Paper Number: 188

Stability and controllability analysis for Ornicopter – a new tailless helicopter

Jia Wan Marilena D. Pavel

PhD student Assistant Professor

Delft University of Technology

Delft, Netherlands

J.Wan@tudelft.nl M.D.Pavel@tudelft.nl

ABSTRACT

The Ornicopter is a relatively new concept of tailless helicopter which actively flap the blades up and down, similar to the movement of a bird's wing. Because of this flapping motion, the blades will propel themselves around the rotor shaft and will at the same time provide a lifting force. Therefore, the tail rotor is redundant. The goal of the present paper is to assess the stability characteristics of such new concept. In this context, a thirteen degree of freedom flight mechanics model for Ornicopter is linearized to form a state-space model. Using this state-space model, Ornicopter helicopter is compared with a reference helicopter in respects to eigenmodes, stability and control derivatives. As reference helicopter, the Bo-105 is considered as this one was adapted to the Ornicopter's configuration by removing its tailrotor and adapting the rotor hub to allow for forced flapping motion. The paper shows that while the Ornicopter's rotor can be adapted to function as a conventional rotor helicopter, the elimination of the tailrotor will have significant influence on the lateral/directional stability characteristics. The Ornicopter's Dutch role mode is low damped and needs special attention.

NOTATION

L,M,N	moments on the c.g. about x-, y- and z-axes
N_b	Number of blades
X, Y, Z	forces on the c.g. along x-, y- and z-axes
p, q, r	angular velocity components of helicopter along fuselage x-, y- and z-axes
u, v, w	translational velocity components of helicopter along fuselage x-, y- and z-axes
x, y, z	coordinates in the body fixed reference
$\beta_0^{(k)}, \beta_{s1}^{(k)}, \beta_{c1}^{(k)}$	Flapping coefficients of the k^{th} blade
Ψ, Θ, Φ	yaw, pitch and roll attitude angle
$\theta_0, \theta_{s1}, \theta_{c1}$	collective and cyclic pitch control of main rotor
θ_{tr}	collective pitch control of tail rotor
$\hat{\xi}$	amplitude of force flapping mechanics

Subscripts

u, v, p, etc.	stability derivatives w.r.t. *u, v, p,* etc.
$\theta_0, \theta_{s1}, \theta_{c1}$	control derivatives for collective and cyclic pitch
yaw	yaw control derivatives

INTRODUCTION

The most general configuration of conventional helicopters is to a large extent determined by the need to transfer torque from fuselage to the main rotor and thus use a tail rotor system in order to counteract the reaction torque of the main rotor. Unfortunately, this 'necessary evil' component of a helicopter represented by the tail rotor has many unfavourable characteristics: it is expensive, consumes power, has only marginal control authority under unfavourable 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. Since 2002, Delft University of Technology has been working on such a revolutionary design - The Ornicopter. The Ornicopter principle is that of a helicopter that flies by flapping its rotor blades up and down, similar to the movement of a bird's wing, so that no reaction torque is created on the main rotor [Ref. 1, 2]. As its name presents, the Ornicopter can be considered as a helicopter version of the Ornithopter, the aircraft that flies like a bird.

The Ornicopter principle has been proved theoretically, and by windtunnel tests [Ref. 2]. Since 2002, three basic rotor configurations were proposed capable of creating the

Paper presented at the 37th European Rotorcraft Forum, Gallarate (Varese) Italy, September 13 -15, 2011

forced-flapping mechanism on the main rotor and propel the blades. These three configurations are, in order of development, the so-called the double teeter configuration, the 2×2 anti-symmetrical configuration (referred as 2×2 AS in the followings), and the 3-in-1-plane configuration (see Figure 1).

The double teeter configuration has been chosen as a concept because of the relative simplicity of its forced flapping mechanism. The rotor consists of two teeters: the two opposite blades are connected like a see-saw, which means that if one blade is flapping upwards, the opposite blade is flapping downwards. All four of the blades are forced to flap with a 1-P frequency. At the moment in time that one of the two teeters is at its maximum flapping angle, the other teeter will be in the neutral position, as shown in Figure 1. The tip path planes of the two teeters are anti-symmetrically tilted with respect to the shaft.

The 2x2 anti-symmetrical configuration is more complicated than that of the double teeter, however this configuration is expected to have more favourable vibration characteristics. The rotor in anti-symmetrical configuration consists of four blades as well, but now the two opposite blades are flapping in the same direction. So (looking at Figure 1.b) if blade k=0 is flapping upwards, blade k=2 is flapping upwards as well, while at the same time the two other blades will be flapping downwards, and vice versa. The blades will pass through the neutral position at the same moment in time.

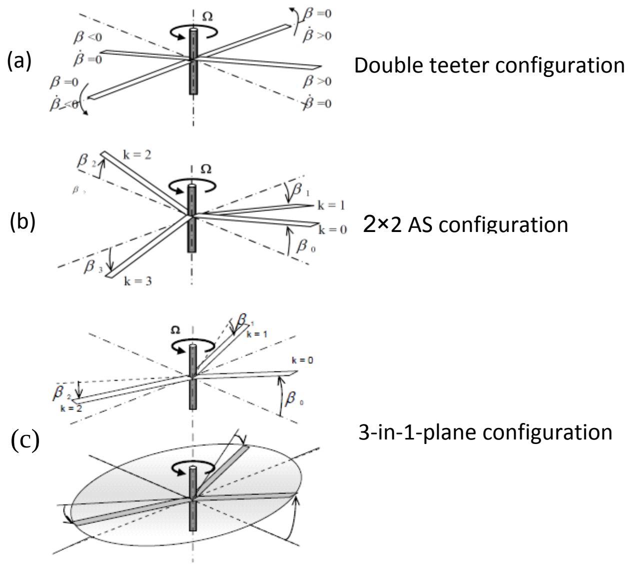

Figure 1. Three Ornicopter configurations

For this three bladed configuration, the three blades are always in one plane although each blade rotates in a different tip path plane (see Figure 1.c). This configuration is considered because of the simplicity of its forced flapping mechanism which could consist of a swashplate rotating at twice the rotational speed of the rotor. The principle of 3-in-1-plane configuration is that when blade k=0 is at its maximum flapping angle, blade k=1 is flapping upwards and blade k=2 is flapping downwards

In previous work, the behaviour of the above-mentioned Ornicopter rotors was compared based on the harmonic components of total forces and moments on the rotor hub [Ref. 3]. Furthermore, a radio controlled Ornicopter demonstrator model was developed and ground tests have been performed [Refs. 4-7]. The impact of flexible blades on Ornicopter behaviours was also previously studied [Ref. 8]. The conclusion was that the 2 × 2 AS configuration has the lowest vibration loads among the three proposed configurations. However, the comparisons were made only for hovering condition and without cyclic pitch controls [Ref. 3].

