Assessing the Longitudinal Handling Qualities of the Flying V by Pilot Evaluation

Gijs Vugts

Research Paper and Preliminary Report

Assessing the Longitudinal Handling Qualities of the Flying V by Pilot Evaluation

by

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Paper

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Abstract— **The handling qualities of an aircraft are an important aspect in aircraft design, especially for novel configurations. The Flying V is a flying wing passenger aircraft designed to transport about 300 passengers. The handling qualities of such a new configuration aircraft are to be investigated before the aircraft can continue in its design process. The first step is to investigate the longitudinal handling qualities of the Flying V in cruise conditions. The handling qualities are heavily affected by the geometry of the aircraft, which has no tail and has a shorter arm to the elevons for the pitch control. These two main differences do not affect the pitch angle control negatively, which is the focus of conventional handling qualities evaluations, but have a strong effect on the flight path angle. This effect is a non-minimum phase response due to the large change in lift needed to generate the pitching moment. To test this flight path angle behaviour, a new evaluation of the handling qualities is implemented which uses flight path angle tracking. Two control allocations were created: one where both inboard and outboard elevons deflect in the same direction, and one where the change in lift the elevons generate is countered by deploying the inboard and outboard elevons in opposite directions. The longitudinal handling qualities in cruise conditions were investigated by pilot opinion in a moving base simulator. Three experiments were conducted: a traditional pitch experiment, the novel flight path angle experiment, and the latter experiment using the second control allocation. The pilots indicated the pitch attitude control to be Level 1 handling qualities, while the normal control allocation flight path experiment was Level 2. The new control allocation improved the performance of the pilots during the experiment, but the lowered control authority was too much for most pilots to rate it at Level 1.**

I. INTRODUCTION

The Flying V is a novel-shaped aircraft designed to be up to 25% more efficient compared to conventional configurations [1, 2]. The new design is a flying wing, where the fuselage is incorporated in the wings of the aircraft. This new aircraft behaves differently from conventional aircraft in many aspects. Most notably, it does not have a tail and thus no tail surfaces which can be used to control the Flying V. A first analysis of the handling qualities, prompted the need for further investigation [3]. A vital aspect of the evaluation of the handling qualities is a test with pilots [4-6]. Therefore, this study will perform the first piloted experiment with the Flying V in a simulator. This study will investigate the longitudinal handling qualities of the Flying V in cruise conditions by pilot opinion.

The handling qualities of an aircraft for a certain task can be characterised by three levels: [4]

- Level 1 is "satisfactory", where the aircraft handling qualities are clearly sufficient for the task requirements. Desired performance is obtainable with at most minimal pilot compensation.
- Level 2 is "acceptable", where the handling qualities are adequate to complete the task, but increased pilot workload and/or lowered task performance is seen.
- Level 3 is "controllable", where the aircraft can be controlled during the task with excessive pilot workload, or inadequate task effectiveness, or both.

The handling qualities of the Flying V were assessed in two ways, an offline analysis and a piloted experiment. In the offline analysis, the eigenmodes of the model were analysed and the response to control inputs was investigated [7]. The flight path angle response is different from conventional aircraft. The flight path angle of the Flying V dips more due to its non-minimum phase response than conventional aircraft after a pitch up input is given [8]. The non-minimum phase response warrants additional research. The handling qualities are assessed by testing with pilots, and will include an assessment of the handling qualities in the flight path response.

The piloted experiment introduces a new design variable: the control allocation. Since the Flying V is in the early stages of design and this is the first piloted experiment of the Flying V, the bare airframe handling qualities will be investigated. This means that there is no augmentation by means of a full flight control system, and the stick is linearly linked to the control surfaces. In a conventional aircraft this allocation would be relatively easy, as the longitudinal control is only affected by the elevator input. However, the Flying V has two elevons i.e., a control surface which can be used as an elevator and aileron, on each wing. Different control allocations will be tested. One of the control allocations will be designed to improve the flight path behaviour found in the offline analysis.

