DIRECTIONAL HANDLING QUALITY ASSESSMENT FOR ORNICOPTER

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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. In this sense, the Ornicopter changes the way of yaw controlling and has different yaw control characteristics. The goal of this paper is to analyse the directional handling qualities of this new helicopter concept. In this sense, an Ornicopter flight mechanic model was developed and adapted for handling qualities assessment. The paper investigates several criteria defined in the ADS-33 handling qualities standard, including: bandwidth, phase delay, attitude quickness, lateral-directional oscillation and the linearity of yaw control in sideslip. By analysing and comparing the directional handling qualities of Ornicopter with the conventional BO-105 helicopter, it is found that the Ornicopter directional handling qualities are slightly poorer than those of BO-105 especially related to the lateral-directional bandwidth and phase delay. The main reason for this is due to the low yaw damping and directional stability of the Ornicopter. This drawback of Ornicopter can be corrected with an additional yaw damping and directional stability through the SCAS system.

NOTATION

L,M,N	moments on the c.g. about x-, y- and z-axes
N_b	Number of blades
$p,\ q,\ r$	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
Ψ , Θ , Φ	yaw, pitch and roll attitude angle
$\beta_0^{(k)}, \beta_{s1}^{(k)}, \beta_{c1}^{(k)}$	Flapping coefficients of the k^{th} blade
$\theta_0, \theta_{s1}, \theta_{c1}$	collective and cyclic pitch control of main rotor
$\hat{\xi}$	amplitude of force flapping mechanics

Subscripts

$u, v, p, etc.$	stability derivatives w.r.t. u, v, p, etc.

1. 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.

Numerous solutions have been proposed to replace the tailrotor. For example the NOTAR system, or NO TAil Rotor-system, which counteracts the reaction torque by blowing air out of the tailboom, it is a very successful concept, however it still has only marginal control authority under unfavorable wind conditions. Most of the existing tailless configurations share the same basic philosophy, which is replacing the tailrotor with another rotor, like coaxial or tandem configurations. Different solutions might be found when the problem is considered the other way around. Instead of struggling to find a perfect anti-torque device, the solution would be to design a rotor without react torque and hence eliminates the need for a tail rotor.

Since 2002, at Delft University of Technology a tailless helicopter configuration has been developed, the so-called 'Ornicopter'. The mechanism of Ornicopter is derived from birds' 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. As its name presents, the Ornicopter can be considered as a helicopter version of the Ornithopter [Ref. 1], the aircraft that flies like a bird. The principle of how to achieve this forced flapping motion at the Ornicopter in order to eliminate the reaction torque has been defined [Ref. 2-4]. The goal of the present paper is to investigate the directional handling qualities of this new concept.

Historically, discussing on the Ornicopter's concept, it appears that a similar concept was firstly proposed by Passat in 1921, which was called "Helithopter" and had a rotor with four blades forced to flap simultaneously [Ref. 5]. In the 1930s, two devises were patented by a German aerodynamicist, Hans Georg Küssner at the 'Gottingen Aerodynamic Test Establishment' [Ref. 6 7]. His invention, the so-called 'Flapping Propulsion Rotor', was based also on forced flapping mechanism of the blades. In his patent, the flapping actuation device was based on an oil-hydraulic pump system to simultaneously flap up and down a pair of centrally hinged rotor blades [Ref. 6]. At the end of 1990s, Dr. Vladimir Savov from the Bulgarian Air Force Academy proposed the so-called "Rotopter" concept, using the same principle of the forced flapping blades in order to eliminate the tailrotor [Ref. 8 9].

As mentioned above, the Ornicopter does not have the tailrotor as the rotor can drive itself to rotate. Therefore, the way of yaw control for Ornicopter is different from that of conventional helicopters. The yaw control handling quality will also be impacted.

To investigate the impacts of this concept on directional handling quality, in this paper the flight mechanic model for Ornicopter developed before will be improved to take more details of the helicopter in account, including control time delay, actuator model and stability and control augmentation system (SCAS). Afterwards, this model will be used for directional handling quality assessment of Ornicopter and BO-105.

Analyses results of Ornicopter and BO-105 will be compared to locate the different yaw control characteristics between them. The SCAS system will be applied to improve the handling quality of Ornicopter and investigate reasons of those differences in yaw handling quality.

2. BACKGROUND OF ORNICOPTER PRINCIPLE

First, a short explanation of the Ornicopter's basic principles is given to have a general overview about the yaw control method of Ornicopter.

2.1. 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 1.

During blade's one revolution, this 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. 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.

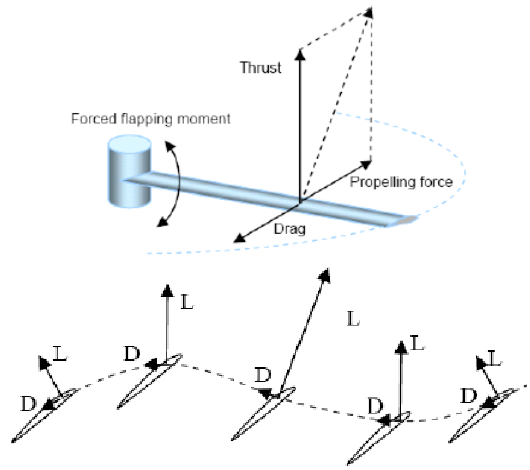

Figure 1. Lift and drag forces acting on an Ornicopter blade during one revolution with constant pitch angle [Ref. 3]

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 2.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 blades (see Figure 2.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.