A flight mechanics model for the Ornicopter concept was developed to investigate its behaviours through the whole flight envelope [Ref. 9]. In this sense, the model has $9+3\times N_b$ degrees of freedom (DoFs) including the 9 DoFs corresponding to a 6 DoFs body motion plus a 3 DoFs Pitt-Peters dynamic inflow model and 3 DoFs corresponding to flapping motion of each blade.

To investigate possible solution for vibratory problem and expand the design envelop of Ornicopter, some new configurations contain higher number of blades were proposed based on 2×2 AS and double teeter configurations, including 3×Teeter(3×T), 3×2 AS, 4×Teeter (4×T) and 4×2 AS configuration [Ref. 9].

In this paper, this model is linearized to get the state-space model for Ornicopter for further analyses. Based on this state-space model, some comparisons are processed for stability and controllability characteristics between Ornicopter and conventional helicopters.

BASIC ORNICOPTER PRINCIPLE

First, a short explanation of the Ornicopter's basic principles is given.

The vanished reaction torque

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 mimic 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 2.

During one revolution of the blade, the blade will be forced to flap both up and down once, resulting in the shown undulating path. While the blades flap down, the angle of attack of blade element will increase. At the same time, the lift force tilts forward. This results in a high forward horizontal force, by which the blade is propelled. When the blades flap up, the lift force tilts backward and the induced drag rises up. 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 up and down a propulsive force is created that will rotate the blades around the rotor hub and an upward force is created that will counteract gravity.

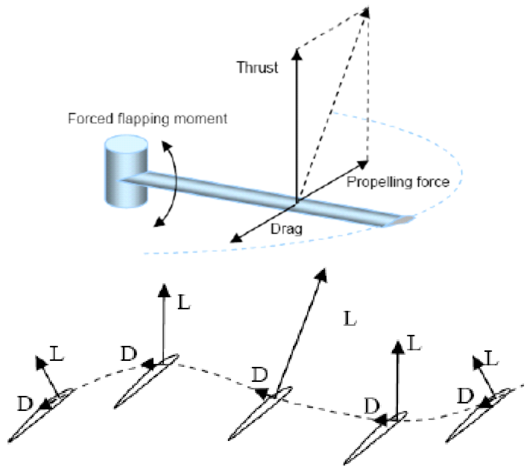

Figure 2. Lift and drag forces acting on an Ornicopter blade during one revolution when a constant pitch angle is applied [Ref. 10]

So why is it, that when the blades are propelled by a flapping motion, there is no reaction torque acting on the fuselage? This can be explained by comparing a conventional helicopter to an Ornicopter, see Figure 3. In a conventional helicopter the drag that is acting on the rotor blades is counteracted by the torque that is exerted on the rotor (see Figure 3.a). 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 propelling force produced by the forced flapping motion of the wing (see Figure 3.b). There is thus no direct 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. And hence an anti-torque device is no longer necessary.

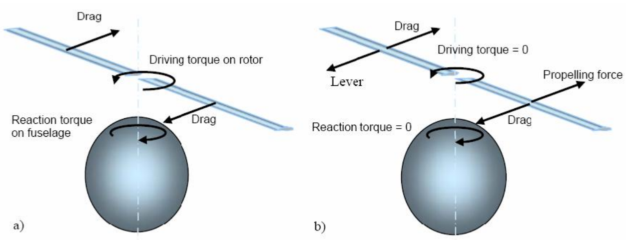

Figure 3. Forces and moments acting on a conventional helicopter (a) and the Ornicopter (b) [Ref. 10]

It should be also mentioned that, for the Ornicopter design, the blades flapping motion has 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 favourable for the load in the blade) and to obtain a flat tip path plane for each rotor blade (which is necessary for cyclic control) [Ref. 2].

Force Flapping Mechanism

To excite the Ornicopter blades to flap, additional mechanisms is needed. The flapping mechanism can be designed in different ways with the same basic principle: to generate extra force flapping moment on the blades, which is required to be adjustable for yaw control as discussed above.

Figure 4 shows the principle of one possible design presented in [Ref. 2]. Besides the normal swash plate, a non-rotating swash plate is also presented. When the rotor is rotating, the push road will move up and down because of the non-rotating swash plate and hence the blades will be forced to flap. The amplitude of this periodic vertical movement depends on the tilt angle of the non-rotating swash plate. So the amplitude of forced flapping motion of blades can be controlled by this swash plate.

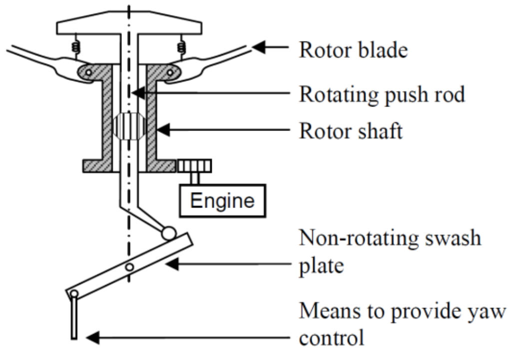

Figure 4. Principle of a flap forcing mechanism using a push-pull rod and swashplate [Ref. 4]

Other possible designs were also discussed in previous researches, including the so-called eccentric mechanism, the gearwheel mechanism, and the multiple disc mechanism [Ref. 10].

Considering the simplicity of flapping mechanisms, the swash plate configuration was used for the windtunnel model [Ref. 10] and the gearwheel mechanism was used on the radio controlled demonstrate model [Refs. 4-7]. Figure 5 shows the sketch of the gearwheel mechanism [Ref. 7].

Controlling the Ornicopter

Yaw control

In a conventional helicopter, yaw control is 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 is needed. How this yaw control for an Ornicopter can be achieved will be explained below. In principle, by introducing a small amount of change in the force flapping amplitude, the yaw control for an Ornicopter can be achieved. From Figure 2, it can be seen that the propelling force is related to the amplitude of flapping motion. Higher amplitude will generate a larger propelling force, and thus change the shaft torque. One would be able to draw same conclusion when analysing the shaft power.