Evaluations of the handling qualities of unconventional aircraft with similarities to the Flying V in the time domain have been reported. However, either the pilot is kept out of the loop [9-11], or the application is completely different from the operational requirements of the Flying V [12, 13]. Handling qualities evaluation schemes for conventional aircraft exist [4, 14, 15], which use a pitch angle target for the pilot to follow. The pilot has to follow the target with a predetermined accuracy, and indicate the handling qualities level using the Cooper-Harper Rating Scale (CHRS) [16].

However, the pitch attitude response is not a complete representation of the handling qualities of the Flying V, because of the differences between the pitch attitude control and flight path angle control found in the offline analysis. In addition, most longitudinal maneuvers performed by commercial aircraft during cruise in operation will focus on the rate

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of climb or descent rather than the pitch angle. In order to test this, a new task focusing on the ability of controlling the flight path angle is created. This task will extend the legacy handling qualities experiments [4, 5]. The longitudinal handling qualities of the Flying V in cruise conditions will be tested by pilot evaluation using a newly designed flight path focused evaluation method for two different control allocations.

The structure of the paper is as follows. The background, which summarizes the main outcomes of the offline research about the Flying V behaviour, is explained in Section II. The design of the traditional pitch attitude experiment, and the process of designing the novel flight path angle experiment is discussed in Section III. The method is discussed in Section IV. Results in the form of pilot ratings, scores, and comments made during and after the experiment are shown in Section V, and discussed in Section VI. The overall longitudinal handling qualities in cruise conditions for the Flying V are given, and recommendations for use of this research and future research are made. Conclusions are drawn in Section VII.

II. BACKGROUND

A. The Flying V

Firstly, the wing geometry of the Flying V will be discussed to gain insight into how the aircraft will behave. The Flying V has two elevons per wing, see Figure 1. The Flying V is about 10 meters shorter compared to the main conventional counterpart, the Airbus A350-900 [1, 3], while still maintaining a similar wingspan and mass. The moment of inertia used to calculate the pitch authority is smaller, which is in line with the expectations for a shorter aircraft. The optimal center of gravity of the Flying V is 31.3 meters behind the nose (55% MAC), the optimal center of gravity for the reference aircraft is at 30.8 meters behind the nose (30.5% MAC) [3]. The midpoint of the control surfaces of the Flying V are placed at 47.1 meters behind the nose for the inboard elevons, and 51.6 meters behind the nose for the outboard elevons. The elevators on the reference aircraft are placed at 65.1 meters behind the nose. The elevons have a pitching moment arm of 15.8 meters and 20.3 meters. The reference aircraft has a moment arm of 34.3 meters.

The inboard or outboard elevons of the Flying V are 46% or 59% as effective in generating a pitching moment compared to the reference aircraft. The effect this has on the aircraft behaviour can be seen in two ways: either the pitch response is more sluggish, or the force generated by the elevons has to increase.

The model used in the rest of the analysis is at maximum take off weight at which the pitching moment of inertia used in the aircraft model is known [3].

B. Aerodynamic Model

The Flying V model which is used is an aerodynamic model created during a previous thesis [3]. A vortex lattice method is used, resulting in a set of coefficients which are used to generate linear force- and moment coefficients. The model is generated using Airbus in-house software at a certain flight condition. The flight conditions, at which the coefficients are generated, are not equilibrium conditions. The angle of attack is always set at 2.5°. There are five different airspeeds expressed in Mach number (0.2M, 0.3M, 0.5M, 0.7M 0.8M) and three different centre of gravity locations (45% MAC, 55% MAC, 57.5% MAC). The coefficients are used to generate an aircraft model using the equations of motion.