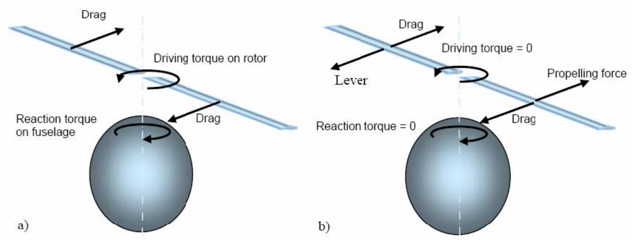

Figure 2. Forces and moments acting on a conventional helicopter (a) and the Ornicopter (b) [Ref. 3]

2.2. Controlling the Ornicopter

2.2.1. 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 1, 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 3.a presents the case when no yaw movement is desired. 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. If now for this same situation a smaller inclination of the swash plate is chosen (Figure 3.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. 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 3.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 3.b, and will therefore cause a yaw movement in the opposite direction.

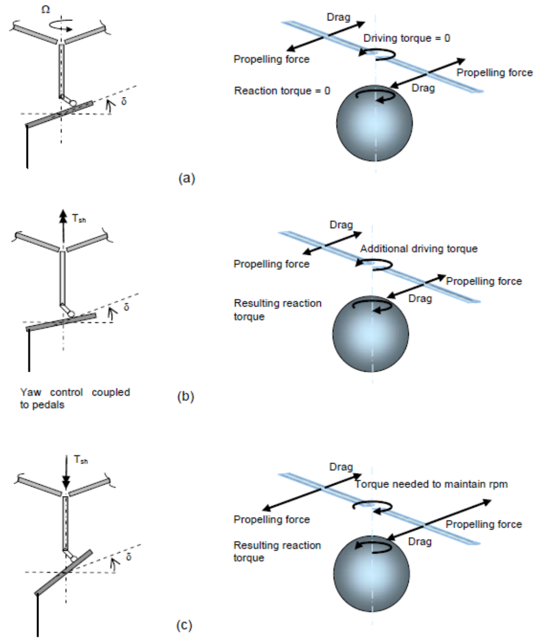

Figure 3. Schematic representation of yaw control by introducing a reaction torque

2.2.2. 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 [Ref. 4].

In conclusion, Ornicopter changes the way of yaw control, and in this configuration, all controls are achieved through the main rotor. The amplitude of forced flapping of blades needs to be controlled to get desired shaft torque. Because of the inertia of blades, the flapping amplitude can not response to control input instantly. Therefore, additional lags will be introduced. At the meanwhile, the Ornicopter does not have tail rotor, which can provide yaw damping and directional stability. Those factors may degrade the yaw handling quality of Ornicopter and they will be analysed in following sections.

3. ORNICOPTER MODELLING

In order to develop the Ornicopter model, a classical 13 DoFs flight mechanics model for conventional helicopters was developed first and then it was adapted for the Ornicopter [Ref. 15]. This Ornicopter model is developed in-house and is based on blade element theory. The full nonlinear model is used for flight simulations and other off-line analyses. A linearized model was also developed, which includes 6 degrees for body motion, 3 degrees for Pitt-Peters dynamic inflow mode, 3 degrees for flapping motion of each blade and two attitude angles (Θ and Φ) [Ref. 16].

In this paper, to calculate the handling qualities bandwidth and phase delay in yaw direction, the heading (Ψ) is also added to the linearized state-space model. In this sense, all states can be written as:

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

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. 14]. The control input of Ornicopter is:

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

The general form of state space model can be written as:

(3)
$$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U}$$

(4)
$$\mathbf{Y} = \mathbf{C}\mathbf{X} + \mathbf{D}\mathbf{U}$$

To simplify the model, the output matrix is set to a unit matrix (**C**=**I**) and the feedthrough matrix is zero (**D**=0). In this case, the output (**Y**) will be identical to system states (**X**). Therefore, following discussions will focus on Equ (3), and Equ (4) will be neglected.

This state-space model represents the bare model for Ornicopter. The input (**U**) is the final control inputs on blades pitch angle and forced flapping amplitude. To obtain more accurate results for the HQs, some detail of the control system should be considered. This paper implements a simple SCAS system, control time delay and an actuator model in the Ornicopter's bare model discussed.

3.1. SCAS

The stability and control augmentation system (SCAS) can be used to improve helicopter handling quality characteristics and reduce the pilot work loads. To investigate the impacts of SCAS system on handling qualities for Ornicopter, a SCAS model is added to the Ornicopter model.

The simple attitude and rate feedback algorithm is used in longitudinal, lateral and yaw axis. This SCAS system can be written as follow:

(5)
$$\begin{cases} \theta_0 = \theta_0^{in} \\ \theta_{s1} = \theta_{s1}^{in} + K_q q + K_\Theta \Delta\Theta \\ \theta_{c1} = \theta_{c1}^{in} + K_p p + K_\Phi \Delta\Phi \\ \hat{\xi} = \hat{\xi}_{s1}^{in} + K_r r + K_v v \end{cases}$$

In which: θ_0^{in}, θ_{s1}^{in}, θ_{c1}^{in} and $\hat{\xi}_{s1}^{in}$ are control input from the pilot, K_q, K_p, K_r and K_v are rate/velocity feedback gains, K_Θ and K_Φ are attitude feedback gains, $\Delta\Theta$ and $\Delta\Phi$ are changes of pitch and roll attitude from trim.

