The Ornicopter: a single rotor helicopter without reaction torque – a short overview

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Abstract

The Ornicopter is a single-rotor helicopter without a reaction torque. A short overview will be given of the basic principles of the Ornicopter, followed by calculations regarding the influence of flexible rotor blades on the characteristics of the Ornicopter.

Keywords: Helicopter; Reaction torque; Ornicopter; Flexible rotor blades; Tail rotor; Blade flapping

1. 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.

2. Basic principles of the Ornicopter

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.

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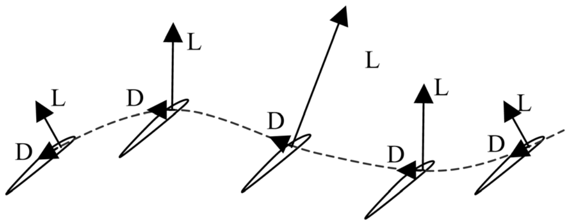

Fig. 1. Aerodynamic forces during one revolution.

2.1. How lift is derived from forced flapping

A useful and simple approximation of the movement of a bird wing can be obtained by applying a constant pitch angle to the Ornicopter blade. The movement of an Ornicopter blade is pictured in Fig. 1. During one revolution, 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 that will propel the blades around the shaft.

2.2. 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. Since there is a torque transferred from the fuselage to the rotor, there will also be a reaction torque from the rotor on the fuselage.

In 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 blade. 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 (van Holten et al. [1,2]).

2.3. Vibrations and rotor lay-out

The forced flapping of the blades might cause severe vibrations in the forces and moments that act about the rotor hub. But, by choosing an appropriate number of blades and an appropriate flapping sequence of the blades, (most of) the vibrations can be canceled out.

The most favorable rotor lay-out from a vibrations point of view (van Holten et al. [3]) is the 2×2 anti-symmetrical configuration. This rotor consists of four blades. While two opposite blades are flapping upwards, the two other blades will flap downwards, and vice versa. The blades will pass through the neutral position at the same moment in time.

For this rotor lay-out, all average values of forces and moments are equal to zero (except for the vertical force), the only vibration that occurs is a 2-P vibration on the rotor torque (which is comparable to single teeter rotor vibrations) [3].

2.4. Ornicopter controls

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. This reaction torque can be introduced by, so to speak, 'over-flapping' or 'under-flapping' of the blades, [1].

The conventional swash plate mechanism is still present in the Ornicopter and will provide cyclic and collective control. Cyclic control and yaw control are completely decoupled [1].

2.5. Power

The following power equation can be derived for the Ornicopter [1]:

$$P_{sh} = P_i + P_p - P_{fl} \tag{1}$$

where P_{sh} denotes the shaft power, P_i the induced power, P_p the profile drag power and P_{fl} the flapping power. If the flapping power is chosen sufficiently large, the shaft power can be reduced to zero. The flapping power thus has to replace the shaft power, and will therefore not be larger than the power that is transferred to the rotor in conventional helicopters.

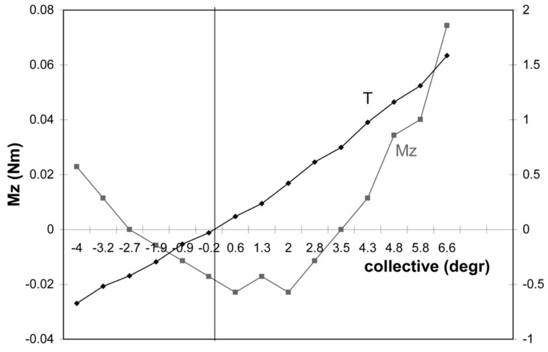

Fig. 2. Rotor torque (M_z) and thrust (T) as a function of collective.

3. Windtunnel test

Windtunnel tests have been performed with a windtunnel model of the Ornicopter, [1]. The most important findings are shown graphically in Fig. 2. While a positive thrust is achieved at 3.5 degrees pitch, the torque on the fuselage is equal to zero. Figure 2 also shows that a positive and a negative reaction torque on the fuselage can be achieved.

4. Flexibility of the blades

The last part of this short paper will focus on the influence of flexible blades on the characteristics of the Ornicopter. Therefore, the equations of motion for a flexible blade during forced vibration will have to be derived. This will be done based on the theory as explained in Bramwell et al. [4].

4.1. Equations of motion for free vibration

The complete solution for the bending of a blade is a function of both time (t) and the radius of a blade element (r):

$$Z = \sum_n \phi_n(t) S_n(r) \tag{2}$$

with ϕ_n the generalized coordinate for a mode shape and S_n the mode shape for a particular eigenfrequency. Using Lagrange's equations, the following equations of motion for free vibration result [5]:

$$(\ddot{\phi}_n + \phi_n \omega_n^2) f(n) = 0 \tag{3}$$

in which:

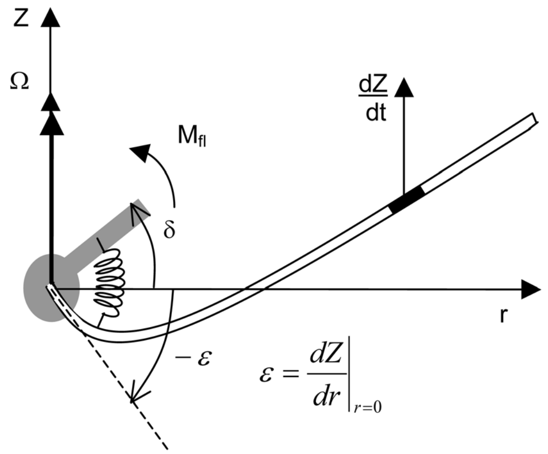

Fig. 3. Flexible blade with forced flapping mechanism.

