Assessment of an H_∞-Based Robust Controller Through Piloted Simulator Testing of Helicopter Handling Qualities

MSc Thesis Report

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TU Delft

Assessment of an H_∞-Based Robust Controller Through Piloted Simulator Testing of Helicopter Handling Qualities

by

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Cover: SIMONA Research Simulator (modified) (https://www.tudelft.nl/lr/organisatie/afdelingen/control-and-operations/facilities/simona-research-simulator)

TU Delft

Preface

This thesis is the culmination of my time studying at the TU Delft. It took years of hard work, not only academically but also personally, but I have reached the end. I look back on my time at the TU Delft with pride, and a sense of accomplishment. I have learned far more than I ever expected beforehand. All the experiences during these years have made my time studying at the TU Delft a very memorable time in my life, that I can look back on with joy. The work I did on this thesis in particular was challenging but in the end, very rewarding. Especially the opportunity to work on the Simona research simulator is an experience I will never forget.

Now to the people who have made a very significant impact on my thesis. First off, I would like to thank my supervisors, Marilena Pavel and Spilios Theodoulis, for their guidance and support throughout the whole process of my thesis. They have helped me through the challenges I faced, and led me through them with their insight and encouragement. I would also like to thank Olaf Stroosma for his help with the set-up, supervision and execution of the flight test performed, his help was invaluable and I am very grateful. A special thanks to Tomasso Capra, on who's research this thesis is a continuation, for his time and effort spend on helping me.

I would also like to sincerely thank the pilots who took time and energy to perform the flight test. Their enthusiasm and meticulous feedback, made it not only a joy to perform the flight tests, but also provided me with the data needed for this research, and gave me insights that elevated the result immensely.

Lastly, I would like to deeply thank my family and friends, who have helped me through the challenging times, and were there to celebrate the accomplishments. Without their constant encouragement, this thesis and my time at the TU Delft would have not been what it is today.

Thom Wennink
Delft, June 2025

Contents

Nomenclature

Symbol	Definition	Unit
a_1	Rotor flapping coefficient	[-]
c	Blade chord	[m]
C_d	Drag coefficient	[-]
C_T	Thrust coefficient	[-]
C_{l_α}	Lift curve coefficient	[-]
D	Drag force	[N]
d_I, d_O	Disturbances, input and output	[-]
F_x, F_z	Resultant force along the x,z-axis of the body frame	[N]
G	Plant	[-]
g	Gravitational constant	[m s^{-2}]
h	Time-step used in the Runge-Kutta method	[s]
I_b	Blade moment of inertia	[kg m^2]
K	Controller element	[-]
k_n	Runge-Kutta factor	[-]
m	Measurement uncertainty	[-]
m	Mass	[kg]
M	Moment force	[Nm]
q	Pitch rate	[deg/s]
R	Radius of the rotor	[m]
r	Reference signal	[-]
S	Blade area	[m^2]
S_I, S_O	Sensitivity function, input and output	[-]
T	Thrust force	[N]
T_I, T_O	Complementary sensitivity function, input and output	[-]
u	Horizontal velocity in the body frame	[m/s]
u	Input	[-]
u_n	Input at a certain time-step	[-]
V	Velocity vector	[m/s]
V_z	Vertical velocity in the earth frame	[m/s]
W	Weighting filter	[-]
w	Vertical velocity in the body frame	[m/s]
X_{cg}	Center of gravity in X-direction	[m]
y	Output	[-]
α_c	Angle of attack of the control plane	[deg]
γ	Lock number	[-]
ϵ_n	Total error at timestep	[deg]
ϵ	Angle of incidence of the velocity	[deg]
ζ	Damping ration	[-]
θ	Pitch angle of the helicopter	[deg]
θ_c, θ_0	Inputs, cyclic and collective, to the helicopter model	[deg]
λ_c	Non-dimensional induced velocity of control plane	[-]
λ_i	Non-dimensional induced velocity	[-]
$\hat{\mu}$	Rotor advance ration	[-]
ρ	Density	[kg/m^3]
σ	Rotor solidity	[-]
τ	Time-constant	[s]

Symbol	Definition	Unit
τ_{λ_i}	Thrust coefficient state derivative factor	[-]
Ω	Rotational speed of the rotor	[deg]
ω	Frequency	[rad/s]
ω_c	Low-pass filter frequency	[rad/s]
ω_n	Natural frequency	[rad/s]

1 Introduction

Helicopters have always been a complex piece of engineering, offering amazing characteristics such as being able to take off and land vertically, hover in the sky, move any direction, and making hard to reach places accessible with ease. However, this mobility does come at price. Instability is a well-known problem that helicopters struggle with, from instability in pitch during forward flight, to instability when hovering, and large coupling effects between different axes(Reeder et al., 1966). To tackle helicopter stability issues and to elevate rotorcraft performance, developments regarding rotorcraft hardware have consistently been made (Stiles et al., 2004). To further aid rotorcraft stabilization, control systems have been implemented since the early development phase of rotorcraft (Prouty and Curtiss, 2003). One important development of modern control theory is robust control. The concept of robust control is to design a stabilizing controller, often imposed with certain performance criteria, with uncertainties taken into account in the design process. Any aircraft in the real world is subjected to uncertainties. This can range from external disturbances, such as wind gusts, to internal hardware uncertainties, for instance sensor errors. Uncertainties can also appear in the form of errors in the model that was used to design the controller. Uncertainties are inevitable, however, robust control methods can guarantee that, when under the effect of a certain level of uncertainty, the controller will not violate constraints imposing desired performance and stability.

When discussing control augmentation techniques an important factor is the handling quality. Handling qualities are a measure of the pilot experience in the cockpit and of their workload to conduct certain tasks. The pilot is a central part of any aircraft system. He is the one in control of the rotorcraft. However, when conditions occur where the pilot workload intensifies, it is vital that the aircraft has good handling qualities. Good handling qualities reduce the pressure on the pilot and keeps dangerous situations from escalating. The 32nd Nikolsky Honorary lecture by Padfield (2013) is fully dedicated to this subject and illustrates how far the development of handling qualities have come. One of the widely used documents on rotorcraft handling qualities is ADS-33 (Anon., 2000), preceded by the MIL documents (Anon., 1961). These documents provide a basis on how to design and test a controller to use control augmentation as a method to minimize the pilots workload.

To achieve a desired level of handling qualities, certain metrics are often used to impose design criteria on the design of a controller. These metrics are developed to represent aspects that would lead to these handling qualities. However, since handling qualities by nature are an experience of the pilot, the pilot experience must be tested in order to verify a controller design produces the desired handling qualities. This leads us to the focus of this thesis: an assessment of the handling qualities of a robust controller, designed for the Bo-105, by means of piloted flight testing. This controller was previously designed by a fellow TU Delft student, presented in his thesis (Capra, 2024). One of the previous goals of this research was the design a controller reaching level 1 handling qualities. This thesis designed and performed a flight test on the Simona research simulator at the TU Delft faculty of Aerospace Engineering, involving experienced pilots, as a method to verify the desired handling qualities set in the previous research, as well as furthering research into helicopter application of robust controllers.

This thesis follows the subsequent structure: the accompanying scientific article to this thesis is presented in chapter 2. A literature review is provided in chapter 3, which discusses handling qualities and robust control. This aims to provide some background for the research performed in this thesis, and aid in the development of research objectives and questions. The background into the model and controller used in this research is discussed in chapter 4. In chapter 5 the design and results of the flight test are discussed. This includes the different tasks that were flown, the comparative controller configuration that was used, and the setup of the simulator. As a result of significant pilot induced oscillations during one of the runs flown during the flight test additional research was done into anti-windup, which is discussed in chapter 6. Lastly, the conclusion to this report and recommendations on further research, are given in chapter 7.

2

Scientific Article

Assessment of an H∞-Based Robust Controller Through Piloted Simulator Testing of Helicopter Handling Qualities

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This paper is on the assessment of handling qualities for a robust controller, previously designed using H∞ techniques for a longitudinal model of the Bo-105. These techniques offer robustness against uncertainties, but for the designed handling qualities to be verified, a flight test was required. During this flight test, the pilots were asked to perform a set of tasks. These include a stick sensitivity task, tracking tasks for the pitch and altitude, being flown at different flight conditions to show robustness, a bob-up, and an acceleration-deceleration task. These tasks were flown for two different controller configurations, the robust controller and a simple pitch rate controller as a base line. The impact of the stick sensitivity is investigated and minimized during the first task, after which the pilots provided a Cooper-Harper rating for the remaining tasks. All task except for the acceleration-deceleration task saw increases in ratings for the robust controller, compared to the baseline configuration. The tracking tasks achieved a handling quality level on the border of 1 and 2. Non-controller factors, such as stick force, missing cueing and performance limits, were commented on to be of impact on the ratings given by the pilots. The acceleration-deceleration task brought significant PIO to light. This was investigated and attributed to integral windup. Anti-windup methods, clamping, and back-calculation were used to successfully combat the problem. Overall the design of the robust controller trends the handling qualities towards level 1, but does not fully reach this level. However, there are indications that most of the deficiencies are not controller related however.

Nomenclature

h	=	Time-step used in the Runge-Kutta method [s]
K	=	Controller element [-]
k_n	=	Runge-Kutta factor [-]
q	=	Pitch rate [deg/s]
S	=	Sensitivity function [-]
u	=	Horizontal velocity in the body frame [m/s]
u_n	=	Input at a certain time-step [-]
V_z	=	Vertical velocity in the earth frame [m/s]
w	=	Vertical velocity in the body frame [m/s]
x_n	=	State in the Runge-Kutta method [-]
ϵ	=	Total error [deg]
ζ	=	Damping ration [-]
θ	=	Pitch angle of the helicopter [deg]
θ_c, θ_0	=	Inputs, cyclic and collective, to the helicopter model [deg]
λ_i	=	Non-dimensional induced velocity [-]
τ	=	Time-constant [s]
ω	=	Frequency [rad/s]
ω_c	=	Low-pass filter frequency [rad/s]
ω_n	=	Natural frequency [rad/s]

I. Introduction

Helicopters have always been a complex piece of engineering, offering amazing characteristics such as being able to take off and land vertically, hover in the sky, move any direction, and making hard to reach places accessible with ease. However, this mobility does come at price. Instability is a well known problem that helicopters struggle with, from instability in pitch during forward flight, to instability when hovering, and large coupling effects between different axes[1]. To tackle helicopter stability issues and to elevate rotorcraft performance, developments regarding rotorcraft hardware have consistently been made [2]. To further aid rotorcraft stabilization, control systems have been implemented since the early development phase of rotorcraft [3]. One important development in modern control theory is robust control. The concept of robust control is to design a stabilizing controller, often imposed with certain performance criteria, with uncertainties taken into account in the design process. Uncertainties are inevitable, however, robust control methods can guarantee that, when under the effect of a certain level of uncertainty, the controller will not violate constraints imposing desired performance and stability.

When discussing control augmentation techniques an important factor is the handling quality. Handling qualities are defined by Cooper and Harper [4] to be "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role", they are a measure of the pilot experience in the cockpit, and of their workload to conduct certain tasks. The pilot is a central part of any aircraft system. However when conditions occur where the pilot workload intensifies, it is vital that the aircraft has good handling qualities. Good handling qualities reduce the pressure on the pilot and keeps dangerous situations from escalating. The 32nd Nikolsky Honorary lecture by Padfield [5] is fully dedicated to this subject and illustrates how far the development of handling qualities have come. One of the widely used documents on rotorcraft handling qualities is ADS-33 [6], which supersedes the first specifications that focused specifically on helicopters, collected in the MIL documents [7]. This document provides a basis on how to design and test a controller to use control augmentation as a method to minimize the pilots workload.

To achieve a desired level of handling qualities, certain metrics are often used to impose design criteria on the design of a controller. These metrics are developed to represent aspects that would lead to these handling qualities. A collection of these and their design process is highlighted by Memon et al. [8]. However, since handling qualities by nature are an experience of the pilot, the pilot experience must be tested in order to verify a controller design produces the desired handling qualities. Apart from the design of the controller, external factors can also impact the handling qualities, such as input design [9] or motion [10].

This leads us to the focus of the research presented in this paper: an assessment of the handling qualities of a robust controller, designed for the Bo-105, by means of piloted flight testing. This controller was previously designed by a fellow TU Delft student, presented in his thesis [11]. One of the previous goals of this research was to design a controller reaching level 1 handling qualities. The presented research designed and performed a flight test on the Simona research simulator at the TU Delft faculty of Aerospace Engineering, involving experienced pilots, as a method to verify the desired handling qualities set in the previous research. A set of interesting examples of research where robust control was used to design a robust controller, including (simulated) flight testing of the controller and assessment of handling qualities of these controller are by Postlethwaite et al. [12], Walker et al. [13], Postlethwaite et al. [14] and Horn et al. [15].

The structure of this paper is as follows: the model used for the design of the flight test is discussed in section II. The design methods and background of the controller can be found in section III. The flight test design is discussed in section IV. The results of the flight test are presented and discussed in section V. As a result of significant pilot induced oscillations during one of the runs flown during the flight test, additional research was done into anti-windup, which is discussed in section VI. Lastly, the conclusion to the this paper is given in section VII.

II. Model

Helicopter

The helicopter model that was used for the flight testing was a 3-DOF, longitudinal adaptation [16] of a 6-DOF version of the model, developed by Pavel [17]. This model is a general helicopter model, which is applied to the specification of the BO-105 during this research. The output of the model is a set of state derivatives, accounting for positional and rotational change, and an added factor for the regulation of the thrust coefficient. The inputs are a collective and longitudinal cyclic angle. The vectors are shown below.

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{\lambda}_i \end{bmatrix}, \begin{bmatrix} \theta_0 \\ \theta_c \end{bmatrix} \tag{1}$$

Actuators

A model for the actuators was obtained from Bouwer and Hilbert [18] in the form of a second order transfer function, with a natural frequency of 50.265 and a damping ratio of 0.95:

$$\frac{2526.6}{s^2 + 95.5s + 2526.6} \tag{2}$$

Apart from a model for the response of the actuators, the physical limits are also of importance. These are in the form of a rate limit and a positional limit, and can be seen in Table 1 [19][11].

Actuator	**Max. + Deflection**	**Max. - Deflection**	**Max. Rate**
Collective	15.0	-0.2	16.0
Cyclic	11.0	-6.0	28.8

Table 1 Actuator position and rate limits in degrees

III. Controller

The controller used in this research was developed by Capra et al. [20]. This section will be a brief summary of the controller and some of the design choices made by Capra et al. [20], that directly impacted this research.

The controller consists of three parts; the feed-forward element, the PI-like element, and the pitch rate element, all shown in Figure 1. Starting with the feed-forward element, K_{ff}, its purpose is to shape the response of the signal it is acting on, and has the shape of second order transfer function. The PI-like element, K_c, is the part of the controller that is used for tracking the pilot inputs. This has a classic PI shape, a proportional element and an integral element, with a low pass filter added to both of these elements. The transfer function of the PI-like element will then be: [20]

$$K_c(s) = \left(K_P + \frac{K_I}{s}\right) \cdot \frac{\omega_c}{s + \omega_c} \tag{3}$$

The last element is the pitch rate element, K_q, which is a stabilizing factor for the pitch rate of the helicopter. Since the phugoid mode of the helicopter is unstable, this element is added to improve the stability of this mode by damping the pitch rate.

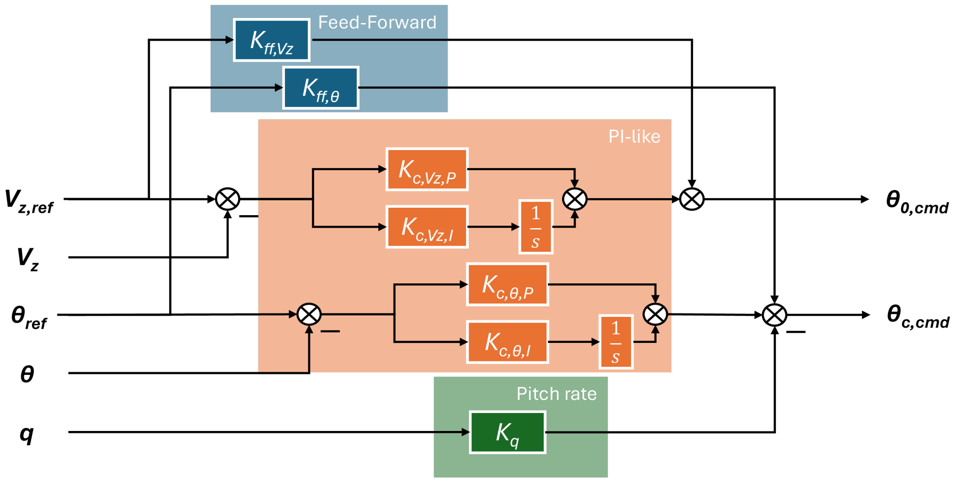

Fig. 1 Schematic overview of the shape of the controller, with its different elements highlighted.

The values for the different elements of the controller are shown below[20], which are found in previous research conducted by a fellow student. H_∞-based constraint optimization methods were used to find these values. This method uses a set of constraints, expanded on below, to find a solution for the controller values, that minimize the soft constraint, while making sure the hard constraints are not violated. The main function of the hard constraints is to impose a stability requirement. These constraints are a constraint on the minimum disk-based stability margins, which resulted in a gain and phase margin of ±7.6dB and ±45°respectively. The second hard constraint was a pole placement based on handling qualities requirements given by ADS-33[6]. The handling requirement set a damping ratio limit of 0.35. Furthermore, the maximum frequency of the poles was limited to 100rad/s, to account for the sampling frequency, assumed to be 100 Hz[20], so that dynamics would not become too fast to detect properly.

$$K_{ff,V_z}(s) = \frac{0.056s - 0.30}{s^2 + 12.24s + 54.04}, \quad K_{ff,\theta}(s) = \frac{-46.87s + 26.46}{s^2 + 11.36s + 46.16} \tag{4}$$

$$K_{c,V_z,P}(s) = \frac{0.064}{s + 5.45}, \quad K_{c,V_z,I}(s) = \frac{0.06592}{s + 5.45}, \quad K_{c,\theta,P}(s) = \frac{-11.09}{s + 4.87}, \quad K_{c,\theta,I}(s) = \frac{-5.6559}{s + 4.87} \tag{5}$$

$$K_q = -1.97 \tag{6}$$

The soft constraints aim to improve a certain aspect of the controller, which include input and output disturbance rejection, model following, and control attenuation. For this research, the constraints relating to the implementation of handling qualities are of importance, while one of the research goals is to validate the designed for handling qualities in a simulation setting.

The first of these handling quality criteria is a constraint on the disturbance rejection of the pitch and heave. More specifically, this is in the form of disturbance rejection bandwidth and peak on the sensitivity function of the signals. These are defined by Berger et al. [21] to be:

$$\omega\left(S_0 = -3dB\right) = DRB\text{rad/s}, ||S_o||_\infty = DRP\text{dB} \tag{7}$$

The values that were used by Capra [11] for this constraint can be seen in Table 2.

	Pitch (θ)	Vertical Velocity (V_z)
DRB (rad/s) ≥	0.5	1.0
DRP (dB) ≤	5.0	5.0

Table 2 Disturbance rejection bandwidth and disturbance rejection peak for the pitch and vertical velocity [21].

The other constraint that aims to achieve a certain handling quality is the constraint that is included to improve the

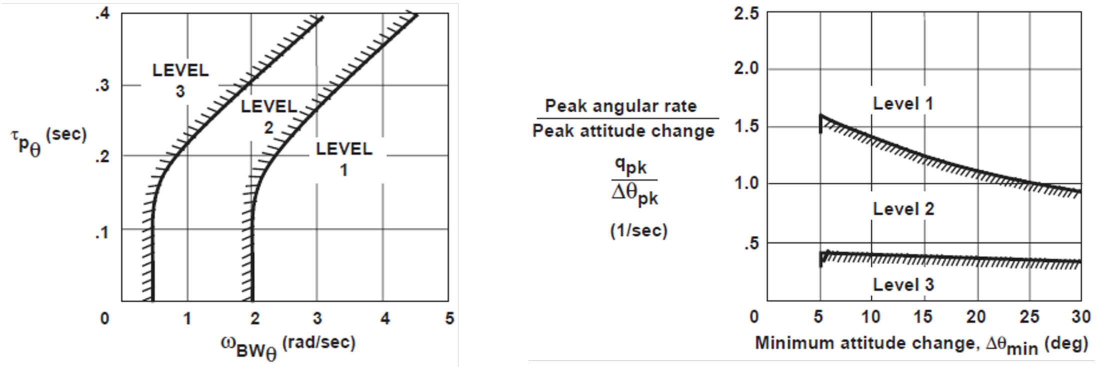

Fig. 2 Bandwidth and phase delay requirements for small-amplitude pitch changes in hover and in low speed flight (left), quickness requirements for moderate-amplitude pitch changes in hover and in low speed flight (right)[6].

model following of the controller. This is a certain response shape in the time domain that is desired for the controller to follow. The model used for the response shape of the controller is defined in ADS-33 [6] as a first order transfer function of the response from the collective input to the vertical velocity:

$$\frac{Ke^{-(\tau_{V_{zeq}} s)}}{T_{V_{zeq}} s + 1} \tag{8}$$

With the parameters that correspond to a handling quality level 1 found by Capra [11] to be:

Parameter	Value
$\tau_{V_{zeq}}$	5 ms
$T_{V_{zeq}}$	1.0 s

Table 3 Parameters used for the response shaping model for vertical velocity.

The model for the pitch signal is based on the work by Tischler et al. [22], and setup as a second order transfer function with the following shape:

$$\frac{\omega_n^2 e^{-\tau_{V_{\theta eq}} s}}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{9}$$

The handling quality level of this model is based on the criteria found in ASD-33[6]. A requirement is put on the quickness, defined as the peak angular rate over the peak attitude change for a specific axis, in this case the pitch. The different levels of handling quality, for a target acquisition and tracking task, that correspond to a certain quickness, are shown in Figure 2. The other requirement that helps shape Equation 9, is another requirement from ADS-33, this time being on the bandwidth and phase delay. The different levels for the phase delay with a certain bandwidth, can be seen in Figure 2.

The parameters for the model to follow for the pitch are presented in Table 4. These correspond to a quickness of 1.6 $\frac{1}{s}$, which was the limiting factor, and a phase delay of 0.05s with a bandwidth of 6.3 rad/s, found by Capra [11].

Parameter	Value
$\tau_{\theta_{eq}}$	7.5 ms
ζ	1
ω_n	4.5 rad/s

Table 4 Parameters used for the response shaping model for pitch.

IV. Flight test setup

1. Configuration

The robust controller was designed to be able to increase the performance of the helicopter, both in stability and performance. To be able to analyze this increase, a configuration of the helicopter was needed to have a comparison baseline case. It was decided to have this baseline configuration only be augmented with a pitch rate controller for added stability. This configuration is shown in Figure 3, and further referred to as the Stability Augmentation System (SAS) configuration. The commanded angles for the collective and cyclic signal were directly controlled by the pilot in the pitch rate controller configuration. The pitch rate controller was only able to influence the cyclic command angle. The value for the pitch rate controller, $K_q = 0.4$, was found with the help of an experienced pilot, who did not further participate in the flight test.

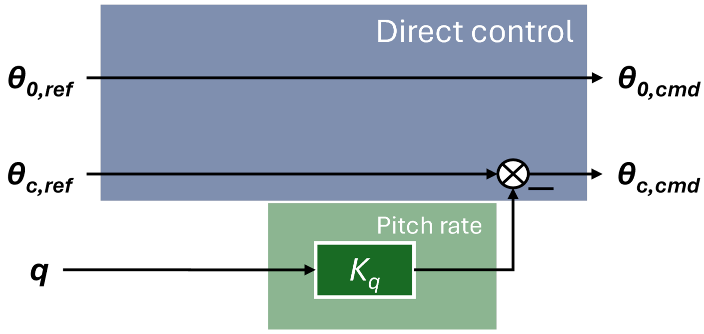

Fig. 3 Schematic overview of the SAS configuration.

2. Tasks

For the selection of the tasks to be flown during the flight test, the tasks needed to be fitted to the setup of the helicopter. This meant that only longitudinal tasks could be considered. Furthermore, the selection of tasks were aimed to test for the pitch and heave response individually at first, and test for their combined response after. Since the controller was not designed for hover, it was decided that the bob-up task was a suitable task for implementing hover aspects into the research, while also including heave response in the test. Lastly, a control configuration task was chosen to be performed, to investigate and reduce the impact of the stick sensitivity on the handling quality ratings. The tasks that were chosen to investigate the different aspects of the design for controller were:

1) Control configuration task: to investigate, and try to lower, the impact the cyclic stick sensitivity has on the ability to control the helicopter, and with that the workload of the pilot.
2) Pitch tracking task: to investigate the pitch response characteristics of the controller in a purely pitch focused task
3) Altitude tracking task: to investigate the heave response characteristics of the controller in a purely altitude focused task
4) Bob-Up task: to investigate the ability to precisely control the heave in a hover situation, while simultaneously checking for any coupling between pitch and heave.
5) Acceleration-deceleration task: to investigate pitch and heave characteristic of the controller in an aggressive setting, where the helicopter is near its performance limits.

Sensitivity configuration task

The first task that was performed is a configuration task for the sensitivity of the cyclic stick. This was done to investigate the effects of the input device on the ability to control the helicopter, and furthermore to lower this impact on the tasks to come. The impact that stick sensitivity can have on the handling qualities was already researched in early stages of helicopter development [9]. In this task, a pitch tracking task (see below) was used to give the pilot a reference to compare different sensitivities. The cyclic stick sensitivity was varied by varying the maximum deflection of the stick, while keeping the corresponding maximum input the same at the new maximum deflection. The different maximum deflections are shown in Table 5. The assessment of the performance of the sensitivities was done based on the pilot's experience, and by performing test runs where the pilot was asked to give an overall preference of the sensitivity. When the preferred sensitivity was found, this sensitivity was locked in and used for the remainder of the flight test.

Sensitivity	1	2	3	4
Max. Stick Deflection (deg)	14.8	12.0	9.0	6.0

Table 5 Maximum deflection of the cyclic stick, with corresponding sensitivity level.

Pitch tracking task

With the sensitivity selected, the next series of tasks are designed to test the controller in different situations. From this task on, the pilot was asked to provide a Cooper-Harper rating to the performed tasks.

The pitch tracking task was designed to test the pitch response of the controller. In this task, the pilot was presented with a reference pitch signal to follow. This reference signal consists of a set of series of ramp and step inputs, which for this specific task were always the same number of inputs, but randomized in their amplitude and length, over the same total time, for each run of the task performed. To put a measurable performance on this task, the pilot will obtain a score based on the total time spend within a certain limit of the reference signal. If he stays within $\pm 0.5°$ of the reference signal, for at least 50% of the run, this will be desired performance. Adequate performance will be if the pilot stays within $\pm 1.0°$ of the reference signal, for at least 50% of the run. The reference signal, as well as the limits to this signal, and the total scores will all be displayed to the pilot. The pilot's display for both the pitch and the following altitude tracking task is shown in Figure 4.

Altitude tracking task

The altitude tracking task is a very similar task as the pitch tracking task. The design is inspired by the hurdles task flown in the experiment on the large motion simulator in Bedford[23]. Instead of the reference signal being for the pitch of the helicopter, it will be for the altitude of the helicopter. The pilot is again asked to follow the reference signal. For this task, a desired and adequate limit is placed on the reference signal, corresponding to 10ft and 20ft respectively. Similarly as the pitch tracking task, this task is deemed to be successful with desired performance when 55% of the total time spent on the run is within the desired limit. This will again be the same for adequate performance.

Both the pitch and altitude tracking tasks were to be flown at different initial speeds, and initial altitudes. During the tasks, these speeds and altitudes will vary because of the input of the pilot. It was up to the pilot to find the best strategy to perform these tasks. To try to keep the focus on the pitch and vertical velocity response, it was not required to stay within a hard limit in regard to the speeds and altitudes, other than at low altitudes not reaching the ground. It was however asked of the pilots to fly the helicopter within a reasonable level of aggressiveness, as would be used in a regular, non-emergency, flight condition. The important aspect of how the helicopter was flown is consistency, since the goal of the experiment is to compare the difference with and without the designed controller.

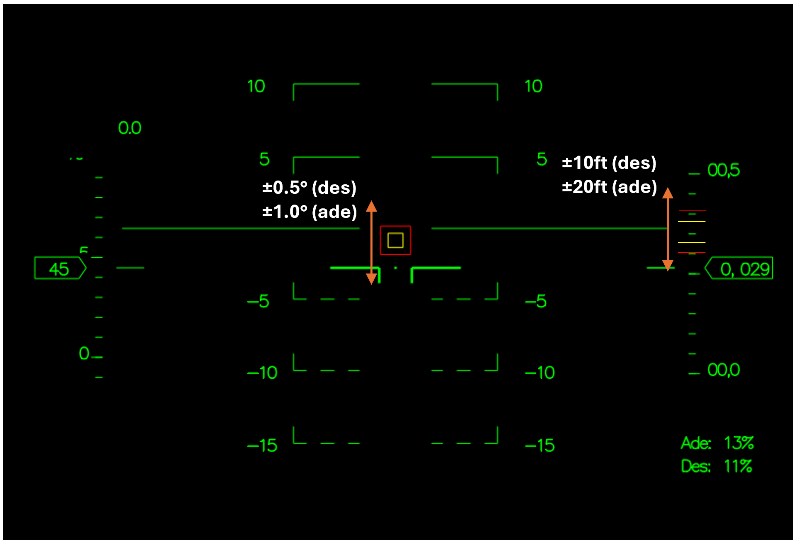

Fig. 4 Tracking task display for the pilot, with the square on the pitch tape being used for the pitch tracking task, and the lines on the altitude tape being used for the altitude tracking task. Additionally, the desired and adequate limits for each task are included as well.