This SCAS can be also written in the matrix format as:

(6)
$$\mathbf{U} = \mathbf{U}_{in} + \mathbf{K}\mathbf{X}$$

This SCAS model will be added to the initial Ornicopter bare model together with an actuator model to be described in the following section.

3.2. Actuator model

Equation (6) defines the control signal after the SCAS system. Those controls will be sent to the actuation system to finally apply desired controls to the main rotor, as well as tail rotor for conventional helicopters.

The response of actuation system is fast and it is believed to be neglectable for low frequency or smooth control input. However, for high frequency or rapid control input, like a step input, the dynamic characteristics of actuators should be taken into account. Therefore, a first order actuator model is added to the Ornicopter model in this paper.

The first order actuator model is defined as:

(7)
$$\tau \dot{U}_{act} = U - U_{act}$$

In which: U is certain control input to the actuator system, τ is the corresponding time constant of the actuator, U_{act} is the output of actuator, which is the final control applied to the main rotor or tail rotor, $\dot{U}_{act}$ is the actuator motion rate.

In matrix form, the actuator model can be written as:

(8)
$$\dot{\mathbf{U}}_{act} = \mathbf{A}_{act}\mathbf{U}_{act} + \mathbf{B}_{act}\mathbf{U}$$

(9)
$$\mathbf{B}_{act} = \begin{bmatrix} 1/\tau_{col} & 0 & \cdots & 0 \\ 0 & 1/\tau_{long} & \ddots & \vdots \\ \vdots & \ddots & 1/\tau_{lat} & 0 \\ 0 & \cdots & 0 & 1/\tau_{yaw} \end{bmatrix}$$

(10) $$\mathbf{A}_{act} = -\mathbf{B}_{act}$$

In which: τ_{col}, τ_{long}, τ_{lat} and τ_{yaw} are time constants of actuators for collective pitch, longitudinal cyclic, lateral cyclic and yaw control respectively. The time constants used in this paper is shown in Table 1.

Table 1. Time constants of actuator

	Actuator time constants (sec)			
	τ_{col}	τ_{long}	τ_{lat}	τ_{yaw}
BO-105	0.04	0.04	0.04	0.02
Ornicopter	0.04	0.04	0.04	0.04

Since the actuator model introduces new dynamics into the system, the state-space model needs to be extended. Combining the bare model (Equ (3)) and Equ (8), one can get:

(11) $$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U}_{act}$$ $$\dot{\mathbf{U}}_{act} = \mathbf{A}_{act}\mathbf{U}_{act} + \mathbf{B}_{act}\mathbf{U}$$

Substituting Equ (6) into Equ (11), the extended state-space model can de derived:

(12) $$\dot{\mathbf{X}} = \mathbf{A}\mathbf{X} + \mathbf{B}\mathbf{U}_{act}$$ $$\dot{\mathbf{U}}_{act} = \mathbf{A}_{act}\mathbf{U}_{act} + \mathbf{B}_{act}(\mathbf{U}_{in} + \mathbf{K}\mathbf{X})$$

(13) $$\begin{bmatrix} \dot{\mathbf{X}} \\ \dot{\mathbf{U}}_{act} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}_{act}\mathbf{K} & \mathbf{A}_{act} \end{bmatrix} \begin{bmatrix} \mathbf{X} \\ \mathbf{U}_{act} \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{B}_{act} \end{bmatrix} \mathbf{U}_{in}$$

So far, the new linearized model with a simple SCAS system and the first order actuator model have been derived.

3.3. Control time delay

Between the pilot control input and the control signal received by the SCAS, a time delay also exists. To simplify the model, constants time delays are applied, and it is assumed that all control channels have the same time delay.

To model this time delay, the state-space model is transferred into the transfer functions as:

(14) $$\mathbf{X}^*(s) = \mathbf{H}(s)\mathbf{U}_{in}(s)$$

In which: $\mathbf{X}^*$ is the extended states vector, and $\mathbf{H}(s)$ is the transfer function matrix.

The system with time delay is developed by multiplying another term for the delay as:

(15) $$\mathbf{X}^*(s) = \mathbf{H}(s)e^{-\tau_d s}\mathbf{U}_{in}(s)$$

$$\mathbf{X}^*(s) = \mathbf{H}(s)e^{-\tau_d s}\mathbf{U}_{in}(s) \quad (16)$$

In which τ_d is the time delay. In this paper, a constant value (*200ms*) is used for all controls of both Ornicopter and BO-105 [Ref. 17].

4. OBJECTIVE ORNICOPTER'S HANDLING QUALITIES ASSESSMENT

Using the Ornicopter model described above, off-line simulation programs are developed for objective handling quality assessments. The linearized model is used for bandwidth/phase delay and eigenmodes analyses. For attitude quickness analyses, the full non-linear model is used for flight simulation.

As the BO-105 and Ornicopter is considered as utility helicopters, criteria for general mission task elements (MTEs) defined by ADS-33 are used in this paper, rather than target acquisition and tracking task.

