Particularities of Rotorcraft in Dealing with Advanced Controllers

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Abstract: *Advanced nonlinear controllers are a desirable solution to rotorcraft flight control as they can solve the system high nonlinear dynamic behavior. However, conventional nonlinear controllers such as Nonlinear Dynamic Inversion (NDI) controller heavily rely on the availability of accurate model knowledge and this can be problematic for rotorcraft. Therefore, incremental control theory can solve the modelling errors sensitivity by relying on the information obtained from the sensors instead. The paper applied the Incremental Nonlinear Dynamic Inversion (INDI) controller to rotorcraft case. It will be demonstrated that, for rotorcraft, the incremental nonlinear controllers depend on the delays introduced in the controller by the rotor dynamics. To correct this behaviour, residualization and synchronization methods need to be applied accordingly in order to remove the effects of rotor flapping (disctilt) dynamics from the controller. These particularities of rotorcraft in dealing with advanced controllers shows that incremental nonlinear controllers can have relatively small stability robustness margin and careful controller design is needed in order to account properly for rotorcraft time delays and unmodelled dynamics.*

Key Words: *Rotorcraft, Nonlinear Control, Nonlinear Dynamic Inversion NDI, Incremental Nonlinear Dynamic Inversion*

1. INTRODUCTION

With the evolution of modern rotorcraft, the advanced controllers used for fixed wing aircraft are continuously adapted and developed towards rotorcraft applications in order to improve aircraft handling qualities and control characteristics. One of the most successful alternate methodologies to linear control law methods applied to fixed wing aircraft dealing directly with nonlinearity of the system corresponds to Nonlinear dynamic inversion (NDI) controller. Nonlinear dynamic inversion (NDI) (also called dynamic inversion (DI)) has been developed for fixed wing aircraft since 1980's. NDI is a model-based controller wherein the nonlinear plant dynamics are cancelled out by effectively multiplying state feedback signals with the inverse of the dynamic equations. Theoretically, this method aims at modeling all of the system's nonlinearities in order to remove them by using direct state feedback linearization. Advantages of NDI controllers are: 1) simple design: no need of tedious gain scheduling (this is why sometimes DI is known as a universal gain scheduling design); 2) easy online implementation: it leads to a closed form solution for the controller; asymptotic (rather exponential) stability is guaranteed for the error dynamics; 4) no problem if parameters are updated (the updated values can be simply used in the formulae of the controller).

However, the NDI control as model-based controllers of nonlinear systems have some common drawbacks. A first drawback is that NDI controller relies on the availability of accurate models of the vehicle. This means that NDI is very sensitive to model inaccuracies (e.g. da Costa, Chu & Mulder 2003, [3]). When the model is inaccurate or the dynamic characteristics of the controlled element change, for instance due to a failure, the controller may become unstable. Obtaining an accurate model is often expensive or impossible with the constraints of the sensors that need to be carried onboard of the vehicle. A second drawback of NDI control method is that it depends on how stable is the system "internal dynamics". The control solution is meaningless unless this issue is addressed explicitly. As "internal dynamics" are not necessarily stable for an aircraft (this is because the vehicle model can be affine in control and/or it can be a non-minimum phase system with unstable zeros, extensive simulation studies need to be caried out to prove that the system is stable. Indeed, a non-minimum phase systems have zeros in the right half plane of the complex plane which become, after inversion, unstable poles. These can become a problem if present in the closed loop system. The full derivation of NDI method was presented in multiple studies (eg. Meyer, Hunt and Su 1982, [12]; Landis and Glusman 1987, [10]; Enns et. al. 1994, [6]). The method has been successfully applied to highly nonlinear systems such as aircraft high angle of attack maneuvering flight (eg. Lane and Stengel 1988, [8], Bugajski and Enns 1992 [2], Reinier, Balas and Garrard 1996, [16]; Hovakimyan et. al. 2001, [7]; Lee et. al. 2007, [9]).

To avoid the drawbacks of the NDI method, the so-called Incremental Nonlinear Dynamic Inversion (INDI) control methods was developed and applied at Delft University of Technology (e.g. Siebeling, Chu and Mulder, 2010, [22], Simplicio et. al., 2013, [19]) and MAVs (Smeur et. al., 2016, [21]). INDI uses synchronized measurements or estimations of angular accelerations and control surface deflections. As such, it is not dependent on an aircraft dynamic model, but it depends on feedback of the reaction of the aircraft to incremental commands. The fundamental difference between INDI and traditional Nonlinear Dynamic Inversion (NDI) is that only partial knowledge of the system dynamics is required as the resulting control law only depends on the control effectiveness. INDI is subsequently less sensitive to model mismatches. However, additional feedback signals are required in the form of state derivatives and the input signals. In addition, the controller should be discretized with a sufficiently high sampling rate (100 Hz in this application). Finally, it should be noted that synchronization between the input and state derivative is required as the calculated control increment is based on a linearization around a specific point in time. Because these characteristics, INDI-based flight control laws are able to cope with large changes in the dynamic behavior of the aircraft, even in case of major system failures or damage to the airframe. Thus, INDI can provide a good basis for fault-tolerant control strategies.