Bob-up task

The bob-up task is a task inspired by a task described in ADS-33 [6], called the vertical maneuver in ADS-33. This task is designed to check the heave response of the controller, especially the precision with which the helicopter can be controller in the vertical axis. The bob-up task starts with the helicopter in a stabilized hover at 15ft. The pilot then ascends to 55ft and stabilizes there for 2 seconds and comes back down to 15ft. For this task, there were outside visuals to assist the pilot. To assist the pilot with the altitude requirement and with maintaining a hover, a board with a ball in front, at a certain distance is shown to the pilot. This board is located at both 15ft and 55ft. A schematic representation of the task is presented in Figure 5.

The performance level achieved by the pilot during this task is based on the time spend to complete this maneuver. A secondary requirement was put on the longitudinal position away from the starting position, however, since there were no screens in the simulator to look downwards, this was indicated to the pilot on the HUD. The limit on this position was taken from the ADS-33 task: ±6 ft for desired performance and ±10 ft for adequate performance.[6] The time to complete the maneuver was set to 15s for adequate performance, and 10s for desired performance, obtained from the vertical maneuver.

The position requirement was checked in the simulator before the actual flight test. The pilot was able to hold position somewhat, but was experiencing difficulties due to the visual cues missing from below the helicopter. The positional requirement was thus deemed to not be leading in the performance criteria.

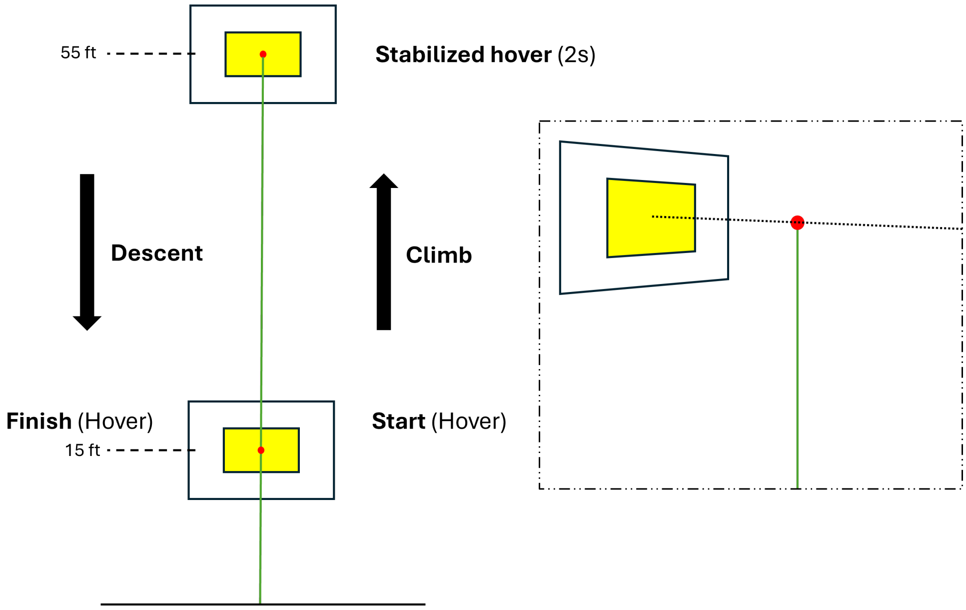

Fig. 5 Schematic representation of the boards used to assist the hover; on the left a front view and on the right a side view.

Acceleration-deceleration task

The last task to be completed was the acceleration–deceleration task, which is also a task described in ADS-33 [6]. The task is used to assess both the pitch and heave response of the helicopter. Especially the coupling between pitch and heave is tested, in the case of large pilot inputs. In this task, the pilot starts in a stabilized hover, and rapidly accelerates to 50 knots, while holding the altitude below 50 ft. When the target speed of 50 knots is reached, the pilot rapidly decelerates to a hover again. The task, and the course used, are shown in Figure 6. A performance requirement is that a certain nose-up pitch angle is reached during the deceleration of the helicopter. ADS-33 considers a desired performance if this angle is at least 30° , and adequate performance if the angle is at least 10°. Since the maximum input to the controller was set to 30°, it was investigated to see if this was a feasible requirement to be used. The helicopter showed responses that could go over 30 °, because of some overshoot during more aggressive maneuvers. It was however decided, similarly as the with the bob-up task, to be slightly lenient with this requirement. This was done to not punish the pilot for going too smoothly if that meant he would fall just short of 30 °, so the requirement was set to 28 °. The total task was to be completed within a distance shown both in the visuals, by the use of pylons on the ground, and indicated on the HUD.

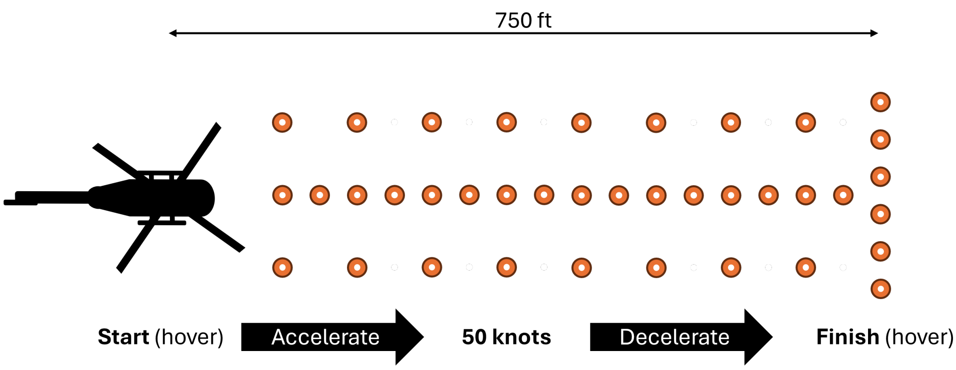

Fig. 6 Top view of the course used in the acceleration-deceleration task.

Simulator

For the flight test the Simona research simulator located at the faculty of Aerospace Engineering at the TU Delft was used. The simulator is a customizable cockpit, sitting on a hexapod motion system. The inside provides a wide angle field of view, provided by three projectors attached to the cabin. However no screens are present to give the pilot a view below the helicopter, which is a limitation on the visual cues the pilot is able to receive. Since the experiment was conducted for a longitudinal model, the cyclic stick was locked in its lateral direction so the pilot would not get a false sense of input in this direction. With the same reasoning the pedals were not used during the experiment. The pilot was assisted with a head-up display, displaying information such as airspeed, altitude, and pitch. This system was also used during the pitch and altitude tracking tasks to display the goal to the pilot. Due to issues with the motion system, motion was not used during this experiment.

V. Results

Sensitivity configuration task

The first task was performed to select the preferred sensitivity setting for the cyclic stick. The first pilot selected sensitivity level 3. The second pilot immediately noticed the somewhat high stick force, and found that slightly distracting at times. His preference on sensitivity setting was between level 2 and level 3. To improve the comparison between the two pilots, it was decided to use level 3. Both pilots completed all the following tasks with this sensitivity selected.

Pitch tracking task

Figure 7 shows the handling quality ratings of the pitch tracking task. This is split up between the two pilots and was performed for different flight conditions.

Comparing the results between the SAS configuration and the robust configuration for this task, the improvement in handling quality is quite apparent. During the runs with the SAS configuration, neither pilot managed to achieve desired performance, however adequate performance was reached for all airspeeds. For the robust controller case, desired performance was reached for nearly all runs. Pilot 1 ranked the robust controller on the border between level 1 and level 2 across his runs. The border represents the pilot deeming improvement necessary or not. The first pilot furthermore noted that he was doubting between a rating of 3 and 4 for both the cases where he awarded a 4(40m/s at sea level, 20m/s at 4000m). The rating by the second pilot was slightly lower, all level 2, indication some improvements were deemed necessary. He commented on the force of the cyclic being too high, and possibly awarding a better rating if this force was less.

The altitude and speed differences are included in the task to test for the robustness of the controller, where the performance is checked when moving away from the design point (sea level, 20m/s). To account for changes in the helicopter dynamics at different speeds and altitudes, the SAS configuration is also tested as a base line here. It can be seen that the robust controller stays relatively consistent across the different speeds and altitudes. This shows how the controller can deal with uncertainties in the model, because the linearized model, on which the controller is based, is not correct for that trim condition.

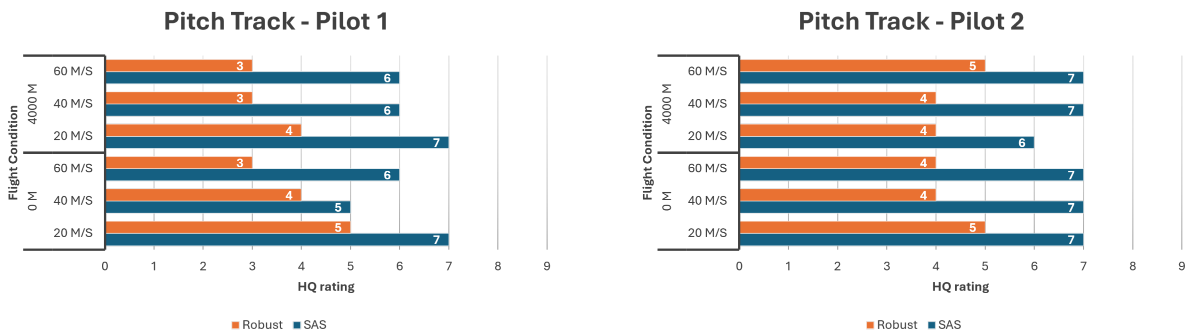

Fig. 7 Handling quality rating by both pilots, at different initial flight conditions, expressed in altitude and airspeed, and configurations, during the pitch tracking task.

Altitude tracking task

The ratings of the handling qualities in the altitude tracking task, seen in Figure 8, differ a bit between the pilots. Part of this is to do with the fact that the second pilot had better performance in the SAS configuration, compared to the first pilot. The first pilot did not manage to achieve desired performance at sea level for this configuration, whereas the second pilot did. Both pilots showed a decrease in performance, and HQ rating, for the faster runs at 4000m altitude, and commented on the slow response of the helicopter. The robust controller did not show this decrease in performance for the pilots at these flight conditions.

Pilot 1 showed significant improvements in ratings when using the robust controller, even showing level 1 handling qualities for all runs. This indicates that he does not believe the robust configuration needs improvement. Pilot 2 gave the robust controller a very consistent rating of 4, being just level 2. He believes that the deficiencies still warrant improvement. The comments he made were however mostly about the force in the stick, and he was missing some cueing. He for instance suggested that he would like to have an indication of the current vertical speed. If these improvements would be implemented it could already be enough to achieve a level 1 HQ rating.

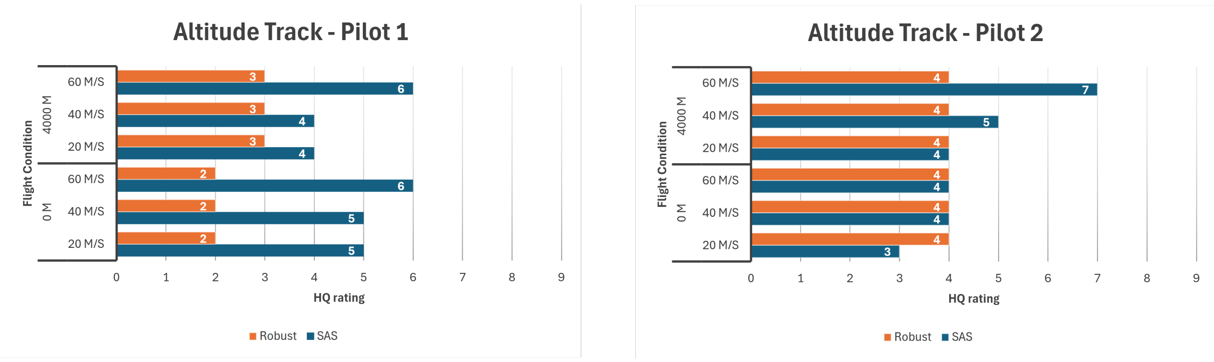

Fig. 8 Handling quality rating by both pilots, at different flight conditions, expressed in altitude and airspeed, and configurations, during the altitude tracking task.

Bob-up

In the bob-up task the helicopter is tested in a flight condition it is not designed for, hover. Results of Capra [11] already show that the robust controller would have significantly different values for its elements, had it been designed for the hover condition. This task was flown to check for heave traits and coupling between pitch and heave.

The results for the best run, for each configuration, are shown in Table 6. The time to complete the task was used as an indication of performance. The pilots did not manage to get adequate or desired performance for the SAS configurations. Both of them reported a lot of PIO and cross coupling between the pitch and vertical velocity. For pilot 2 the controllability even required significant pilot compensation, resulting in a rating of 9. The robust controller removed the cross coupling, according to the pilots, and reduced their workload significantly. However, neither pilot managed to achieve desired performance, limiting their maximum rating to 5.

During this task, the pilots also noted that they would have preferred to have some motion cueing. This would have helped them feel the hover more, and have extra senses to rely on to keep a steady hover. A point that was brought up by pilot one, is that the desired performance felt unattainable. The bob-up task flown in this research was an adaptation of an ADS-33 task [6], but due to already existing visuals that were used, it was slightly different. The task could be tuned better to the performance levels that are more realistic for this model.

Bob-Up				
	Pilot 1 - SAS	Pilot 2 - SAS	Pilot 1 - Robust	Pilot 2 - Robust
Time (s)	**18.5**	**18**	**14**	**10.5**
HQR	**7**	**9**	**5**	**5**

Table 6 Scores, in time to complete the task, and handling quality rating of both pilots, of the bob-up task.

Acceleration-deceleration task

During the acceleration-deceleration task, both pilots managed to obtain desired performance. The handling quality rating of each pilot is shown in Figure 9. The first pilot rated both configurations with a 1. He did however, have some comments about this task. He felt like he was missing some elements that were not tested in this task. One of the main ones is that the model used does not use a model for the governor, it just uses a constant RPM for the rotor. However, since the acceleration-deceleration task is an aggressive maneuver, the dynamics of the blade and the engine play a role in this task. Another comment, repeated from the bob-up task, is the missing visual cues, since the field of view was limited in the simulator, at high pitch attitudes, the pilots lost sight of the horizon. When comparing the robust controller to the SAS, the pilot noted that the way of flying was different, but that overall, after getting used to this way of flying, it required less workload than the SAS.

Pilot 2 did not reach level 1 handling qualities for this task. Pilot 2 was experiencing PIO during his runs, with the robust controller configuration. In one run these oscillations became so large that the pilot lost control. This run forms the basis of what is discussed in the next section. This pilot, just as pilot 1, showed no increase in handling quality rating between the different configuration.

After having completed the bob-up task and the acceleration-deceleration task, it became apparent that the design of these tasks, and with what set-up of the model and simulator they were performed, is a large impact on the handling qualities the pilots awarded them. It is important to tune everything around the flight test so that the result closely matches the handling qualities of the actual controller.

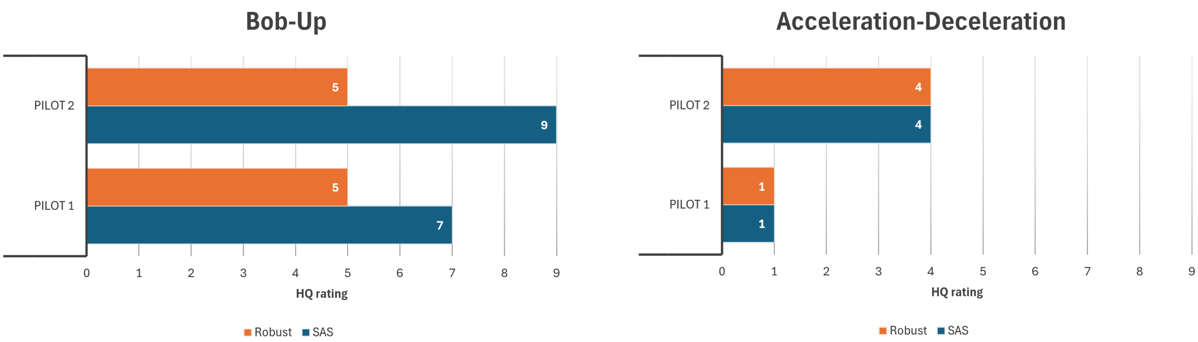

Fig. 9 Handling quality ratings of the bob-up and the acceleration-deceleration task.

VI. Anti-windup

In Figure 10 the pitch angle, commanded pitch angle and the cyclic actuator angle can be seen for one of the runs pilot 2 flew. In this run, he was asked to perform the acceleration-deceleration task. However, the helicopter got into an uncontrolled state. The pilot was trying to regain control, but as can be seen, the inputs he gave only made the oscillation grow bigger. During the flight test with the pilot, the simulation got stopped around 28s, but to show that the instability is a result of pilot inputs, the simulation was continued outside of the simulator, with an input of 0 degrees pitch angle. It can be seen that the controller does manage to stabilize the helicopter. The actuator angle is also provided in the plot, to show what is happening at the inputs of the model. This shows that the actuator is saturated during the worst oscillations.

The issue that could be the cause of this, and that is investigated in this section, is integral windup, occurring when the actuator is saturated. In short, integral windup occurs when the error feeding into the integral element of the controller is non-zero, but the actuators cannot command more input into the model. The controller is still adding extra signal to its output due to the integral component, and will continue to do so until the sign of the error term flips.

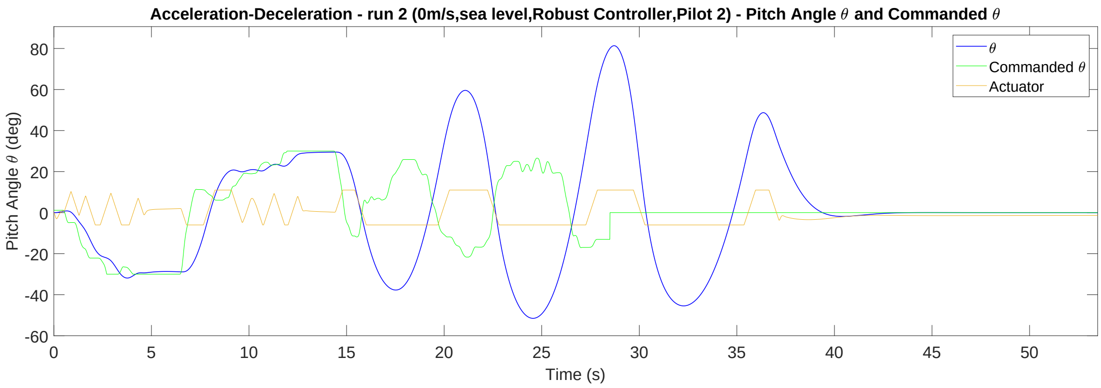

Fig. 10 Pitch angle, commanded pitch angle and actuator angle of an acceleration-declaration run performed by pilot two, extended with 0 degree input.

Clamping

The first method, tried to improve the issue of integral wind-up, is the clamping method [24]. This method is, simply put, to set the error signal input to the integral part of the controller to zero when the actuator is in a saturated state. This stops the addition of extra cumulative error when the actuator is saturated, and will resume immediately when the actuator is not saturating anymore, meaning that the error term is decreasing again. This makes it so that the integral term does not need the time to reduce the accumulated output that would have been added during saturation. A schematic overview is shown in Figure 11 to visualize the set-up of this method in the controller. The blue blocks are a representation of a method to determine if the controller is saturated. This can be done in different ways, depending on how the simulation is run. Examples are to use a series of logic blocks in Simulink to determine if the saturation is occurring, or, in the case of the discretized model used in this research, as a boolean in the code. The model for the actuator accounts for both a rate and a position limit, which means that when either occurs, the actuator is considered saturated for the clamping method. When this happens, the blue block activates a switch, to follow the new path (dashed), to set the input of the $K_{c,\theta,I}$ block to zero, meaning that the output of the integral part of the controller will remain constant from that point on.

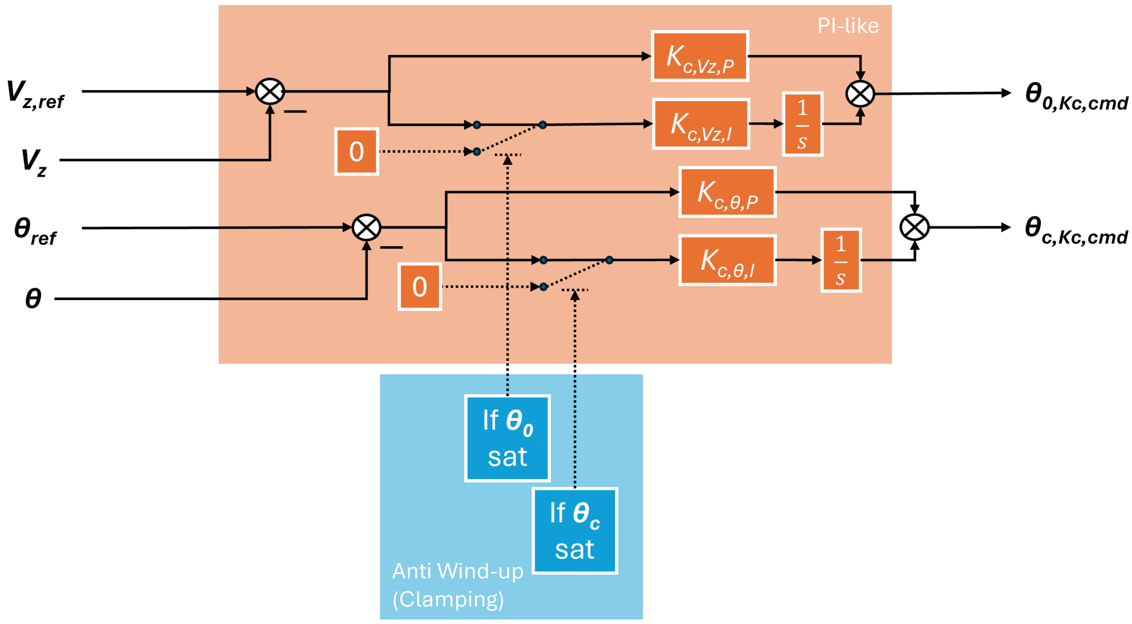

Fig. 11 Schematic overview of the clamping method. The blue block indicating the method used to determine saturation, whichever is applicable in the simulation, leading to a switch, which lets through a constant 0 whenever saturation occurs, and otherwise the error term of the respective signal.

Back-calculation

The second anti-windup method implemented is back-calculation[25]. In this method, instead of setting the input to the integral term of the controller directly to zero when saturation of the actuator occurs, the input signal is reduced proportional to the difference between the input and output of the actuators. This is visualized in Figure 13. It shows that the signal going into the integrator of the controller is first reduced by the difference in the actuator in- and output, which can be seen in Figure 12, scaled with a factor K_a. This means that the error term that goes into the integrator, and gets added to the cumulative error, is reduced based on not only if, but also on "how much" the actuator is saturating. What this also means is that the error signal is not immediately zero when saturation occurs, but that it decreases gradually, but also that it can even become the opposite sign and reduce the cumulative error before saturation stops. Choosing an adequate value for K_a is still required. Åström and Hägglund [25] suggests using a value between the scaling factor of the derivative and integral part of a classic PID-controller. Since there is only a integral part to the PI-like part of the controller, it was chosen to make K_a equal to $K_{c,I}$, for the corresponding signals.

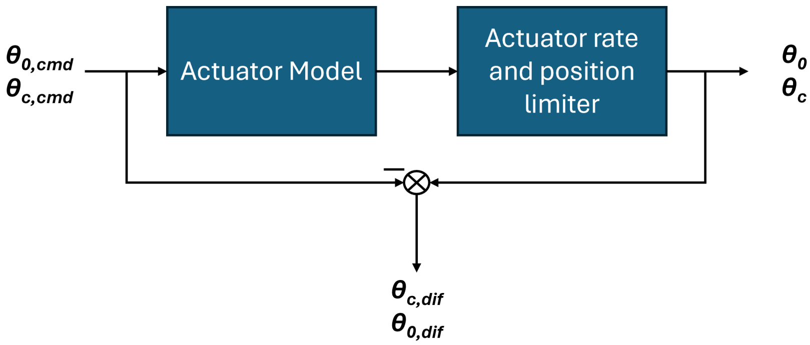

Fig. 12 Overview of actuator system, with the difference in input and output being calculated.

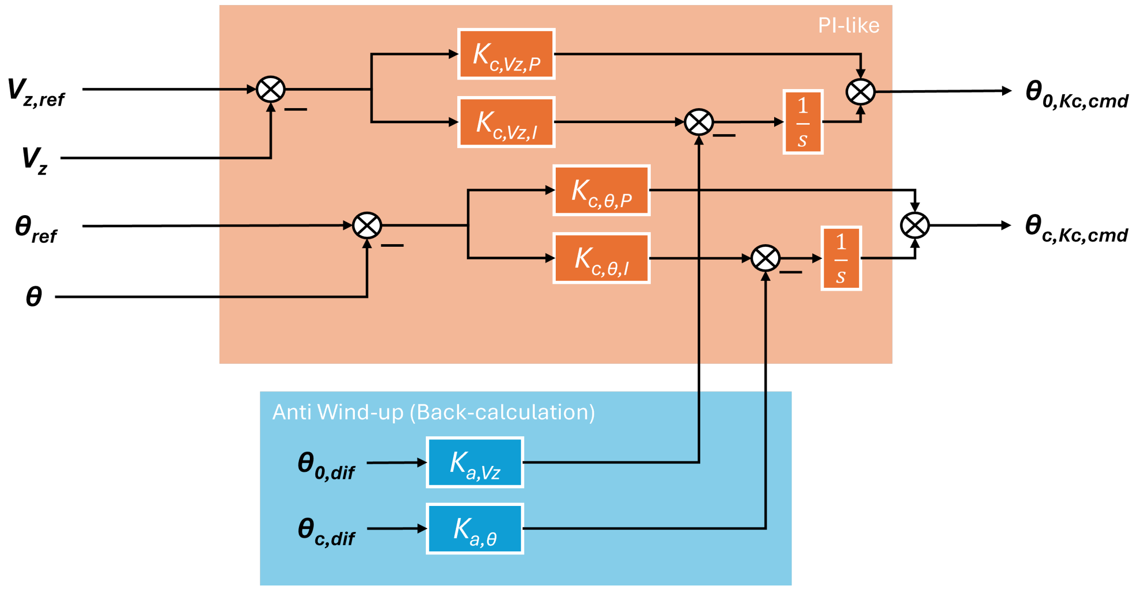

Fig. 13 Schematic overview of the back-calculation method. The blue block taking the difference between the input and output of the actuators, and feeding this into the integral loop.

Results

In Figure 14 the (commanded) pitch angle for the acceleration-deceleration run of pilot 2 is plotted for three different controllers. The first, the dashed line, is the case where no anti-windup method is used to counteract the oscillations, which is the simulated response that occurred during the flight test. The recorded pilot input is used for the other two cases as well. The second case is the simulation run with the clamping method implemented as an anti-windup technique. And the third case is where back-calculation is used. The commanded pitch angle is also plotted, to show how well the response is following the input. What can be seen is that for both methods of anti-windup, the suspected pilot induced oscillation is very significantly improved. As for the difference between the methods, the clamping method seems to overall require a bit more time to respond, whereas the back-calculation method seems to respond much more immediate.

The performance of each method is visualized in Figure 15, in which the total error up to the current time-step is plotted, with the total error being the difference between the commanded pitch and the actual pitch of the helicopter.

$$\epsilon_n = (\theta_{cmd,n} - \theta_n) + \epsilon_{n-1} \tag{10}$$

This is done for the three cases that were plotted before: no anti-windup, clamping anti-windup and back-calculation anti-windup, with the additional graph for the "no actuator limits" case. For this last case, a simulation was run where the limits on the actuators, both rate and absolute limit, were removed. This was done to have a bottom line to the performance of the controller without actuators. What can be seen is a significant increase for both cases of anti-windup, but with a better performance increase in the back-calculation case.