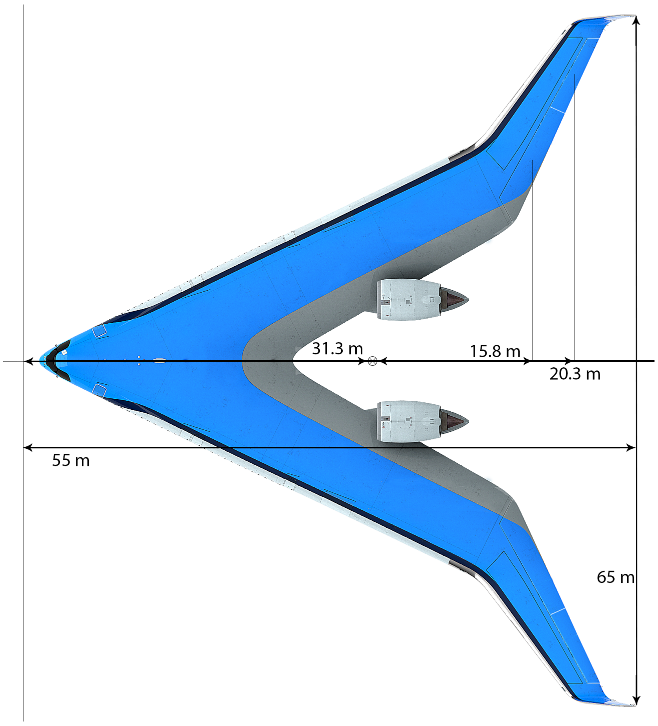

Figure 1. Flying V with inboard and outboard elevon location from the centre of gravity.

The aircraft in this research is in cruise flight so the airspeed of 0.8M is chosen since it is closest to its cruise velocity, which is 0.85M. The optimal centre of gravity is chosen, which is 55% MAC [3]. The force- and moment coefficients depend on the angle of attack, the sideslip angle, the roll rates, and the control surface deflections.

This aerodynamic model poses multiple limitations to the validity of the results. First, the vortex lattice method generates a linearized model of the aircraft force- and moment coefficients. Second, the model is generated at 2.5° angle of attack. This is far from its trimmed angle of attack of 7°. Third, a nonadjustable thrust force is incorporated in the model. In addition to that, the deflections used in the experiment could cause effects which are not included in this model such as flow separation, or heavily increased drag due to control surface deflection.

C. Offline Analysis

The lack of a separate horizontal tail surface has a pronounced effect on the behaviour of the aircraft apart from the control inputs. To see this, the eigenmodes of the aircraft model are analysed. Specifically the short period is of interest for the handling qualities [4].

The Control Anticipation Parameter (CAP) is commonly used as a handling qualities evaluation method. Calculating the CAP relies on the complex part of the eigenmode corresponding to the short period [4]. However, the eigenmode analysis shows that the eigenvalues corresponding to the short period are real instead of complex. Alternatively, the handling qualities can be evaluated by looking at the time domain response. This approach will also evaluate the short term response, like the CAP does, but looks at the pitch rate. The time domain evaluation measures the effective time delay, effective rise time, and transient peak ratio. The effective time delay is the time it takes the pitch rate to reach its maximum rate of change. The effective rise time is the time it takes the pitch rate to reach its steady state pitch rate starting at the effective time delay. The transient peak ratio is the ratio between the magnitude of the overshoot of the pitch rate, and magnitude of the undershoot following [4]. In order to determine these values, the response of the aircraft and the eigenmodes are computed. The eigenmodes can be further analysed by looking at the eigenvector. This shows the relative contribution of each state to the eigenmode. These relative contributions are shown in Table I. The eigenvectors are calculated with the velocities in meters per second, and the pitch- angle and rate in degrees and degrees per second.

TABLE I
RELATIVE CONTRIBUTIONS OF THE STATES IN THE EIGENVECTORS

Short period		
u	0.12	[m/s]
w	-0.99	[m/s]
q	1.3	[°/s]
θ	-0.26	[°]

Flight path subsidence		
u	-0.16	[m/s]
w	0.99	[m/s]
q	-0.081	[°/s]
θ	0.12	[°]