For fixed wing aircraft it has been indeed proven that INDI is less sensitive to model mismatches and that requires minimal a priori knowledge of the vehicle model and therefore it is more robust. This is ensured by relying on sensor measurements of the controlled states instead of relying on system dynamics modeling and therefore this approach belongs to 'incremental controllers'as such controllers are not very sensitive to modeling errors. The INDI has been also described in the literature (e.g.Bacon and Ostroff, 2000, [1]; Ostroff and Bacon, 2002, [13]; Bugajski and Enns, 1992, [2]; Chen and Zhang, 2008, [5]; Lee, Ham and Kim, 2005, [11]; Cox and Cotting, 2005, [4]), sometimes referred to as "simplified NDI" (Smith, 1998, [20]) or "enhanced NDI" (Ostroff and Bacon, 2002, [13]) NDI. Next section gives the principles for transiting from NDI to INDI control methods.

2. FROM NDI CONTROLLER TO INDI CONTROLLER

The first step when applying incremental controllers to a system is to create an incremental system description. Consider the aircraft rotational dynamics described using the nonlinear dynamic system as following:

$$\dot{\underline{x}} = f(\underline{x}) + g(\underline{x}, \underline{u}) \tag{1}$$

where $\underline{x}$ denotes the aircraft state vector, $\underline{u}$ is the control input vector, f is the system dependent dynamics and g is the control dependent dynamics.

To this system one can applying a Taylor series expansion on the dynamics that need to be controlled. Consider $[\underline{x}_0, \underline{u}_0]$ the state at the current time point assume that its state derivative $\dot{\underline{x}}_0 = \underline{f}(\underline{x}_0, \underline{u}_0)$can be measured. Using a standard Taylor series expansion one can obtain the first-order approximation of the state derivative for $\underline{x}$ and $\underline{u}$ in the neighborhood of $[x_0, u_0]$ as:

$$\begin{aligned}\dot{\underline{x}} = \underline{f}(\underline{x}_0, \underline{u}_0) + \underline{g}(\underline{x}_0, \underline{u}_0) + \frac{\partial}{\partial \underline{x}}\left[\underline{f}(\underline{x}) + \underline{g}(\underline{x}, \underline{u})\right]\Bigg|_{\substack{\underline{x}=\underline{x}_0 \\ \underline{u}=\underline{u}_0}} (\underline{x} - \underline{x}_0) \\ + \frac{\partial}{\partial \underline{u}}\left[\underline{f}(\underline{x}) + \underline{g}(\underline{x}, \underline{u})\right]\Bigg|_{\substack{\underline{x}=\underline{x}_0 \\ \underline{u}=\underline{u}_0}} (\underline{u} - \underline{u}_0) + O((x - x_0)^2, (u - u_0)^2)\end{aligned} \tag{2}$$

$$\dot{\underline{x}} = \dot{\underline{x}}_0 + F(\underline{x}_0, \underline{u}_0)\Delta\underline{x} + G(\underline{x}_0, \underline{u}_0)\Delta\underline{u} + O((x - x_0)^2, (u - u_0)^2) \tag{3}$$

Equation (3) can be simplified when some assumptions are made. First, the system sample rate should be high enough, i.e. the sensors and controller operate at a sufficiently high frequency. Second, the actuators are assumed to react instantly to command signals. Finally, it is assumed that, for very small time increments (high sampling frequencies of the controller), the changes in the states x are slow compared to the changes in control input u, in other words the u can change significantly faster than x (so that $x \approx x_0$ even if $u \neq u_0$). This is so-called "time scale separation". By assuming time scale separation, it follows that the assumption $x - x_0 = 0$ can be made. This means that as $\underline{x}$ approaches $\underline{x}_0$ the term in $F(\underline{x} - \underline{x}_0)$ vanishes so that eq. (3) can be simplified as:

$$\underline{\Delta\dot{x}} \approx G(\underline{x}_0, \underline{u}_0)\Delta\underline{u} \tag{4}$$

where G represents the so-called 'control effectiveness' matrix and $\Delta\underline{u} = \underline{u} - \underline{u}_0$ an incremental input control.

Therefore, the system coefficients in F do not need to be estimated and only control effectiveness G remains. The resulting system of Equation (4) is a simplified description of the system which, assuming that all of the controlled states can be measured and the sampling rate is sufficiently high, it can be used to construct an incremental controller controlling the system using increments of control input $\Delta\underline{u}$.

Incremental control methods are usually used only for the dynamics part of a system, since the kinematics part is well known and can be dealt with using classic control methods. Using the incremental system description given by eq. (4) one can implement several incremental control algorithms.