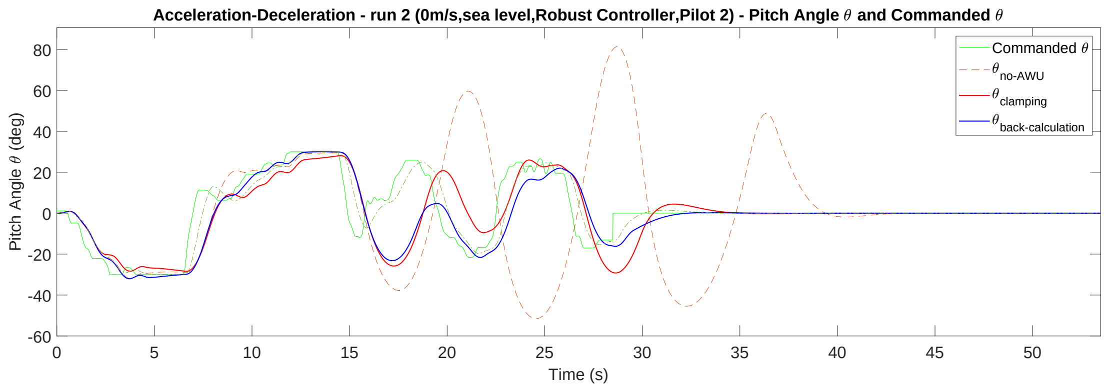

Fig. 14 Commanded pitch angle in green, and the resulting pitch angle of the helicopter, when using both anti-windup techniques, and a dashed line for the original pitch angle. This is an extended simulation, that was performed on Matlab after the flight test, that uses one of inputs for the acceleration-deceleration task, flown by pilot 2.

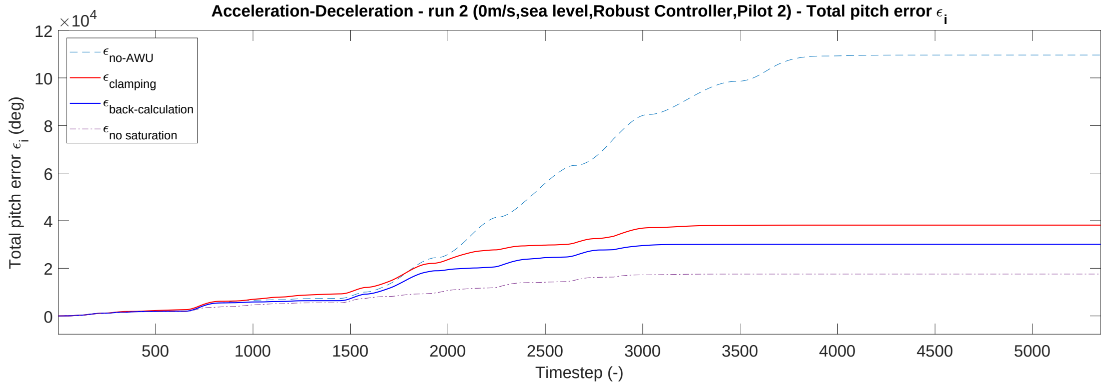

Fig. 15 Total error at each time step for the case with no anti-windup applied, the case for both the anti-windup methods applied and when no saturation limits were imposed on the actuators.

VII. Conclusion

The aim of this research was to assess the handling qualities of the robust controller designed by Capra et al. [20]. The flying quality metrics that were used in this design were an important factor in this research, to validate if these metrics served their intended goal to achieve a level 1 handling qualities.

The ratings from the pilots indicate that the robust controller is around the border between level 1 and level 2 handling qualities for most of the tasks. Between the pilots, one pilot had consistently lower rating over all of the tasks. The pilot did not however, believe that this was mainly due to the response that the robust controller produced, but due to external factors. One factor that he consistently mentioned during the different tasks was the stick force, and he believed that this did increase his workload and with that rating to level 2 handling qualities.

The bob-up task did show another factor that could have an impact on the overall rating, the performance goal. This was believed to be set to an unattainable level, with the set-up that was used in the flight test. This would require more research to conclude that this was in fact the case, especially since other factors such as a lack of motion cueing could also have an impact on the rating of the pilots.

A factor that has been further researched is the actuator saturation, and anti-windup methods to combat this problem. This showed a clear increase in response directness and removing the pilot induced oscillations that were experienced in one of the pilots runs. The method that was most suitable was based on back-calculation. Since this was done after the flight test, a potential handling quality rating increase was not obtained with the anti-windup method implemented. However, it was shown that the simulated runs with the same pilot input no longer became unstable.

Overall, it is concluded that the design of the controller has a strong indication that it satisfies level 1 handling qualities, in a situation where the external factors are tuned for properly. The metrics that are used in the design aim to represent handling qualities in a quantitative way, when handling qualities are inherently a complex and encompassing rating, put on the experience of the pilot. Coupled with the a flight test having many factors that influence the experience of the pilot as well, it is difficult to conclusively say that the controller need to be improved to reach level 1 handling qualities, but the method used to design the controller shows good promise for reaching desired handling qualities.

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3

Literature Review

3.1. Handling Qualities

Flying or Handling Qualities

When investigating how well an aircraft behaves, the words flying qualities and handling qualities frequently come up. Although they are commonly used terms, as Padfield (2013) says, there is no universally accepted distinction between the two concepts. However, a generalized distinction can perhaps be made. Flying qualities are defined by Phillips (1989) as: ”the stability and control characteristics that have an important bearing on the safety of flight and on the pilots’ impression of the ease of flying an airplane in steady flight and in maneuvers”. Handling qualities are defined by Cooper and Harper (1969) to be ”those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role” and ”Other factors that influence the handling qualities are the cockpit interface, the aircraft environment and stress...”. Combining both definitions allows for the handling qualities to be described as the flying qualities during the execution of a set task, taking into account the visual cues and the environment. Flying qualities can usually also be estimated from certain responses of the helicopter, without the subjective opinion of the pilot. This is not the case for handling qualities, where the pilot himself is used to subjectively judge the behavior of the helicopter in a predetermined situation.

These flying and handling qualities have been documented and expanded over the years. The first specification of handling qualities, discussing specifically helicopters, was released in 1952, known as MIL-H-8501, which was followed in 1961 by the first major revision, MIL-H-8501A (Anon., 1961). These document describe, for instance, the time response requirements for stability and damping of the response of the helicopter. The MIL documents have been used extensively for the design of helicopters and their controllers, and have been updated over the years. In the late 80s, the U.S. army was working on a revision of the handling qualities used for the design and assessment of helicopters. This resulted in the creation of the Aeronautical Design Standard, better known as ADS-33(Anon., 2000). This document not only included frequency domain requirements and specifications of visual cueing, but also a very important factor for the assessment of handling qualities, mission task elements.

Mission Task Elements

Arguably the most important factor in the assessment of the handling qualities of a helicopter or the controller of a helicopter, is consistency. The addition of specified tasks in ADS-33, and having specific mission task elements are vital for the consistency of the pilot feedback (Anon., 2000). These predetermined tasks present a consistent performance demand for each pilot to partake in testing, allowing for result comparability, as well as imposing performance requirements on controllers. This aims to put a goal on the task, so that every pilot flying them will be expected to perform with the same amount of workload.

An example of one of these tasks, the hover task from ADS-33, can be seen in Figure 3.1. The provided set-up is described clearly and thus provides accurate test repeatability. The associated performance goals can be seen in Table 3.1. This table shows a clear distinction between desired and adequate performance expectations. Setting well-defined and measurable performances goals is of the utmost importance to provide scientific accuracy of the test results. Nonetheless, there are requirements that cannot be assessed objectively and call for the feedback perception of pilots, such as the last requirement in the desired performance category. This shows the handling quality ratings are still inherently subjective, since it is on the pilot to deem oscillations objectionable. Furthermore, a distinction is made between different types of helicopters to account for different variations of aggressiveness required, as well as an indication of the environment, indicated by GVE(Good Visual Environment) and DVE (Degraded Visual Environment). ADS-33 introduced a system to consistently conduct flight tests, supporting subsequent researchers to develop and fly their personalized tasks with scientific consistency. An example of a task not developed by the ADS-33 documentation, is the hurdles task, flown on the flight simulator in Bedford, presented in a paper on the evaluation of handling qualities on that specific flight simulator, compared to the ADS-33 handling quality requirements(Padfield et al., 1992).

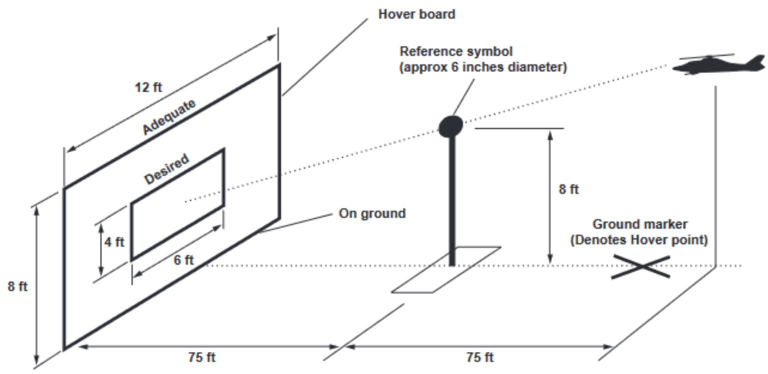

Figure 3.1: Schematic overview of the setup of the hover task, presented in ADS-33 (Anon., 2000).

	Scout/Attack		Cargo/Utility		Externally Slung Load	
	GVE	DVE	GVE	DVE	GVE	DVE
DESIRED PERFORMANCE						
• Attain a stabilized hover within X seconds of initiation of deceleration:	3 sec	10 sec	5 sec	10 sec	10 sec	13 sec
• Maintain a stabilized hover for at least:	30 sec	30 sec	30 sec	30 sec	30 sec	30 sec
• Maintain the longitudinal and lateral position within ±X ft of a point on the ground:	3 ft	3 ft	3 ft	3 ft	3 ft	3 ft
• Maintain altitude within ±X ft:	2 ft	2 ft	2 ft	2 ft	4 ft	4 ft
• Maintain heading within ±X deg:	5 deg	5 deg	5 deg	5 deg	5 deg	5 deg
• There shall be no objectionable oscillations in any axis either during the transition to hover or the stabilized hover	✓*	✓	✓	✓	✓	NA*
ADEQUATE PERFORMANCE						
• Attain a stabilized hover within X seconds of initiation of deceleration:	8 sec	20 sec	8 sec	15 sec	15 sec	18 sec
• Maintain a stabilized hover for at least:	30 sec	30 sec	30 sec	30 sec	30 sec	30 sec
• Maintain the longitudinal and lateral position within ±X ft of a point on the ground:	6 ft	8 ft	6 ft	6 ft	6 ft	6 ft
• Maintain altitude within ±X ft:	4 ft	4 ft	4 ft	4 ft	6 ft	6 ft
• Maintain heading within ±X deg:	10 deg	10 deg	10 deg	10 deg	10 deg	10 deg

*Note: For all tables, ✓ = performance standard applies; NA = performance standard not applicable

Table 3.1: Desired and adequate performance criteria, that accompany the hover task (Anon., 2000).

Usable cue environment

Just as the helicopter gets its input from the pilot, the pilot in turn gets many of his inputs from the visual environment around him. If this is compromised, it generally means that the pilot will have spent more effort to still get sufficient input, which in turn means that he has less capacity for the control of the rotorcraft. This is accurately described by Roger (1998) saying that the pilot's workload is distributed between attentional demand for control and situational awareness. Additionally, when the pilot has insufficient situational awareness the potential for an incident increases. This insufficient situational awareness can be caused either by an increase in attentional demand for control or by factors that increase the demand for obtaining cues from situational awareness. In the aeronautical design standard (ADS-33)(Anon., 2000) a definition for the rating of visual cues (VCR) is given, and shown in Figure 3.2. It is a rating that is assessed by the pilot, who is asked to give a rating to both attitude as well as translational rate, based on the precision and aggressiveness of the corrections that can be made. The usable cue environment level is then determined from the VCR, as a combination of the attitude VCR and the translational rate VCR. This rating is shown in Figure 3.6. Research is being done on the design of augmentation systems for UCE levels below 1, either with the use of added sensors and displays (Waanders et al., 2019) or with the use of different response types for the controller (Baillie et al., 1997). Moreover, research is conducted on the implementation of machine learning algorithms to design and implement auto-navigation and obstacle avoidance into rotorcrafts (Gaston et al., 2019).

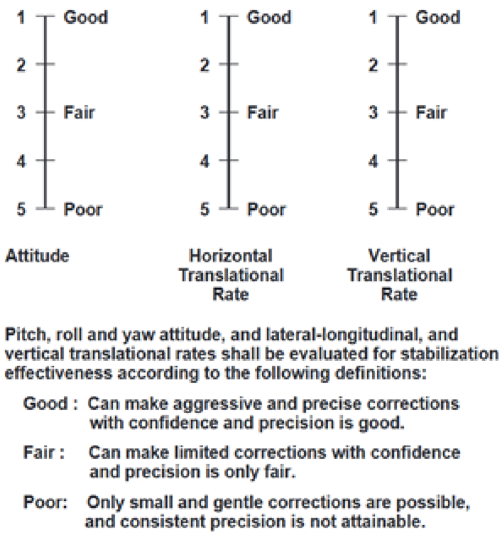

Figure 3.2: Rating of visual cues(Anon., 2000).

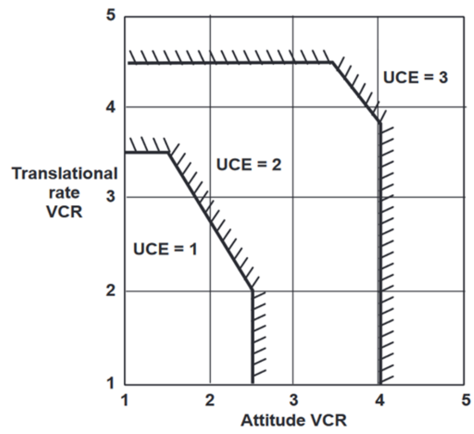

Figure 3.3: Usable cue environment determination for VCR(Anon., 2000).

Metrics of handling qualities

When looking at the handling qualities desired for a controller, certain metrics will have to be implemented in the design process. Since the handling qualities cannot be designed for directly, these are given to specific tasks and their mission task elements, metrics need to be used to capture parts of expected needed qualities. This is done in an attempt to achieve desired levels of handling qualities of a helicopter when flown by a pilot using a controller.

These metrics can form a basis on which to design a controller. These are not only metrics that can be put on the design of the helicopter's response, but this can also be extended to limit the motion that pilot experiences, thus keeping the workload low (Albion and Larson, 1974). An example of how different levels of motion, in the form of a specific frequency of vibrations and pitch rate, affects pilot rating is shown in Figure 3.4. This is a collection of results from different tests.

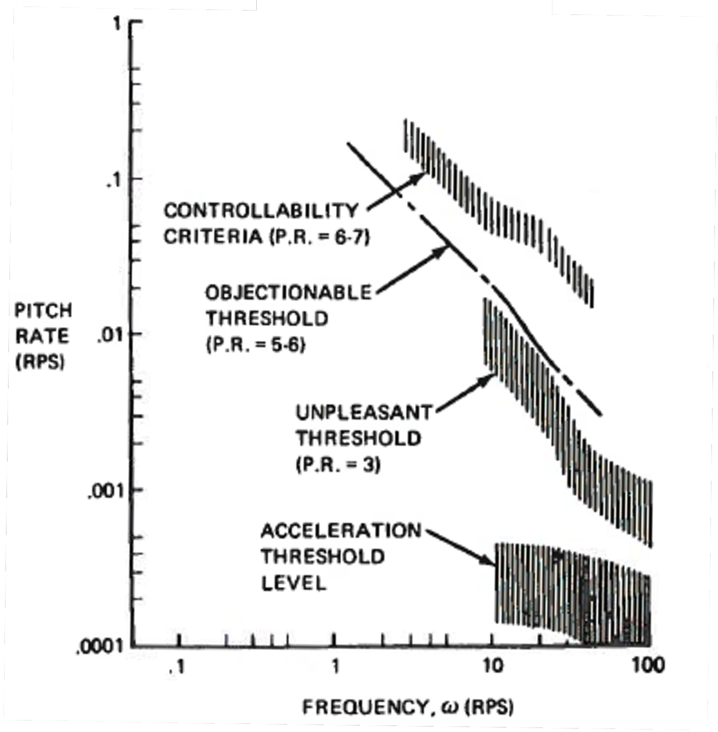

Figure 3.4: Motion comfort levels (Albion and Larson, 1974)

Another important metric that is often used to formulate handling quality criteria are bandwidth and phase delay. Bandwidth, in the definition that is used for the handling quality criteria, is defined in Figure 3.5. Notice the classical gain and phase margins of 6dB and 45°show up in this definition. The bandwidth is the lesser of the frequencies at which the gain or phase margin occurs, for a rate response-type, meaning the input of the pilot produces a rate of change. If the response type is attitude command/attitude hold, the bandwidth is always the phase bandwidth. This bandwidth can be used to design criteria, for instance having a minimum bandwidth requirement.

Lastly, in Figure 3.6, a handling quality criteria is shown that is put on the pitch oscillations in hover and low speed flight of a helicopter. Compared to the bandwidth, this is a criteria that is put on the response shape of the helicopter. The limit is specifically for a certain damping that is required, for different levels of handling quality rating. This can for instance be used to restrict the placement of the poles of the designed for system.

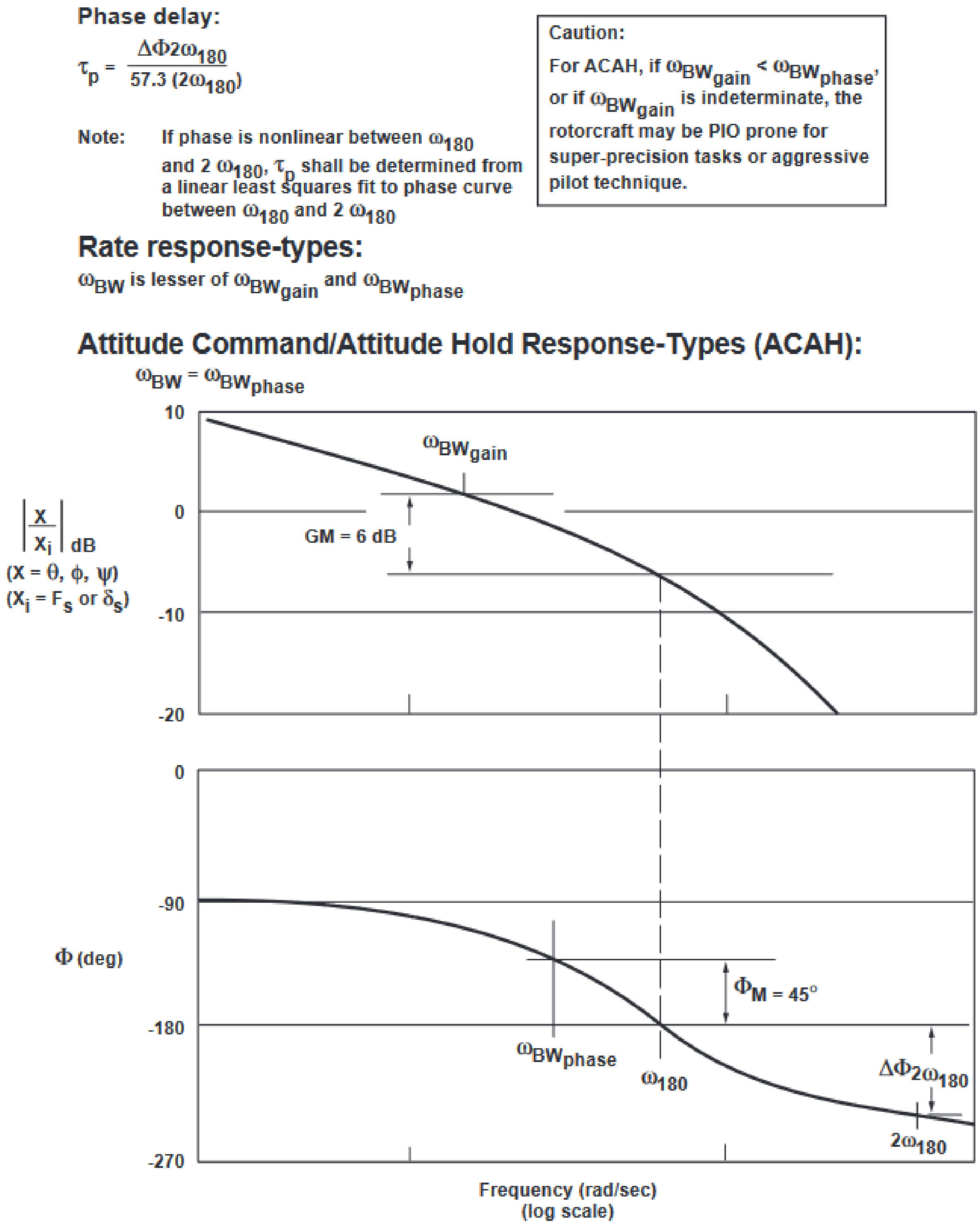

Figure 3.5: Definition of bandwidth and phase delay (Anon., 2000).

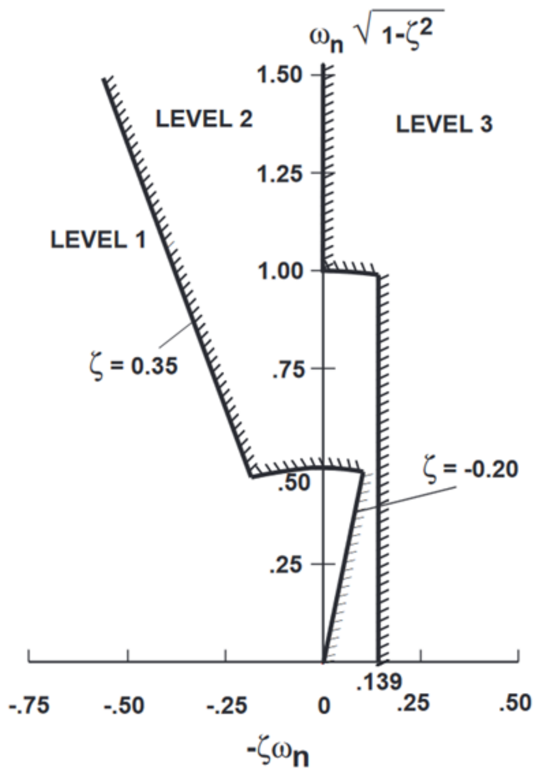

Figure 3.6: Limit on pitch oscillation in hover and in low speed flight (Anon., 2000).

3.2. Robust Control

The control structure of a system is usually designed using a model of the system to be designed, a way to describe the system in a mathematical sense. But this does remain a description, with many assumptions and limitations. A real system, let's say a helicopter, flying in the real world will be far too complex to model without any uncertainties. Furthermore, the real world also has many complex phenomena happening that are too hard to accurately model, introducing further uncertainties in the mathematical description of the system. So, when applying optimal control techniques, such as LQG, in a system with uncertainties, the expected stability can suddenly disappear. A very famous quote in the field of control describes the problem perfectly. "There are none", which is the abstract to the paper titled: Guaranteed margins for LQG regulators, by John C. Doyle (Doyle, 1978). In this paper, Doyle showed in less than a page that there are no guaranteed stability margins for the optimal LQG controller. This called for a new way of looking at control. The measure of how well a system behaves in the presence of uncertainty, is a measure of robustness against this uncertainty. That is what the field of robust control is concerned with.

In this chapter, the concept of H_∞-control is discussed, as well as specific methods to obtain controllers for specific design objectives. The theory presented in this section mostly comes from the books by Bates and Postlethwaite (2002) and Skogestad and Postlethwaite (2005). A set of interesting examples of research where robust control was used to design a robust controller, including (simulated) flight testing of the controller and assessment of handling qualities of these controller are by Postlethwaite et al. (1999), Walker et al. (1999), Postlethwaite et al. (2005) and Horn et al. (2012). This provides a practical side to the theory discussed in this chapter.

H_∞-control

The basis of H_∞-control lies with the H_∞-norm. Which in essence is a measure of the energy a certain signal carries. It is the maximum singular value over all frequencies of the frequency response of a system. This is essential when looking at multivariable systems, since this norm value encapsulates the system in its entirety. The element of a multivariable system that is of importance in this case is the direction of the input and output signals. When minimizing the H_∞-norm, the cross-coupling between multiple signals is taken into account, and the maximum energy of the worst performing signal is actually minimized.

To talk about ways of designing a robust controller, the typical feedback control system should be looked at. In Figure 3.7 a depiction of the standard feedback control system is shown, including uncertainties(Bates and Postlethwaite, 2002). From this figure, the following equations for y and u can be deduced:

$$y = T_O r + S_O G d_I + S_O d_O - T_O m \tag{3.1}$$

$$u = KS_O r - KS_O d_O + S_I d_I - KS_O m \tag{3.2}$$

These equations give a clear indication of what functions, the (co-)sensitivity functions for the in- and output signals, S_I, S_O, T_I or T_O, should be tweaked to obtain a certain design goal. Here the singular values come in. For instance, the maximum singular value for the output sensitivity function $\overline{\sigma}(S_O)$, should be minimized to attenuate the output disturbance signals, at the plant output. Many more of these objectives can be formulated, but it is also clear that objectives arise that cannot be satisfied at the same time. The way to solve this will be discussed in the next sections, about the specific controller design methods.

In robust control, usually a different form of this system is used. Two versions are shown in Figure 3.8 and Figure 3.9, introduced by Doyle (1983). The first is a general configuration, where the input signal w represents all the external signals coming into the generalized plant, P, and z is the regulated output of the system, which consists of all the signals used to formulate the design requirements. The other signals depicted are the in- and outputs for the uncertainty block, Δ, and the controller, K. In the second figure, the controller is incorporated into the single block M.

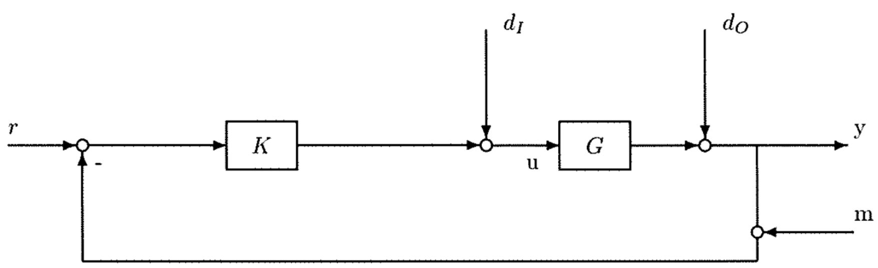

Figure 3.7: Feedback control system with plant input and output uncertainty, as well as measurement uncertainty (Bates and Postlethwaite, 2002).

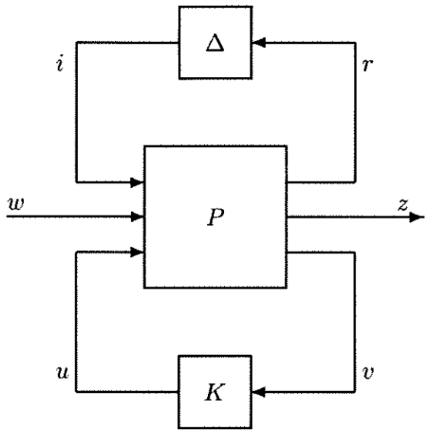

Figure 3.8: A general set-up of a robust control system (Bates and Postlethwaite, 2002).

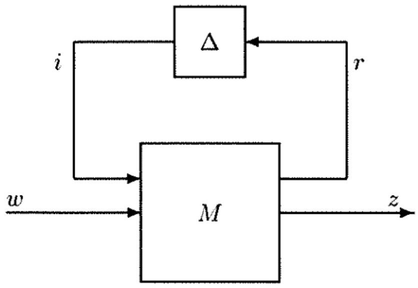

Figure 3.9: A general set-up of a robust control system, used for analysis (Bates and Postlethwaite, 2002).

Mixed Sensitivity

Mixed sensitivity H_∞-control is a method of using the closed loop transfer function, to shape the response of certain signals to match a desired design objective. Since, as said before, these design objectives are usually not simultaneously obtainable, a problem arises. However, these objectives are usually frequency dependent, for instance measurement noise is prevalent in the higher frequencies, or a reference should be followed in the lower frequencies. Weighting filters are used on the signals of interest to translate this frequency dependency to the system. After which the H_∞-controller is synthesized. The H_∞-norm of the transfer function from w to z is minimized over all stabilizing controllers. This process will return a γ value, the maximum value of this norm, and is then used to evaluate whether the selected weighting filters make the controller violate the design objectives.

Now what needs to be talked about is the closed-loop transfer functions to be shaped. One method where the S_O and KS_O transfer functions are shaped (mixed sensitivity S/SK) can be used to attenuate the output disturbance, by minimizing $\|S_O\|_\infty$, and to minimize the control signal and measurement noise, by minimizing $\|KS_o\|_\infty$(Bates and Postlethwaite, 2002). This method is, for example, used in the controller design for the Bell 205 helicopter(Walker et al., 1999), which was flight tested on the NRC Bell 205 airborne simulator(Sattler, 1984). Furthermore, this provides robust stability to additive uncertainty. The weighting functions applied to both these transfer functions provide the designer of the controller with the ability to balance between the robustness and performance of the controller, or any other objectives set-up within the design objectives. So the controller obtained is the one that minimizes the following:

$$\left\| \begin{bmatrix} W_1 S_O \\ W_2 K S_O \end{bmatrix} \right\|_\infty \tag{3.3}$$

Another transfer function that could be shaped is the T_O, which has an effect on the reference tracking and the measurement noise, as can be seen in Equation 3.2. It furthermore has an important impact on the robust stability with respect to multiplicative perturbations at the plant output. This is the S/T or $S/SK/T$ mixed sensitivity method, the second also still including the S_OK transfer function in the shaping process. An example of where this $S/SK/T$ method is used in the paper by Luo et al. (2003), where a robust controller was designed for a model of the UH-60 Black-Hawk. The flying qualities, the quickness and phase delay margin, were used to test the robustness of the controller.