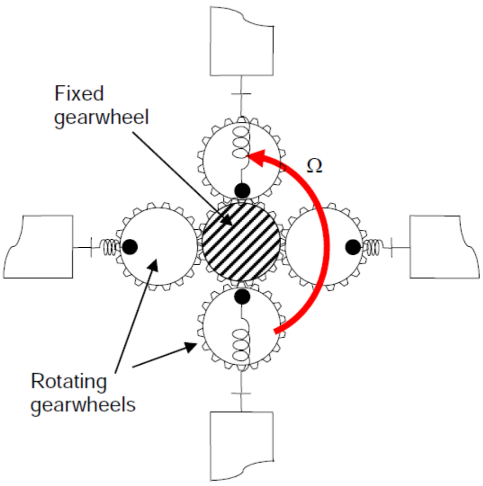

Figure 5. Gearwheel mechanism

Figure 6.a presents the case when no yaw movement is desired for the example flapping mechanism of Figure 4. In this case 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. To realize this reactionless situation a certain inclination (δ) of the swash plate will be necessary. In this case, 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 6.b), this implies that the flapping of the blades will not be sufficient to keep the rotor at its required rotational speed (the rotor will tend to slow down), 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. To create a yaw movement in the opposite direction a larger inclination of the swash plate needs to be applied (Figure 6.c). 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 6.b, and will therefore cause a yaw movement in the opposite direction.

Cyclic and collective control

The cyclic and collective controls for Ornicopter are the same as those of conventional helicopters. A normal swash plate is presented on Ornicopter. Using this conventional swash plate, pitch angles of blades can be controlled as conventional helicopters.

As each blade is forced to flap, their tip-path planes will be tilted towards certain direction according to the force flapping moment. To minimise additional hub shears and moments, the average tip-path plane of all blades should not be changed by the force flapping motion. One possible way is to excite blades anti-symmetrically, like shown in Figure 7.a. Those two tip-path planes tilt towards opposite directions to maintain the average tip-path plane level. When the cyclic pitch control is applied, tip-path planes of all blades will tilt in the same way, as shown in Figure 7.b. This is true for both Ornicopter and normal helicopters. When both the force flapping and cyclic control are given at the same time, the combined effect of them is shown in Figure 7.c. In this way, longitudinal and lateral controls of Ornicopter can be achieved.

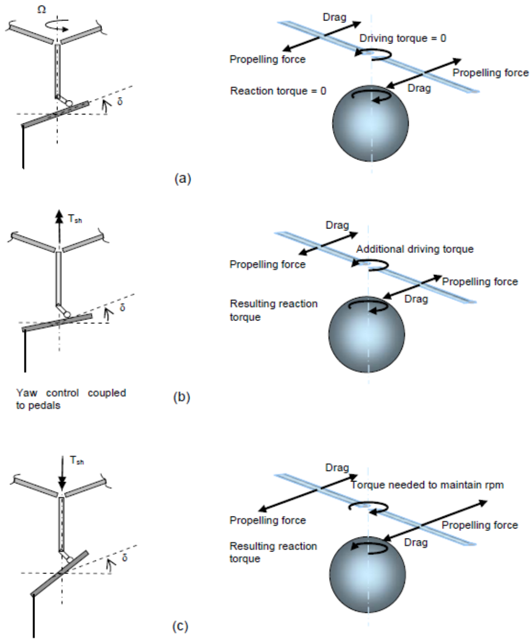

Figure 6. Schematic representation of yaw control by introducing a reaction torque

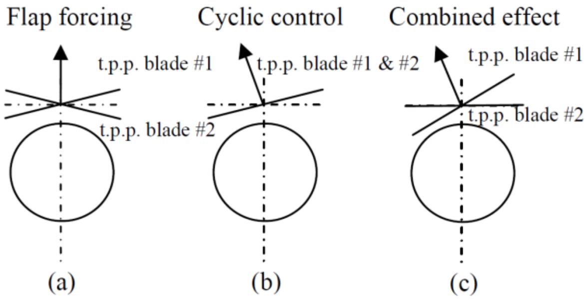

Figure 7. Cyclic control of Ornicopter [Ref. 2]

In conclusion, Ornicopter changes the way of yaw control, and in this configuration, all controls are achieved through the main rotor. Therefore, more research should be done for the yaw control and control coupling, especially in forward flight.

ORNICOPTER MODELING

In order to develop the Ornicopter model, a 13 DoFs flight mechanics model for conventional helicopters was developed first, including 6 body motion degrees, 3 flapping motion degrees, 3 degrees for Pitt-Peters dynamic inflow of the main rotor and 1 degree for tail rotor inflow, and then it was adapted for the Ornicopter [Ref. 9].

This Ornicopter model is developed in-house and is based on blade element theory. The model includes 6 degrees for body motion, 3 degrees for Pitt-Peters dynamic inflow mode and 3 degrees for flapping motion of each blade. With two attitude angles (Θ and Φ), the Ornicopter model has 11+3×N_b states variables. All states can be written as:

$$\begin{aligned}\mathbf{X} = [&u, v, w, p, q, r, \Theta, \Phi, \lambda_0, \lambda_{s1}, \lambda_{c1} \\ &\beta_0^{(1)}, \beta_{s1}^{(1)}, \beta_{c1}^{(1)}, \ldots, \beta_0^{(N_b)}, \beta_{s1}^{(N_b)}, \beta_{c1}^{(N_b)}]^T\end{aligned} \quad (1)$$

The collective and cyclical pith controls of Ornicopter are the same as those of conventional helicopter, and the amplitude of the force flapping motion ($\hat{\xi}$) replaces tail rotor pitch (θ_{tr}) as the yaw control [Ref. 9]. The control input of Ornicopter is:

$$\mathbf{U} = [\theta_0, \theta_{s1}, \theta_{c1}, \hat{\xi}]^T \quad (2)$$

Considering available flight test data and theoretical researches, the Bo-105 is chosen as the reference helicopter in this paper. To focus on differences caused by the Ornicopter concept, all design parameters used in the Ornicopter model are the same as those of Bo-105. Since Bo-105 has four blades, the Ornicopter model is also using 4-blade configuration. Considering vibratory loads, the 2×2 AS configuration will be used in this paper.