For the INDI control law one needs to invert the system description of eq. (4), see eq. (5). Thereafter, the state derivative variable $\dot{x}$ is replaced by virtual control input v, see eq. (6).

$$\Delta\underline{u} = G^{-1}(\underline{x}_0, \underline{u}_0)\Delta\underline{\dot{x}}$$
$$\Delta\underline{u} = G^{-1}(\underline{x}_0, \underline{u}_0)(\underline{\dot{x}} - \underline{\dot{x}}_0) \tag{5}$$

$$\Delta\underline{u} = G^{-1}(\underline{x}_0, \underline{u}_0)(\underline{v} - \underline{\dot{x}}_0) \tag{6}$$

Usually $\underline{v}$ is generated by linear controllers of aircraft rotational velocities (p roll rate, q pitch rate, r yaw rate). At this point, the main advantage of the INDI can already be identified: the control law (6) for u does not depend anymore on the direct nonlinear feedback term $f(x)$ needed in the regular explicit NDI control. This means that the INDI controller is insensitive to the part of the model that only depends on the system states x. In other words, changes in $f(x)$ are reflected in the measurement of state varying rate $\underline{\dot{x}}_0$, so the controller sensitivity to aircraft aerodynamic model, uncertainty and perturbation is decreased. In the outer control loop of the plant, the system that determines virtual control $\underline{v}$, will have a linear behaviour of the inner loop system. Virtual control $\underline{v}$can be governed by a PID controller that minimizes the error between a reference signal and a certain state, for instance pitch attitude or rate (Note: A downside of INDI is that stability cannot be guaranteed and the outer-loop PID controller still needs tuning.). However, the disadvantage of the INDI controller is that it does need the vehicle's control derivatives G_0, as well as the online measurements (or estimation) of the state derivative $\underline{\dot{x}}_0$ and the control position $\underline{u}_0$. The effectiveness of the controller is therefore dictated by the accuracy of the sensors (or filtering processes).
The robustness evaluation of this controller follows the same procedure applied for the NDI. Assuming ideal sensors, all the model inaccuracies lie in G (uncertainties in f are reflected in $\underline{\dot{x}}_0$). When $\underline{\dot{x}}_0$ is measureable, the only uncertainty within the INDI controller is in the control effective matrix $G(\underline{x}_0, \underline{u}_0)$. When uncertainties exist in the control effectiveness matrix *G*, the system can be rewritten as:

$$\underline{\dot{x}} = \underline{\dot{x}}_0 + G_0(\underline{x}_0, \underline{u}_0)\Delta\underline{u} + \Delta G(\underline{x})\Delta\underline{u} \tag{7}$$

Applying INDI to the uncertain system (7) and using the nominal control increment, the closed-loop system becomes:

$$\begin{aligned}\underline{\dot{x}} &= \underline{\dot{x}}_0 + G_0(\underline{x}_0, \underline{u}_0)G_0^{-1}(\underline{x}_0, \underline{u}_0)[\underline{v} - \underline{\dot{x}}_0] + \Delta G(\underline{x}_0, \underline{u}_0)G_0^{-1}(\underline{x}_0, \underline{u}_0)[\underline{v} - \underline{\dot{x}}_0] \\ &= \underline{v} + \Delta G(\underline{x}_0, \underline{u}_0)G_0^{-1}(\underline{x}_0, \underline{u}_0)\underline{v} - \Delta G(\underline{x}_0, \underline{u}_0)G_0^{-1}(\underline{x}_0, \underline{u}_0)\underline{\dot{x}}_0\end{aligned} \tag{8}$$

With the assumption of high sample rate, the difference between two consecutive measurements of the state vector derivative can be neglected, i.e. $\underline{\dot{x}}_0 \approx \underline{\dot{x}}$. The uncertain closed-loop system is further simplified as:

$$\underline{\dot{x}} = \underline{v} + \Delta G(\underline{x})G_0^{-1}(\underline{x})\underline{v} - \Delta G(\underline{x})G_0^{-1}(\underline{x})\underline{\dot{x}} \tag{9}$$

resulting in:

$$\underline{\dot{x}} = A^{-1}A\underline{v} = \underline{v} \tag{10}$$

where $A = [I + \Delta G(\underline{x})G_0^{-1}(\underline{x})]$. Therefore, when the sampling frequency of the controller is high enough, the result $\underline{\dot{x}} = \underline{v}$ still holds, meaning that uncertainties in the control effectiveness matrix *G* do not significantly affect the INDI-based control loop and no robust control design is needed in this case. This is a remarkable result under the conditions that the angular acceleration is measured and sample rate is high. The control structure is simple, there is no need for all state accelerations (derivatives), different controlled outputs require different state accelerations.

The angular acceleration can be obtained (processed) from angular rate sensors (rate gyros) which are available in most cases in the aircraft. n Delft INDI has been implemented as Fly-by-wire capability on the Cessna Citation Aircraft and has been flight tested as a modified flight control computer together with DGLR.