Loop Shaping

Another method of designing a robust H_∞ controller is a method called H_∞ loop-shaping, first proposed by McFarlane and Glover (1992). In this method, the H_∞ optimization is still used, with the main difference to mixed sensitivity being that the open-loop transfer functions are shaped, compared to the closed-loop. This is again done with the use of shaping filters. This method focuses on maximizing the robustness to coprime factor uncertainty, rather than the additive or multiplicative uncertainty, in the case of mixed sensitivity. This design method provides a way to design the shape of the singular values in the open-loop frequency response, and provide preferable behavior, after which the controller is designed to robustly stabilize the system. The shaping of the singular values leads to an upper and lower bound on them, for the transfer function GK. In Figure 3.10 (Bates and Postlethwaite, 2002), a graphical representation is shown that also includes certain boundaries, based on certain design objectives, that drive the shape of the open loop. These are the lower frequency performance objectives, and the higher frequency boundary, related to robust stability, noise attenuation, and control input.

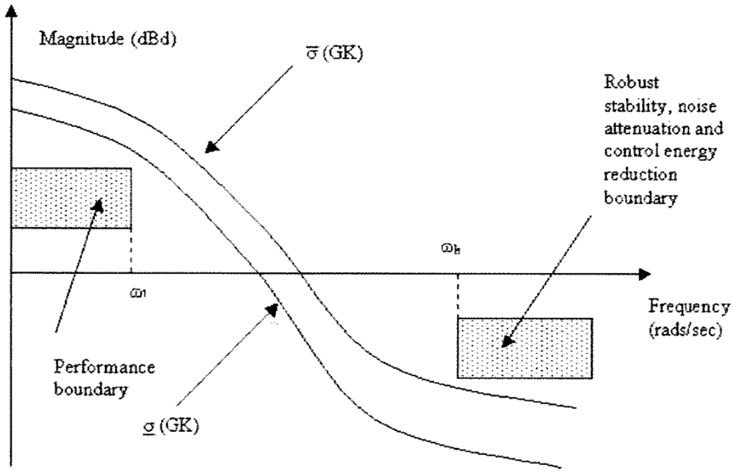

Figure 3.10: Upper and lower bounds on the singular values for the open-loop system (Bates and Postlethwaite, 2002).

In Figure 3.11 the generalized structure of the control loop used in H_∞ is shown (Bates and Postlethwaite, 2002). The loop shaping method is essentially a two-step procedure, with the first being the shaping of the response, which is done with the weighting filter W_1, which is generally diagonal. k is a constant weighting matrix, used to adjust the control actuation. The second weighting filter, W_2, used to prioritize controlled variables over others, where needed. The second step in the method is then to robust stabilize the plant, in the presence of uncertainty. This uncertainty is introduced to the plant using coprime factorization, a block diagram representation is shown in Figure 3.12(Bates and Postlethwaite, 2002). The design of the controller is done by solving two Riccati equations, for a given minimal realization of the plant. This will result in a controller that has a certain guaranteed stability margin, resulting from the equation:

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - GK)^{-1} M^{-1} \right\|_\infty \leq \gamma \tag{3.4}$$

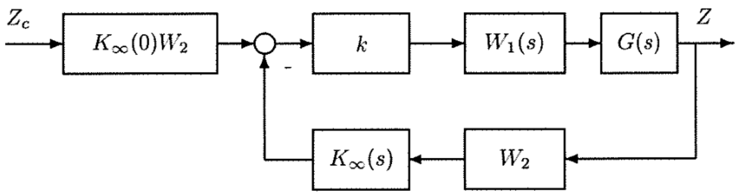

Figure 3.11: Generalized structure of the H_∞ Loop-Shaping system (Bates and Postlethwaite, 2002).

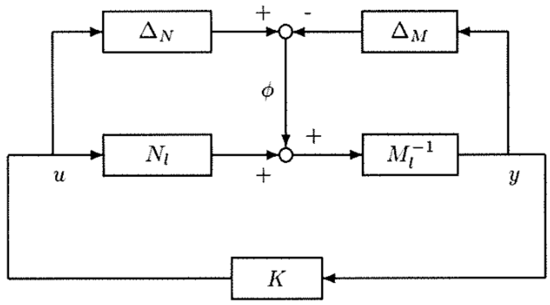

Figure 3.12: Block diagram of coprime factor uncertainty acting on a plant (Bates and Postlethwaite, 2002).

The last step in the process is to add a constant pre-filter $K_\infty(0)W_2$, which is present in this case because W_1 was shaped to provide an integral behavior.

The main advantages of H_∞ loop-shaping that Bates and Postlethwaite (2002) lists, are that the method needs no iteration for γ, the optimal γ can be found without this need, that the mixed sensitivity method does require. The minimum achievable robustness margin can be calculated before the synthesis of the controller. Furthermore, it provides robustness against uncertainty in the case of lightly damped resonant poles, such as the phugoid mode. Also, the pole-zero cancellation, which can be a common occurrence in certain mixed sensitivity designs, can be avoided with the loop-shaping technique. Lastly, this technique provides balanced robustness and performance properties at the plant input and output.

Integration of flying qualities

When designing a controller, stability is a major factor that is designed for, however, usually it is desired for the controller, and in extension the whole aircraft, to exhibit certain behavior in the time domain, for instance a certain response time or damping behavior. Mixed sensitivity, in the form that has been described in the section above, has one degree of freedom, one block is designed, and it is hard to shape the exact behavior that is wanted. H_∞ loop shaping technically has two degrees of freedom, it consists of a controller block and a pre-filter block, however this pre-filter block is used to offset a steady state error, and is in fact completely constrained by this. Usually, there is a certain reference response that represents the desired behavior. In Figure 3.13 a revised version of the general structure used in loop shaping is shown. In this setup, K_1 is a pre-filter, K_2 is the feedback controller and T_{ref} is the desired reference response that the system should try to mimic. The parameter ρ is used to balance between robust stability and robust performance, in the sense that it tells the system how much relative importance should be placed on the outside or inside loop. In this method, first the singular values of G are shaped, in the same way as the standard loop shaping method, however the general shape should be similar to T_{ref}. Then $[K_1 K_2]$ are found by solving the standard H_∞ for the generalized plant P, using the shaped plant W_1G, T_{ref} and the scaling parameter ρ.

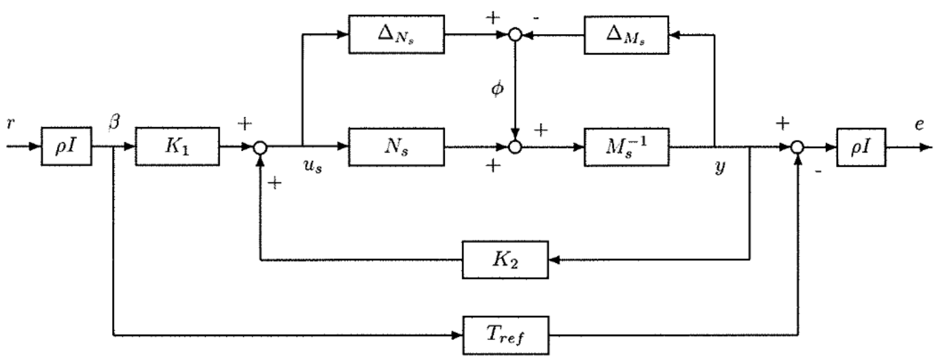

Figure 3.13: Revised version of the general structure of loop shaping (Bates and Postlethwaite, 2002).

3.3. Research Proposal

In the research on robust controllers for helicopters, the area of pilot handling qualities is an important factor that needs to be investigated. The addition of certain flying quality criteria in the design is the first step. However, these criteria only capture a fraction of the overall handling qualities, since they are a measurable value. Therefore, the need arises for a pilot in the loop experiment. The feedback and assessment of the pilots are of vital importance of capturing the overall handling qualities, and serve as a way to validate the flying qualities used in the design of the controller. Therefore, the proposed research is to conduct a flight test on the Simona Research Simulator, with the following research objectives:

Research Objective

The primary research objective is to quantify the handling qualities of a robust controller designed using H_∞ methods, in which desired flying qualities were used in the design. These handling qualities will be assessed on a set of tasks, to be performed by experienced pilots.

Research Objective

The secondary research objective is a comparison between the handling qualities of a helicopter while using a robust controller and the handling qualities without the use of a robust controller. This allows the change in pilot effort, when using the designed controller, to be quantified as well as to provide an insight in the strength of the robust control techniques.

Research Question 1

What are the handling qualities for a robust controller designed using H_∞ methods of specific tasks, when assessing them with pilots flying a simulated flight test of the helicopter and controller?

RQ 1.1 How are these handling qualities quantified in a consistent manner?
RQ 1.2 What tasks are most suitable for the assessment of handling qualities of the designed controller?
RQ 1.3 Do the flying qualities that were used in the design produce the expected level of handling qualities?
RQ 1.4 What is the impact of the flight test set-up on perceived handling qualities?

Research Question 2

What is the increase in handling qualities of the H_∞ controller compared to a helicopter with minimal control augmentation, and what are benefits of using an H_∞ controller?

RQ 2.1 What control method is suitable to make a comparison with?
RQ 2.2 What are the handling qualities for the helicopter with minimal control augmentation?
RQ 2.3 How can robustness be tested in the flight test?

4 Background: Helicopter Model & Robust Controller

The work in this research has as one of the main focus goals to validate the handling qualities criteria that were used in the design of a robust controller, in a piloted flight test setting. This means that the focus does not lie in the (re-)design of an existing controller, but to utilize the research of fellow students and continue to add more knowledge and insight to have as a goal to advance the controller, and the methods to design these. This chapter will provide some background and insight into the design process of the controller used. This is based on the work by Capra (2024). Firstly, it starts with the introduction of the model used for the design of the controller and the flight test that was performed for this research. Following, it includes a section about the discretization of the model. The chapter will continue by showing the general shape of the controller, followed by the set of constraints that were used to design the controller. Lastly the values that were found for the elements of the controller.

4.1. Model

In this section, the model used in the research, for calculations and simulation, is presented. This model is a 3-DOF, longitudinal adaptation (Maurer, 2023) of the 6-DOF model by Pavel (1996). Before the model can be discussed, the controls of a general helicopter should be briefly discussed. This description will focus on the longitudinal case, with purely the cyclic and collective stick as input. A helicopter uses a swashplate, shown in Figure 4.1, to control the pitch of the blades of the rotor. This is done through moving the lower stationary plate shown, which in turn moves the rotating plate. This plate is connected to the blades. This set-up allows for varying pitch within one rotation of the rotor blades. The pilot can influence this plate by either moving the whole assembly up, with the collective stick. This creates the first input angle that is used in the model, θ_0. By giving a longitudinal cyclic input, the plate tilts forward, creating a varying pitch within one rotation, and with that tilting the lift vector that the rotor creates. This is represented in the model with the second input, θ_c.

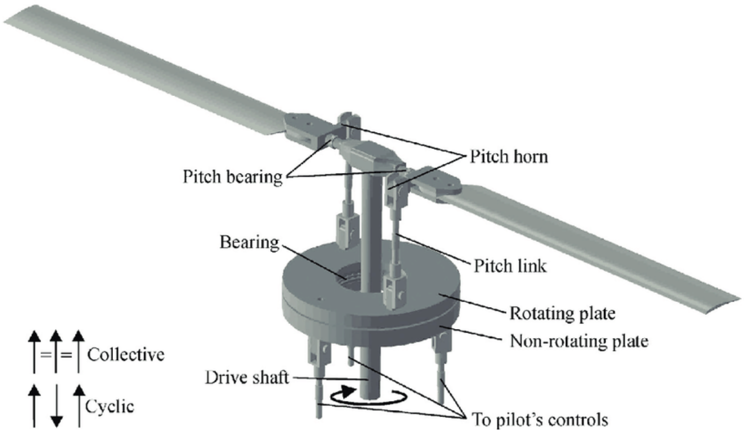

Figure 4.1: Swashplate assembly showing the pilot input controls (Rotaru and Todorov, 2018).

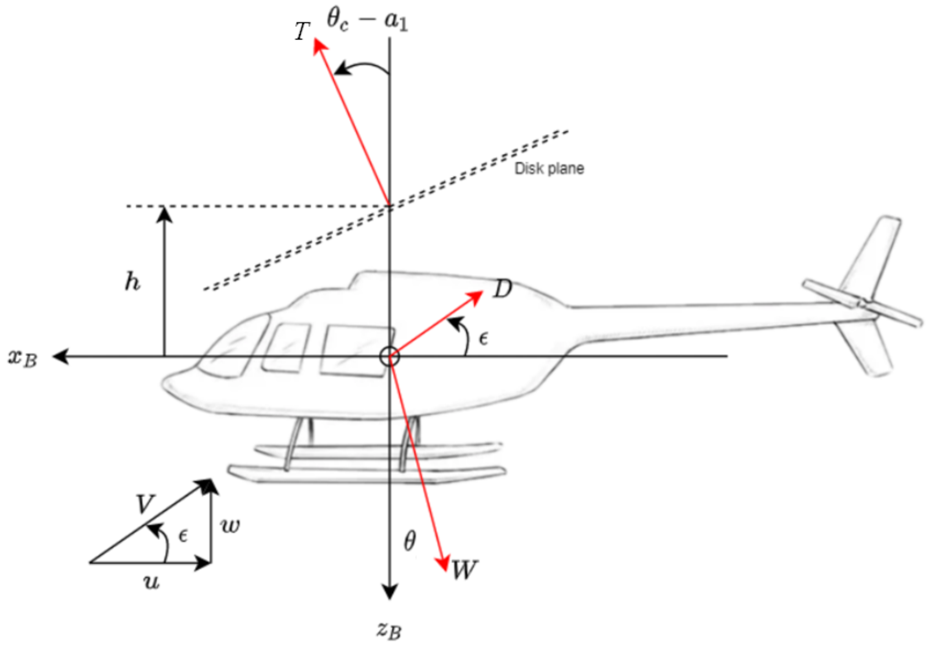

Figure 4.2: Schematic overview of helicopter for longitudinal model (Maurer, 2023).

A schematic overview of the helicopter model can be seen in Figure 4.2. This figure shows a number of important angles for the calculation of the helicopter states. Firstly, the angle between the fuselage of the helicopter and the weight vector pointing down, essentially the tilt angle of the fuselage, is shown as θ. Furthermore, the angle of incidence of the velocity, is defined as ϵ. Another important angle is the angle of the disk plane with the body frame of the helicopter, and with that the angle of the thrust vector acting on the system. For this, the horizontal disk tilt, a_1 is used for the modeling of the rotor dynamics. The last angle that should be discussed is the angle of attack of the control plane of the rotor, which is simply the input angle, θ_c minus the incidence angle of the velocity. These angles, and the way to calculate them, are shown in Equation 4.1 to Equation 4.6. Note that the non-dimensional induced velocity of the control plane, λ_c, and the rotor advance ratio, $\hat{\mu}$ are also shown, and used in further calculations as well. Lastly, in Equation 4.6, γ is the Lock number.

$$\epsilon = \arctan\left(\frac{w}{u}\right) \tag{4.1}$$

$$V = \sqrt{u^2 + w^2} \tag{4.2}$$

$$\alpha_c = \theta_c - \epsilon \tag{4.3}$$

$$\lambda_c = \frac{V \sin(\alpha_c)}{\Omega R} \tag{4.4}$$

$$\hat{\mu} = \frac{V \cos(\alpha_c)}{\Omega R} \tag{4.5}$$

$$a_1 = \frac{\frac{8}{3}\hat{\mu}\theta_0 - 2\hat{\mu}(\lambda_c + \lambda_i) - \frac{16q}{\gamma\Omega}}{1 - \frac{1}{2}\hat{\mu}^2} \;, \; \gamma = \frac{\rho C_{l_\alpha} c R^4}{I_b} \tag{4.6}$$

Next, the forces and moments caused by the thrust and drag on the helicopter are calculated in the body frame, these are derived and shown in Equation 4.7 to Equation 4.9.

$$F_x = -D\cos(\epsilon) + T\sin(\theta_c - a_1) \tag{4.7}$$

$$F_z = -D\sin(\epsilon) - T\cos(\theta_c - a_1) \tag{4.8}$$

$$M = -Th\sin(\theta_c - a_1) + X_{cg}\cos(\theta_c - a_1) \tag{4.9}$$

Equation 4.10 and Equation 4.11 show two ways of calculating the thrust coefficient. The first is based on the blade element method, and the second on the Glauert method. These use the non-dimensional induced velocity, λ_i, and the pilot inputs, together with the lift coefficient of the blade, C_{l_α}, and the rotor solidity parameter, σ. Either one is then used to calculate the thrust, T. The drag is calculated using Equation 4.13.

$$C_{T_{BEM}} = \frac{C_{l_\alpha}\sigma}{4}\left[\frac{2}{3}\theta_0(1 + \frac{3}{2}\hat{\mu}^2) - (\lambda_c + \lambda_i)\right] \tag{4.10}$$

$$C_{T_{Glau}} = 2\lambda_i\sqrt{\left[\frac{V\cos(\alpha_c - a_1)}{\Omega R}\right]^2 + \left[\frac{V\sin(\alpha_c - a_1)}{\Omega R} + \lambda_i\right]^2} \tag{4.11}$$

$$T = C_T \rho (\Omega R)^2 \pi R^2 \tag{4.12}$$

$$D = C_D \frac{1}{2}\rho V^2 S \tag{4.13}$$

With all the forces and moments calculated, the equations of motion can be set up for the longitudinal model, resulting in the state-derivatives for the translational movement in x and y direction and the pitch rate and angle. The induced velocity state is added to govern the change of the thrust coefficient over time.

$$\dot{u} = \frac{F_x}{m} - g\sin(\theta) - qw \tag{4.14}$$

$$\dot{w} = \frac{F_z}{m} + g\cos(\theta) + qu \tag{4.15}$$

$$\dot{q} = \frac{M}{I_{yy}} \tag{4.16}$$

$$\dot{\theta} = q \tag{4.17}$$

$$\dot{\lambda}_i = \frac{C_{T_{BEM}} - C_{T_{glau}}}{\tau_{\lambda_i}} \tag{4.18}$$

Trimming

The trim is performed so that the helicopter is in steady flight, meaning all state-derivatives should be 0. Recognizing that this means that the moment, M, should be zero, given that the rotor has no offset in the x-direction. The following relationship can be found with that knowledge:

$$M = 0 \rightarrow sin(\theta_c - a_1) = 0 \rightarrow \theta_c = a_1 \tag{4.19}$$

This results in F_x reducing to Equation 4.22. Putting this into Equation 4.14 and setting to zero, together with the knowledge that $q = 0$, gives an explicit expression for ϵ and θ, since it the flight path angle, the angle between θ and ϵ, is zero. This is shown in Equation 4.21

$$F_x = -D\cos(\epsilon) \tag{4.20}$$

$$\dot{u} = 0 = \frac{-D\cos(\epsilon)}{m} - g\sin(\epsilon) \rightarrow -\frac{D}{mg} = \tan(\epsilon) \rightarrow \epsilon = \theta = \arctan\left(-\frac{D}{mg}\right) \tag{4.21}$$

In the same manner, F_z is found and plugged into Equation 4.15, and an expression for the required C_T is found, in Equation 4.24

$$F_z = -D\sin(\epsilon) - T \tag{4.22}$$

$$\dot{w} = \frac{-D\sin(\epsilon) - T}{m} + g\cos(\epsilon) \rightarrow T = gm\cos(\epsilon) - D\sin(\epsilon) \tag{4.23}$$

$$C_T = \frac{T}{\rho(\Omega R)^2 \pi R^2} \tag{4.24}$$

By equating this required thrust coefficient to the thrust coefficient calculated with the Glauert method an expression is found for the induced velocity, λ_i, shown in Equation 4.26. This does result into more than one root, but the one required for the trim will be the real and positive root.

Lastly, the pilot inputs are the two remaining unknowns. These can be obtained by solving Equation 4.27 and Equation 4.28.

$$\alpha_c - a_1 = \theta_c - \epsilon - a_1 = -\epsilon \tag{4.25}$$

$$C_T = C_{T_{Glau}} \rightarrow \lambda_i^4 + 2\frac{V\sin(-\epsilon)}{\Omega R}\lambda_i^3 + \left[\frac{V\cos(-\epsilon)}{\Omega R} + \left(\frac{V\sin(-\epsilon)}{\Omega R}\right)^2\right]\lambda_i^2 - \left(\frac{C_T}{2}\right)^2 = 0 \tag{4.26}$$

$$a_1(\theta_c, \theta_0) = 0 \tag{4.27}$$

$$C_{T_{BEM}}(\theta_c, \theta_0) = C_T \tag{4.28}$$

The required trim setting for the collective and cyclic input is plotted over a range of airspeeds at sea-level in Figure 4.3. The shape is as expected for a standard helicopter, having the cyclic input rise from a zero input at hover, as the airspeed increases, and the collective showing a rise as the speed decreases in the low speed regime. This indicates that the trimming is done correctly.

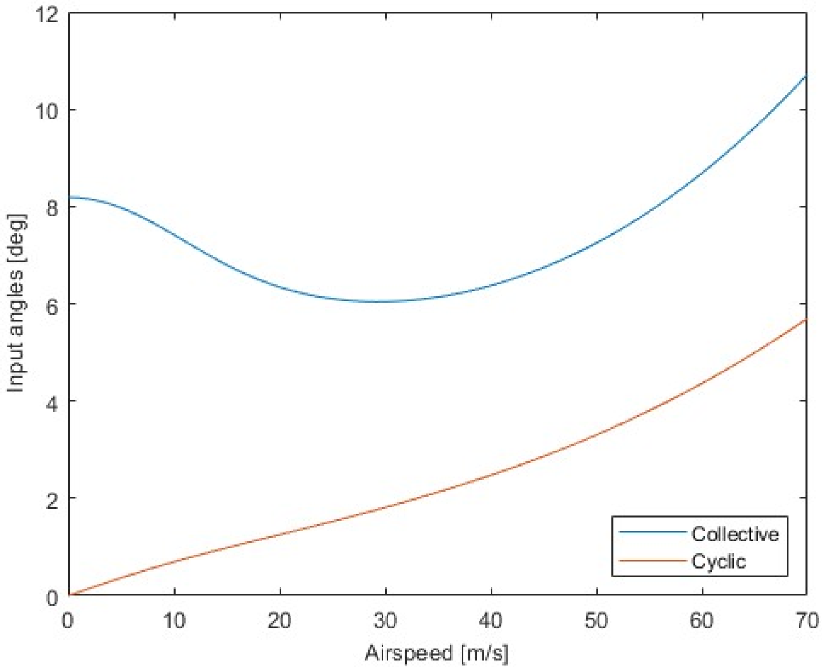

Figure 4.3: Collective and Cyclic inputs required for trim at sea-level.

To give insight into the modes of the helicopter, a pole-zero map is shown in Figure 4.4. This shows the pitch and heave subsidence, and the phugoid mode. The zeros and poles are plotted for the airspeeds at which the test will be performed. What is initially observed, is that the helicopter has an unstable phugoid mode. This mode decreases in oscillation frequency but increases in amplitude growth, with increasing airspeed. Both the heave and pitch subsidence are in the stable left hand plane of the pole-zero map. With increasing speed the heave subsidence shows a decrease in damping. In contrast, the pitch subsidence shows an increase in damping with increasing speed.

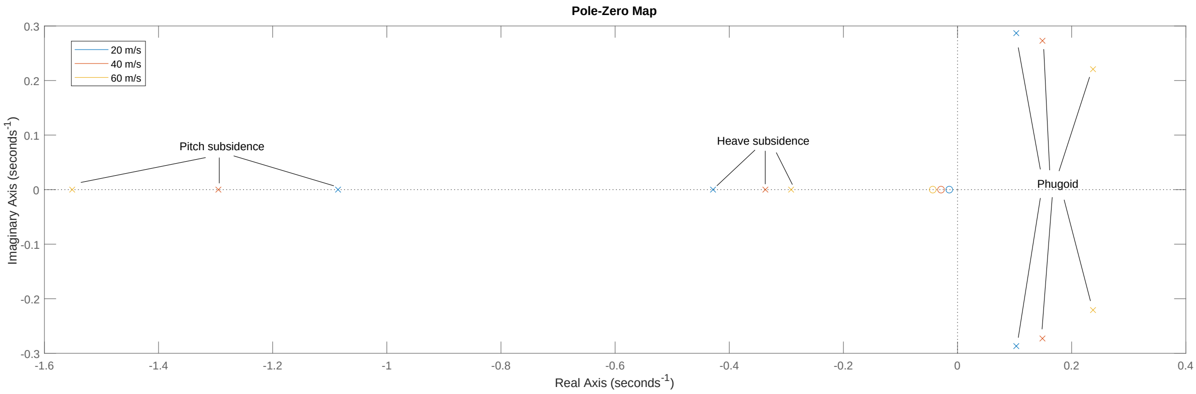

Figure 4.4: Pole-zero map of the helicopter model, at varying airspeeds at which the model was linearized.

Actuators

A model for the actuators was obtained from Bouwer and Hilbert (1986) in the form of a second order transfer function, with a natural frequency of 50.265 and a damping ratio of 0.95:

$$\frac{2526.6}{s^2 + 95.5s + 2526.6} \tag{4.29}$$

Apart from a model for the response of the actuators, the physical limits are also of importance. These are in the form of a rate limit, and a positional limit, and can be seen in Table 4.1 (Voskuijl et al., 2010)(Capra, 2024).

Actuator	Max. + Deflection	Max. - Deflection	Max. Rate
Collective	15.0	-0.2	16.0
Cyclic	11.0	-6.0	28.8

Table 4.1: Actuator position and rate limits in degrees.

Implementation for simulation

Since the research performed in this thesis has been based around a piloted flight test, the theoretical model, and other calculations needed, had to be implemented in a way that was usable for the simulator. The simulator and the set-up will be discussed in a later chapter, but it is important to note that the simulator software is based on C++, and that it is a discrete step simulation. This means that the model had to be implemented in a numerical, discrete way to be used. To accomplish this, a commonly implemented method called the Runge-Kutta fourth order method (RK4) is used. In the following equation the state in the current time step x_n, and the pilot input in the current time step u_n, is used to calculate the state in the next time step x_{n+1}, with a given time-step h:

$$x_{n+1} = x_n + \frac{1}{6}h(k_1 + 2k_2 + 2k_3 + k_4) \tag{4.30}$$

where

$$\dot{x} = f(x, u) \tag{4.31}$$

$$k_1 = f(x_n, u_n) \tag{4.32}$$

$$k_2 = f(x_n + \frac{hk_1}{2}, u_n) \tag{4.33}$$

$$k_3 = f(x_n + \frac{hk_2}{2}, u_n) \tag{4.34}$$

$$k_2 = f(x_n + hk_3, u_n) \tag{4.35}$$

This is a slight adaptation from the standard form of the RK4 method, namely that since the system is time-invariant, the time dependency of the derivative has been removed, and the pilot input is treated as a constant over the time step.

The derivative in this case is simply given by Equation 4.14 until Equation 4.18. The Runge-Kutta method essentially takes the weighted average of the derivatives at the initial state, at the mid-point of the timestep by using both k_1 and k_2 as a linear slope coefficient, and at the next time-step with k_3 as a linear slope.

4.2. Controller design

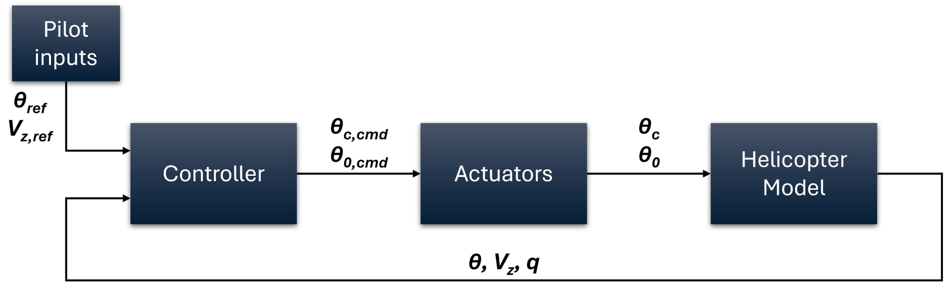

Figure 4.5: Schematic overview of the loop with the robust controller being implemented.