After the model is trimmed for forward flight, it can be linearized by calculating derivatives at the trim point. For Ornicopter, the states-space model can be written as:

$$\begin{aligned}\dot{\mathbf{X}} &= \mathbf{AX} + \mathbf{BU} \\ \mathbf{Y} &= \mathbf{CX} + \mathbf{DU}\end{aligned} \quad (3)$$

in which:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_B & \mathbf{A}_{\lambda B} & \mathbf{A}_{\beta B} \\ \mathbf{A}_{B\lambda} & \mathbf{A}_\lambda & \mathbf{A}_{\beta\lambda} \\ \mathbf{A}_{B\beta} & \mathbf{A}_{\lambda\beta} & \mathbf{A}_\beta \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{B}_B \\ \mathbf{B}_\lambda \\ \mathbf{B}_\beta \end{bmatrix} \quad (4)$$

$$\mathbf{C} = \mathbf{I}, \mathbf{D} = 0$$

As the flapping motions of blades are independent to each other, the sub matrix $\mathbf{A}_\beta$ is:

$$\mathbf{A}_\beta = \begin{bmatrix} \mathbf{A}_\beta^{(1)} & 0 & \cdots & 0 \\ 0 & \mathbf{A}_\beta^{(2)} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \mathbf{A}_\beta^{(N_b)} \end{bmatrix} \quad (5)$$

Now the states space model is available for further analyses. However, this system has 23 states, and hence matrix **A** and **B** are huge for comparisons. At the same time, the model for Bo-105 only has 15 states, which are:

$$\begin{aligned}\mathbf{X}_{BO105} = [&u, v, w, p, q, r, \Theta, \Phi, \\ &\lambda_0, \lambda_{s1}, \lambda_{c1}, \lambda_{tr}, \beta_0, \beta_{s1}, \beta_{c1}]^T\end{aligned} \quad (6)$$

To reduce the complexity of the state space model and provide insight into the stability characteristics for Ornicopter and Bo-105 helicopters, it was decided in the followings to reduce the initial 13 DoFs model to a 6 DoFs representing only body motion

For Ornicopter, the new matrix $\mathbf{A}^*$ and $\mathbf{B}^*$ are calculated as follow:

$$\begin{aligned}\mathbf{A}_B^* &= \mathbf{A}_B - [\mathbf{A}_{\lambda B} \;\; \mathbf{A}_{\beta B}] \begin{bmatrix} \mathbf{A}_\lambda & \mathbf{A}_{\beta\lambda} \\ \mathbf{A}_{\lambda\beta} & \mathbf{A}_\beta \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{A}_{B\lambda} \\ \mathbf{A}_{B\beta} \end{bmatrix} \\ \mathbf{B}_B^* &= \mathbf{B}_B - [\mathbf{A}_{\lambda B} \;\; \mathbf{A}_{\beta B}] \begin{bmatrix} \mathbf{A}_\lambda & \mathbf{A}_{\beta\lambda} \\ \mathbf{A}_{\lambda\beta} & \mathbf{A}_\beta \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{B}_\lambda \\ \mathbf{B}_\beta \end{bmatrix}\end{aligned} \quad (7)$$

After those two models are transformed to standard 6 DoFs models, some comparisons can be done between the Ornicopter and Bo-105.

Eigenvalues of the natural modes of motion for the 6 DoFs body can be calculated through the system matrix. Figure 8 shows the root loci of Ornicopter and Bo-105 in different flight velocity. It can be found that loci of Ornicopter and Bo-105 are almost identical expect the Dutch roll mode.

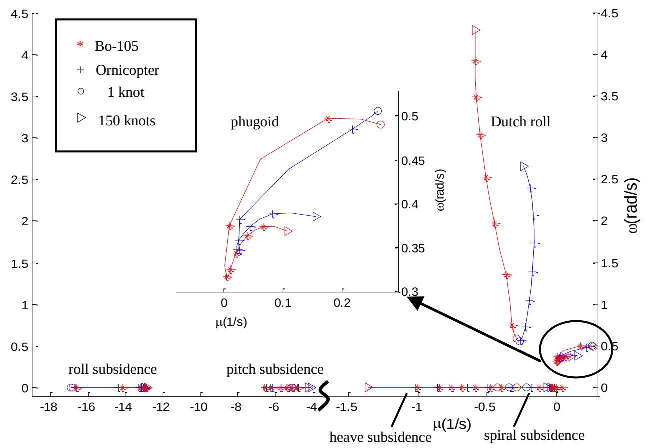

Figure 8. Loci of Ornicopter and Bo-105 eigenvalues as a function of forward speed

The Ornicopter's Dutch roll mode is closer to the imaginary axis than that of Bo-105. This indicates a lower damping. Since Ornicopter does not have tail rotor and controls the yaw differently, this difference may be attributed to a decrease in yaw damping characteristic to Ornicopter.

The time to half amplitude of Dutch roll motion $t_{1/2}$ and the period of this periodic mode T can be calculated though the eigenvalues, as shown in Figure 9.

It shows that Ornicopter has much higher half time than Bo-105 especially at high velocity. This is due to the lower Ornicopter's Dutch roll damping. The Ornicopter's disturbances will need much more time to be damped off, and this is not a favorable characteristic, which needs to be improved in Ornicopter design. Solutions like bigger stabilizer or additional damping through controller design might be applied.

Meanwhile, Ornicopter has higher Dutch roll period (lower frequency) than Bo-105. This longer period can reduce the number of oscillation cycles and decrease pilot work load.

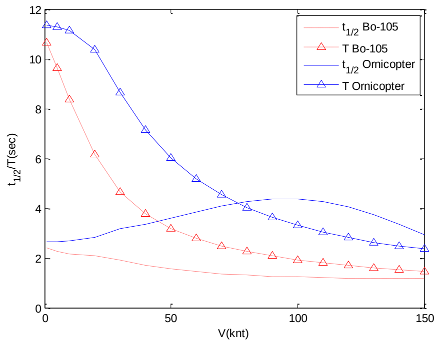

Figure 9. $t_{1/2}$ and T as functions of velocity

The eigenvectors of system matrix also offer some useful information for the amplitudes and phase angles of oscillations of each states. Table 1 presents the major part of the eigenvector for Dutch roll at 80 knots, from which one can find that phase angles of different motions are almost the same between Ornicopter and Bo-105. However, the ratio of roll to yaw velocity is smaller in the case of Ornicopter. Since Ornicopter has lower oscillation frequency, the roll attitude of Ornicopter will reach higher amplitude.

Table 1. Eigenvector for Dutch roll mode (partial)

		states			
		v	p	r	Φ
Bo-105	amplitude	1.0m/s	1.1deg/s	3.9deg/s	0.40deg
	phase(deg)	0	174	-79.7	68.8
Ornicopter	amplitude	1.0m/s	0.94deg/s	2.0deg/s	0.61deg
	phase(deg)	0	174	-83.4	74.8

To understand the physical reasons of the differences between Ornicopter and Bo-105 eigenvalues next paragraph will discuss some more detailed comparisons are done for some stability and control derivatives.