4.1. Bandwidth and phase delay

4.1.1. Pitch and roll

Reference 16 demonstrated that the values of the stability and controllability derivatives for Ornicopter have almost identical characteristics in longitudinal and lateral directions when compared to the ones of BO-105(with the assumption that the two helicopters are similar in dimensions). In this sense, the bandwidth and phase delay calculation show the same conclusion, as seen in Figure 4, this when, all SCAS gains are set to zero and only actuator model and time delay are applied

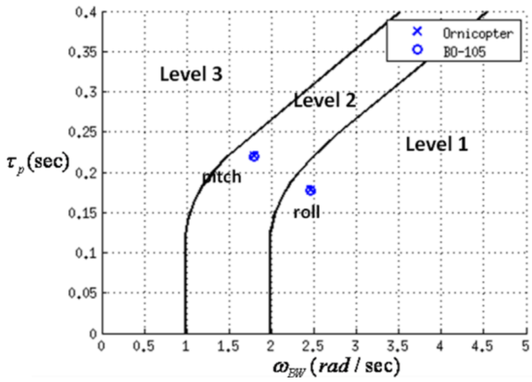

Figure 4. Bandwidth and phase delay in pitch and roll directions (10 knot)

Since the pitch and roll handling quality of Ornicopter and BO-105 are very similar, they will not be discussed in details in this paper.

4.1.2. Yaw

By comparing stability and controllability derivatives between Ornicopter and BO-105 [Ref. 16], the conclusion has been made that main differences between Ornicopter and BO-105 appear in yaw direction like N_r and lateral-yaw coupling terms, such as N_v and L_r. Therefore, more differences between Ornicopter and BO-105 are expected in directional handling qualities.

For yaw direction, the bandwidth and phase delay without SCAS system are calculated both for low speed and forward flight, as shown in Figure 5 and 7.

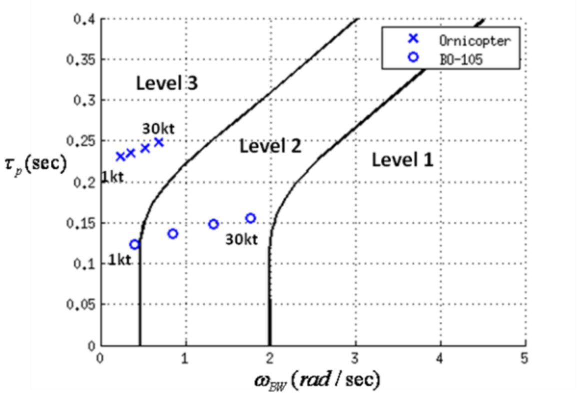

Figure 5. Bandwidth and phase delay in yaw direction (hover and low speed)

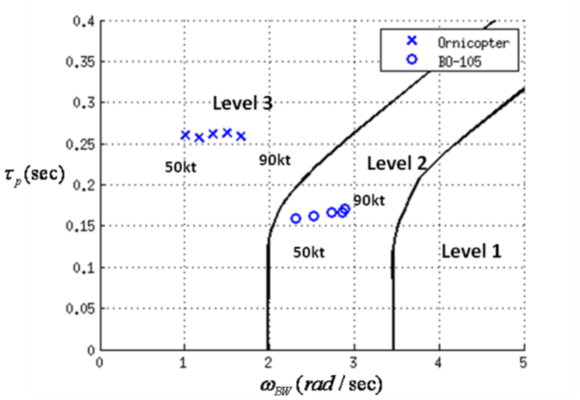

Figure 6. Bandwidth and phase delay in yaw direction (forward flight)

It can be found that with the increasing of helicopter forward velocity, the bandwidth of both Ornicopter and BO-105 increases and the level of handling quality have the general trends of moving toward higher level. However, the Ornicopter has higher phase delay and lower bandwidth than BO-105 for all analysed velocities (50 kts to 90 kts with an increase step of 10 kts) and hence it corresponds to one level lower as seen in Figure 10. To understand the reason of this Ornicopter's drawback, flight dynamics models with different fidelity are extracted from the baseline model described above. Bode plots for those models are made to show the impacts of different parts of the Ornicopter model, as shown in Figure 7.

For the 'baseline model' used in Figure 7, only the body motion degree-of-freedom is considered. The dynamics of flapping motion and inflow model are not included. In other words, the flapping motion of blades and induced velocities can response to the control input or changes of body motion instantly. Moreover, time delay, SCAS system and the actuator model are also neglected in this baseline configuration. Therefore, it can be found that the phase angle does not exceed -180 degrees. Obviously, this model cannot represent all characteristics of Ornicopter with sufficient accuracy. However, it provides a reference for more detailed models.

Based on this 'baseline model', the flapping dynamics, the actuator dynamics and the control time delay are added to the baseline model separately. All models are analysed and plotted in Figure 7, as well as the full model including all dynamics and time delay.