In Figure 4.5 the basic loop for the simulation using the robust controller is shown, including the in- and output signals of each block. Notice that it is somewhat simplified, for instance V_z is not a state of the helicopter model, but can be calculated with the states, shown in Equation 4.36. This is not explicitly shown in the schematic.

$$V_z = -w\cos(\theta) + u\sin(\theta) \tag{4.36}$$

The controller itself, consists of three parts; the feed-forward element, the PI-like element and the pitch rate element, all shown in Figure 4.6. Starting with the feed-forward element, K_{ff}, its purpose is to shape the response of the signal it is acting on, and has the shape of second order transfer function. The PI-like element, K_c, is the part of the controller that is used for tracking the pilot inputs. This has a classic PI shape, a proportional element and an integral element, with a low pass filter added to both of these elements. The transfer function of the PI-like element will then be: (Capra et al., 2025)

$$K_c(s) = \left(K_P + \frac{K_I}{s}\right) \cdot \frac{\omega_c}{s + \omega_c} \tag{4.37}$$

The last element is the pitch rate element, K_q, which is a stabilizing factor for the pitch rate of the helicopter. Since the phugoid mode of the helicopter is unstable, this element is added to improve the stability of this mode by damping the pitch rate.

The method that was used to develop the controller relied on a set of constraints that were put on the specific transfer functions of the controller. The constraints were divided into two groups: hard constraints and soft constraints. The method used to find the controller attempts to find the minimum of the soft constraints, while always satisfying that the hard constraints are not violated. A summary of the constraints used, and especially those that were based on certain handling quality criteria, is given now, for a more extensive explanation on the constraints, and the design as a whole, refer to the work done by Capra (2024).

Hard Constraints

The hard constraints that were used relate to the stability requirements. The first of these was the implementation of disk-based stability margins at the input of the actuators, and the output of the helicopter model, for the commanded actuator angles and vertical velocity, pitch rate, and pitch, respectively. Compared to classic gain and phase margins, the disk based margins can guarantee robustness to

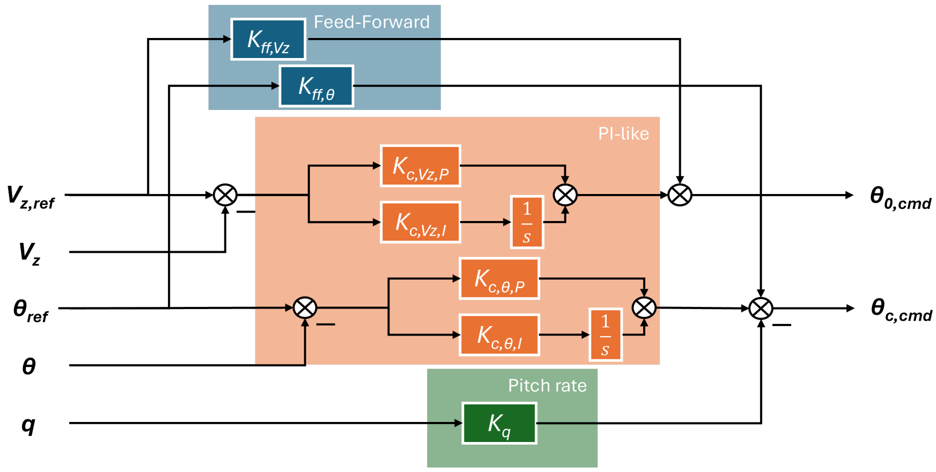

Figure 4.6: Schematic overview of the shape of the controller, with its different elements highlighted.

both gain and phase changes at the same time (Seiler et al., 2020). To find the margins used for the constraint, the required classical gain and phase margin of ± 6dB and $\pm 45°$ from (Anon.) were used. Since the limiting factor was the phase margin, the margins used for the constraints on the signals by Capra (2024) were ± 7.6dB and $45°$.

The other stability requirement that was used for the design of the constraints came from ADS-33 (Anon., 2000). In Figure 4.7 the limits of pitch oscillations at hover and low speed are shown, presented in the form of a certain damping ratio and natural frequency, resulting in three different regions for level 1 to 3 handling quality. This led to a damping ratio chosen of 0.35 and, to ensure that the dynamics were not too fast to detect for the controller, the maximum natural frequency was set to 100rad/s.

Soft Constraints

The soft constraints aim to improve a certain aspect of the controller, which include input and output disturbance rejection, model following, and control attenuation. For this research, the constraints relating to the implementation of handling qualities are of importance, while one of the research goals is to validate the designed for handling qualities in a simulation setting.

The first of these handling quality criteria is a constraint on the disturbance rejection of the pitch and heave. More specifically, this is in the form of disturbance rejection bandwidth and peak on the sensitivity function of the signals. These are defined by Berger et al. (2016) to be:

$$\omega\left(S_0 = -3dB\right) = DRB\text{rad/s}, ||S_o||_\infty = DRP\text{dB} \tag{4.38}$$

The values that were used by Capra (2024) for this constraint can be seen in Table 4.2.

	Pitch (θ)	Vertical Velocity (V_z)
DRB (rad/s) $\geq$	0.5	1.0
DRP (dB) $\leq$	5.0	5.0

Table 4.2: Disturbance rejection bandwidth and disturbance rejection peak for both the pitch and vertical velocity (Berger et al., 2016).

The other constraint that aims to achieve a certain handling quality is the one that is included to improve the model following of the controller. This is a certain response shape in the time domain that is desired for the controller to follow. The model used for the response shape of the controller is defined in ADS-33 (Anon., 2000) as a first order transfer function of the response from the collective input to the vertical velocity:

$$\frac{Ke^{-(\tau_{V_{zeq}} s)}}{T_{V_{zeq}} s + 1} \tag{4.39}$$

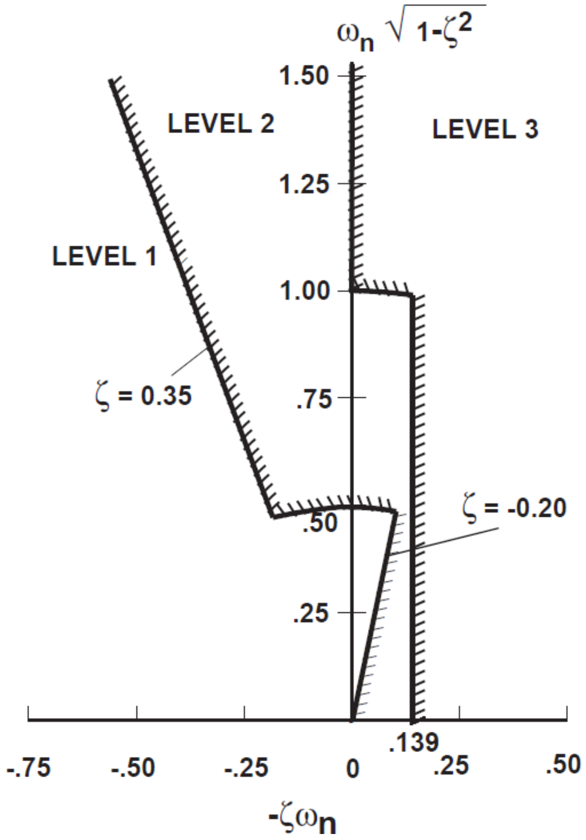

Figure 4.7: Limit on pitch oscillation in hover and in low speed flight (Anon., 2000).

With the parameters that correspond to a handling quality level 1 found by Capra (2024) to be:

Parameter	Value
$\tau_{V_{z_{eq}}}$	5 ms
$T_{V_{z_{eq}}}$	1.0 s

Table 4.3: Parameters used for the response shaping model for vertical velocity.

The model for the pitch signal is based on the work by Tischler et al. (2017) and is set up as a second order transfer function with the following shape:

$$\frac{\omega_n^2 e^{-\tau_{V_{\theta_{eq}}} s}}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{4.40}$$

The handling quality level of this model is based on the criteria found in ASD-33(Anon., 2000). A requirement is put on the quickness, defined as the peak angular rate over the peak attitude change for a specific axis, in this case the pitch. The different levels of handling quality, for a target acquisition and tracking task, that correspond to a certain quickness, are shown in Figure 4.8. The other requirement that helps shape Equation 4.40, is another requirement from ADS-33, this time being on the bandwidth and phase delay. The different levels for the phase delay with a certain bandwidth can be seen in Figure 4.8.

The parameters for the model to follow for the pitch are presented in Table 4.4. These correspond to a a quickness of $1.6\ \frac{1}{s}$, which was the limiting factor, and a phase delay of 0.05s with a bandwidth of 6.3 rad/s, found by Capra (2024).

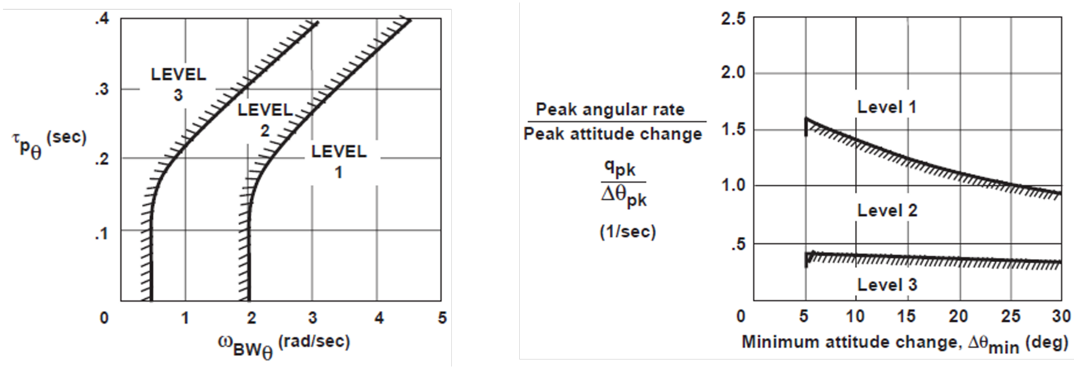

Figure 4.8: Bandwidth and phase delay requirements for small-amplitude pitch changes in hover and in low speed flight (left), quickness requirements for moderate-amplitude pitch changes in hover and in low speed flight (right) (Anon., 2000).

Parameter	Value
$\tau_{\theta_{eq}}$	7.5 ms
ζ	1
ω_n	4.5 rad/s

Table 4.4: Parameters used for the response shaping model for pitch.

Controller values

After the brief summary on the design of the controller, the values for all the different elements of the controller are now presented below. This controller is designed for the linearized model at the flight condition of 20m/s at sea-level.

$$K_{ff,V_z}(s) = \frac{0.056s - 0.30}{s^2 + 12.24s + 54.04}\,, \quad K_{ff,\theta}(s) = \frac{-46.87s + 26.46}{s^2 + 11.36s + 46.16} \tag{4.41}$$

$$K_{c,V_z,P}(s) = \frac{0.064}{s + 5.45}\,, \quad K_{c,V_z,I}(s) = \frac{0.06592}{s + 5.45}\,, \quad K_{c,\theta,P}(s) = \frac{-11.09}{s + 4.87}\,, \quad K_{c,\theta,I}(s) = \frac{-5.6559}{s + 4.87} \tag{4.42}$$

$$K_q = -1.97 \tag{4.43}$$

4.3. Discretization

Similarly to the model, the controller also needs to have a discrete time representation to function in the simulator environment. The bilinear transform, also known as Tustin's method, is used to find a discrete expression for the transfer functions of the controller. This is a variable transform, also called a z-transform. As an example, the feed forward part of the controller for the pitch is transformed by the MATLAB function $c2d()$, using the Tustin method as input, to obtain the new expression:

$$K_{ff,V_z}(z) = \frac{Y^{K_{ff,V_z}}(z)}{U^{K_{ff,V_z}}(z)} = \frac{-0.2209 + 0.001251z^{-1} + 0.2221z^{-2}}{1 - 1.888z^{-1} + 0.8926z^{-2}} \tag{4.44}$$

The ease of this method is that the signal, Y or U, multiplied by $\frac{1}{z}$ results in simply the value of that signal in the last time step, shown in Equation 4.45. Applying this to Equation 4.44, an expression for the current time-step output of the transfer function of the pitch feed-forward controller is found in Equation 4.46. This is based on the current input, but also on the input and output at the last two time-steps. For the first two time-steps, the input and output of time-steps before the start of the simulation, are simply set to the values of the trim. Note that the Tustin method uses the time-step as an input, which means that care should be taken when selecting the required time-step, and that the found expression

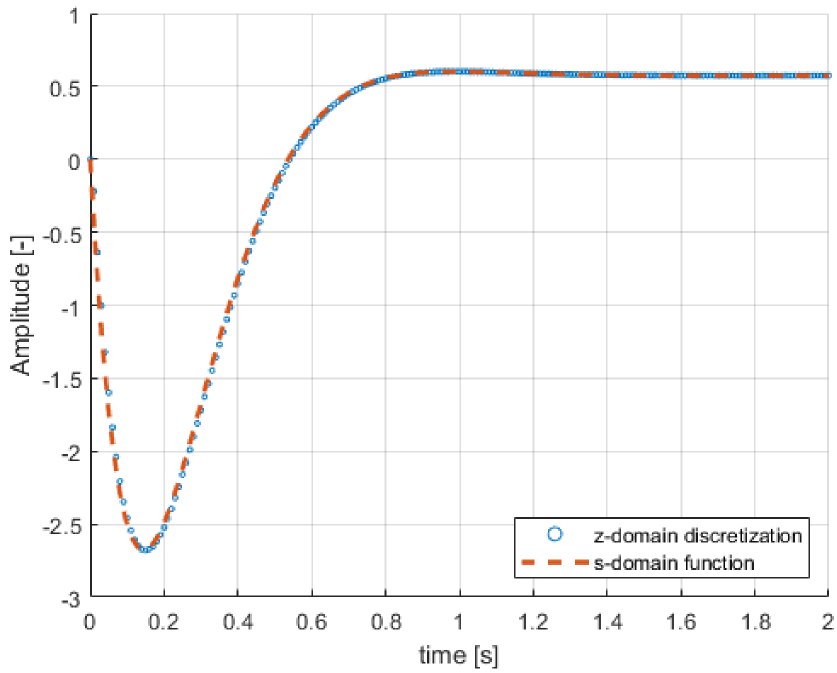

Figure 4.9: Step response of the feed-forward transfer function for the commanded pitch channel, displayed for the s-domain transfer function, and the discretized function using the z-domain.

only works with the right calculation frequency. If another frequency is required, the transfer function should be re-discretized.

$$Y(z) \cdot \frac{1}{z} = y_{i-1} \tag{4.45}$$

$$y_i^{K_{ff,V_z}} = -0.2209 u_i^{K_{ff,V_z}} + 0.001251 u_{i-1}^{K_{ff,V_z}} + 0.2221 u_{i-2}^{K_{ff,V_z}} - (-1.888 y_{i-1}^{K_{ff,V_z}} + 0.8926 y_{i-2}^{K_{ff,V_z}}) \tag{4.46}$$

As a validation of correct discretization, the response to a step input is shown, for both the s-domain transfer function, and the discretized function, is shown in Figure 4.9. It can be seen that the discretized function very closely follows the original transfer function.

$$K_{ff,V_z}(z) = \frac{2.5646 \cdot 10^{-4} - 1.4117 \cdot 10^{-5} z^{-1} - 2.7058 \cdot 10^{-4} z^{-2}}{1 - 1.8797 z^{-1} + 0.8848 z^{-2}}, \quad K_{ff,\theta}(s) = \frac{-0.2209 + 1.2505 \cdot 10^{-3} z^{-1} + 0.2221 z^{-2}}{1 - 1.888 z^{-1} + 0.8926 z^{-2}} \tag{4.47}$$

$$K_{c,V_z,P}(z) = \frac{3.115 \cdot 10^{-4} + 3.115 \cdot 10^{-4} z^{-1}}{1 - 0.9469 z^{-1}}, \quad K_{c,V_z,I}(s) = \frac{1.604 \cdot 10^{-6} + 3.209 \cdot 10^{-6} z^{-1} + 1.604 \cdot 10^{-6} z^{-2}}{1 - 1.9469 z^{-1} + 0.9469 z^{-2}} \tag{4.48}$$

$$K_{c,\theta,P}(z) = \frac{-0.05413 - 0.05413 z^{-1}}{1 - 0.9525 z^{-1}}, \quad K_{c,\theta,I}(s) = \frac{-1.3804 \cdot 10^{-4} - 2.7607 \cdot 10^{-4} z^{-1} - 1.3804 \cdot 10^{-4} z^{-2}}{1 - 1.9525 z^{-1} + 0.9525 z^{-2}} \tag{4.49}$$

5

Flight Test: Design and Results

This chapter will be on the design and results of the flight test that was flown for this research. To complete the research goal of quantifying the increase in handling qualities compared to a baseline control configuration, this baseline configuration is presented. Furthermore, to test for robustness of the controller, the flight test was performed in multiple flight conditions during the tracking tasks. The full set of tasks is also presented in this chapter, which consists of their description and implementation into the flight test. This is followed by an overview of the simulator hardware and instruments is shown and discussed. Afterwards, the results of the flight test, presented per task, is presented and discussed. The chapter ends with a wider discussion on the results of the flight test, which aims to link the different findings of the flight test, to answer the research questions.

5.1. Controller Configuration

The robust controller was designed to be able to increase the performance of the helicopter, both in stability and performance. To be able to analyze this increase, a configuration of the helicopter was needed to have a comparison baseline case. It was decided to have this baseline configuration only be augmented with a pitch rate controller for some stability, but no performance enhancing elements were added, further called the Stability Augmentation System (SAS) configuration. The commanded angles for the collective and cyclic signal were directly controlled by the pilot in the pitch rate controller configuration. The pitch rate controller was only able to influence the cyclic command angle. A schematic overview of this configuration is shown in Figure 5.1. The value for K_q was found with the help of the pilot during initial test runs of the simulation and controller. The value was further discussed with the supervisors and set to -0.4, agreeing to values used before in cases with this set-up. This value, however, is significantly lower than the pitch rate controller element in the robust controller. The reason for this is that in the robust case, the pitch rate controller is not the only element that has impact on the commanded angle, and will never be able to single-handedly influence the controller output. This makes it so that in the whole system of the controller, it balances out.

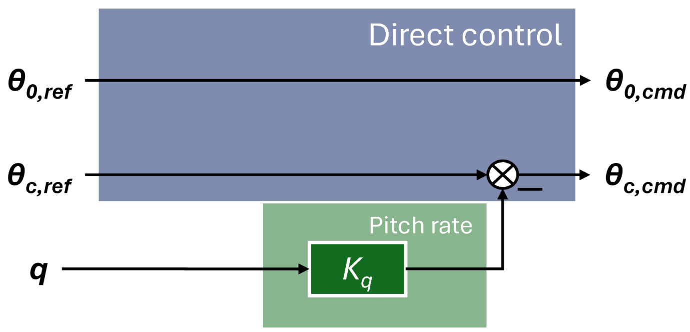

Figure 5.1: Schematic overview of the SAS configuration.

The inputs for both configurations of the controller, the SAS and the robust controller, are different from each other, which means the input range to the physical sticks of the in the cockpit corresponds to different ranges of input to the model. The different types of control input, to which the physical input of the stick relates to, and their respective ranges, are shown in Table 5.1. These are all reference inputs from the pilots, that relate to the commanded inputs to the actuators in their respective control scheme.

Controller	Input cyclic stick	Input range cyclic stick	Input collective stick	Input range collective stick
SAS	*Actuator angle*	-6.0° to 11.0°	*Actuator angle*	-0.2° to 15.0°
Robust	*Pitch angle*	-30.0° to 30.0°	*Vertical velocity*	-10m/s to 10m/s

Table 5.1: The varying ranges of the controller inputs that the pilot input through the cyclic and collective stick relate to.

Other than having an extra setup of the helicopter to test against, it was also decided to test in different flight conditions. Since the controller is a robust controller, meaning that it can handle uncertainties, this was also something that should be reflected in the flight test in some way. By altering the flight condition, in terms of altitude and speed, but still using the controller designed for a specific altitude and speed, this controller would be tested for robustness. This stems from the fact that the linearization of the model, on which that specific controller is based, would differ in different conditions, thus introducing a model uncertainty. The initial flight conditions for every task are shown in the table below. Depending on the task, the helicopter will reach different flight conditions as well, which further tests the controller in a wide flight envelope.

Task	Initial Speed (m/s)	Altitude (m)
Stick Sensitivity	**20**	**0**
Pitch Tracking	**20 - 40 - 60**	**0 - 4000**
Altitude Tracking	**20 - 40 - 60**	**0 - 4000**
Bob-Up	**0**	**0**
Acceleration-Deceleration	**0**	**0**

Table 5.2: Overview of the flight conditions that will be tested for each task.

5.2. Tasks

Before the tasks are discussed in detail, the output of the tasks and the reasoning behind the choices made should be addressed. The research goal of this thesis project is to assess the handling qualities of the robust controller, and compare it with a base line setup. Since handling qualities are assessed by pilots, and will inherently be somewhat subjective, a method should be used that is measurable and consistent. Not only for the results to be consistent but also for the pilots to have a system on which they can rely to relay their experiences. Cooper and Harper (1969) developed a rating to assess handling qualities, for a specific task. This means that an aircraft does not have a handling quality rating overall, but in a specific situation. The rating system is shown in Figure 5.2. This rating is in the form of a flow chart, where the pilot is asked to assess the adequacy in which the selected task can be performed, regarding performance of the task, which requires the task to have a measurable level of performance, and the workload it required for the pilot to achieve that level of performance. The pilot is given a selection of ten rating levels that he can select, with the lower ratings indicating better performance and less pilot workload. On the side of the chart, the different levels of handling qualities are then listed, showing a pilot rating of 3 or higher, on the Cooper-Harper scale, relating to a handling quality level of 1.

For the selection of the tasks to be flown during the flight test, the tasks needed to be fitted to the setup of the helicopter. This meant that only longitudinal tasks could be considered. Furthermore, the selection of tasks were aimed to test for the pitch and heave response individually at first, and test

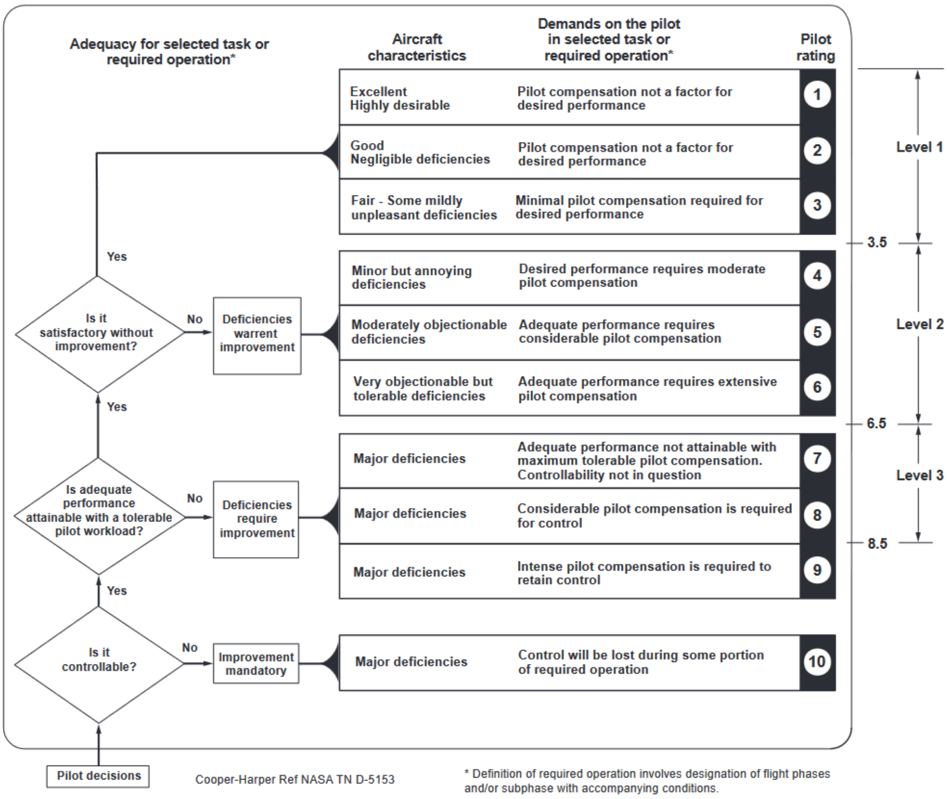

Figure 5.2: Cooper-Harper handling qualities rating scale (figure by Saetti (2019).

for their combined response after. Since the controller was not designed for hover, it was decided that the bob-up task was a suitable task for implementing hover aspects into the research, while also including heave response in the test. Lastly, a control configuration task was chosen to be performed, to investigate and reduce the impact of the stick sensitivity on the handling quality ratings. The tasks that were chosen to investigate the different aspects of the design for controller were:

1. Control configuration task: to investigate, and try to lower, the impact the cyclic stick sensitivity has on the ability to control the helicopter, and with that the workload of the pilot.
2. Pitch tracking task: to investigate the pitch response characteristics of the controller in a purely pitch focused task
3. Altitude tracking task: to investigate the heave response characteristics of the controller in a purely altitude focused task
4. Bob-Up task: to investigate the ability to precisely control the heave in a hover situation, while simultaneously checking for any coupling between pitch and heave.
5. Acceleration-deceleration task: to investigate pitch and heave characteristic of the controller in an aggressive setting, where the helicopter is near its performance limits.

Sensitivity configuration task

The first task that was performed is a configuration task for the sensitivity of the cyclic stick. This was done to investigate the effects of the input device on the ability to control the helicopter, and furthermore to lower this impact on the tasks to come. Inspiration for this task came from the effects on the pilot ratings that were observed by Miller and Clark (1964), with varying sensitivity. In this task, a pitch tracking task (see below) was used to compare different sensitivities, which was done to give the pilot a reference. It was decided that, since this task does not have a level of performance that encompasses the performance of the different sensitivities properly, to not ask the pilot for a Cooper-Harper rating for this task. The different sensitivities are implemented as a different maximum deflection of the stick, which still correspond to the same maximum input of $30°$ commanded pitch attitude. In Table 5.3, the maximum stick deflections are shown for the different stick sensitivity settings. The choice was made to have pre-set sensitivities, to make for more straight forward testing. Sensitivity 1 corresponds to the full physical deflection of the stick, and with increasing sensitivity the maximum stick deflection gets reduced. The assessment of the performance of the sensitivities was done based on the pilot's experience, and by performing test runs where the pilot was asked to give an overall preference of the sensitivity. When the preferred sensitivity was found, this sensitivity was locked in and used for the remainder of the flight test.

Sensitivity	1	2	3	4
Max. Stick Deflection (deg)	14.8	12.0	9.0	6.0

Table 5.3: Maximum deflection of the cyclic stick, with corresponding sensitivity level.

Pitch tracking task

With the sensitivity selected, the next series of tasks are designed to test the controller in different situations. From this task on, the pilot was asked to provide a Cooper-Harper rating to the performed task, to be able to determine a handling quality level for that tasks.

The first task of this series, that the pilots will be asked to perform, is the pitch tracking task. This task is designed to test the pitch response of the controller. For this task, the pilot was presented with a reference pitch signal to follow, that is shown on the Head-Up display. The view for both the pitch and altitude tracking task is shown in Figure 5.3. This reference signal consists of a set of series of ramp and step inputs. More on the design of this signal can be found later in this chapter. The objective of this task is for the pilot to follow the reference signal. To put a measurable performance on this task, the pilot will receive the classification of desired performance if he stays within ± 0.5° of the reference signal, and subsequently, adequate performance if he stays within ± 1.0° of the reference signal. The total score will be the time, in percentages of the total run, spend within a certain limit. The goal, as well as the limits to this goal, and the total scores will all be displayed on the HUD. The limits will be in the form of two squares around the target, one red, for the desired limit, and one yellow, for the adequate limit. These squares will turn green when the actual pitch is within the limit. To have a consistent input of the pilot, the total score will be used as a performance goal to the task. A certain total score over the whole run will correspond to either the task being completed in a desired fashion, an adequate fashion, or when neither of these scores are reached, the task is failed. This goal was set to 50%, meaning if the pilot manages to complete the task with at least 50% of the time spend within desired limits, the task is deemed to be completed with desired performance. If the pilot does not manage but does manage to keep within adequate limits for at least 50% of the run, the task is instead completed with adequate performance, and logically, if he does not manage to do either, the task fails. This percentage goal was obtained with test runs before the official flight tests with the help of an experienced pilot, who did not participate in the official tests.

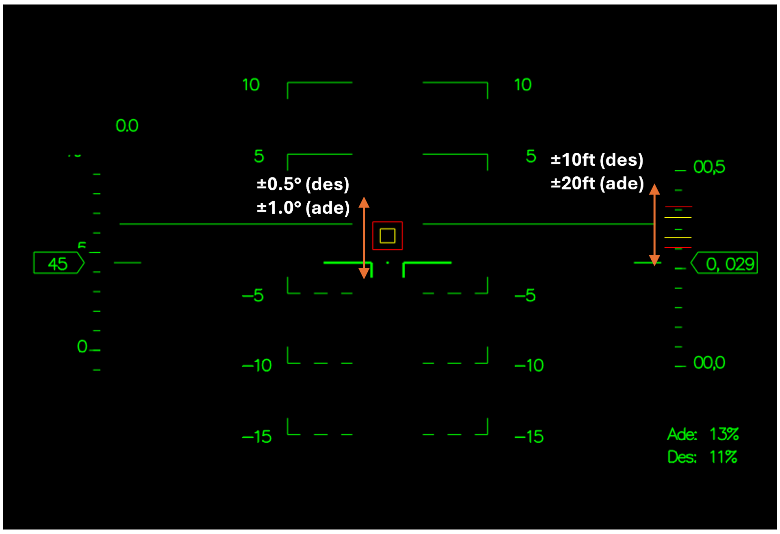

Figure 5.3: Tracking task display for the pilot, with the square on the pitch tape being used for the pitch tracking task, and the lines on the altitude tape being used for the altitude tracking task. Additionally, the desired and adequate limits for each task are included.