STABILITY DERIVATIVES

The system matrix $\mathbf{A}^*$ contains derivatives of accelerations for each states, such as $\partial\dot{u}/\partial v$. To get a more direct view of changes of forces and moments on Ornicopter, the derivatives of forces and moments with regard to all states are used in follow comparisons. The force derivatives are normalized by aircraft mass, and the moments derivatives are normalized by the moments of inertia, like:

$$X_u \equiv \frac{\partial X}{\partial u}\cdot\frac{1}{M_a}(s^{-1}) \qquad X_q \equiv \frac{\partial X}{\partial q}\cdot\frac{1}{M_a}(m(s\cdot rad)^{-1}) \tag{8}$$

$$L_v \equiv \frac{\partial L}{\partial v}\cdot\frac{1}{I_x}(rad(s\cdot m)^{-1}) \qquad L_p \equiv \frac{\partial L}{\partial p}\cdot\frac{1}{I_x}(s^{-1}) \tag{9}$$

Those derivatives contain contributions from different components of the helicopter, including the main rotor, the tail rotor, fuselage and stabilizers. Since the Ornicopter has exactly the same configuration as Bo-105 for the fuselage and stabilizers, the impacts of those components on the change of derivatives should be neglectable. Therefore, those disparities between Ornicopter and Bo-105 are mainly generated by the new main rotor or the vanishment of tail rotor.

To distinguish different impacts from the main rotor and the tail rotor, the derivatives for the Bo-105 helicopter have been calculated without the contribution of the tail rotor, the so-called Bo-105* configuration. In this way, disparities between the Bo-105* and Ornicopter's derivatives indicate only the effects of their different main rotors.

For the reduced 6 DoFs body model there are 36 stability derivatives and 24 control derivatives. Next, the more important derivatives of Ornicopter and Bo-105/Bo-105* will be discussed, emphasizing the differences in behaviour between these two different helicopters.

Force/Translational velocity derivatives X_u, Y_u, X_v, Y_v

The direct (X_u, Y_v) and the coupling force/velocity derivatives (X_v, Y_u) are presented in Figure 10 as a function of forward flight velocity variation. The direct derivatives X_u and Y_v are principally due to the disc tilts to aft and right (for a counterclockwise rotor helicopter) following perturbations in u and v.

It can be found that in the derivatives of the X force - X_u and X_v, the Ornicopter's values are nearly the same as in the case of Bo-105, and the difference increasing a little for high flight velocity. The tail rotor does not contribute to the X force and the curves for Bo-105 and Bo-105*(Bo-105 without tail rotor) are overlapped.

However, for Y force derivatives, the situation is different. Looking at Figure 10, one can see that the Y-force derivatives for Ornicopter and Bo-105 have similar trends, their orders of magnitude being different. However, subtracting the tail rotor impact from the Y-derivative, shows that the Y-derivatives for Ornicopter and Bo-105* are almost identical. This indicates that the tail rotor is the main responsible for the changes in the side force derivatives between the Ornicopter and Bo-105 the new main rotor design for Ornicopter having the same lateral characteristics in Y-forces as the hingeless Bo-105.

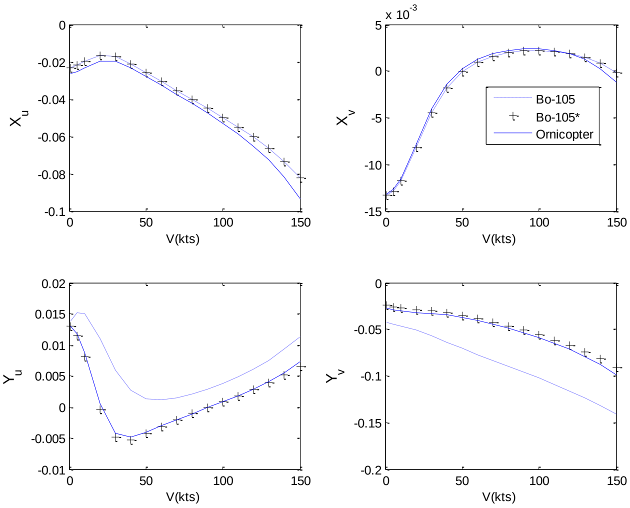

Figure 10. Direct and coupling force derivatives as a function of flight velocity

The speed and incidence static stability derivatives M_u and M_w

The speed and incidence stability derivatives M_u and M_w give the static stability characteristics of the aircraft. The derivative M_u represents the change in pitching moment about the aircraft's centre of mass when the aircraft is subjected to a perturbation in longitudinal velocity u. Figure 11 shows these two derivatives as a function of flight velocity.

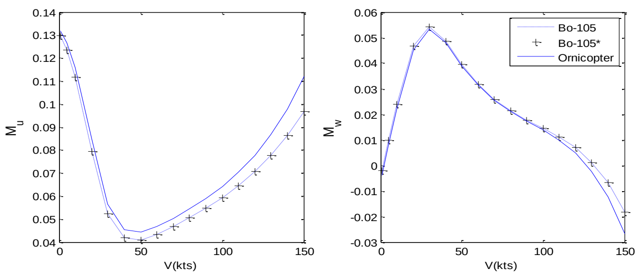

Figure 11. Variation of M_u and M_w with forward speed

Looking at this figure, only a slight difference can be found between Ornicopter and Bo-105 static derivatives at high flight speed. The speed static derivative M_u of both helicopters exhibit static speed stability: an increase in forward speed causes the disc to flap back, together with an increase in the download on the tailplane, resulting in a nose-up pitching moment and a tendency to reduce speed. According to Padfield, [Ref. 11], this positive (apparent) sped stability is important for good handling qualities in forward flight but can degrade dynamic stability in both hover and forward flight. Furthermore, concerning the incidence static stability M_w, a negative M_w corresponds to a statically stable aircraft (a positive normal velocity perturbation results in a pitch-down moment). Looking at Figure 10 one can see that M_w is positive for a large range of forward speeds. This is characteristic to most helicopters, as they are inherently unstable in pitch. The effect of hingeless rotors on M_w is striking, leading to a large destabilizing moment at high speed.

The heave damping derivative Z_w

The heave damping derivative Z_w gives the vertical response characteristics of a helicopter in response to a vertical gust. In the case of the heave damping derivative Z_w, the Ornicopter has the same damping as Bo-105, as shown in Figure 12. For hover, the value of Z_w is about -0.33/s, giving a heave motion time constant of about 3 sec (this is a typical heave time constant for most helicopters in hover). With such a long time constant, the helicopter vertical response of both Ornicopter and Bo-105 would seem more like an acceleration-control response than a velocity-control response, thus requiring more anticipation from pilot point of view.