Figure 1. The INDI cockpit instruments/ displays developed on Cessna Citation Aircraft as fly-by-wire technology (int' Veld et. al., 2018)

The application of INDI to fixed wing aircraft proved indeed the INDI's: 1) the control structure is simple; 2) re-allocation of control power and the reconfiguration of control law can be achieved conveniently and rapidly; 3) it is a semi-model free approach; 4) no model identification is needed; 5) the controller is inherently robust 6) since it makes use of sensor measurements, it is considered a sensor-based approach. This way, any unmodeled dynamics, including wind gust disturbances, are measured and compensated. The INDI major challenges found were: 1) the measurement of angular acceleration is often noisy and requires filtering. This filtering introduces a delay in the measurement, which needs to be compensated and; 2) the method relies on inversion and therefore needs a control effectiveness model.

3. APPLICATION OF INDI TO ROTORCRAFT

In 2016 the potential of INDI approach to control the Apache helicopter was also tested at Delft university (Pavel et. al. 2020, [14]). Soon it was observed that the application of INDI to rotorcraft it is not straightforward as in the case of fixed wing aircraft. The reason for this are: 1) rotorcraft **simulation models are often non accurate and have various states which cannot be measured**, which is problematic as feedback linearization requires full state feedback. 2) **rotorcraft are known to be a non-minimum phase** systems especially in low speed envelope and therefore the nonlinear controllers are problematic. 3) rotorcraft models can be **not-affine in the control inputs 4)** Actuator dynamics and rotor dynamics (most likely flapping dynamics) can cause the designed INDI controller to overcontrol the helicopter. It can be proven that in order to account for rotor dynamics one needs to 'residualize' and 'synchronize' the controllers's Parameters in order to account for the rotor delays.

4. UNDERSTANDING THE PARTICULARITIES OF ROTORCRAFT IN DEALING WITH ADVANCED CONTROLLERS

In order to get some physical feeling for the problem, a very simple manoeuvre is used as an example, i.e. the first few instants during the transition from hover to forward flight, after a step input of longitudinal cyclic pitch.

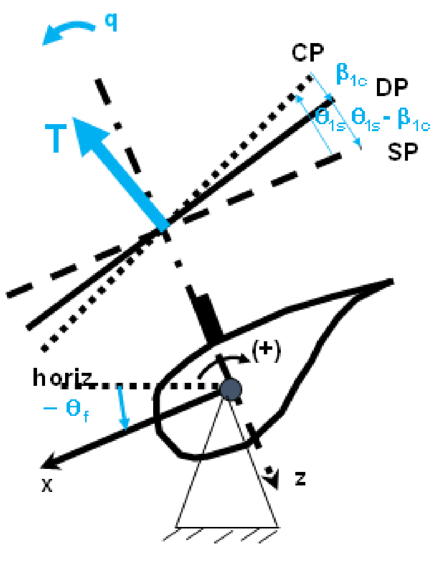

Figure 2. Helicopter pitch motion after a longitudinal cyclic pitch step (CP=control plane, SP = shaft plane, DP = disc plane)

One may assume that just a pitching motion of the helicopter occurs at the very beginning of this manoeuvre, before forward speed builds up and begins to have an influence.

For notations, see Figure 2. In classical treatments of the subject, the rotor disc tilt is often assumed to respond instantaneously to control inputs, as well as to pitching motion and helicopter velocity.

This in fact is equivalent to neglecting the transient flapping motion, which indeed damps out very quickly after a disturbance. Just the quasi-steady response of the rotor disc is taken into account in this classical approach. In the case considered, backward tilt of the rotor disc with respect to the control plane (CP) is given by:

$$\beta_{1c} \cong -\frac{16}{\gamma}\frac{q}{\Omega} \tag{11}$$

where β_{1c} is the longitudinal disc tilt w.r.t. plane of control CP, γ = Lock number, q = pitching velocity of body, Ω = angular speed of rotor.

Eq. (11) can be combined with the equation describing the pitching rate of the helicopter body q:

$$\dot{q} = -\frac{T}{I_y} h \sin(\theta_{1s} - \beta_{1c}) - \frac{N}{2I_y} K_\beta(\theta_{1s} - \beta_{1c}) \tag{12}$$

where I_y = mass moment of inertia around lateral axis, h = distance between body CG rotor hub, N = number of blades, K_β rotor spring constant, θ_{1s} = longitudinal tilt of swashplate (cyclic stick displacement). Assuming small angle approximation, $sin(\beta_{1c} - \theta_{1s}) \approx \beta_{1c} - \theta_{1s}$ and substituting (11) into (12) results in:

$$\dot{q} = -K\left(\frac{16}{\gamma}\frac{q}{\Omega} - \theta_{1s}\right) \quad ; \quad K = \frac{Th + \frac{N}{2}K_\beta}{I_y} \tag{13}$$

where K represent the moment exerted on the body per radian of disc tilt, due to thrust vector offset w.r. to center of gravity, as well as due to direct spring moments.
Looking at the pole of this motion described by eq. (13) this motion is always stable and nonoscillatory. $s = -\frac{16}{\gamma}\frac{q}{\Omega}$. The resulting INDI controller for this system will be:

$$\begin{aligned} \theta_{1s} &= \theta_{1s,0} + G_q^{-1}\left(-\dot{q} + \dot{q}_{ref} - C_q z_q\right) \\ z_q &= q - q_{ref} \\ G_q &= K \end{aligned} \tag{14}$$

Furthermore, there is a direct relation between the control input θ_{1s} and the pitch acceleration q. This suggests that there is no delay between applying cyclic control input and producing pitch acceleration. While this might be true when the controlled helicopter model is given by eq. (13), as can be seen in Figure 3.