Altitude tracking task

The altitude tracking task is a very similar task as the pitch tracking task. Instead of the reference signal being for the pitch of the helicopter, it will be for the altitude of the helicopter. The pilot is again asked to follow the reference signal, which will start to move up and down the altitude tape of the HUD. A desired and adequate limit is placed on the reference signal, for this task, corresponding to 10ft and 20ft respectively. Similarly as the pitch tracking task, this task is deemed to be successful with desired performance when 55% of the total time spent on the run is within the desired limit. This will again be the same for adequate performance, or a failed task if neither performance level is attained. The altitude tracking task is designed to check for the response of the vertical velocity controller.

Both the pitch and altitude tracking tasks were to be flown at different initial speeds, and initial altitudes. During the tasks, these speeds and altitudes will vary because of the input of the pilot. It was up to the pilot to find the best strategy to perform these tasks. To try to keep the focus on the pitch and vertical velocity response, it was not required to stay within a hard limit in regard to the speeds and altitudes, other than at low altitudes not reaching the ground. It was however asked of the pilots to fly the helicopter within a reasonable level of aggressiveness, as would be used in a regular, non-emergency, flight condition. The important aspect of how the helicopter was flown is consistency, since the goal of the experiment is to compare the difference with and without the designed controller.

Bob-up task

The bob-up task is a task inspired by a task described in ADS-33 (Anon., 2000), called the vertical maneuver in ADS-33. This task is designed to check the heave response of the controller, especially the precision with which the helicopter can be controller in the vertical axis. In this task, the helicopter starts in a stabilized hover at an altitude of 15ft. The pilot then ascends to 55ft and stabilizes there for 2 seconds and comes back down to 15ft. For this task, there were outside visuals to assist the pilot. The outside visuals used during the task are shown in Figure 5.5. To assist the pilot with the altitude requirement and with maintaining a hover, a board with a ball in front, at a certain distance is shown to the pilot. This board is located at both 15ft and 55ft. A schematic representation is shown in figure Figure 5.4.

The performance level achieved by the pilot during this task is based on the time spend to complete this maneuver. A secondary requirement was put on the longitudinal position away from the starting position, however, since there are no screens in the simulator to look downwards, this was indicated to the pilot on the HUD. The limit on this position was taken from the ADS-33 task: ± 6 ft for desired performance and ± 10 ft for adequate performance.(Anon., 2000) The time to complete the maneuver was set to 15s for adequate performance, and to 10s for desired performance. These values were obtained from the vertical maneuver. The position requirement was checked in the simulator before the actual flight test. The pilot was able to hold position somewhat, but was experiencing difficulties due to the visual cues missing from below the helicopter. The positional requirement was thus deemed to not be leading in the performance criteria. Meaning that if the only reason the pilot did not achieve a certain level of performance purely because of the position, and this still met the consistency of the aggressiveness the pilot has been using during the flight test, the task was still considered successful with that certain level of performance. This was aimed to still protect the main goal of this task, to ascertain a handling rating for the helicopter while performing this task, by not overstraining the pilots with an increased workload causes by missing cues. Furthermore, since the situation is the same for both configurations of the helicopter, this should also not impact the comparison between the two cases.

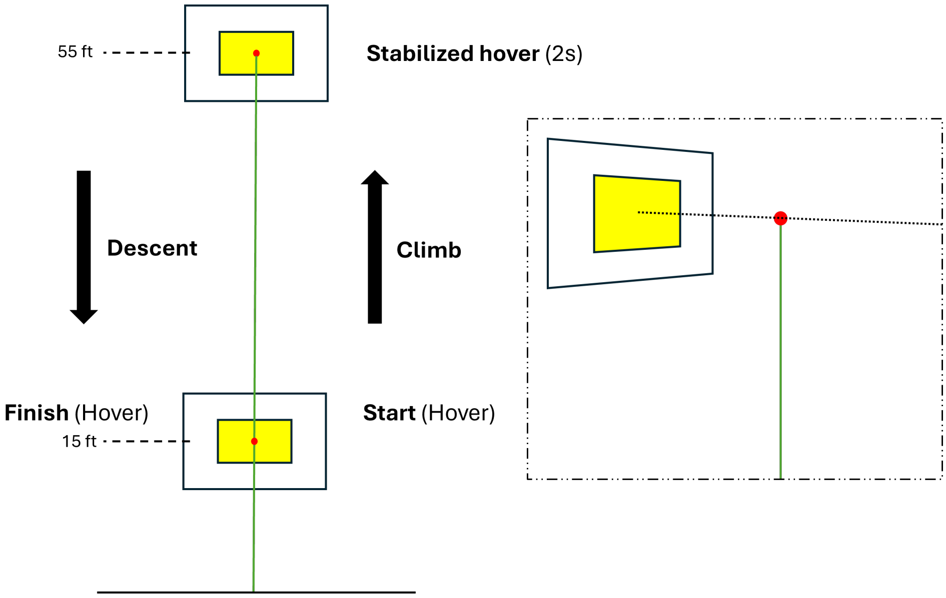

Figure 5.4: Schematic representation of the boards used to assist the hover; on the left a front view and on the right a side view.

Figure 5.5: Outside visuals used during the bob-up task.

Acceleration-deceleration task

The last task to be completed was the acceleration–deceleration task, which is also a task described in ADS-33 (Anon., 2000). The task is used to assess both the pitch and heave response of the helicopter. Especially the coupling between pitch and heave is tested, in the case of large pilot inputs. In this task, the pilot starts in a stabilized hover, and rapidly accelerates to 50 knots, while holding the altitude below 50 ft. When the target speed of 50 knots is reached, the pilot rapidly decelerates to a hover again. A performance requirement is that a certain nose-up pitch angle is reached during the deceleration of the helicopter. ADS-33 considers a desired performance if this angle is at least $30°$, and adequate performance if the angle is at least $10°$. Since the maximum input to the controller was set to $30°$, it was investigated to see if this was a feasible requirement to be used. The helicopter showed responses that could go over 30 °, because of some overshoot during more aggressive maneuvers. It was however decided, similarly as the with the bob-up task, to be slightly lenient with this requirement. This was done to not punish the pilot for going too smoothly if that meant he would fall just short of 30 °, so the requirement was set to 28 °. The total task was to be completed within a distance shown both in the visuals, by the use of pylons on the ground, and indicated on the HUD. The outside view for the pilot during this task is shown in Figure 5.7, and is schematically presented in Figure 5.6. For this task the aggressiveness of the pilot should be addressed briefly, since by design this task requires the pilot to go towards the extremes of the helicopters performance. The pilot was not required to keep the same level of aggressiveness as with the other tasks, but again consistency between the two configurations was of importance, to make for a fair comparison.

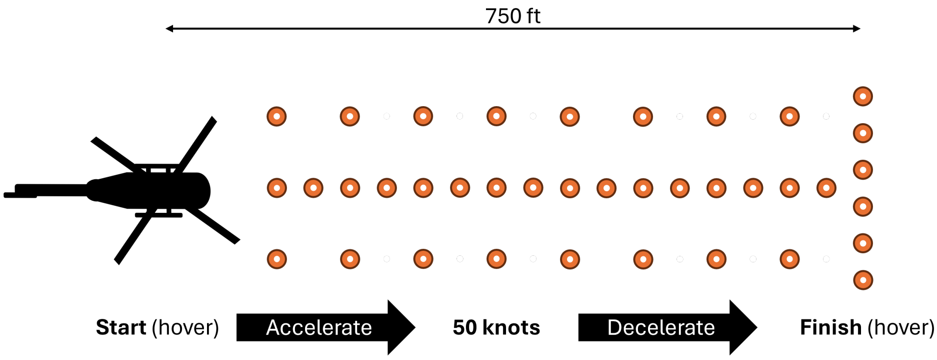

Figure 5.6: Top view of the course used in the acceleration-deceleration task.

Figure 5.7: Outside visuals used during the acceleration-deceleration task.

Forcing functions

The pitch tracking and altitude tracking both use a reference signal, or forcing function, that is to be tracked by the pilots. To limit the impact of a learning effect occurring during the progression of the tasks, a different signal is used for different runs. It was decided to have a unique signal for each different test flight condition. The same forcing function is used between the SAS and the robust controller, to be able to have a clear comparison between the two controllers. The signal consists of a series of ramps and step inputs. All signals are the same length, of 93s, and start and end with a 3s time period at trim, to give the pilot time to prepare. An example signal for the pitch tracking task is shown in Figure 5.8. The signal consists of 9 ramp inputs and 9 step inputs, not including the reset to trim, each receiving an equally spaced time slot of the total time of the task. These inputs have a randomized amplitudes and occurrences within the time slot, and durations for the ramp input. To have a consistent signal over all configurations ran during the flight test, the change from one time step to the next was used as an indication of how much input is needed. The variance of this change was used as an indicating factor, and kept within a certain limit between different signals, to have some sense of measurable equivalence. The signals used were tuned for the specific task where applicable, for instance, to not force too close to the ground, the altitude tracking task at sea-level was built with a limit. An example of a reference signal used during the altitude tracking task is shown in Figure 5.9. This signal is created and checked with the same method as for the pitch tracking task, except that it has less inputs, namely 7 ramp inputs and 6 step inputs, again not counting the reset to trim.

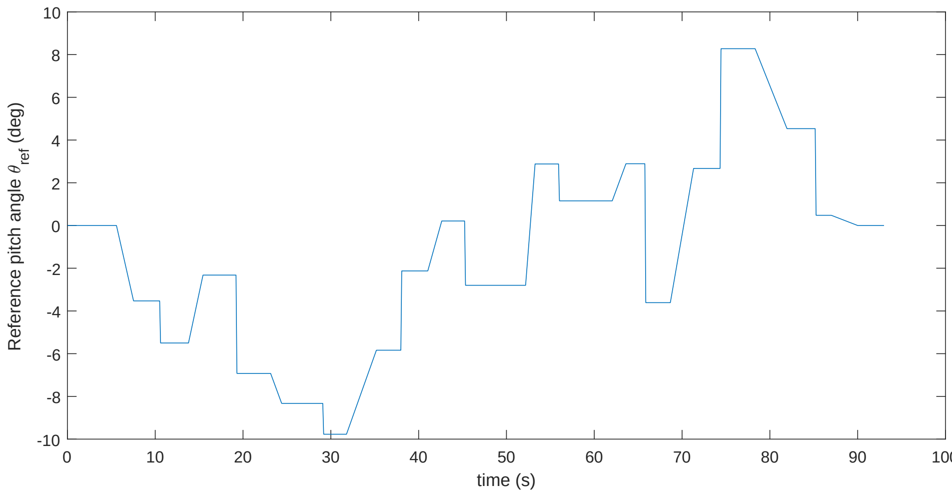

Figure 5.8: Example of a reference signal used in the pitch tracking task.

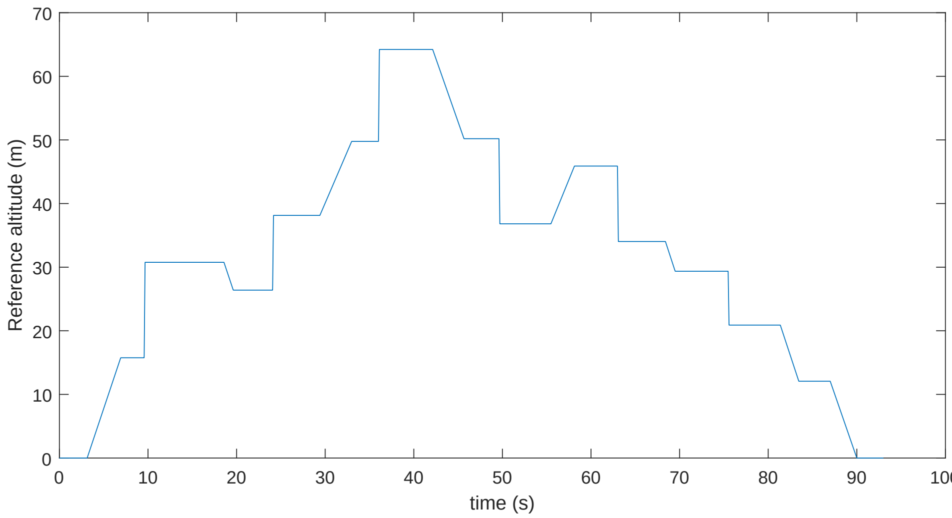

Figure 5.9: Example of a reference signal used in the altitude tracking task.

5.3. Simona research simulator

For the flight test the Simona research simulator located at the faculty of Aerospace Engineering at the TU Delft was used. The simulator is a customizable cockpit, sitting on a hexapod motion system, shown in Figure 5.10. The inside provides a wide angle field of view, provided by three projectors attached to the cabin. The inside of the simulator and an overview of the cockpit and its controls and instruments is shown in Figure 5.11. Since the experiment was conducted for a longitudinal model, the cyclic stick was locked in its lateral direction so the pilot would not get a false sense of input in this direction. With the same reasoning the pedals were not used during the experiment. The pilot was assisted with a head-up display, further explained in the next section, and a indicator for trim position of the controls.

What should be noted is that the simulation was run without motion active, due to issues with the motion system.

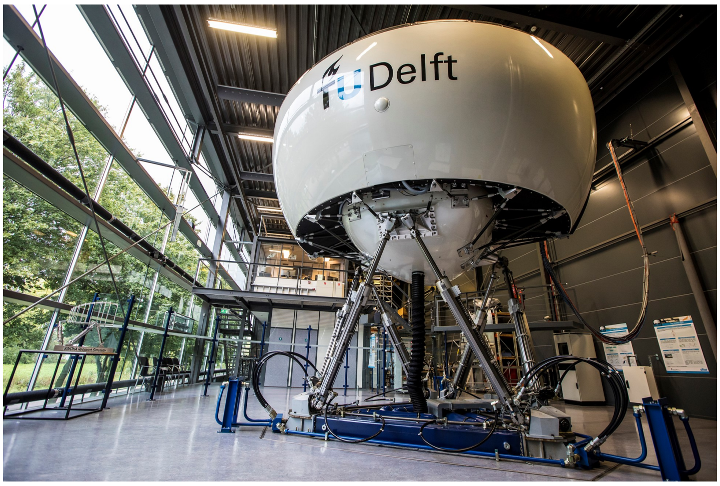

Figure 5.10: The Simona research simulator at the faculty of aerospace engineering at the TU Delft.

1. The cyclic stick (longitudinal inputs only, lateral movement is locked)
2. The collective stick
3. The Head-Up Display (HUD) used during the experiment
4. Stick trim display
5. Pedals (will not be used during the experiment)

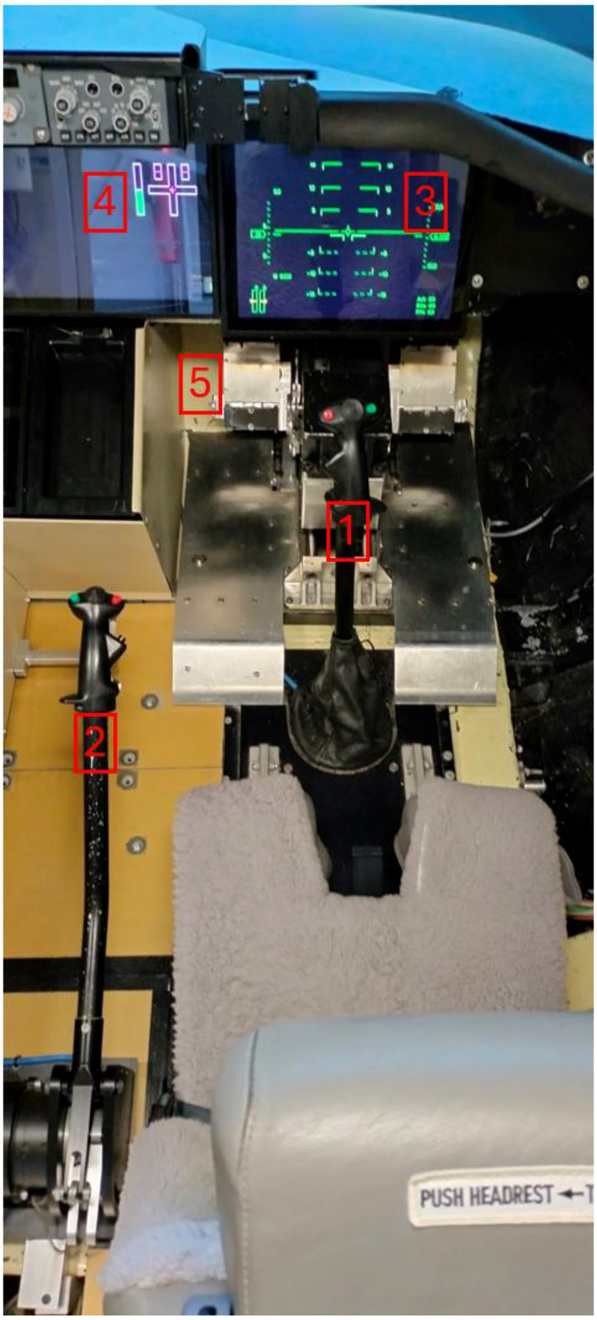

Figure 5.11: Controls and instruments of the Simona simulator.

HUD setup

The Head-Up Display (HUD) is an instrument in the simulator that shows the pilot important information about the state of the helicopter. Not only is it used to show common information, such as pitch, velocity and altitude, it is also used in the tasks to show specific information needed. The standard configuration of the HUD, with its elements indicated, can be seen in Figure 5.12. When the pilot is in the pitch tracking task, a double rectangle appears on the HUD, as is shown in Figure 5.13. This is an indicator of the reference signal, and its performance limit angles. This rectangle will move up and down the pitch tape, at the angle of the reference signal. The yellow rectangle is the indicator for the desired limit, with an angle of $0.5°$, and the red rectangle represents the adequate limit, at a $1.0°$ angle. These rectangles will change their color to green when the pilot is within a certain limit, as an extra indication for the pilot.

A similar indication system is used for the altitude tracking task, shown in Figure 5.14. The altitude tape now has lines, yellow for the desired limit of 10ft, and red for the adequate limit of 20ft. Both of the tracking tasks also show a score, in percentage of time spent within a a certain limit, which as discussed in the task description, is used to assign a performance level to the whole task.

1. The speed tape, with the current speed shown, in knots
2. The current pitch angle of the helicopter
3. The horizon indicator
4. The pitch tape, in deg
5. The altitude tape, with the current altitude show, in ft
6. Distance indication from the starting point during the bob-up or the distance to the end line during the acceleration-deceleration task
7. The reference indicator for the pitch tracking task, showing the desired(red) and adequate(yellow) limit as squares around the reference signal
8. The total scores of time (in percentage) spent within the corresponding limit to either the pitch or altitude reference
9. The reference indicator for the altitude tracking task, showing the desired(red) and adequate(yellow) limit as lines around the reference signal

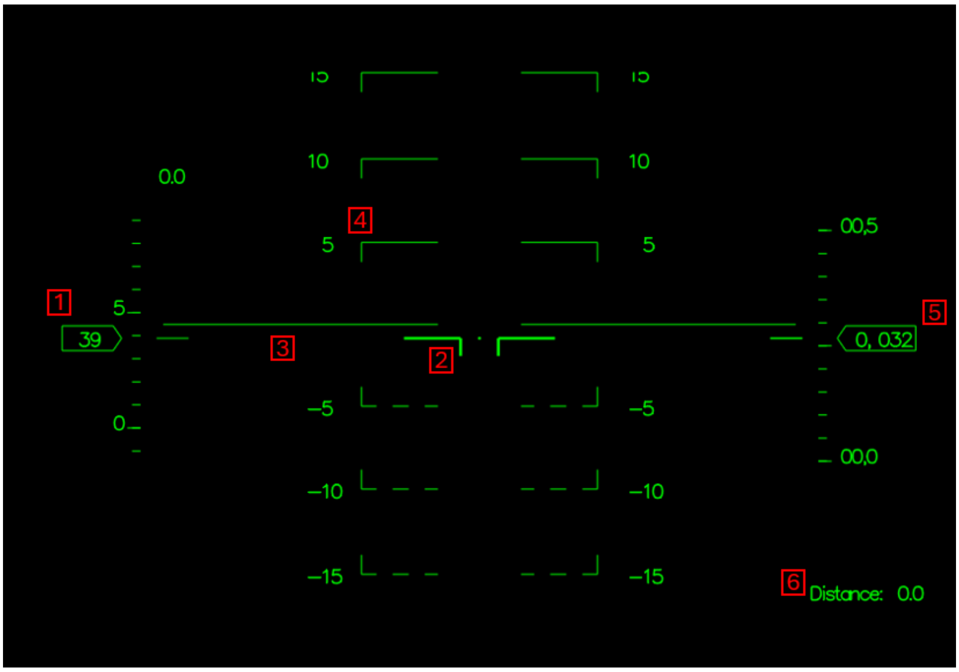

Figure 5.12: Standard HUD configuration.

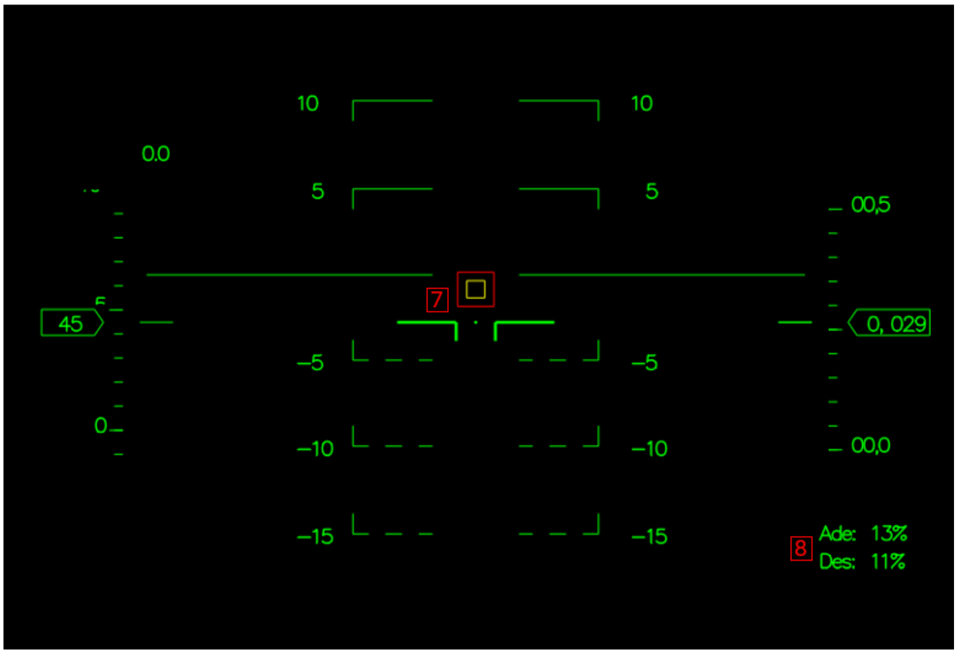

Figure 5.13: HUD configuration during the pitch tracking task.

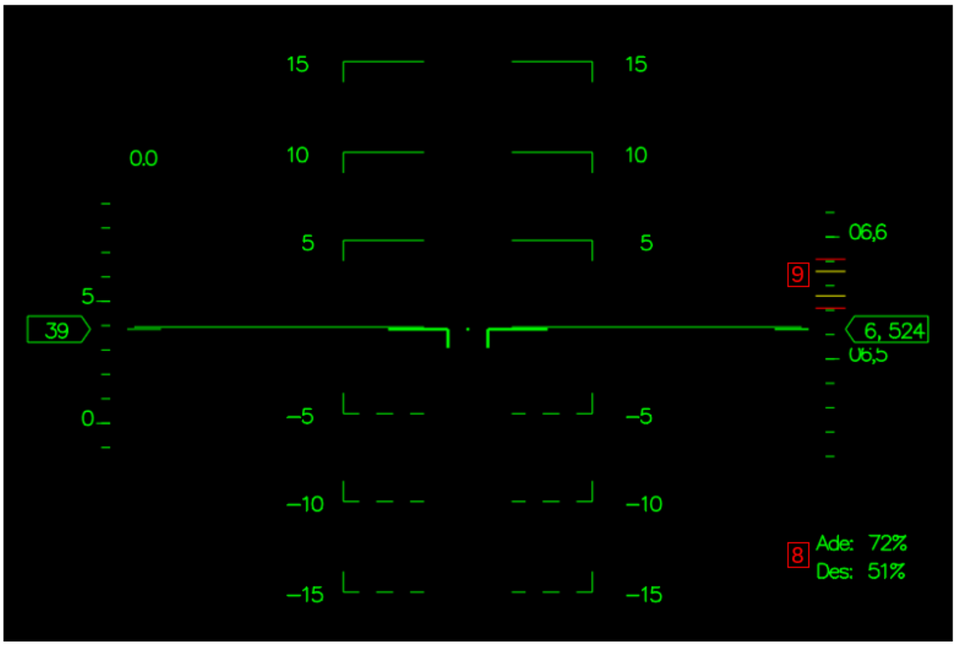

Figure 5.14: HUD configuration during the altitude tracking task.

5.4. Flight Test Results

One of the main results from the flight test is the determined Harper-Cooper ratings, for the specific tasks. The flight test was performed by two pilots, to add an extra layer of filter for the inherent subjectivity in handling quality ratings, that will always be somewhat presented, as discussed before. The scores that the pilots managed to achieve accompany the rating that was given at each task. However, they serve to show if a certain level of performance was achieved. It does not serve as a continuously measured level of performance, since the objective to the pilots was to achieve a certain score, to indicate a success(either with desired performance or adequate)/fail performance. Lastly, the pilot was asked to comment on the performance on each task, and to elaborate on his thought process with regard to the selected Cooper-Harper rating. This last step is crucial, since the secondary goal of the assigning of any rating, is to open up a dialog between engineer and pilot. If the rating of the handling qualities is a measurable method of assessing the current state of the controller, the comments from the pilot are a way of localizing the problem of the current state, and providing direction of how to improve the performance.

Sensitivity configuration task

The sensitivity configuration task was performed first, to select the preferred sensitivity setting for the cyclic stick. During the design of the controller, an input filter was added to the controller to smoothen out the pilot inputs provided to the controller. Both pilots immediately notices a delay in input, which caused some pilot induced oscillations. This was experienced for all sensitivities. It was decided to do a test run with this filter removed. The pilots experienced less PIO and felt the controller got more direct. They both preferred to have the filter taken out. The first pilot decided that sensitivity 3 was the preferred sensitivity, and the remainder of the tasks were completed with this sensitivity.

Pilot two had a comment on the control force of the sticks. This pilot preferred a lower force on the cyclic stick, and that it was slightly distracting at times. The force on the collective stick, added only for the robust controller to help find the neutral point, he said he could do without, since he felt like he needed to apply small input corrections on the collective and this hindered him slightly. As for the preferred sensitivity, the second pilot was split between sensitivity 2 and 3. It was discussed to use the same sensitivity as the first pilot, to improve the comparison between the pilots, so pilot two also performed all the remaining tasks with sensitivity 3.

Pitch tracking task

Figure 5.15 shows the handling quality ratings of the pitch tracking task. This is split up between the two pilots and was performed for different flight conditions. The associated scores can be seen in Figure 5.16, which consist of the desired and adequate scores, the total time spent within a certain limit, that the pilots achieved for each flight condition. It also shows a dashed line for the performance goal for the associated task.

As a side-note to both the pitch tracking and the altitude tracking tasks is that to reduce the impact of learning the tasks the order in which the combinations were flown were mirrored. The combinations were split up in altitude and configuration, so SAS or robust controller. The first pilot started at sea level with the robust controller and then swapping the configuration to SAS, after which this was repeated for 4000m altitude. The second pilots started with the SAS configuration at sea level.

When examining the handling qualities for the SAS configuration, both the pilots rate it similarly, where the biggest difference is the 40m/s run at sea level, where pilot 1 gave a handling quality of 5, indicating less workload. The pilots did not manage to achieve desired performance, however adequate performance was reached for all airspeeds. Most of the values for the rating come out to $6-7$, which is on the border of level 2 and 3, meaning that adequate performance was reached with extensive pilot compensation, to the pilot compensation needed to achieve the adequate performance not being tolerable. The pilots comment on the overshoot that the pitch response has with the SAS configuration, and that they need to apply inputs slowly, or risk losing precision.