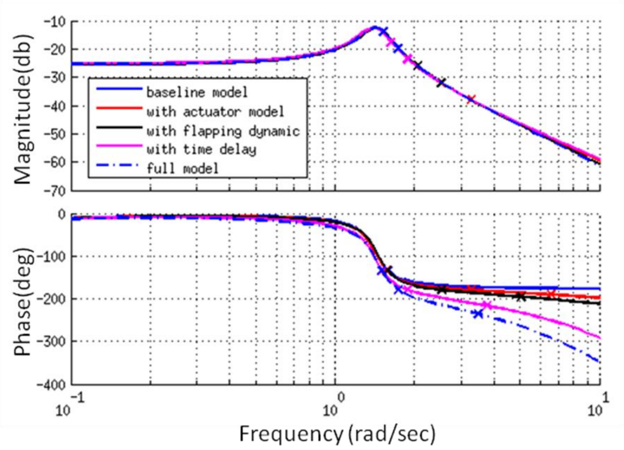

Figure 7. Magnitude and phase responses of different Ornicopter models in yaw direction (80 knot)

By comparing different models, the impact of each part motioned above on yaw bandwidth and phase delay can be determined qualitatively and some conclusions can be drawn.

Firstly, for all frequency, the response magnitudes for all models are almost identical.

Secondly, at low frequency (<2 rad/sec), additional dynamics and control time delay have very small impacts on phase angle. Therefore, the baseline model can predict the bandwidth for phase delay with good accuracy, where the error is less than 5% in the case shown in Figure 7. This is caused by the fact that the time lags between response of helicopters and control input, which are introduced by flapping dynamics, actuator dynamics or time delay, are relatively small comparing with the period of control input (> 3sec) at low frequency. Hereby, their impacts on phase angle are neglectable.

Thirdly, increasing the range of frequencies, the impacts of additional dynamics and control time delay also go up. Moreover, since the actuator model time constants are very small, the actuator dynamics has little impact on the phase angle response comparing with control time delay and flapping dynamics. Comparing the complete model and the simplified model including only time delay, one can see that the control time delay has the highest impact on phase delay, and the flapping dynamics is of secondary importance.

4.1.3. Impact of SCAS on handling qualities

As discussed above, the yaw direction bandwidth and phase delay of Ornicopter is mainly impacted by the characteristics of body motion DoFs, the control time delay and the flapping dynamics. Since the yaw control of Ornicopter is achieved by varying the amplitude of its active flapping blades, additional dynamics needs to be introduced in the yaw direction in comparison with the conventional helicopters. This is the inherent characteristics of the Ornicopter concept. It is not easy to reduce the impact of flapping dynamics on phase delay, however it is less important when comparing this to other HQs characteristics.. Concluding, in order to improve Ornicopter's yaw handling quality of Ornicopter with regard to bandwidth and phase delay, efforts should be made to reduce the control time delay and change the dynamic characteristics of body motion, e.g. the yaw damping.

The values for the control time delays for Ornicopter and BO-105 are considered the same in this paper. Apparently these should be reduced in order to improve Ornicopter's handling qualities.

By changing design parameters of Ornicopter, those derivatives can be tuned. However, it is more efficient to enable the SCAS system and tune the gains to investigate the influence of different dynamic characteristics of body motion on the yaw handling quality at this stage. Therefore, the bandwidth and phase delay of Ornicopter are re-calculated with different SCAS settings, in which only the gains for yaw channel are set while other gains are all zero.

One of the bode-plot is presented as Figure 8, in which K_r is 0.15 and K_v is -0.015. It can be found that by applying yaw gains in SCAS, the phase angle response of Ornicopter can be improved dramatically, especially at low frequency. The bandwidth for both phase margin and phase delay can be also improved for Ornicopter. However, at high frequency, the improvement caused by SCAS is limited, since the high frequency response is dominated by the flapping dynamic and control time delay.

It should be noticed that the magnitude response of Ornicopter reduces dramatically (about 10 dB) at low frequency. The bandwidth for gain margin in this case is not available. Hereby, the overall effects of using SCAS to improve handling quality for Ornicopter and more advanced SCAS algorithm design should be considered in further researches.

To understand better the impact of SCAS on Ornicopter HQS, the bandwidth and phase delay parameters were calculated for different SCAS gains and are plotted in Figure 9.

Looking at this figure, one can see that the bandwidth of Ornicopter can be considerably improved by using SCAS, as the bandwidth is determined by the low frequency response. Meanwhile, the SCAS only slightly influences the phase delay, which is related to high frequency response of the system.

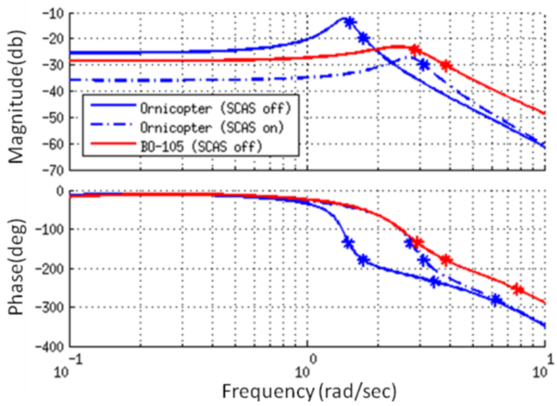

Figure 8. Magnitude and phase responses of BO-105 and Ornicopter in yaw direction (80 knot)

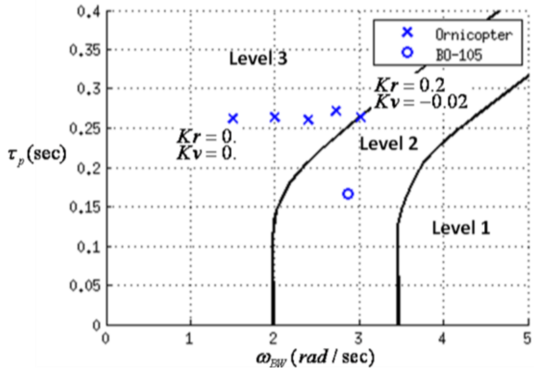

Figure 9. Bandwidth and phase delay in yaw direction with different SCAS gains (80 knot)

4.2. Attitude quickness

For moderate-amplitude attitude changes, the ratio of peak rotational rate (pitch, roll or yaw) to the change of attitude angle shall meet the limits specified by the ADS-33.