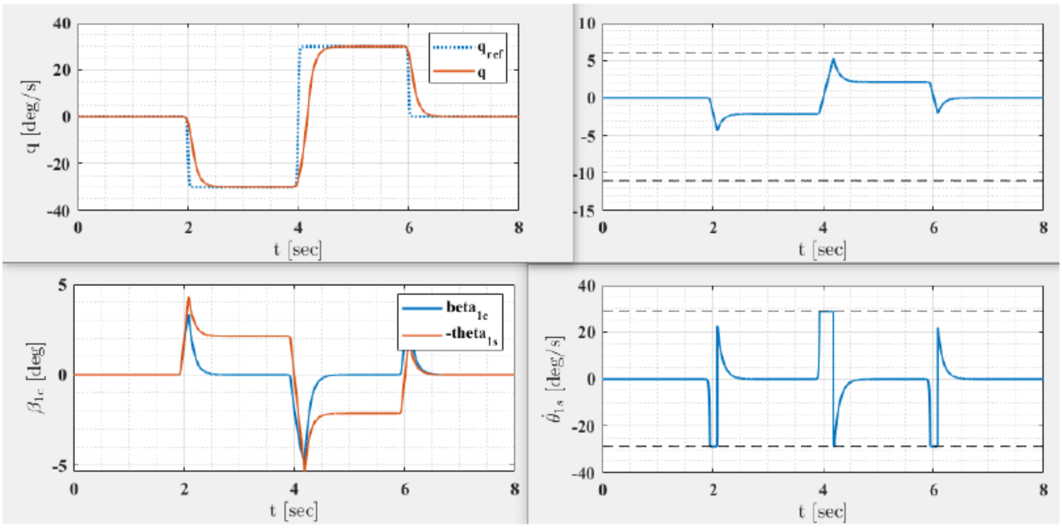

Figure 3. Tracking a helicopter pitch rate doublet with an INDI controller, no flapping dynamics

As discussed above, the rotor dynamics affects body dynamics, and therefore a refinement of eq. (11) can introduced.
Assume in a first approximation that flapping dynamics affects the tilting of the rotor disc by means of a time constant τ_β:

$$\tau_\beta \dot{\beta}_{1c} + \beta_{1c} \cong -\frac{16}{\gamma}\frac{q}{\Omega} \tag{15}$$

This disc tilt approximation corresponds to taking into account the –low frequency - regressing flapping mode on top of the steady solution. Adding eq. (15) to eq. (12) the INDI controller is again applied to the system for tracking a 25 deg/sec doublet in body pitch rate, see Figure 4

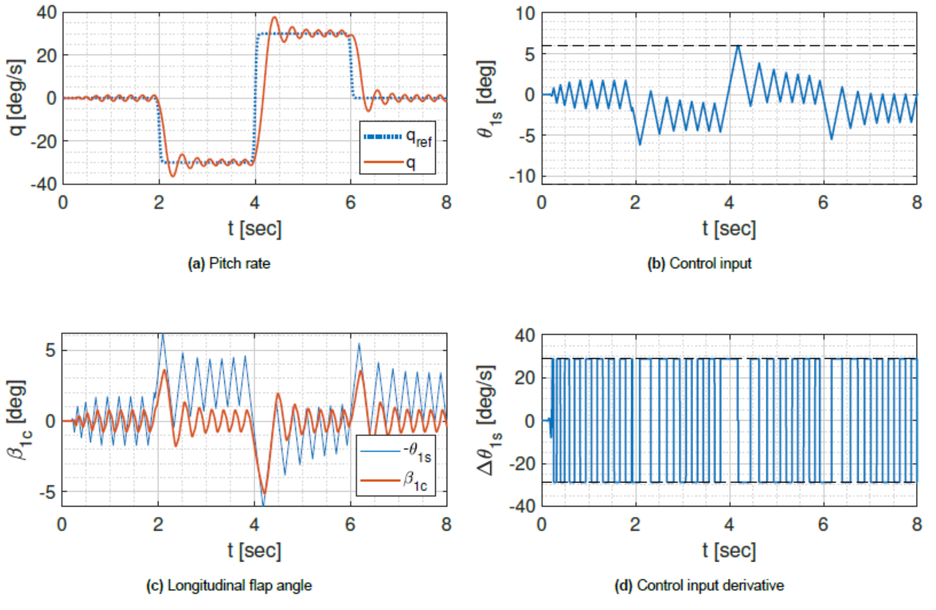

Figure 4. Tracking a helicopter pitch rate doublet with an INDI controller, first order flapping dynamics