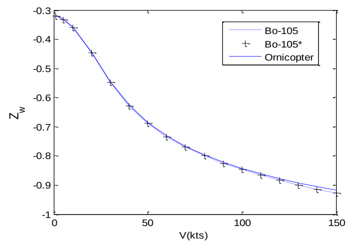

Figure 12. Variation of Z_w with forward speed

The sideslip derivatives L_v and N_v

The sideslip derivatives – the dihedral effect derivative L_v and the weathercock stability N_v are significant for the lateral/directional DoFs. Figure 13 shows the variation of these two derivatives with forward speed for both Bo-105/Bo-105* and Ornicopter helicopters.

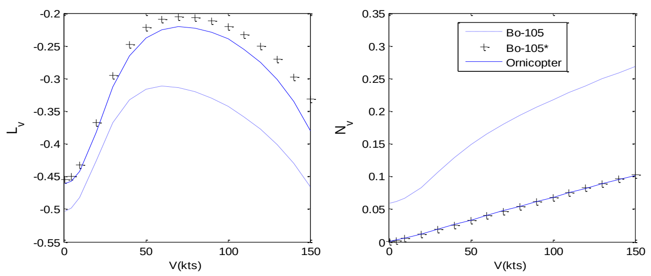

Figure 13. Variation of L_v and N_v with forward speed

Since the tail rotor contributes strongly to both derivatives, there are big discrepancies in their values between Ornicopter and Bo-105. The main reason for this is the tailrotor, once the tailrotor effect has been removed from the Bo-105 derivatives, the resulting Bo-105* configuration being very similar to Ornicopter behavior. In general, a positive value of N_v is stabilizing, while a negative value of L_v is stabilizing. Looking at Figure 11, one can see that Ornicopter has lower lateral/directional static stability.

The derivatives N_u, N_w, L_u, L_w

The derivatives N_u, N_w, L_u and L_w are important for the coupled low-frequency longitudinal and lateral motions of the helicopter. As shown in Figure 14, only a slight disparity for Ornicopter's N_u can be found at low flight velocity as compared to Bo-105.

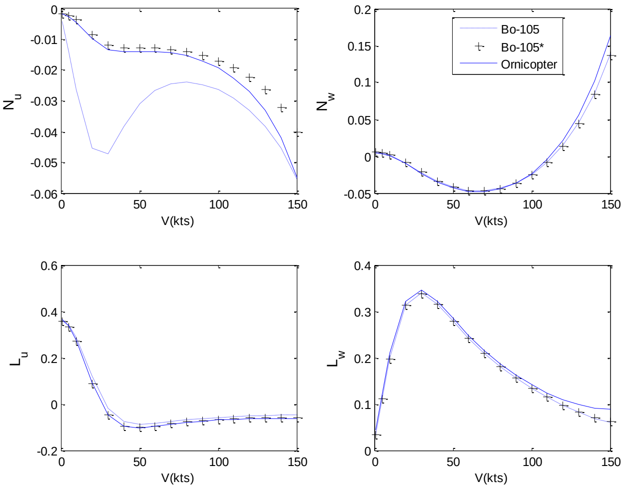

Figure 14. Coupling derivatives for longitudinal and lateral motions

The angular velocity derivatives

Figure 15 and Figure 16 shows the force/angular velocities derivatives X_q and Y_p and the moment/angular velocities M_q, L_p, M_p and L_q for both Ornicopter and Bo-105 helicopters. All these derivatives are contributed mainly by the main rotor. The M_q, L_p, M_p and L_q derivatives are also the so-called direct and coupled damping derivatives. According to Padfield [Ref. 11], the direct damping derivatives reflect short-term, small and moderate amplitude handling characteristics, while cross-dampings play a dominant role in the level of pitch-roll and roll-pitch couplings."*They are the most potent derivatives in handling qualities terms, yet because of their close association with short-term rotor stability and response, they can also be unreliable as handling parameters.*" [Ref. 11]

Looking at Figure 15 and Figure 16 it appears again that the Ornicopter rotor has almost the same characteristic as a "normal" rotor system.

The derivatives N_r, L_r and N_p have a primary influence on the character of the lateral/directional stability and control characteristics of the helicopter. As shown in Figure 17, these three derivatives are also dominated by the tail rotor, which causes relatively big differences between Ornicopter and Bo-105, especially in the yaw damping.

Concluding, there are major discrepancies between the stability characteristics of Ornicopter and conventional helicopters. However, these disparities can be attributed to tailrotor vanishment in the case of Ornicopter, its main rotor showing same behavior as normal helicopters. Consequently, the all derivatives dominated by the tail rotor are very different for Ornicopter. Such derivatives include L_v, N_v, N_r, L_r and N_p, all of them influencing significantly the lateral/directional stability and control characteristics of Ornicopter. Also, the Dutch roll mode of Ornicopter is different from that of the Bo-105 helicopter, being less damped.