To obtain the attitude quickness, different rectangular step inputs are applied to the full nonlinear model. Responses of the model are calculated, and parsed for the quickness parameters.

As expected, in longitudinal and lateral directions, the attitude quickness of Ornicopter and BO-105 are very similar. Calculation results for pitch channel at 30 knots are presented in Figure 10.

Step inputs with two amplitudes (1 and 2 degrees) were applied for the simulation. For each amplitude, various length of control input were used, which is from 1 second to 3 seconds. This control setting will also be used for the yaw attitude quickness calculation.

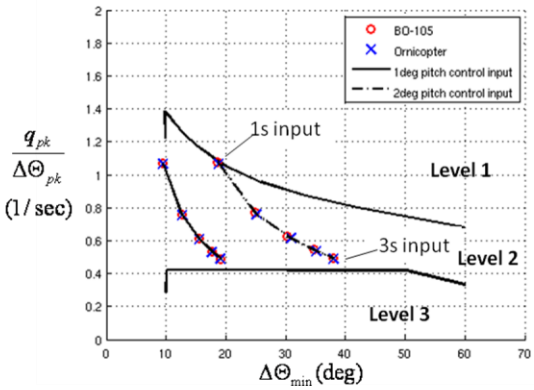

Figure 10. Pitch attitude quickness of BO-105 and Ornicopter (30 knot)

Similarly, the yaw attitude quickness of Ornicopter and BO-105 are also calculated, as shown in Figure 11. It shows that the attitude quickness of Ornicopter is lower than that of BO-105, especially for short control input. However, they are still graded as the same level for most of cases, and Ornicopter even reaches level one for large heading change.

The attitude quickness and the minimum heading change of Ornicopter follow the same trend as those of BO-105 when the control input is varying. However, the reduction of attitude quickness of Ornicopter is smaller than that of BO-105. This leads the result that BO-105 has much higher quickness than Ornicopter for short control input, whereas they are close in quickness when longer control are applied.

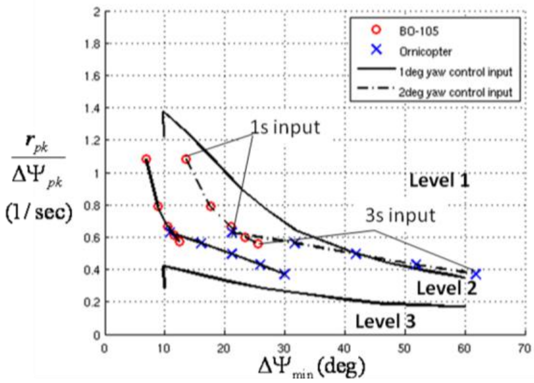

Figure 11. Yaw attitude quickness of BO-105 and Ornicopter (30 knot)

The yaw response of Ornicopter and BO-105 are presented in Figure 12, this in order to investigate the reason that causes the attitude quickness differences.

From the yaw rate response, one can see that after the yaw control is applied, the BO-105 can reach the maximum yaw rate very quickly (in less than 1 second), because of the relatively high yaw damping comparing with Ornicopter [Ref. 16]. Afterwards, increasing further the yaw angle results an increase in the corresponding sideslip. This sideslip generates additional yaw moment (N_v), thus the helicopter intends to yaw back to the neutral position. This effect leads the deceleration of yaw rate of BO-105 after the maximum yaw rate has been reached, and it lasts till the end of the step control input. After the yaw control returns to trim position, the yaw rate decelerates and reverses very quickly, at the meanwhile the yaw attitude reaches the peak heading change.

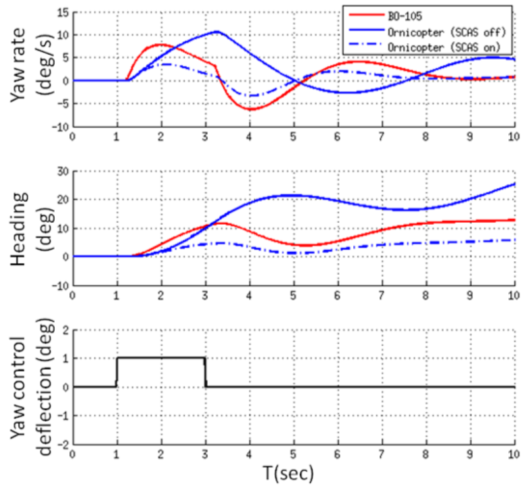

Figure 12. Yaw responses of BO-105 and Ornicopter for rectangular step control input

From the comparison of stability derivatives, the yaw damping (N_r) and sideslip derivative (N_v) were found to be lower than those of BO-105 [Ref. 16]. Consequently, the yaw response of Ornicopter differs from that of BO-105 a lot.