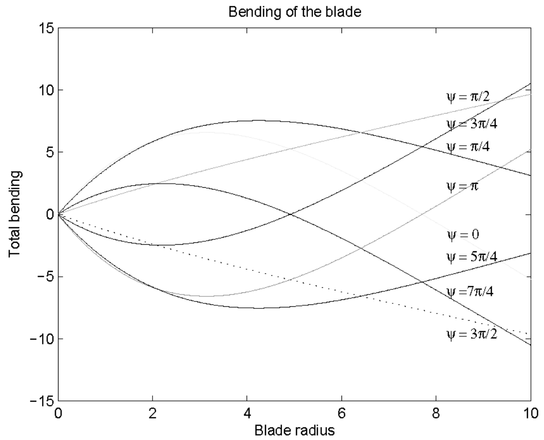

Fig. 4. Bending of a flexible blade.

$$f(n) = \int_0^R m S_n S_m dr \quad \text{for} \quad n = m \tag{4}$$

$$\ddot{\phi}_n = \frac{d^2\phi_n}{dt^2} \tag{5}$$

4.2. Equations of motion for forced vibration

The equations of motion for a flexible blade during forced vibration can be derived by using Fig. 3. The expression for the part of the lift on a blade element due to the flapping of the blade becomes:

$$dL = -C_{l_\alpha} \frac{\frac{\partial Z}{\partial t}}{\Omega r} \frac{1}{2} \rho (\Omega r)^2 c dr \tag{6}$$

with Ω the rotational velocity of the rotor, c the blade chord, $C_{l\alpha}$ the slope of the lift curve and ρ the air density. The generalized force or moment due to the damping effect of the lift for a flexible rotor blade can now be expressed as:

$$Q_n = \int_o^R S_n \frac{\partial F}{\partial r} dr = -\frac{\gamma}{2} \frac{I\Omega}{R^4} \sum_m \dot{\phi}_m \int_0^R S_n S_m r dr \tag{7}$$

in which R is the blade radius and γ the Lock number:

$$\gamma = \frac{\rho C_{L_\alpha} c R^4}{I} \tag{8}$$

Using Lagrange's equation and incorporating the effects of the spring and the general expression for the generalized forces and moments (Eq. (7)) in Eq. (3) yields:

$$(\ddot{\phi}_n + \phi_n \omega_n^2) f(n) - K\left(\delta - \sum_m \phi_m S'_m(0)\right) S'_n(0) =$$

$$-\frac{\gamma}{2} \frac{I\Omega}{R^4} \sum_m \dot{\phi}_m \int_0^R S_n S_m r dr \quad \text{for} \quad n = (0, 1, 2, ...) \tag{9}$$

Starting with the following displacement function [4]:

$$\frac{\gamma_i}{R} = (i+2)(i+3)\frac{x^{i+1}}{6} - i(i+3)\frac{x^{i+2}}{3} + i(i+1)\frac{x^{i+3}}{6} \tag{10}$$

assuming the Lock number equal to 8 and k^2 equal to

$$k^2 = \frac{EI}{m\Omega^2 R^4} = \frac{1}{270} \tag{11}$$

and following Bramwell et al. [5] the resulting bending motion for both a one mode (rigid) approximation and a two mode (flexible) approximation can be derived [5], see also Fig. 4:

$$Z_{rigid} = \hat{m}_{fl} \cos\left(\psi - \frac{\pi}{2}\right) r \tag{12}$$

$$Z_{flexible} = 1.029 \hat{m}_{fl} \cos(\psi - 1.39) r +$$
$$-0.71 \hat{m}_{fl} \cos(\psi - 0.066)\left[-\frac{13}{2} r + 15\frac{r^2}{R} - 10\frac{r^3}{R^2} + \frac{5}{2}\frac{r^4}{R^3}\right] \tag{13}$$

In these equations $\hat{m}_{fl}$ is the amplitude of the non-dimensional flapping moment m_{fl}, which in its turn is given by:

$$m_{fl} = \frac{M_{fl}}{I\Omega^2} = \frac{K}{I\Omega^2}\left(\delta - \sum_m \phi_m S'_m(0)\right) \tag{14}$$

4.3. Main differences caused by the flexibility of the blades

The root angle (ϵ) of a flexible blade will be larger than the root angle of a rigid blade, this will have consequences for the stroke that the forced flapping mechanism will have to deliver. The root angle is defined by:

$$\varepsilon = \left.\frac{dZ}{dr}\right|_{r=0} \tag{15}$$

It thus follows by using Eqs. (12) and (13):

$$\varepsilon_{flexible} = \hat{m}_{fl}(4.79\cos\psi + 1.32\sin\psi) \tag{16}$$

$$\hat{\varepsilon}_{flexible} = 4.96\hat{m}_{fl} \tag{17}$$

$$\varepsilon_{rigid} = \hat{m}_{fl}\cos\left(\psi - \frac{\pi}{2}\right) \tag{18}$$

$$\hat{\varepsilon}_{rigid} = \hat{m}_{fl} \tag{19}$$

The amplitude of the root angle of a flexible blade is almost five times as large as for a rigid blade. Further it can be calculated [5] that the shear force in the blade root diminishes by approximately 6% and that the flapping power needed for a flexible blade is equal to the flapping power needed for a rigid blade.

5. Conclusions

The Ornicopter is a feasible concept: a torqueless situation can be achieved while yaw, cyclic and collective control are still operational. Moreover, vibration levels are controllable and the flapping power that is transferred to the blades is the same as the power needed for rotors in conventional helicopters.

The influence of the flexibility of the blades mainly concerns the magnitude of the root angle which will increase compared to the root angle of rigid blades. This might have consequences for the lay-out of the flapping system.

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