The handling quality scores show a clear improvement when the robust controller is in use. Desired performance is reached for nearly all runs. Both pilots said that the controller was easier to use since no input to the collective was needed. The handling quality ratings according to pilot 1 are around the border of level 1 and level 2, which is the border between the controller being satisfactory without improvement or not. Where the workload was reduced with increasing speed and altitude. The first pilot also commented on the predictability of the response, saying that it increased with increasing speed. He furthermore noted that he was doubting between a rating of 3 and 4 for both the cases where he awarded a 4(40m/s at sea level, 20m/s at 4000m). The second pilot rated the controller between 4 and 5. He commented on the force of the cyclic being too high, and possibly awarding a better rating if this force was less. He too mentioned that he was doubtful to perhaps award a rating of 3 in some cases.

The altitude and speed differences are included in the task to test for the robustness of the controller, where the performance is checked when moving away from the design point (sea level, 20m/s). To account for changes in the helicopter dynamics at different speeds and altitudes, the SAS configuration is also tested as a base line here. It can be seen that the robust controller stays relatively consistent across the different speeds and altitudes. This shows how the controller can deal with uncertainties in the model, because the linearized model, on which the controller is based, is not correct for that trim condition.

Overall, the robust controller shows a significant increase in handling quality rating over the SAS configuration of the helicopter, increasing from being around the border between level 2 and 3 to being on the border of level 1 and 2. This means that the pilots deem that the robust controller for a the pitch tracking task would warrant some improvement. It should be noted that this improvement could also be achieved by altering not the controller, but the physical control set-up. For instance by tuning the stick force. However, the conclusion with this set-up does remain that the controller, used in a pitch task, across multiple flight conditions, does not meet the expected, designed for, handling qualities, but is close to meeting those requirements. This could then be an indication that the flying qualities used as a basis for predicting handling qualities in the design phase, don't completely cover the handling characteristics for the pitch tracking task. Again it should be re-iterated that this might not be the main improvement that should be made.

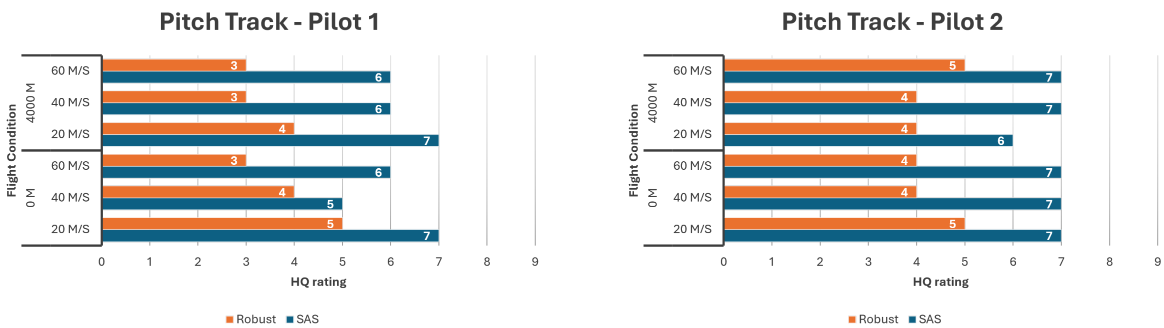

Figure 5.15: Handling quality rating by both pilots, at different flight conditions, expressed in altitude and airspeed, and configurations, during the pitch tracking task.

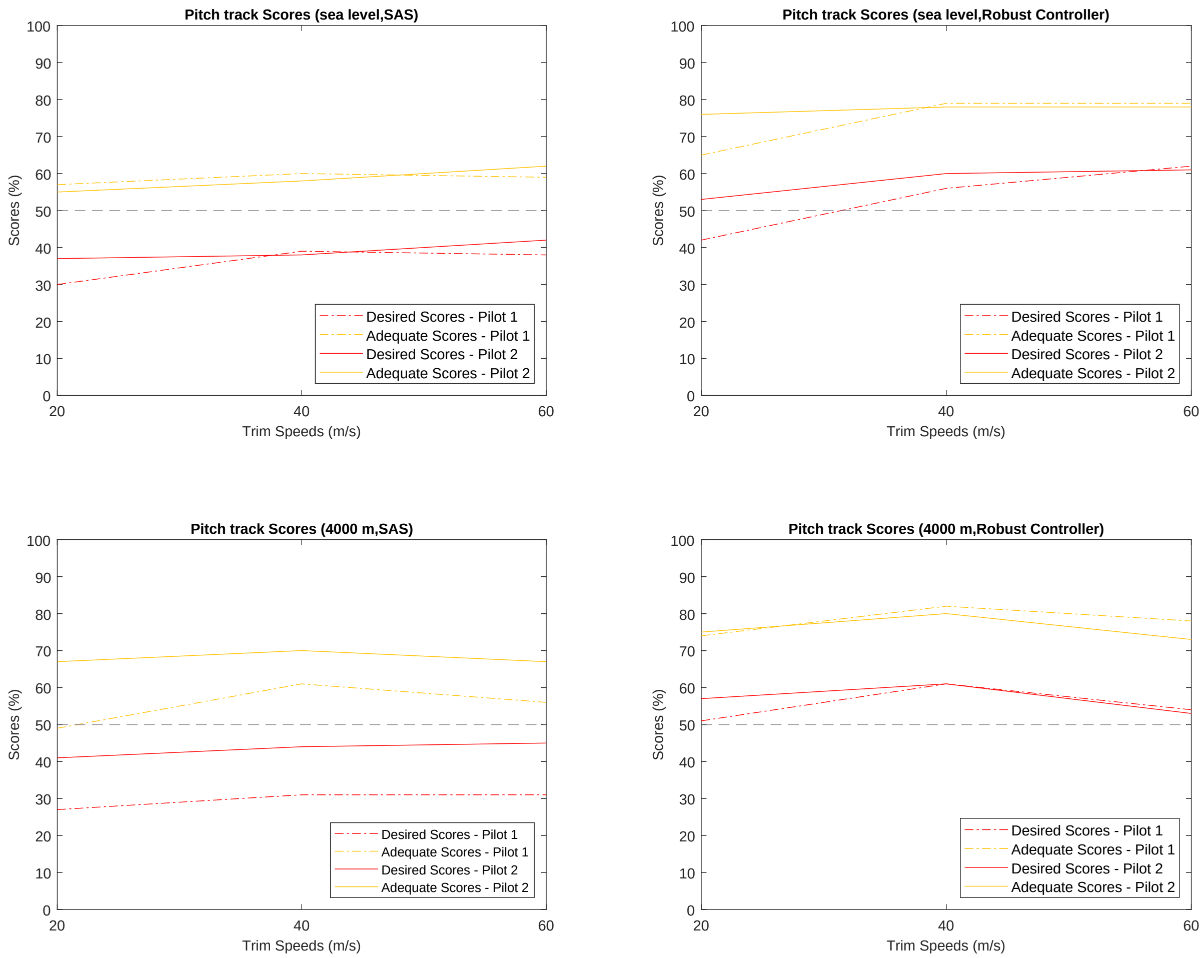

Figure 5.16: Scores of both pilots, at different flight conditions and configurations, during the pitch tracking task. Red indicating desired performance and yellow indicating adequate performance, with a gray dashed line indicating the minimum score required for each performance level.

Altitude tracking task

The output of the altitude tracking task is very similar to the pitch tracking task, where the handling qualities are accompanied by score plots for each condition that was flown in. The handling quality and scores can be seen in Figure 5.19 and Figure 5.20.

Concerning the handling quality ratings of this task, the pilots did not align as much, especially when it comes to the increase in rating between the SAS and the robust controller. What should be noted is that the first pilot did not manage to achieve desired performance for any of the sea level runs, and neither did he at the highest speed at 4000m, when in the SAS configuration. Pilot 2 did manage to achieve desired performance for almost all runs, SAS and robust control, except for the higher speeds at high altitude, showing the same decrease in performance as the first pilot. Both pilots commented on these SAS, high speed, high altitude, runs and said that the response was very slow and full deflection was not enough to compensate.

Since both controllers have the same actuator input range, and after examining the inputs to the actuator in both configurations, it was seen that they were similar. Since the robust controller did not seem to exhibit this behavior, a look is taken at the altitude graph of the fastest run at 4000m. In Figure 5.17 and Figure 5.18, the altitude trace, including the performance limits, is shown for both pilots and both configurations. What can be seen is that the SAS has much higher amplitudes, and looks a lot less damped, whereas the response from the robust controller is much lower amplitude, and seems much more direct. The response shaping of the controller is very apparent in this case, it has a smooth, damped response when reaching the reference velocity, which, especially in this case, gives the pilot the time to respond to the next reference input. Lastly, considering this is the flight condition most removed from the design point, and the controller showing very consistent behavior over all flight conditions, the altitude task is a very clear example of the controller showing good robust behavior. This builds nicely on the robustness that was shown in the pitch tracking task as well.

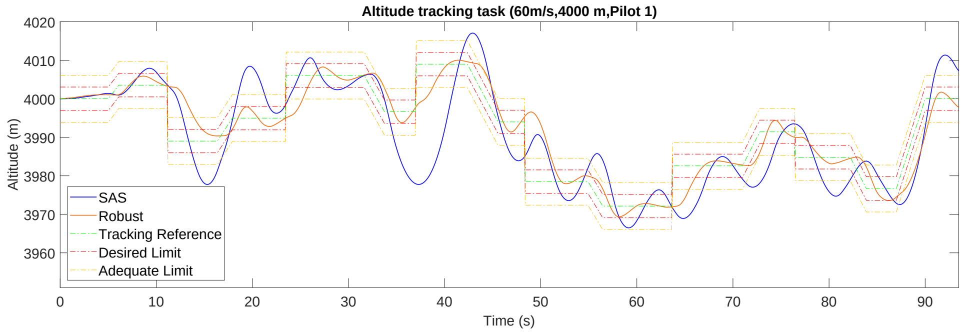

Figure 5.17: Altitude trace of the first pilot's altitude tracking run at 60m/s, 4000m. The blue line indicating the SAS configuration and the orange line indicating the robust controller configuration. Tracking reference signal, and accompanying limits are also shown in dashed lines.

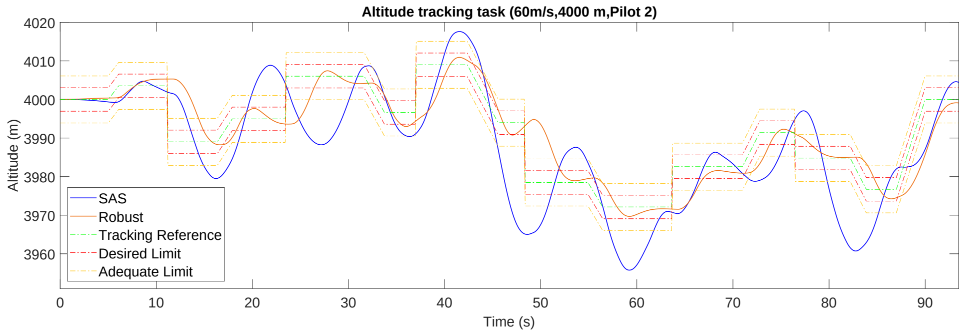

Figure 5.18: Altitude trace of the second pilot's altitude tracking run at 60m/s, 4000m. The blue line indicating the SAS configuration and the orange line indicating the robust controller configuration. Tracking reference signal, and accompanying limits are also shown in dashed lines.

Outside of these flight conditions, the robust controller also shows a significant increase in rating for the runs performed by pilot 1. His ratings are even all at level 1 handling qualities, which it was designed for. However, pilot 2 does not show this increase in rating. His ratings for the SAS were significantly lower than the rating given by pilot 1, even showing a decrease in rating for the flight condition of 20m/s at sea level. Interestingly this is the design point, and the only run in the whole flight test that showed not at least the same rating. What could be a factor in this is that pilot 2 started the altitude tracking task with this run. His comments on this run specifically were that the inputs he needed to make were quite large, and that the force in the collective stick distracted him. Furthermore, he noticed, as did pilot 1, that he needed to change his control strategy. They both developed a high deflection strategy, where they tried to find the perfect time to just release and obtain the desired altitude. Lastly, pilot 2 did mention multiple times that he was close to giving a rating of 3 for the robust controller, and was doubting to give a rating of 5 to some of the SAS runs. Had he decided to do this, the rating would already start to look more similar.

Overall, pilot 1 awarded the robust controller level 1 handling qualities for the altitude tracking task over all flight conditions, indicating that he believes the robust controller in this task is satisfactory without improvement. It should be noted that the SAS configuration according to this pilot was at a level 2 HQ rating, never level 3. Pilot 2 gave the robust controller a very consistent rating of 4, being just level 2. He believes that the deficiencies still warrant improvement. The comments he made were however mostly about the force in the stick, and he was missing some cueing. He for instance suggested that he would like to have an indication of the current vertical speed. If these improvements would be implemented it could already be enough to achieve a level 1 HQ rating.

Another change that could be made without altering the controller is the input values, both pilots indicated that they needed a lot of stick deflection to achieve the desired result. Perhaps a different mapping of the stick deflection to input, or even a non-constant mapping, where there is a more sensitive part close to the neutral position to account for small changes, and a larger input per stick deflection after a certain point to account for larger inputs.

Since the flying quality used to design for the handling qualities of the vertical velocity signal part of the robust controller is mainly the model following criteria, and the pilots were happy with the shape of the response, it could be said that this criteria did function as intended. It for sure did for pilot 1, level 1 was achieved. Pilot 2 could be level 1 if his comments were implemented, but another flight test would be needed to confirm this.

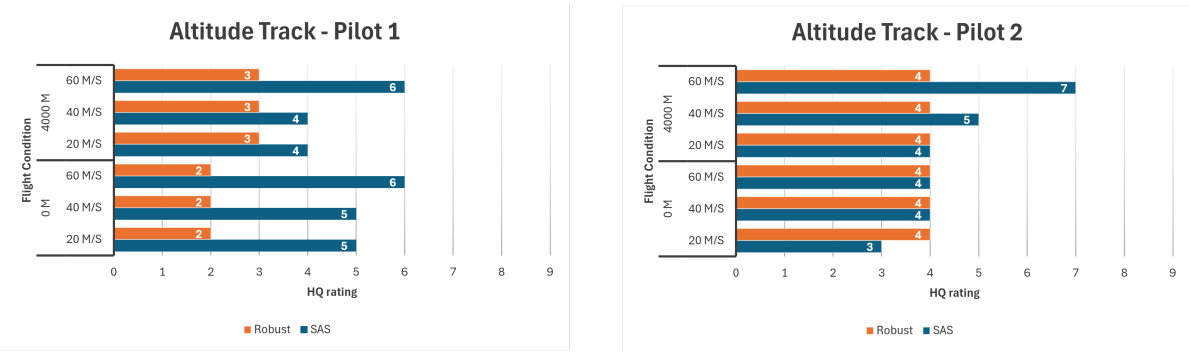

Figure 5.19: Handling quality rating by both pilots, at different flight conditions, expressed in altitude and airspeed, and configurations, during the altitude tracking task.

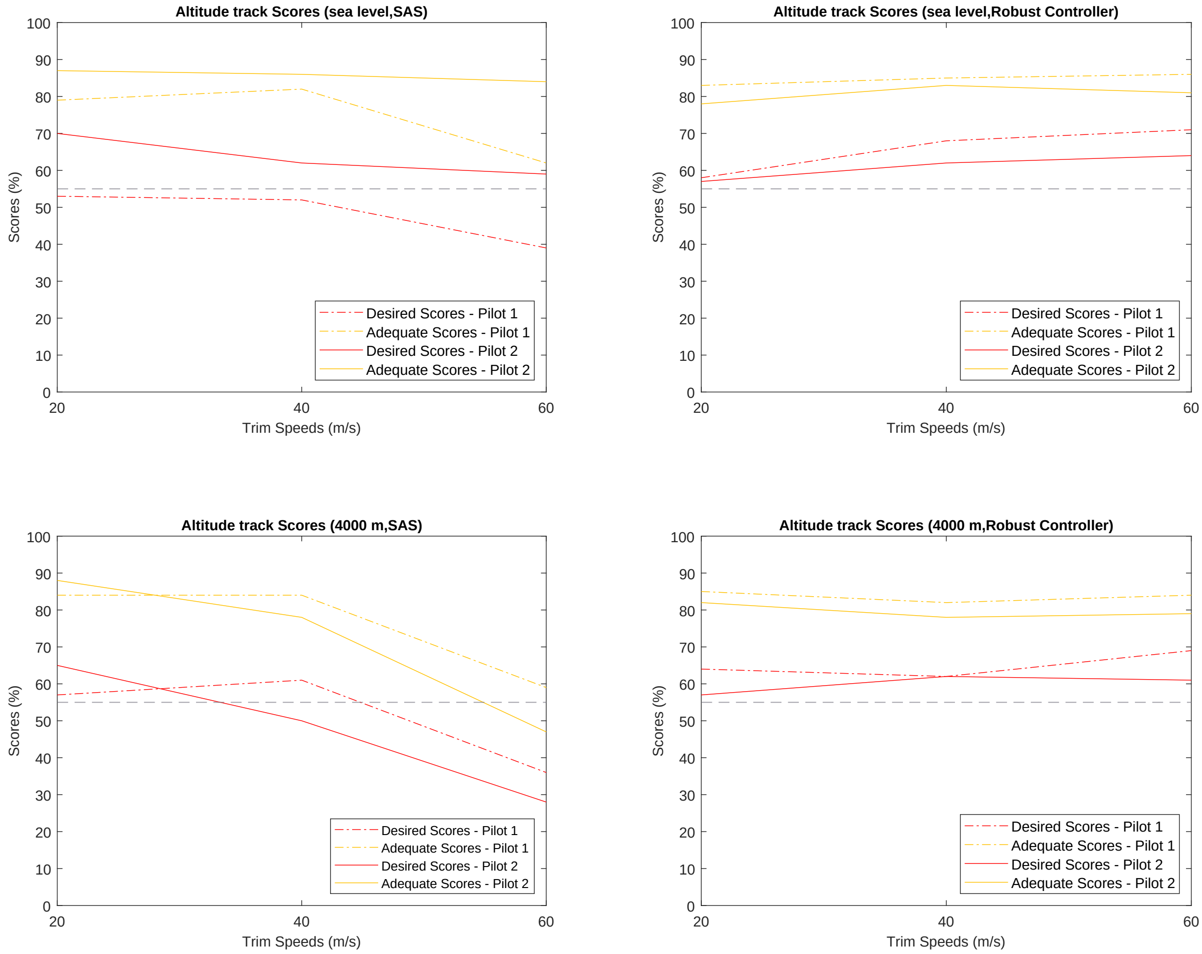

Figure 5.20: Scores of both pilots, at different flight conditions and configurations, during the altitude tracking task. Red indicating desired performance and yellow indicating adequate performance, with a gray dashed line indicating the minimum score required for each performance level.

Bob-up

In the bob-up task the helicopter is tested in a flight condition it is not designed for, hover. Results of Capra (2024) already show that the robust controller would have significantly different values for its elements, had it been designed for the hover condition. Since the pure hover task was decided to not be very relevant in a 3-DOF model, it was decided to still test some of the helicopters characteristics in a hover setting in the bob-up task. Especially since this is a task that checks for heave traits and coupling between pitch and heave.

The results, in the form of the best time to complete and the corresponding handling qualities, are presented in Table 5.4. As a reminder, to reach adequate performance the pilot needed to complete the maneuver in 15s or less and in 10s or less for desired performance. Furthermore, there was a requirement set on the distance the pilots were allowed to be from the starting point. As discussed before, since there was cueing missing to the pilots in the form of visual cues below them, the distance requirement was hard for the pilots to obtain. However, both pilots did manage to stay within adequate limits during their best run of the task, and it was deemed that this should not be the limiting factor in the performance criteria. The times to complete the task were still taken as leading, but did show that adequate performance was not obtained in the SAS configuration case, and only adequate performance was reached for the robust controller case.

In the SAS configuration the pilots reported a lot of PIO and coupling between pitch and heave. Their handling quality ratings, shown in Figure 5.21, also reflect the poor performance in this case, where pilot 2 even awarded it a 9, meaning that intense pilot compensation was needed to keep in control. The robust controller took away the cross coupling between pitch and heave, the pilots commented.

Their scores are also improved, now both achieving a 5, which is still level 2.

One other issue both pilots addressed, was the lack of motion cueing. Both pilots felt like having motion, in combination with visual cueing below them, would have helped them complete the task. Pilot 2 was the closest to desired performance but did say that even if he would achieve this, he would not award higher than a 4, still indicating that improvement would be needed.

This brings up a point that also pilot one brought up, the desired performance goal seem unattainable. The bob-up task is an adaptation of an ADS-33 task (Anon., 2000), but does use existing visuals, to aid with the hovering. These visuals used slightly more distance, 40ft, between the boards than the task describes, namely 25ft. Unfortunately, the task was not tested for this specific set-up and specific helicopter. That could have provided a more realistic goal for this specific task.

Bob-Up				
	Pilot 1 - SAS	Pilot 2 - SAS	Pilot 1 - Robust	Pilot 2 - Robust
Time (s)	**18.5**	**18**	**14**	**10.5**
HQR	**7**	**9**	**5**	**5**

Table 5.4: Scores, in time to complete the task, and handling quality rating of both pilots, of the bob-up task.

Acceleration-deceleration

The acceleration-deceleration is the last task to be discussed. The performance criteria of this task related to keeping the helicopter below a specific altitude and achieve a specific nose up attitude. Both of the pilots managed to reach desired performance for both configurations. The handling quality rating that they gave this task are shown in Figure 5.21.

Pilot 1 rated both configurations with a 1, but he did have some comments about the task itself. He felt like he was missing some elements that were not tested in this task. One of the main ones is that the model used does not use a model for the governor, it just uses a constant RPM for the rotor. However, since the acceleration-deceleration task is an aggressive maneuver, the dynamics of the blade and the engine play a role in this task. Furthermore, since the pitch attitudes in this task are quite large as well, the limited field of view of the simulator made it so that the visual cues to the pilot were quite limited. When comparing the robust controller to the SAS, the pilot noted that the way of flying was different, but that overall, after getting used to this way of flying, it required less workload than the SAS. He did mention that the deceleration part was the hardest part of the task, mostly because this required a different control strategy.

The second pilot did rate both cases lower, with a 4, but did show the same consistency as pilot 1. He commented on the different strategy as well, especially during deceleration, where he was on the limits of the input in the SAS configuration. Another aspect of the runs for this pilot while using the robust controller, is that the pilot experienced PIO. In one of the runs even so much that he lost control of the helicopter. This is something that will be discussed in chapter 6.

After having completed the bob-up task and the acceleration-deceleration task, it became apparent that the design of these tasks, and with what set-up of the model and simulator they were performed, is a large impact on the handling qualities the pilots awarded them. It is important to tune everything around the flight test so that the result closely matches the handling qualities of the actual controller. Especially since one of the research questions was to try to validate the flying qualities that the design was made with. In these last two tasks, it is difficult to give a answer to this question, since there were quite some aspects that could give a different handling quality rating, while using the same controller.

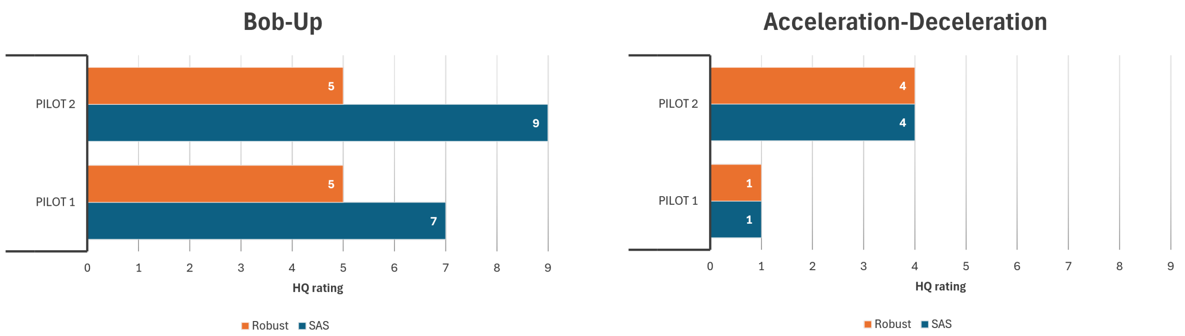

Figure 5.21: Handling quality ratings of the bob-up and the acceleration-deceleration task.

5.5. Discussion

One of the research objectives is to gain insight in the handling qualities of the controller, and the flying qualities that were used to design the controller. These flying qualities aim to provide a quantified criteria that correlates to certain in flight handling qualities. However, as was demonstrated by conducting the flight test, handling qualities are defined to be applied in a certain task. It is difficult to isolate just one characteristic of the controller, and link that to an even harder to isolate, single aspect of what a pilot experiences, but the design of these tasks aim to focus on a particular response. This means that to properly test the validity of a certain flying quality, the task needs to be tuned right.

This becomes clear in the bob-up task, where there is a case where the desired performance seemed out of reach. To a certain point it was possible to determine that this was not due to the robust controller, since the increase in performance compared to the SAS is still clearly present. It seemed that the performance limits were simply set too high. To either conclusively say that the limit was too high, or to account the issue to the model or the controller, more data would be needed.

Furthermore, the test setup also has quite an impact on the workload and subsequently the handling quality rating a pilot provides. This is well demonstrated by pilot 2 commenting on the distracting nature of a non-ideal control force. This is something that can be accounted for, but does require attention and time to be accounted for. Further on this point, the control force was even tuned with a pilot before the flight testing, but different pilots have different preferences and are accustomed to different set-ups.

Another impact that showed up during the flight test, was that of the cueing. This flight test was not run with motion cueing. This had a different impact on different tasks, during the tracking tasks, the pilots did not comment on the missing motion cues. However, in the bob-up task, because they were asked to hover, both pilots were missing this motion, and reported that they felt like they could have had less workload if this had been the case. Visual cueing was also not necessarily tuned completely to a helicopter. The simulator has a cockpit design of a general aviation passenger aircraft, therefor missing some of the field of view that is usually present with a helicopter. This does cause the tasks to be somewhat harder to complete, for instance in the acceleration-deceleration task, the

A factor that was tried to be accounted for, was the stick sensitivity. After the selection of the preferred sensitivity for the cyclic stick, the pilots did not comment on issues with this in the later tasks. The collective stick, which was not tuned in a task, however did get a comment by the pilot. This comment was regarding the expected range of movement in the robust controller case. This makes sense, since the controller uses a different input mapping, the setting for no altitude change, will always be the neutral point of the stick for the configuration used. Furthermore, this mapping means that a similar vertical velocity in the SAS case and the robust case, will require different styles of input.

With all this taken into account, the simple answer to the question of how well the flying qualities predict, and relate to handling qualities in a piloted flight test is: it's complicated. However, this would be too shallow of an answer, while its true, there are still very measurable results that came from performing the flight test. Most tasks show a clear increase in performance, by a significant amount. With a level corresponding to 3 ratings in the Cooper-Harper scale, both pilots show around a full level of increased handling qualities in the pitch tracking task. Level 1 handling qualities are achieved in the pitch tracking task for higher speeds by pilot 1, and on the lower side of level 2 for higher speeds, as well as level two for pilot 2. This is an indication that the criteria set on the pitch response are definitely trending towards level 1. As for the criteria on the heave, pilot 1 rates all his runs at level 1. With just pilot 1 it could be concluded that the criteria are well designed to achieve level 1 handling qualities. As for the other pilot, the handling qualities are just level 2, but not showing an increase. Based on this pilot, the criteria fall short of producing a level 1 result for altitude tracking. However with the second pilots comments taken into account, and that they were more concerning the input method. An argument for the robust controller showing increased performance in this task is that where the SAS started to deteriorate at higher speeds and altitude, and not providing the pilot with enough control authority, the robust controller fixed this issue and let the pilots control the helicopter in the same capacity as the other flight conditions.

With the more complex tasks, the controller did perform decently. The bob-up task also shows the same increase, for the second pilot even making the almost uncontrollable SAS, to a point where adequate performance could be reached. The last task, acceleration-deceleration, did not show any increase in performance, where the first pilot was already maxed out with his ratings for both cases, and the second pilot being just on the border towards level 1 handling qualities. However, with the comments the pilots gave on this task, it turned out that this task might not have been most suitable for the set-up of the model and controller. For this reason it is hard to take away any significant findings towards the validation of the flying qualities from this task.

Overall, when taking into account all the non controller related factors that impact the handling qualities, there is a decently strong argument that the controller is well designed and that the criteria decently predict requirements that lead to level 1 handling qualities. To definitely say that that is the case, the flight test could be repeated with actions taken to reduce these non controller related factors. This flight test should spend more time on tuning the set-up with the pilots flying, and could even be extended to develop for instance a different mapping of the stick to controller input, that better suits the inputs to the controller. This does bring in the question of personal human experience. Clearly the set-up of the simulation in the flight test was not equally preferred by the two pilots. However, a real-life helicopter should not be redesigned for every single pilot. If the flight test would be tuned, multiple pilots should be used to find a average that works for most pilots, and if the range is too wide, perhaps this could be solved with a preset of different tunings, where the pilot can easily swap to his preferred setting, in the same way that a pilot would adjust his seat to the correct setting.