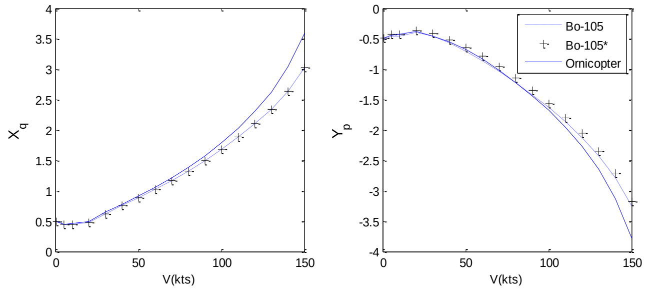

Figure 15. X_q and Y_p as a function of flight speed

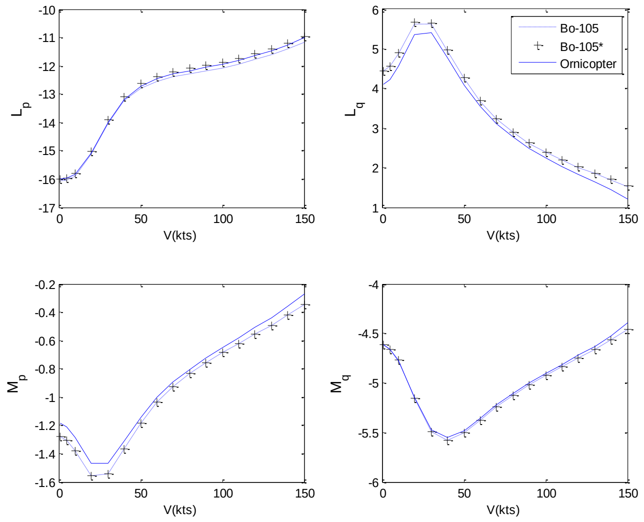

Figure 16. Variations of the direct and coupled damping derivatives

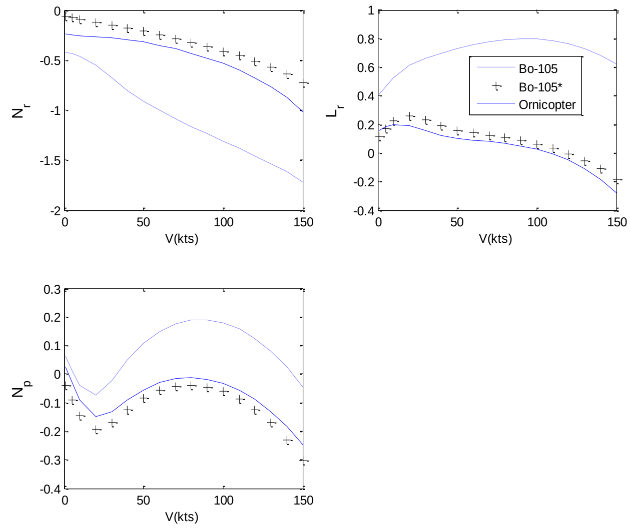

Figure 17. N_r, L_r and N_p as a function of flight speed

CONTROL DERIVATIVES

From the 24 control derivatives characteristic to the 6 DoFs model, 11 have been selected to be discussed in more detail in the followings. Figure 18 presents the first set of control derivatives corresponding to the derivatives of thrust with main rotor collective and longitudinal cyclic Z_{θ_0}, $Z_{\theta_{s1}}$ and the pitch and roll generated by the application of main rotor collective L_{θ_0} and M_{θ_0}. The first two derivatives are primarily influenced by the blade loading and tip speed. Figure 19 presents the second group of derivatives corresponding to the direct and coupled response for cyclic pith control including $L_{\theta_{s1}}$, $L_{\theta_{c1}}$, $M_{\theta_{s1}}$ and $M_{\theta_{c1}}$. Since these two sets of derivatives are contributed primarily by the main rotor, no significant differences between the Ornicopter and Bo-105 helicopters can be found. These small disparities are probably caused by the slightly different trim values of Ornicopter.

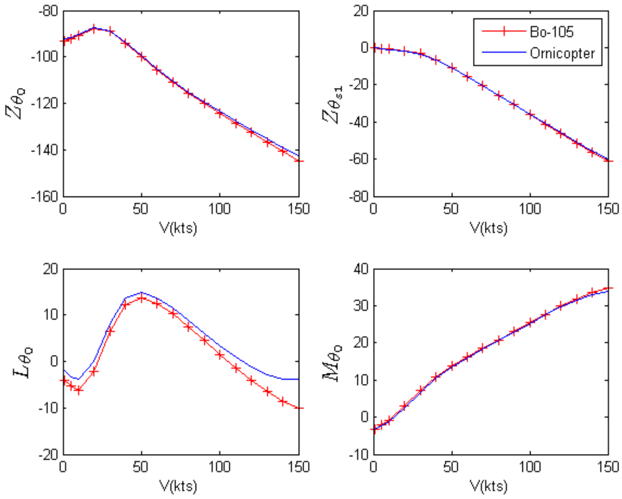

Figure 18. First set of control derivatives a function of flight speed

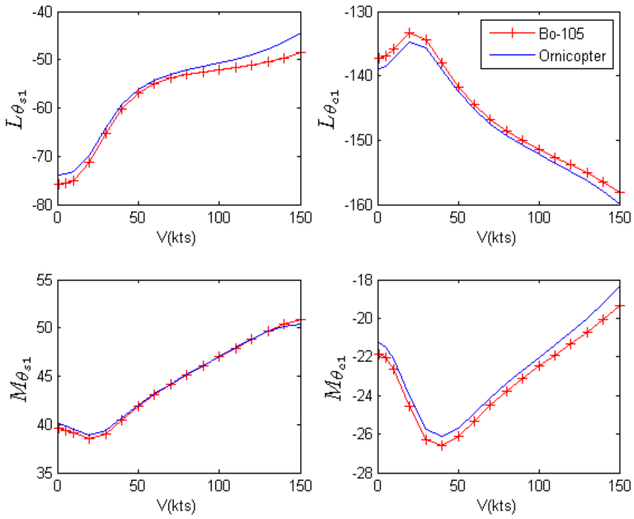

Figure 19. Variation of direct and coupling moment derivatives

Figure 20 presents the third set of control derivatives corresponding to the yaw control generated by applying collective pitch control of tailrotor for Bo-105, or in the case of Ornicopter changing the amplitude of force flapping motion. As the Ornicopter has a fundamental new way for yaw control, these control derivatives are very different from Bo-105.

Looking at Figure 20, it can be found that Ornicopter's coupled response for yaw control input is different from that of conventional helicopters. For Bo-105, the yaw control causes relatively high side force and roll moment, while these two coupling terms are nearly nought for Ornicopter. This is caused by the fact that the Ornicopter controls the shaft torque directly instead of the side force generated by the tail rotor.

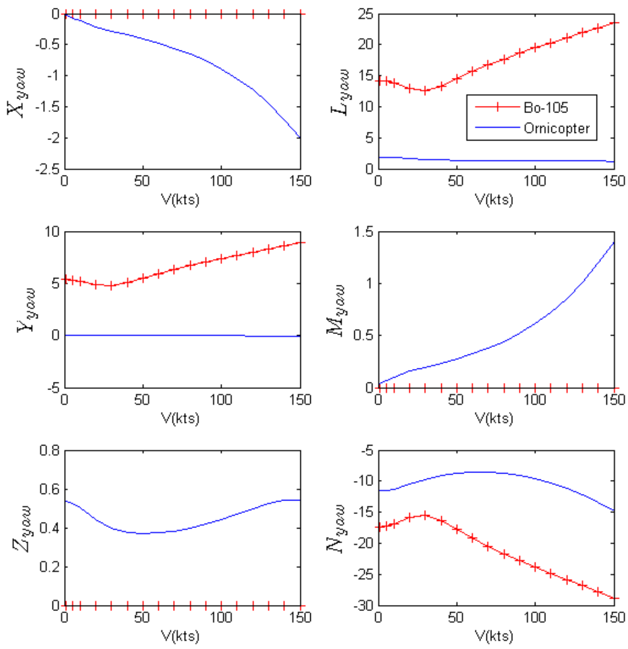

Figure 20. Yaw control derivatives a function of flight speed

At the same time, there are some additional coupling terms for Ornicopter, i.e. X_{yaw}, Z_{yaw} and M_{yaw}. The blades flapping motion is highly nonlinear with regard to control input, especially at high velocity. The yaw control of Ornicopter will change the magnitude of force flapping motion, as well as the tilt angle of the average tip-path plane. In forward flight, this nonlinear effect mainly causes additional longitudinal flapping on the blades, and hence perturbations in *X*, *Z* and *M*. However, these additional coupling derivatives of Ornicopter are small comparing with coupling terms of Bo-105. Concluding, the Ornicopter's yaw control coupling characteristics seem better than those of a conventional helicopter.