Looking at this figure one can see that the INDI controller is unable to track the pitch rate resulting in controller instability. It follows that the delay introduced between the input of cyclic control and the desired pitch acceleration (in this case through flapping dynamics) is responsible for the nonlinear controller instability. As the controller is “unaware” of the flap delay delays, it keeps increasing its control input. The signal is still bounded due to the imposed maximum deflection and the rate limits; otherwise, the helicopter body response would quickly diverge. To correct this instability in an incremental nonlinear control approach, a standard procedure would be to control the pitch acceleration $\dot{q}$ by means of controlling flap angle β_{1c} with θ_{1s}. However, this is not possible with current helicopters since there are no sensors that can be installed on the blades to measure the flap angle of the rotor blades. This would be indeed needed for the incremental control law. Therefore, it is necessary to remove somehow the flap angle from the state vector and increase the control dependency of body pitch rate q on the control input.

As demonstrated in Figure 4, the longitudinal control input θ_{1s} indirectly influences the helicopter angular acceleration through the rotor disk tilt angle β_{1c}. Since the system dependent dynamics are neglected through the time scale separation assumption and the direct control effectiveness of the control input on pitch acceleration is negligible, the INDI controller is unable to control the helicopter. Essentially, this boils down to the fact that the time-scale separation assumption is violated. The flap dynamics has non-negligible influence on the body accelerations. Therefore the controller model on which the INDI control law is based has to be adapted. Furthermore, in the simple case analyzed above it was assumed that the actuators and sensors operate at a sufficiently high frequency. While this is true for the majority of sensors, actuator delays and dynamics cannot be usually neglected. Furthermore, filters are used to obtain certain states, so the filters induce some kind of delay as well. It follows that the incremental controllers have relatively low robustness when subjected to time delays and unmodelled dynamics that influence the feedback path. Two solutions can be used to correct this problem: residualization and synchronization.

Residualization procedure was applied by Skogestad and Postlethwaite 2001, [18]) to separate slow and fast states in a state space system and thereby simplifying the system. The fast states are assumed to be constantly at steady state compared to the slow states, and their dynamics have therefore no effect on the slow states In the case of helicopter, residualization is performed by setting the derivatives of the flapping states equal to zero and fold their dynamics into the remaining states. This will transfer the control dependency of the flapping states to the remaining states, such that the time scale separation principle is less likely to be violated. The residualized state vector for a 6 degree of system will be $xres = [u\ v\ w\ x\ y\ z \mid p\ q\ r\ \phi\ \theta\ \Psi]$. The residualization procedure for flap angle involves writing the flapping dynamics as follows:

$$\ddot{\beta} = F_{\dot{\beta},x_{res}} x_{res} + F_{\dot{\beta},\beta}\beta + F_{\dot{\beta},\dot{\beta}}\dot{\beta} + G_{\dot{\beta}} u \tag{16}$$

Assuming zero flap dynamics transforms equation (16) into:

$$\beta = -F_{\dot{\beta},\beta}^{-1} F_{\dot{\beta},x_{res}} x_{res} - F_{\dot{\beta},\beta}^{-1} G_{\dot{\beta}} u \tag{17}$$

For the body dynamics, the equation of motion is:

$$\dot{x}_{res} = F_{x_{res},x_{res}} x_{res} + F_{x_{res},\beta}\beta \tag{18}$$

Substituting (17) into (18) results in the final residualized system as:

$$\dot{x}_{res} = \left(\underbrace{F_{x_{res},x_{res}} - F_{x_{res},\beta} F_{\dot{\beta},\beta}^{-1} F_{\dot{\beta},x_{res}}}_{F_R}\right) x_{res} + \left(\underbrace{G_{x_{res}} - F_{x_{res},\beta} F_{\dot{\beta},\beta}^{-1} G_{\dot{\beta}}}_{G_R}\right) u \tag{19}$$

After residualizing the state space system for the controller model, the controller dependency on the remaining states in G_R becomes proper for applying an incremental control law. However, now there is a large difference between the controller model and the actual model describing the helicopter dynamics. Namely, the latter model includes dynamics and time delays from flap dynamics. This means that the controller model expects the helicopter to react much faster than it is in reality. Furthermore, sensors, filters and actuator dynamics also have an influence on the control deflection feedback and state measurement feedback. When not accounting for these time differences, instabilities and divergent behavior can occur. Therefore, usually a so-called “synchronization” filter is introduced in the system (Sieberling, Chu and Mulder 2010, [17]), see Figure 5.