Because of the Ornicopter's low yaw damping and directional stability, its yaw rate will continue accelerating with approximately constant gradient after yaw control is applied. For the same reason, the yaw motion is slowly decelerated after the step input. In this sense, the heading change peak of Ornicopter is much higher than that of BO-105. In spite of the higher yaw peak rate, the high heading change peak results lower attitude quickness for Ornicopter, as well as higher minimum heading change.

From Figure 12, it can also be found that the Ornicopter can be roughly considered as a acceleration control system in yaw direction, whereas the BO-105 is more close to a rate control system. Therefore, while step controls with the same amplitude and different time duration are given, the maximum yaw rate will keep constant for BO-105, as long as the control input duration is longer than the rise time of the yaw response (which is about 0.5s in case shown in Figure 12). At the same time, the peak and minimum heading changes will increase with increasing of the control input duration. Hence, the attitude quickness of BO-105 decreases greatly as shown in Figure 11. In Ornicopter's case, since its characteristics correspond to an acceleration control system, the yaw rate peak, the yaw peak and the minimum yaw heading change will increase simultaneously. Therefore, the attitude quickness of Ornicopter declines only slightly in comparison with that of BO-105 helicopter.

As discussed above, the yaw response of Ornicopter differs from the behaviour of BO-105. This is due to the different stability derivatives of these two helicopters. . Similarly as bandwidth and phase delay, the yaw attitude quickness of Ornicopter can also be improved by applying SCAS. The yaw response of Ornicopter with SCAS is also calculated and shown in Figure 12, in which K_r is 0.15 and K_v is -0.015.

With SCAS system, the dynamic characteristics of Ornicopter change rapidly. In this case, Ornicopter has very similar yaw response as BO-105 expect lower amplitude, which is caused by the higher equivalent yaw damping and directional stability improved by the SCAS system.

By using SCAS, it was demonstrated that the Ornicopter's yaw attitude quickness can be improved. Meanwhile, the effect of SCAS on yaw response corresponds with an amplitude reduction as shown in Figure 8. This influence on attitude quickness is shown in Figure 13. One can see that the yaw quickness of Ornicopter is improved by the SCAS and it is even higher than that of the equivalent BO-105. Moreover, the yaw attitude quickness curves move to the left-hand side of the figure, indicating lower attitude changes for the same control input.

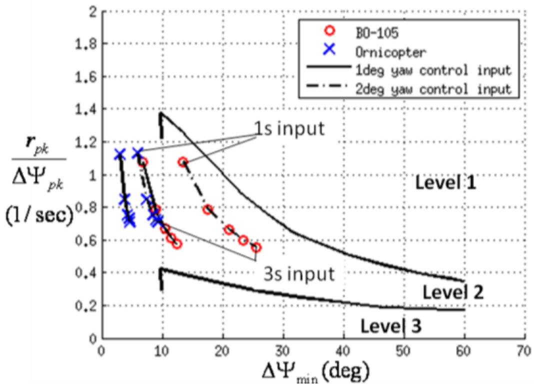

Figure 13. Yaw attitude quickness of BO-105 and Ornicopter with SCAS (30 knot)

4.3. Lateral-directional oscillatory requirements

The Dutch roll modes of the Ornicopter and BO-105 were calculated and compared [see Ref 16]. Using the enhanced SCAS/actuator model, the impact of SCAS on lateral-directional HQs as defined in ADS-33 are presented in Figure 18. As described in Reference 16, the Dutch roll mode of Ornicopter has lower damping and frequency than BO-105. From Figure 14, one can see that the with respect to lateral-directional characteristics of Ornicopter are poorer than that of BO-105, while the locus of Ornicopter is very close to the boundary between level 2 and 3 (for other MTEs).

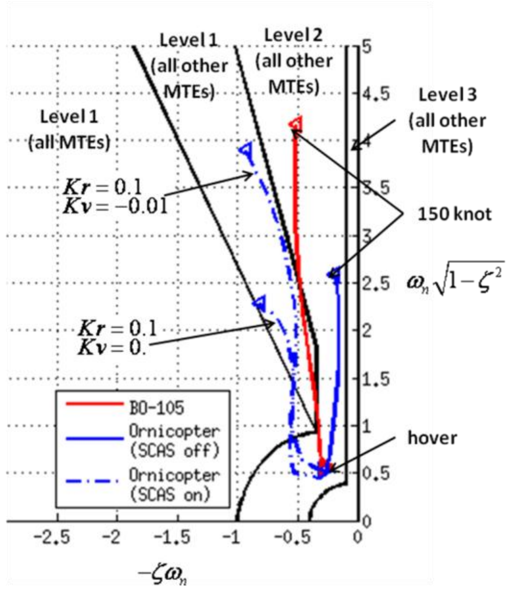

Figure 14. Lateral-directional oscillation grading

To improve the handling quality of Ornicopter, again SCAS is used. It can be found from Figure 14 that by applying a yaw damper, the Ornicopter's lateral-directional handling qualities can be improved dramatically, where it reaches the highest handling quality level for moderate velocity and keeps very close to it for other speed. Meanwhile, when the sideslip feedback is present, the frequency of Dutch roll mode of Ornicopter will increase. This effect is not beneficial for the handling qualities, while the higher directional stability is desired for bandwidth and attitude quickness. Therefore, more detailed analyses should be done in further researches to acquire an optimal control system design.