For the on-axis characteristics, since different yaw control mechanics are used for Ornicopter and Bo-105, values of N_{yaw} derivatives cannot be compared directly. More handling qualities analysis, such as quickness and bandwidth parameters need to be investigated in relation to the yaw control response.

Figure 21 presents the Ornicopter's response to yaw step input. To acquire the same amplitude of yaw response as Bo-105, the yaw control input for Ornicopter is slightly higher than the one of Bo-105. From this figure, it can be found that Ornicopter has similar yaw response, showing also a yaw velocity control characteristic as in the case of conventional helicopters. The figure shows also that Ornicopter has lower coupled responses, especially for roll and pitch motions.

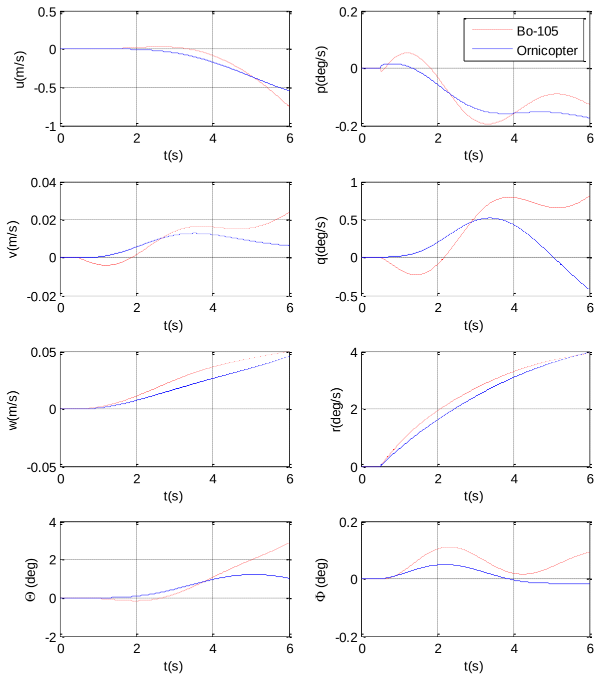

Figure 21. Response to yaw step control input

CONCLUSION

The goal of the present paper was to analyse the stability characteristics of the new concept helicopter, the Ornicopter. In this sense, a state-space model was developed for Ornicopter based on a non-linear flight mechanics model. The Ornicopter design was obtain by modifying the Bo-105 helicopter adapting them to a new flapping rotor and eliminating the tail rotor. In this sense, the Ornicopter eigen modes, stability derivatives and control derivatives were compared to a conventional Bo-105 helicopter.

The following conclusions can be drawn:

1. The Ornicopter's rotor has stability characteristics very close to that of a conventional helicopter.

2. Since Ornicopter does not have tail rotor, the stability derivatives dominated by tail rotor change dramatically. These derivatives are significant for lateral/direction stability properties, and cause a large difference in the Ornicopter Dutch roll mode as compared to the Bo-105

3. Ornicopter has considerably lower damping than Bo-105 in the Dutch roll mode. Low stability of this mode will cause large roll/yaw/sideslip oscillatory motions during gusty conditions. This is very uncomfortable for passengers and put high workload for the pilot keeping on track. It follows that for Ornicopter this mode has to be analysed in more detail in the future and cured either by increasing directional stability either by increasing the dihedral effect.

4. The Ornicopter has lower coupling responses for yaw control as compared to Bo-105. This is because the shaft torque is controlled directly.

REFERENCES

1. Van Holten, T., "A Single Rotor without Reaction Torque: a Violation of Newton's Laws or Feasible?" 28th European Rotorcraft Forum, Bristol, United Kingdom, 2002.
2. Van Holten, T., Heiligers, M., and Van de Waal, G., "The Ornicopter: a Single Rotor without Reaction Torque, Basic Principles," 24th International Congress of the Aeronautical Sciences, Yokohama, Japan, 2004.
3. Van Holten, T. and Heiligers, M., "Configuration Analysis of a Torqueless Helicopter Concept," 24th International Congress of the Aeronautical Sciences, Yokohama, Japan, 2004.
4. Heiligers, M., Van Den Bulcke, S., Van Holten, T., and Kuiper, R., "A Radio-Controlled Ornicopter Model," 31st European Rotorcraft Forum, Florence, September, 2005.
5. Heiligers, M., Kuiper, R., Van Holten, T., and Van den Bulcke, S., "Development of a Radio-Controlled Ornicopter: a Single Rotor Helicopter without Reaction Torque," SAE Transactions, Vol. 114, (1), October, 2005.
6. Heiligers, M., Van Holten, T., and Van den Bulcke, S., "Test results of a radio-controlled Ornicopter: a single rotor helicopter without reaction torque," 44th AIAA Aerospace Science Meeting, Reno, NV, January, 2006.
7. Van Gerwen, D., and Van Holten, T., "Ornicopter Yaw Control: Testing a Single Rotor Helicopter without Reaction Torque," 45th AIAA Aerospace Sciences Meeting, Reno, NV, January, 2007.
8. Van Holten, T. and Heiligers, M., "The Influence of Flexible Blades on the Characteristics of the Ornicopter," 30th European Rotorcraft Forum, Marseille, France, September, 2004.
9. Wan, J. and Pavel, M., "Mimicking Birds to Invent a Tailless Helicopter-the Ornicopter," 67th American Helicopter Society Annual Forum, Virginia Beach, VA, May, 2011.
10. Straathof, M., Van Holten, T. and Van Gerwen, D., "Ornicopter Behavior in Forward Flight," 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January, 2008.
11. Padfield, G.D., Helicopter Flight Dynamics, Second Edition, Blackwell Publishing, 2007.
12. Van Holten, T., Heiligers, M., Kuiper, R., Vardy, S., Van de Waal, G., and Krijnen, J., "Forced Flapping Mechanisms for the Ornicopter: a Single Rotor Helicopter without Reaction Torque," 30th European Rotorcraft Forum, Marseille, France, September, 2004.
13. Van Gerwen, D., and Van Holten, T., "A New Approach to Forced Flapping for the Ornicopter," 8th AIAA Aviation Technology, Integration and Operation (ATIO) Conference, Anchorage, AK, September, 2008.