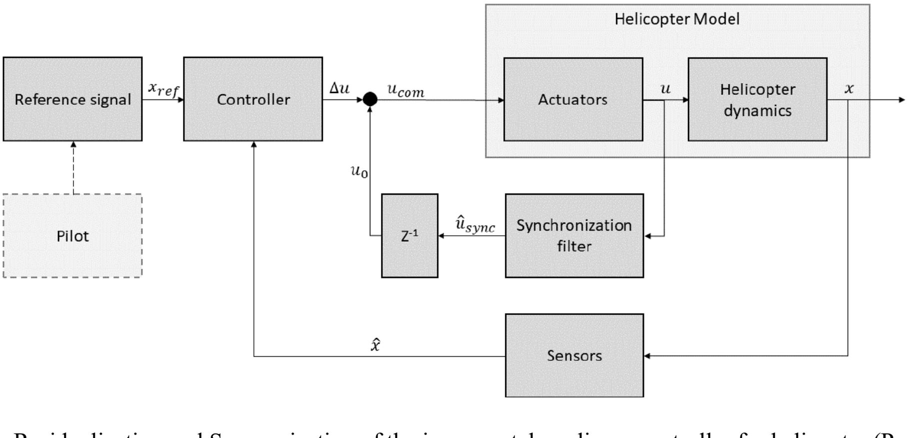

Figure 5. Residualization and Syncronization of the incremental nonlinear controller for helicopter (Pavel 2022, [15])

The synchronization filter delays the feedback measurement of the control input to mimic the delay that the control input otherwise had due to the flap dynamics and other uncontrolled signal manipulations. A downside of this synchronization filter is that some system dynamics coefficients have to be estimated, as it needs to map the expected effect of the controller input by the controller to the real effect of the rotorcraft including the time delay. However, this is just a portion of the total amount of system dynamics coefficients in *f(x)* that would have been estimated if a non-incremental controller was used. As the flapping dynamics plays an important role in the response of a helicopter, it should be investigated whether this needs to be residualized and included in the synchronization filter. The time delay that is removed during the residualization process can be synchronized using the following equation:

$$\begin{bmatrix}\dot{\beta}_{sync}\\ \theta_{sync}\end{bmatrix}=\begin{bmatrix}F_{\dot{\beta},\beta}\\ G_R^{-1}F_{x_{res,\beta}}\end{bmatrix}\beta_{sync}+\begin{bmatrix}G_{\beta}\\ G_R^{-1}G_{x_{res}}\end{bmatrix}\theta_{meas} \tag{20}$$

where β represents the flapping dynamics and θ represents the control vector. Using eq. (20) results in synchronization of the control output of the controller model with the actual control deflection of the relevant actuation system. The filter is placed in the feedback path of the actuator deflection measurement, converting the measured actuator deflections to a synchronized actuator deflection. The sensor dynamics could be accounted for by placing the model of the sensors also on the actuator feedback path. Therefore, in Figure 6, the sensor block is also placed inside the synchronization block. This will cause the possible delay of the sensors to by applied to both the state estimation signal as the actuator feedback, thereby cancelling out any effect of the sensors.

Applying the residualization (to solve for the time scale separation assumption) and synchronization (to solve for the time delay of the flapping dynamics) for the instability of the nonlinear controller as presented in Figure 4 results in an improved tracking performance for the doublet controller as seen in Figure 6. Looking at the figure one ca see that the controller performance is much improved. Some oscillations are still visible in the control input derivative, but they die out as the signal stabilizes.

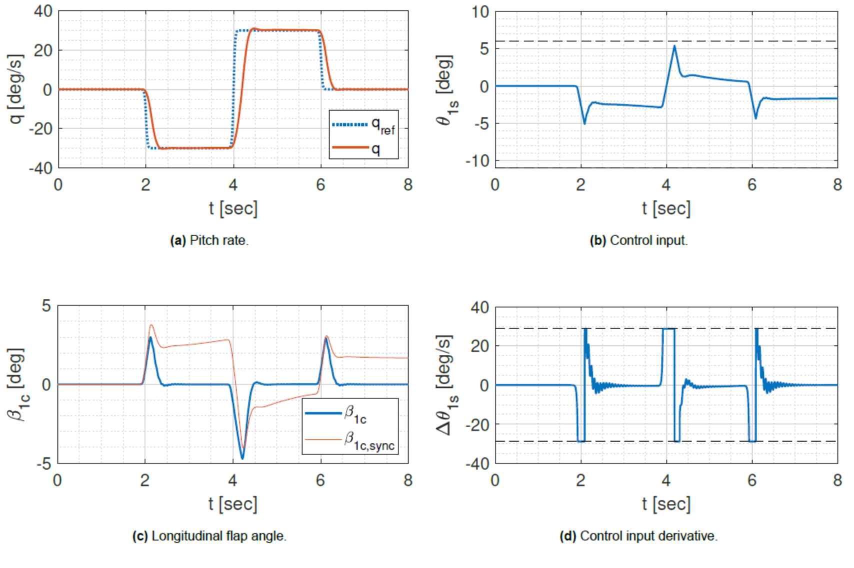

Figure 6. Tracking a helicopter pitch rate doublet with an INDI controller, first order flapping dynamics, residualization and syncronization filter included in the nonlinear controller

This finding demonstrates the importance of including correct rotor dynamics in the design of incremental nonlinear controllers for helicopters. Especially the value of the time delay in the rotor dynamics should be carefully determined and handled in these controllers. Indeed, recent investigations into the robustness of INDI flight control laws on fixed-wing aircraft demonstrated that adequate synchronization formed a key factor in the design of incremental control laws (Pollack and van Kampen 2022, [24]).