4.4. Yaw control in sideslip

In trimmed sideslip flight, the yaw control varies with the sideslip angle or sideslip velocity. A linear variation is desired for better handling quality, since it is more predictable for the pilot.

As the yaw control method of Ornicopter is completely different from that of conventional helicopters, the yaw control in sideslip also changes, especially in sideward flight, as shown in Figure 15 and 17.

Figure 15 shows the yaw controls of Ornicopter and BO-105 in pure sideward flight (no forward velocity). It can be found that the yaw control of BO-105 is almost linear function of the sideward speed, whereas the Ornicopter requires high non-linear yaw control, which has the same sign for both left and right sideward flight.

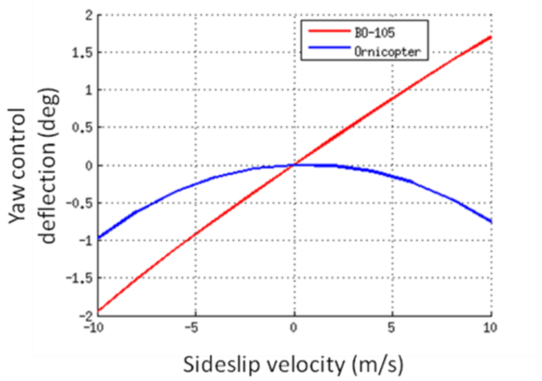

Figure 15. Yaw control deflection as a function of sideslip velocity (u=0knot)

The reason for this non-linearity is that the variation of main rotor torque is the dominating factor for the yaw control input of Ornicopter in sideward flight. From the hovering condition, as the increasing of flight velocity, the main rotor torque reduces firstly because of lower induced power. In this sense, on both sides of sideward flight, the main rotor torque will be lower than the torque corresponding to the hovering condition. This is true for both Ornicopter and BO-105. However, Ornicopter has very low sideslip derivatives (N_v) at low speed [Ref. 16]. Therefore, the main rotor torque is the dominating factor for Ornicopter and the same direction of yaw control deflections is needed for both sides of sideward flight. Since the main rotor torque is not linear as the flight velocity, the yaw control of Ornicopter in sideward flight is also non-linear as the sideward flight speed. For BO-105, in sideward flight, the inflow condition of tail rotor changes dramatically, and hence it is the main fact for the variation of yaw control. In this case, the yaw control of BO-105 has the same sign as the sideward flight speed and is almost linear with the speed.

Figure 16 shows the yaw control deflections for different sideslip angle in forward flight. The forward flight velocity is kept constant (80 knots). In this case, the vertical fin has more impact on the yaw moment and the change of total velocity is relatively small. Hereby, the Ornicopter has similar yaw control deflection with different sideslip angle as BO-105.

Concluding, the yaw control in sideslip condition, high non-linearity can be found for Ornicopter at hovering and low flight velocity, which will change the pilot's control strategy. This should be considered in the design of control system: keep the sideslip and yaw control deflections to have the same sign. In forward flight, this effect does not appear since the vertical fin is more effective. Moreover, in the flight conditions discussed above (50 to 90 kts), the yaw control deflection of Ornicopter is less than that of BO-105. This is beneficial for Ornicopter as this new concept may have more control margin in yaw direction, and hence be more controllable.

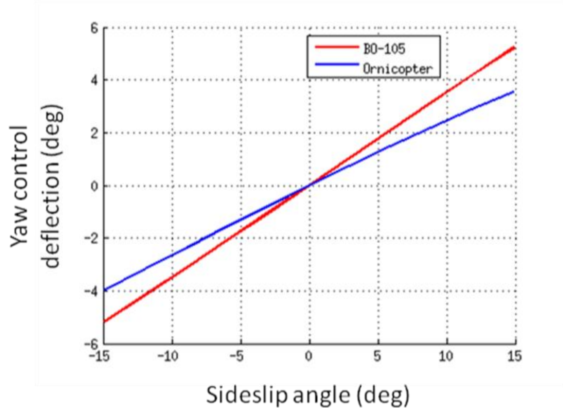

Figure 16. Yaw control deflection as a function of sideslip angle (u=80knot)

CONCLUSION

The goal of the present paper was to analyse the directional handling qualities of Ornicopter and compare them with the conventional BO-105 HQs. The predicted levels of handling quality defined in ADS-33 were used in this paper w.r.t. bandwidth and phase delay, attitude quickness, lateral-directional oscillation and yaw control in steady sideslip. The following conclusions can be drawn based on analyses above:

1. As expected, the bandwidth, phase delay and attitude quickness of Ornicopter in longitudinal and lateral directions are almost identical as those of BO-105. The main difference of handling qualities between Ornicopter and BO-105 correspond to the yaw direction.

2. Ornicopter has worse handling quality than BO-105 with regard to bandwidth and phase delay, lateral-directional oscillation and yaw control in steady sideslip. For yaw attitude quickness, all these parameters have similar handling qualities and Ornicopter is better for large yaw control input.

3. The directional handling quality of Ornicopter can be improved by applying additional yaw damping and directional stability using SCAS system.

The Ornicopter concept changes the dynamic characteristics of the classic Helicopter, and degrades the yaw handling qualities. In further researches, the impacts of different designs on handling qualities should be still analysed in order to determine the optimal SCAS design. More detailed analyses should be done for the SCAS system to improve the handling quality of Ornicopter without introducing new problems, such as system oscillation and pilot induced oscillations.

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