Especially the second short period mode is interesting, as it does not affect the pitch attitude much, but does affect the velocities. This means that it would influence the angle of attack, or the flight path angle. Because of this effect, this eigenmode will be called the flight path subsidence in this paper. Using the eigenvector and eigenvalue, it is possible to isolate the response of the eigenmodes. This is done by using the modal form [17]. The absolute value of the modal form is the Mode Participation Factor (MPF), which shows how much which mode is active. The modal state can display a linear state space system in the following way,

$$\begin{aligned} r(t) &= \underbrace{e^{\Lambda t} V^{-1} x(0)}_{\text{ZIR}} + \underbrace{\int_0^t e^{\Lambda(t-\tau)} V^{-1} B u(\tau) d\tau}_{\text{ZSR}} \\ y(t) &= C V r(t) \end{aligned} \tag{1}$$

where $r(t)$ is the modal state, V is the eigenvector, and Λ is a matrix containing the eigenvalues on its diagonal. To look at the response from one eigenmode, only the Zero Input Response (ZIR) is taken since no input is given to start the eigenmode. This equation shows that if the start value $(x(0))$ is an eigenvector, the only part left in the output is $e^{\lambda t}$. This will be the isolated response of that specific eigenmode. The second part of the equation, the Zero State Response (ZSR), shows the model response to an input.

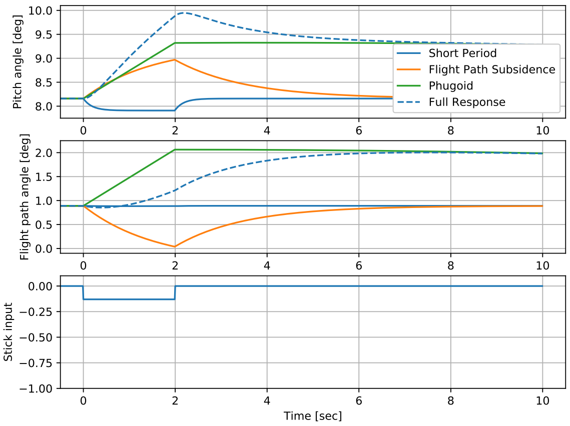

Figure 2. Response of different eigenmodes to a step input using normal control allocation.

The modal form can be used to isolate the eigenmodes in a specific response. This is done for the three main eigenmodes −short period, flight path subsidence, and phugoid− in Figure 2. This plot shows how the pitch angle and flight path angle are affected by each mode, while a 2 second input is given at the beginning. All three modes combined result in the full response the aircraft will exhibit.

The short period is not affecting the response much, since its contributions are low in magnitude and fast. The pitch angle is dominated by the phugoid to rise it to its steady state value. The flight path subsidence makes the pitch angle rise also, and causes the slow sink to the steady state value after the input is stopped, contrary to the phugoid which holds its attitude after the input is stopped. The flight path angle has the phugoid and flight path subsidence affecting the angle in different directions. In addition to that, the contribution of both eigenmodes is even. The flight path subsidence is faster in its initial rise, but levels off. Because of this, the flight path angle dips below its starting point before starting to rise. When the input is stopped, the flight path subsidence lowers in magnitude, making the flight path angle rise quickly. This is a non-minimum phase response.

The non-minimum phase response is expected to be a problem for pilots when controlling the Flying V, because the input will be out of phase with the aircraft response. Therefore, a new control allocation is created where this effect is corrected. In order to achieve that, it is necessary to know where the effect comes from. In Subsection II-A, it was already mentioned that the short pitching moment arm could have two effects; either a slow pitching response, or an increased force on the elevons. An increased force on the elevons can explain where the effect comes from. A downward force on the elevons will result in a pitching rotation upwards, while pulling the aircraft down. This will result in the non-minimum phase response. This information can be used to create a new control allocation which changes the response from non-minimum phase response to minimum phase response.

From this response, the effective rise time, effective time delay, and transient peak ratio are calculated. The handling qualities evaluation of these values is performed. In order to accurately do this, a maximum rate of deflection in the elevons is set to 40 degrees per second for this analysis. This results in an effective time delay of 0.18 seconds, which is within Level 3. The effective rise time is 0.5 seconds, and is within Level 1. Since there is no second peak, the transient peak ratio cannot be calculated. However, this can be assumed to be Level 1 since the absence of the undershoot is favorable. It is also noted that the maximum rate of deflection, which is the reason for all of the effective time delay, is not implemented in the piloted experiment. With no maximum deflection rate, the effective time delay is zero. This means that the time delay comes only from the elevon deployment speed, and not the aircraft dynamics. Therefore, it can be concluded that following this analysis the pitch angle handling qualities will be within Level 1.