Pilot in the loop real time simulation in the Simona Research Simulator (SRS) at Delft University were performed with the Apache's helicopter when the INDI controller was implemented. (Pavel et. Al. 2020, [14]).

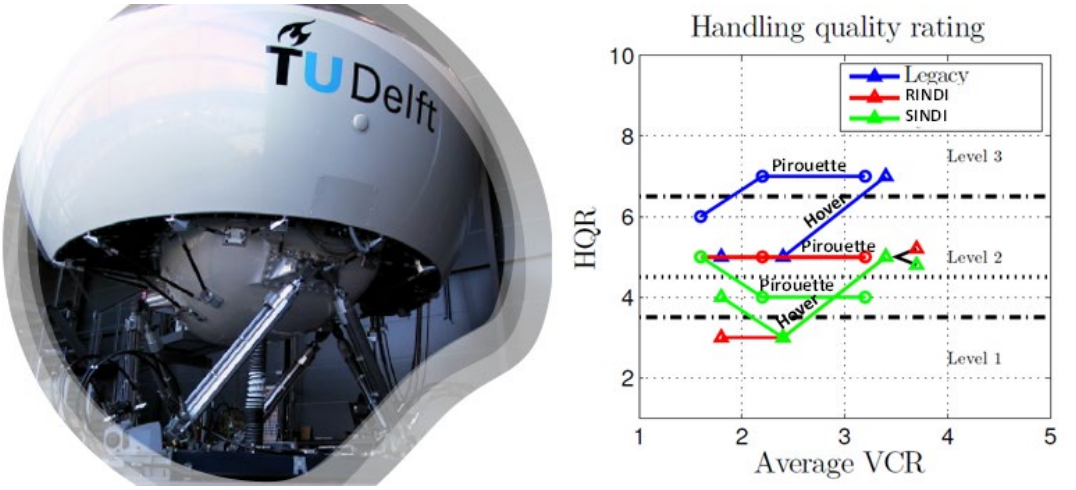

Figure 7. Handling Qualities Ratings in Simona Research Simulator at Delft University for a Rotorcraft in Hover (triangles) and Pirouette (circles) manoeuvres using the legacy and the INDI controller. (Pavel et. al. 2020, [14])

As mission task elements (MTEs), the hover and pirouette maneuvers of the ADS-33E standard were selected to be flown in SRS with and without the INDI enhanced. Both maneuvers were tested in good visual conditions (GVE), a moderately deteriorated environment (DVE 1) and a brownout condition (DVE 2). Figure 7 presents the HQR when flying hover and pirouette maneuvers with legacy, RINDI (a kind of residualized INDI) and SINDI (a kind of synchronized INDI) controllers. The figure plots the Level 1, Level 2 and Level 3 borders according to the HQs rating scale (HQR). (Pavel et. al. 2020 [14]). The pilot comments when flying the INDI controllers were that, in general, INDI seems to achieve a better performance when compared to the legacy controller. This can be seen in Figure 7where better HQs ratings were given to the INDI solutions as compared to the legacy controller (e.g., in GVE pirouette had a 6 with legacy and a 5 with INDI). It should be noted that with the legacy controller, the test pilot complained that the FLYRT model was very sensitive to longitudinal cyclic inputs; this resulted in very small cyclic inputs needed to maintain attitude when flying the legacy. Evaluating the trends in the HQ rating (HQR) of Figure 7 one can see that the HQ of the legacy model deteriorates for both maneuvers. The test pilot motivated this due to the increased workload needed to attain the required performance.

5. CONCLUSIONS

When applying an incremental controller, one relies on sensor measurements instead of a mathematical model to obtain the state of the system. This is an important advantage, since estimation errors in the mathematical model are excluded. However, a rotorcraft has multiple rotor dynamics states that cannot be measured while this should be done for successful control. This is because of the fact that whereas in conventional fixed-wing aircraft, control moments are transmitted directly from the control surfaces to the aircraft, in rotorcraft, the control inputs are transmitted through the swashplate to the blade pitch, causing the rotor to flap and thence transmitting moments to the aircraft. cyclic inputs are. Thus, low-frequency pilot inputs (applied at 1/rev-frequency through the swashplate mechanism) generate high-frequency blade excitations. Clearly, rotor blade excitations, in the form of rotor flap and lag motion, can be transformed back to the fixed airframe system as disc plane motion, influencing thus the plant. Based on flight experience with modern rotorcraft, excitations of the rotor flap and lag motions coming from pilot/controller inputs result in vehicle roll/pitch vibrations. Since the rotor dynamics are neglected while assuming time scale separation in the INDI controllers and because the direct control effectiveness of the control input on vehicle pitch/roll accelerations is negligible, the rotorcraft nonlinear controller are not probably not robust. This situation needs to be corrected by applying 1) resdualization of the higher-order rotor dynamics and 2) synchronization of the input signal.

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