.

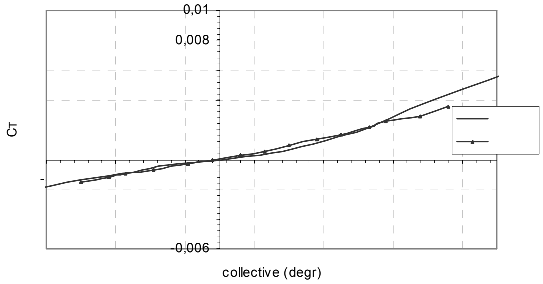

Fig. 10: Relation between thrust and collective pitch for Ornicopter with twelve degrees flapping and for Ornicopter without flapping

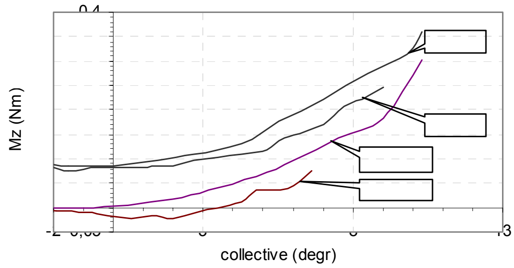

Fig. 11: Rotor torque as a function of collective pitch for various flapping values

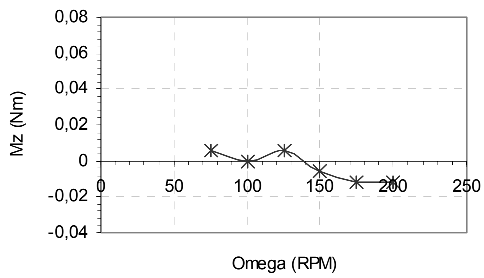

Fig. 12: Rotor torque as a function of rotor speed with twelve degrees flapping

Since the experiments were carried out at low Reynolds numbers, one might wonder whether higher Reynolds numbers change the reaction torque on the fuselage. Figure 12 shows the relation between the torque on the fuselage and the rotational speed. It can be seen that the torque is hardly influenced by the Reynolds number, and thus that, despite the low Reynolds number during the tests, a relative insensitivity for changes in Reynolds numbers is achieved.

To conclude the power consumed by the Ornicopter configuration has been compared to the power needed by a conventional helicopter configuration. In figure 13 the electric power input is shown as a function of the collective pitch input, both for a helicopter configuration and for an Ornicopter configuration. It should be noted that both curves only differ by a constant value of 5 Watts.

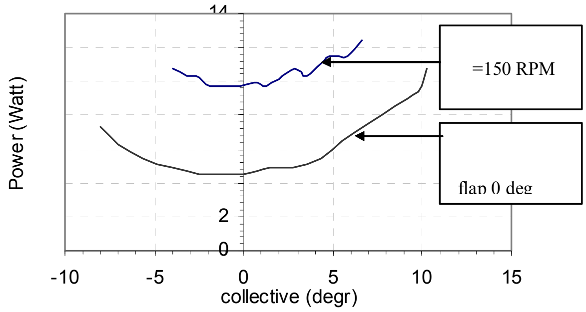

Fig. 13: Power curves for a conventional helicopter and Ornicopter

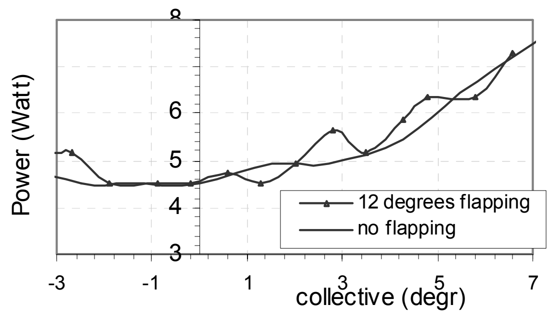

Fig. 14: Adjusted power curves for a conventional helicopter and Ornicopter

When 5 Watts are subtracted from the power of the Ornicopter configuration, a situation as sketched in figure 14 is created. These 5 Watts represent the power in the flapping mechanism. The windtunnel model has not been optimized for friction in the forced flapping mechanism, and, although difficult to measure, calibrations showed that this friction consumed about 3 to 5 Watts of the total power. This quantity is confirmed by the test results in figure 13 since friction is the only torque that remains constant when the collective is varied. If these 5 Watts are subtracted (figure 14) it appears that the induced power of the Ornicopter and conventional helicopter correspond quite well, and thus that the forced flapping does not have a significant influence on the induced power.

Recapitulating, the windtunnel tests have shown that a single rotor without reaction torque can be designed and that both a negative and positive reaction torque can deliberately be introduced to provide yaw control. They also proved that the thrust achieved by the Ornicopter is equal to the thrust achieved by a conventional helicopter under the same circumstances, and that the induced power for the Ornicopter and conventional helicopter correspond quite well. Additionally the tests demonstrated that only modest flapping angles are needed to arrive at a torqueless state.

6 Conclusions

The basic principles of the Ornicopter have been explained and issues concerning the feasibility of the concept have been addressed. The theory has been backed up by windtunnel tests which proved that the Ornicopter is a feasible concept: a torqueless rotor can be achieved by forced flapping of the blades, using relatively small flapping angles,and yaw control is still possible.

Generally speaking the Ornicopter is a feasible concept which holds an interesting promise for the future. At the moment a radio controlled free flying scale model of the Ornicopter is being developed, and construction has started on a full scale (fixed base) test stand for the rotor of the Ornicopter [4].

7 References

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