Something that has not been discussed, but should be, is to change the model to increase handling qualities. For instance a horizontal stabilizer could reduces pitch oscillations. Not only would this have the potential to increase the handling qualities, but this would also be done passively. Meaning that the controller could, and since the the model would be different would have to, be re-tuned, but if less effort is needed in the stability part, this could leave resources in the design method for an increase in performance. Another elements that could be added, which would make the model more realistic, is a model for the governor, and with that rotor dynamics. As the model currently is, the RPM of the rotor is constant. In a real life situation, when the rotor feels changing forces, the engine will have to compensate to keep a steady RPM. The governor takes care of this part automatically, but this will in aggressive maneuvers produce a noticeable effect on the engine and rotor. This could is another topic that should be investigated in further research, since this could potentially have an effect of the handling qualities of the helicopter.

Lastly, the heavy PIO that occurred in one of the runs of the acceleration-deceleration task is an interesting result. The question is, how did this occur, and did it fully destabilize the helicopter and the controller or would the run have been savable. And most importantly, can this behavior be improved or prevented. The answers to these questions require a bit more research, and a closer look at this specific run, and therefor deserves its own chapter.

6 Anti-Windup

Based on the flight test runs that the pilots performed, and specifically one seemingly unstable run, this chapter discusses a potential issue of integral windup that occurs when the actuators of the rotor are saturated. This starts with investigating the pitch and controller elements of this specific run. After which, two anti-windup methods to combat this problem, clamping and back-calculation, are presented and implemented to see their effect on the response of the helicopter.

6.1. Actuator Saturation and Integral Windup

In Figure 6.1 the pitch angle, commanded pitch angle and the cyclic actuator angle can be seen for one of the runs pilot 2 flew. In this run, he was asked to perform the acceleration-deceleration task. However, the helicopter got into an uncontrolled state. The pilot was trying to regain control, but as can be seen, the inputs he gave only made the oscillation grow bigger. What should be noted is that the pilot inputs were quite extreme, as is warranted for the acceleration-deceleration task, but also that the inputs are almost opposite to the actual pitch. The pilot tried to stop the growing pitch angle but got into a state of pilot induced oscillation. The simulation performed during the flight test stopped at 28.5 seconds, but to show that the helicopter was not in an unstable state, and was recoverable, the simulation was extended after the flight test, as a Matlab simulation without the pilot. The input was set to 0 degrees after the initial simulation time was completed. It can be seen that the pitch oscillation does settle down and goes to the commanded pitch angle. Lastly, the actuator angle is shown in this figure too, to provide a better understanding of what is going on. The actuator is reaching its physical limits and saturating when the worst of the oscillation occurs.

The issue that could be the cause of this, and that is investigated in this chapter, is integral windup, occurring when the actuator is saturated. The concept behind an integral term in a controller is to integrate the error term coming into it, which means the error over time will be the output of this element. But when the actuator is saturated, the controller would usually like the actuator to provide more input, but it reached its limit. This means that the output of any integral term of a controller is still growing, without getting more actual physical result. For an integral term to go down again, and eventually reach a steady state, the error term will have to become the opposite sign of what it currently is, and then it will take some time to bring the term down. This time will depend on how long the actuator was saturated for. So before the integral term can add any meaningful input to the whole of the controller, it needs to have ”recovered” from the saturation. To illustrate this effect, Figure 6.2 shows the output of the PI-like controller, broken down into the proportional and integral part. It can be seen that the integral output is lagging behind the proportional signal significantly, and that the proportional part starts to become unstable, since it is just a directly scaled term with the current error in pitch.

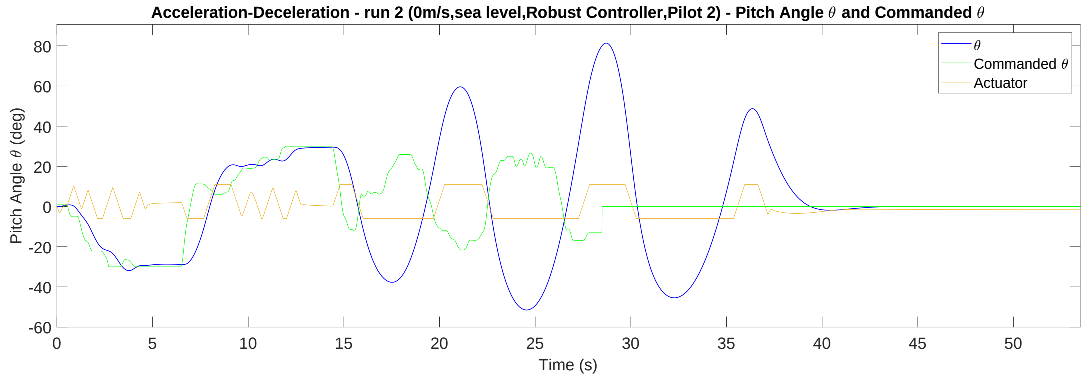

Figure 6.1: Pitch angle, commanded pitch angle and actuator angle of an acceleration-declaration run performed by pilot two, extended with 0 degree input command.

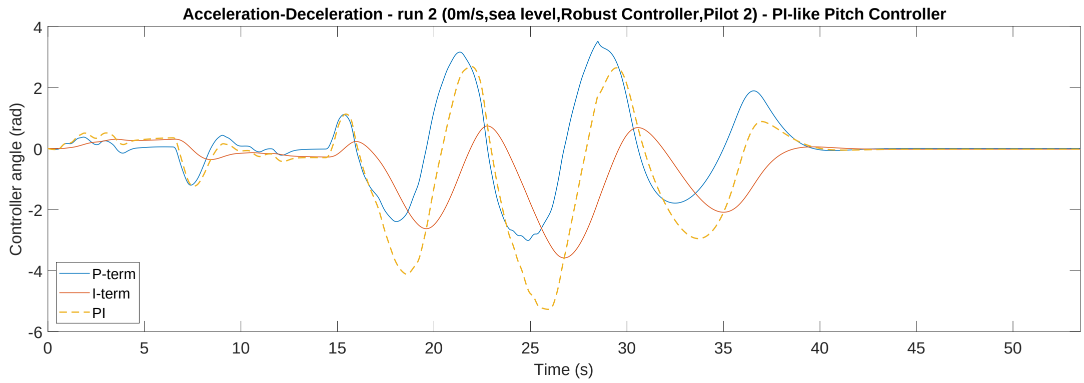

Figure 6.2: Commanded angle produced by each part of the PI-like element of the controller.

6.2. Method

Clamping

The first method, tried to improve the issue of integral wind-up, is the clamping method (Douglas, 2018). This method is, simply put, to set the error signal input to the integral part of the controller to zero when the actuator is in a saturated state. This stops the addition of extra cumulative error when the actuator is saturated, and will resume immediately when the actuator is not saturating anymore, meaning that the error term is decreasing again. This makes it so that the integral term does not need the time to reduce the accumulated output that would have been added during saturation. A schematic overview is shown in Figure 6.3 to visualize the set-up of this method in the controller. The blue blocks are a representation of a method to determine if the controller is saturated. This can be done in different ways, depending on how the simulation is run. Examples are to use a series of logic blocks in Simulink to determine if the saturation is occurring, or, in the case of the discretized model used in this research, as a boolean in the code. The model for the actuator accounts for both a rate and a position limit, which means that when either occurs, the actuator is considered saturated for the clamping method. When this happens, the blue block activates a switch, to follow the new path (dashed), to set the input of the $K_{c,\theta,I}$ block to zero, meaning that the output of the integral part of the controller will remain constant from that point on.

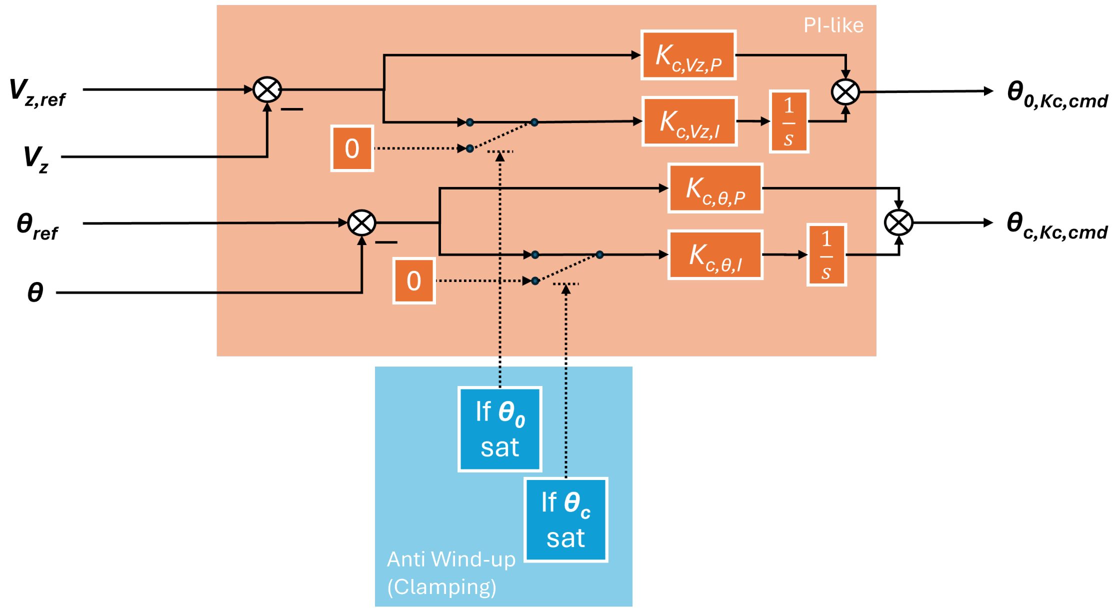

Figure 6.3: Schematic overview of the clamping method. The blue block indicating the method used to determine saturation, whichever is applicable in the simulation, leading to a switch, which lets through a constant 0 whenever saturation occurs, and otherwise the error term of the respective signal.

Back-calculation

The second anti-windup method implemented is back-calculation (Åström and Hägglund, 1995). In this method, instead of setting the input to the integral term of the controller directly to zero when saturation of the actuator occurs, the input signal is reduced proportionate to the difference between the input and output of the actuators. This is visualized in Figure 6.5. It shows that the signal going into the integrator of the controller is first reduced by the difference in the actuator in- and output, which can be seen in Figure 6.4, scaled with a factor K_a. This means that the error term that goes into the integrator, and gets added to the cumulative error, is reduced based on not only if, but also on "how much" the actuator is saturating. What this also means is that the error signal is not immediately zero when saturation occurs, but that it decreases gradually, but also that it can even become the opposite sign and reduce the cumulative error before saturation stops. Choosing an adequate value for K_a is still required. Åström and Hägglund (1995) suggests using a value between the scaling factor of the derivative and integral part of a classic PID-controller. Since there is only a integral part to the PI-like part of the controller, it was chosen to make K_a equal to $K_{c,I}$, for the corresponding signals.

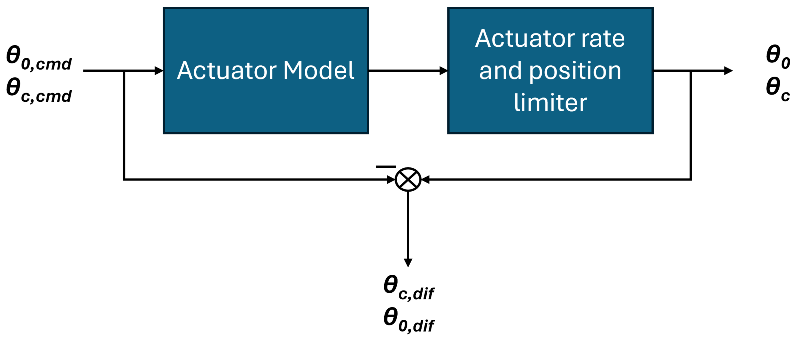

Figure 6.4: Overview of actuator system, with the difference in input and output being calculated.

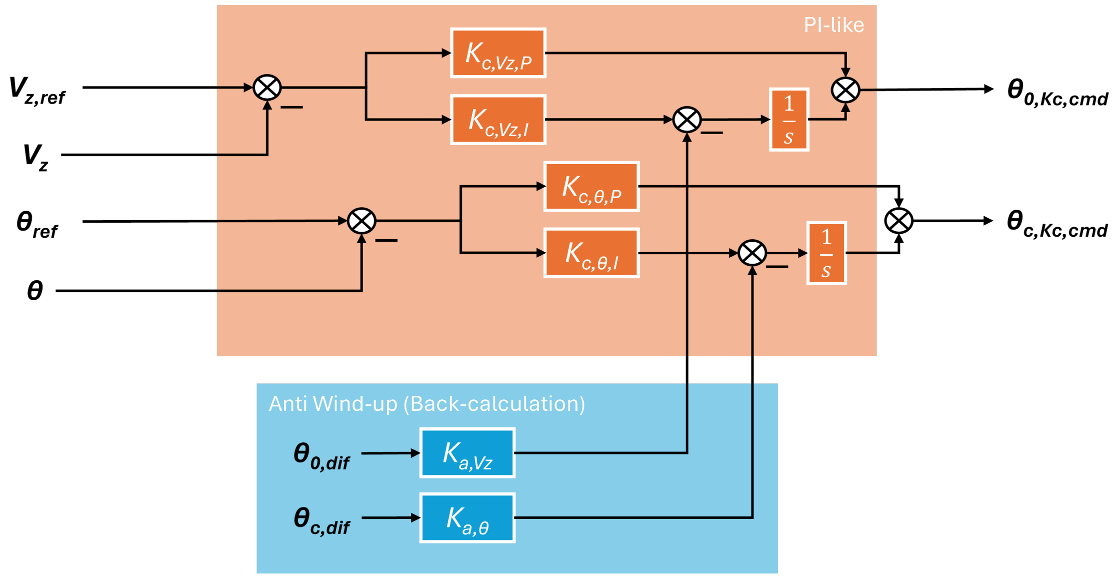

Figure 6.5: Schematic overview of the back-calculation method. The blue block taking the difference between the input and output of the actuators, and feeding this into the integral loop.

6.3. Results

Acceleration-deceleration run of pilot 2

In Figure 6.6 the (commanded) pitch angle for the acceleration-deceleration run of pilot 2 is plotted for three different controllers. The first, the dashed line, is the case where no anti-windup method is used to counteract the oscillations, which is the simulated response that occurred during the flight test. The recorded pilot input is used for the other two cases as well. The second case is the simulation run with the clamping method implemented as an anti-windup technique. And the third case is where back-calculation is used. The commanded pitch angle is also plotted, to show how well the response is following the input. What can be seen is that for both methods of anti-windup the pilot induced oscillation is very significantly improved. As for the difference between the methods, the clamping method seems to in general require a bit more time to respond, whereas the back-calculation method seems to respond much more immediate.

The performance of each method is visualized in Figure 6.7, in which the total error up to the current time-step is plotted, with the total error being the difference between the commanded pitch and the actual pitch of the helicopter.

$$\epsilon_n = (\theta_{cmd,n} - \theta_n) + \epsilon_{n-1} \tag{6.1}$$

This is done for the three cases that were plotted before: no anti-windup, clamping anti-windup and back-calculation anti-windup, with the additional graph for the ”no actuator limits” case. For this last case, a simulation was run where the limits on the actuators, both rate and absolute limit, were removed. This was done to have a bottom line to the performance of the controller without actuators. What can be seen is a significant increase for both cases of anti-windup, but with a better performance increase in the back-calculation case.

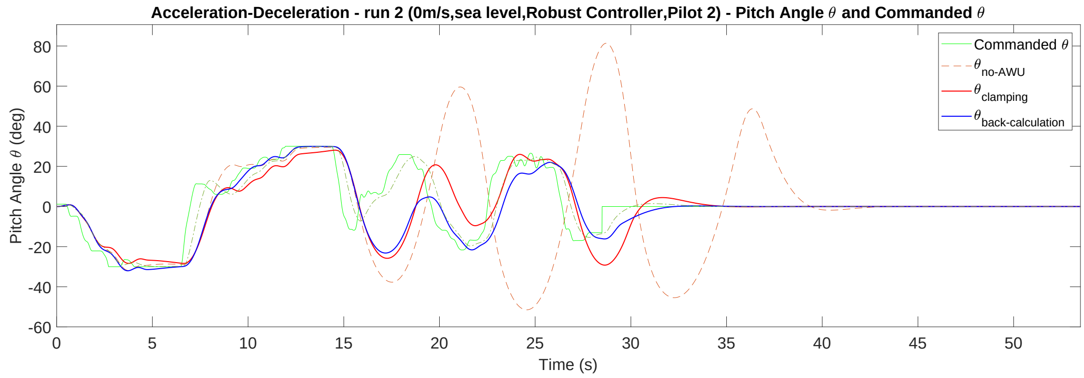

Figure 6.6: Commanded pitch angle in green, and the resulting pitch angle of the helicopter, when using both anti-windup techniques, and a dashed line for the original pitch angle. This is an extended simulation, that was performed on Matlab after the flight test, that uses one of inputs for the acceleration-deceleration task, flown by pilot 2.

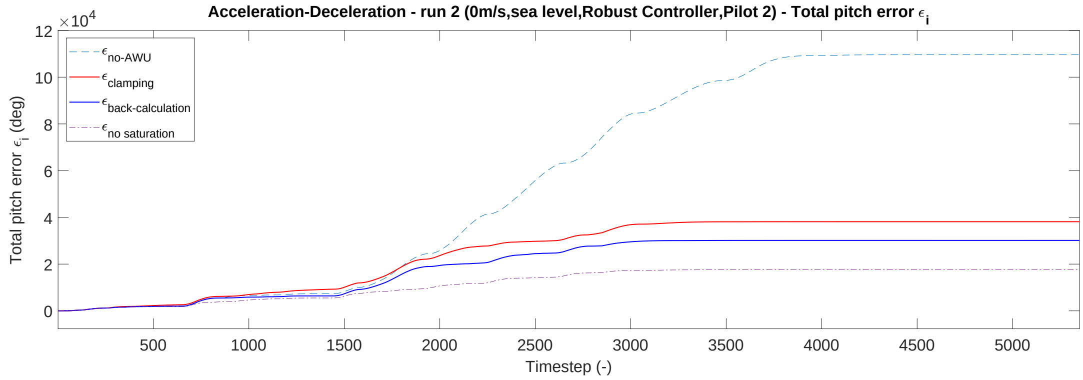

Figure 6.7: Total error at each time step for the case with no anti-windup applied, the case for both the anti-windup methods applied and when no saturation limits were imposed on the actuators.

Simulated high amplitude runs

To analyze the performance of the anti-windup methods further, more simulations were performed with different commanded pitch inputs. The inputs are a series of high amplitude (full deflection) step functions. The inputs were tuned to find a response of the system that showed problematic behavior. What should be noted that the inputs are quite extreme, this analysis is theoretical in nature, during normal operations, a pilot would never input these inputs.

Once again, the simulation was run for the three different configurations of the controller with and without anti-windup. The results are shown in Figure 6.8 and Figure 6.9. The dashed line is the case for no anti-windup, it clearly has trouble following the commanded pitch, with high overshoot and inconsistent responses to inputs. Both anti-windup methods perform significantly better, as can be seen in Figure 6.9. Interestingly, in the total error graph, the clamping method outperforms the back-calculation method. However, when looking at the actual response of the pitch angle, it can be seen that the back-calculation method shows a more damped and consistent response, compared to the clamping method that still experiences overshoot. Furthermore, it seems to struggle to reach the actual commanded for pitch angle, likely caused by the integrator function being completely canceled when saturation occurs. For a smooth, damped and predictable response for the pilot, the back-calculation method seems to be the preferred option.

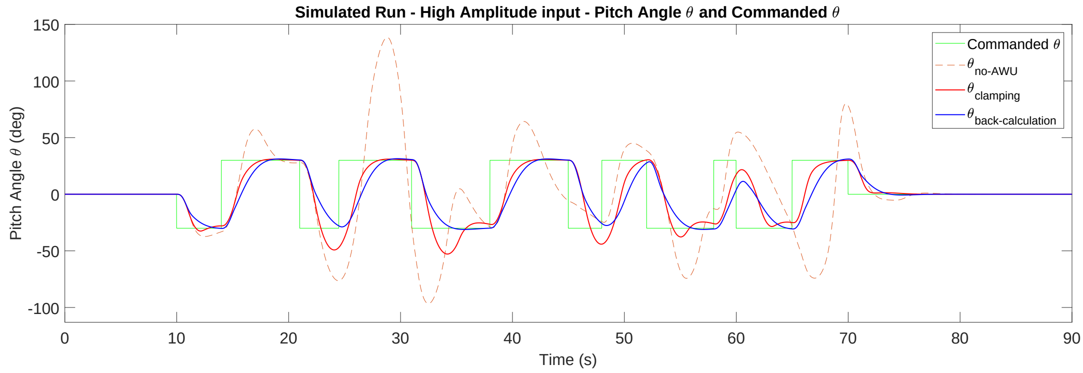

Figure 6.8: Pitch and commanded pitch angle for a Matlab simulated, high amplitude run, for the controller without any anti-windup and with the two anti-windup methods implemented.

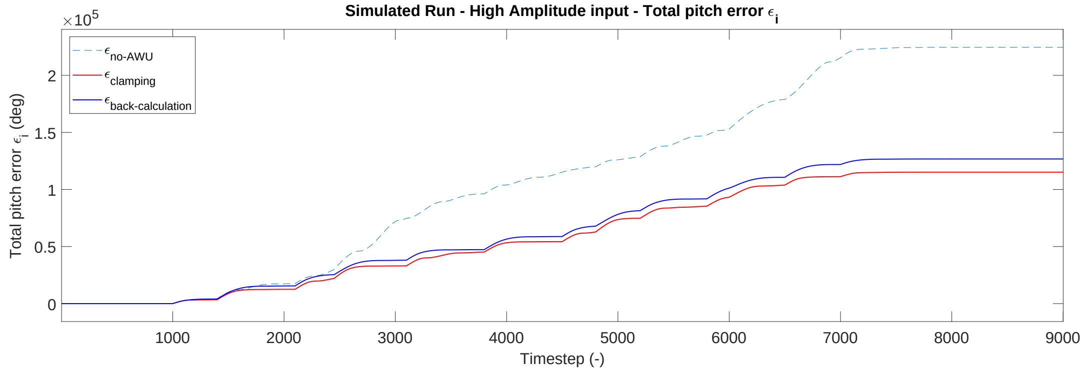

Figure 6.9: Total error for the high amplitude, Matlab simulated run. Showing the no anti-windup case, and both techniques of anti-windup that were implemented.

7 Conclusion & Recommendations

The aim of this research was to assess the handling qualities of the robust controller designed by Capra et al. (2025). The flying quality metrics that were used for this design were an important factor in this research, to validate if these metrics served their intended goal to achieve level 1 handling qualities. Handling qualities are used to quantify the amount of workload that is required to perform a certain task. Since the flying qualities are not necessarily tailored to a specific task, rather a specific characteristic of the helicopter during a specific task, the question is raised how well these flying qualities predict the handling qualities. To achieve this, a flight test was performed where two pilots were asked to perform a set of tasks:

1. Control configuration task: to investigate, and try to lower, the impact the cyclic stick sensitivity has on the ability to control the helicopter, and with that the workload of the pilot.
2. Pitch tracking task: to investigate the pitch response characteristics of the controller in a purely pitch focused task
3. Altitude tracking task: to investigate the heave response characteristics of the controller in a purely altitude focused task
4. Bob-Up task: to investigate the ability to precisely control the heave in a hover situation, while simultaneously checking for any coupling between pitch and heave.
5. Acceleration-deceleration task: to investigate pitch and heave characteristic of the controller in an aggressive setting, where the helicopter is near its performance limits.

The results of this flight test were handling quality ratings for each of these tasks, with the configuration task resulting in a preferred sensitivity setting to complete the remaining task with. To complete the second research aim, to show the increase in performance that was reached with the robust controller, a second configuration of the helicopter was also tested. The pilot inputs were directly linked to the model input angles, with a pitch rate controller influencing the cyclic actuator angle for added stability.

The pilot ratings show that the robust controller has a significant increase in handling qualities for the pitch and altitude tracking tasks and for the bob-up. Pilot 1 rated slightly higher in general, with reaching level 1 handling qualities for a few of the pitch tracking task runs, and just level 2, nearly level 1, for the other runs. The second pilot rated all pitch tracking runs at level 2. Importantly, the second pilot did comment that his rating could have been higher, potentially level 1, if it was not for the slightly large stick force causing him more workload. The same pattern between the two pilots shows for the altitude tracking task. The first pilot rates all flight conditions level 1, while the second pilot rates it just level 2, all a Cooper-Harper rating of 4. Important for this task is that the SAS configuration showed a decrease in performance and control authority at higher speeds and altitude, which the robust controller did not show.

The results of the bob-up task showed a clear increase in rating by both pilots when the robust controller was being used compared as to the SAS. However, neither pilot managed to achieve desired performance, which resulted in a rating by both pilots of 5 on the Cooper-Harper scale. The SAS however, showed very poor performance, to a point where controllability was in question. This was due to cross-coupling effects and PIO in hover. The robust controller managed to remove most of the cross-coupling and reduce the PIO as well, according to the pilot comments. A potential reason for the level 2 HQ rating in this task is that the desired performance goal is too high. One of the pilots also noted this during the task, as he was doubtful that he would be able to reach desired performance at all. This could be because the task was slightly altered in the flight test, compared to the task it was based on, and this could be improved by performing a tuning flight test.

The acceleration-deceleration task showed the same rating for both the configurations. Pilot 1 rated it a level 1 and pilot two a level 2 HQ rating. Pilot one did comment on this task, saying it was not a realistic enough representation of a real life scenario. He felt like there were elements missing, such as the interaction of the engine to the rotor. Overall, the acceleration-deceleration task seemed not fully suitable for the set-up of the model and controllers used in this flight test.

After the flight test was performed, and the rating and comments of the pilots were analyzed, it became clear that handling qualities are a complex aspect of a helicopter configuration. The pilots commented on external factors ranging from having an undesirable control force, to not having enough visual cueing, in the form of field of view, and missing motion in some tasks. This makes it difficult to isolate the robust controllers performance, and give a clear answer to whether the design method met level 1 handling qualities. Something that can be said with certainty, is that there is a clear increase in performance especially on the tasks that designed to focus on one criteria designed for. Taking into account the comments by the pilots, indicating why some of the ratings were lower, there is a decently strong impression that with the right tuning of external factors, the handling qualities could reach level 1 for all tasks and flight conditions.

One improvement that was still implemented in this research was anti-windup on the saturating actuators. In the acceleration-deceleration task, the actuators were saturating a substantial amount of time, due to aggressive maneuvering. This caused the integral term in the controller to windup, meaning it induced a delay in reaction time of the controller overall, leading to destabilizing PIO. To combat this behavior, two anti-windup methods were implemented: clamping and back-calculation. Both methods showed significantly improved responses, the response was more direct and destabilizing effects no longer occurred. The response of the back-calculation method were however more desirable, and would thus be the most suitable of the two tested methods.

With the research finished, a lot of insights into the impacts on the handling qualities of the robust controller have been uncovered. The simulator setup and the task design had a significant impact on the ratings of the pilots. To be able to isolate the performance and impact of the controller that is tested during the flight test, it would be recommended to perform a tuning flight test with pilots. Even though the factors that have an impact on the handling quality rating, such as the performance goals, or the control forces, had been tuned theoretically, and to some extend with the help of a pilot, this impact was not minimized. The mapping of the control input could also be investigated at the same time. Since the control strategy was different for the pilots, and this required some getting used to, it is interesting to spend some time working on the connection of the pilot to controller. This could increase the usability of the controller, and reduce the workload for the pilot.

Another logical step for this research into robust control for helicopters, is to expand the model to also include lateral motion. The addition of lateral motion will also make the behavior of the helicopter to be designed for to be more complex, coupling effects between the longitudinal and lateral motions will have to be investigated, to determine the shape of the controller. The controller could consist of an additional part that governs of the lateral stability and control and, together with the existing controller for the longitudinal motion, be the basis of the complete controller. It could however, also warrant a full redesign of the controller where the coupling effects need to be taken into account also. Research into the need for a coupled or decoupled controller would be the next step to take if lateral motion is to be added. Especially if a coupled controller would be designed, the handling quality criteria that will be used for that design should be expanded on, to capture the coupling effects that influence the handling qualities, not just the lateral motion criteria by themselves.

However, other aspects of the helicopter should not be ignored. The addition of a horizontal stabilizer could provide more natural stability and open up design space for a new iteration of the controller. Other effects such as the dynamics of the engine, in the form of a governor, could also enhance the fidelity of the model and result in a more accurate representation of reality on which the controller can be based. This could increase the performance of the current longitudinal controller even further.

With anti-windup methods being looked at in this research it did show that the robust controller got significant increase in performance with this implemented. However, it also highlighted that each design method comes with its own strengths and weaknesses. It is therefore recommended to perform more research into anti-windup methods, and perhaps have them integrated into the design of the controller beforehand, and investigate the effects this could have on the result of the design.

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