D. *Control Allocation*

In order to tackle the non-minimum phase response, which is seen in the flight path angle when a stick input is given, two different control allocations are designed. A linear control allocation is chosen, in contrast to a full flight control system, to test to the bare airframe handling qualities.

The first control allocation will be where both inboard and outboard elevons deflect in the same direction, as an elevator would on a conventional aircraft. The outboard elevons will deflect twice as much as the inboard elevons. This ratio is chosen such that it is identical to the new control allocation designed later on. This will mean that the total deflection of the elevons is identical in both control allocations. If the stick is pulled back, both surfaces will move up and the lift at these elevons will decrease causing the aircraft to pitch upwards. The response of this system is shown in the offline analysis in Figure 2. The stick input is shown in the bottom plot as a fraction of the maximum stick input. The maximum stick input is 30°. There is no rate limit on the deflection of the control surfaces.

The new control allocation will have both elevons deflect in different directions. This is to counter the non-minimum phase behaviour the Flying V has. For a pull up, the outboard elevons will still deflect up, while the inboard will deflect downwards to compensate the lift lost by the outboard elevons. The inboard elevons will have a deflection half that of the outboard elevons. This will decrease its pitching effectiveness, but will eliminate the non-minimum phase response. This means that the new control allocation focuses more on the flight path angle than the pitch angle. The response of this control allocation while giving a two second constant input that results in a flight path angle of 2° is shown in Figure 3.

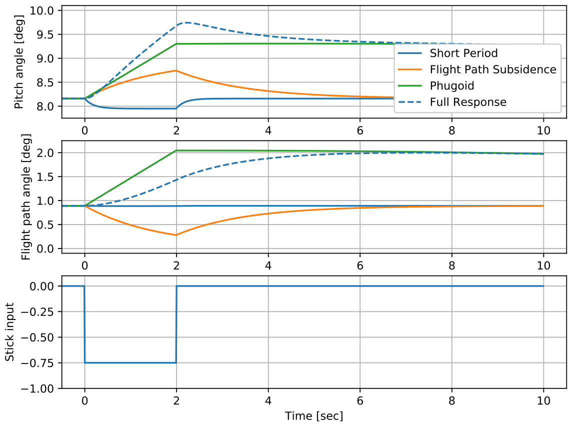

Figure 3. Response of different eigenmodes to a step input using the new control allocation.

The new control allocation can be compared to the normal control allocation response shown in Figure 2. The flight path subsidence is the main mode which is affected by this new control allocation. The magnitude of this mode is lowered. The elevons are no longer causing the non-minimum phase response, and the transition after the input is stopped is smoother.

The non-minimum phase response is usually indicated via the transfer function by zeros with a positive real component [18]. The effect of eliminating the non-minimum phase response of the new allocation is validated by the fact that the positive zeros have moved to the left hand plane.

Since the other modes did not change much, the pitch angle response is still very similar. The only result is that the pitch angle decreases less after the input is stopped since the flight path subsidence is less present.

A disadvantage of the new control allocation is the reduced effectiveness. The input for the normal control allocation is only 13% of the maximum control surface deflection. The new control allocation is at 75% of the maximum control surface deflection to generate the same flight path angle change in the same amount of time.

The new control allocation is expected to make the flight path angle easier to control, due to the absence of the non-minimum phase response. The handling qualities experiment will investigate whether the non-minimum phase response is degrading to the handling qualities, and whether the new control allocation improves the response of the Flying V.

E. *Cooper-Harper Pilot Rating Scale*

The handling qualities will be evaluated using the Cooper-Harper Rating Scale [16, 19]. This widely used scale uses pilot opinion, and is is presented to the pilot performing the experiment [20]. The scale is ordered around the three handling qualities levels as shown in Section I. Here a Rating 1-3 results in handling qualities Level 1, Rating 4-6 results in Level 2, and Rating 7-9 results in Level 3.

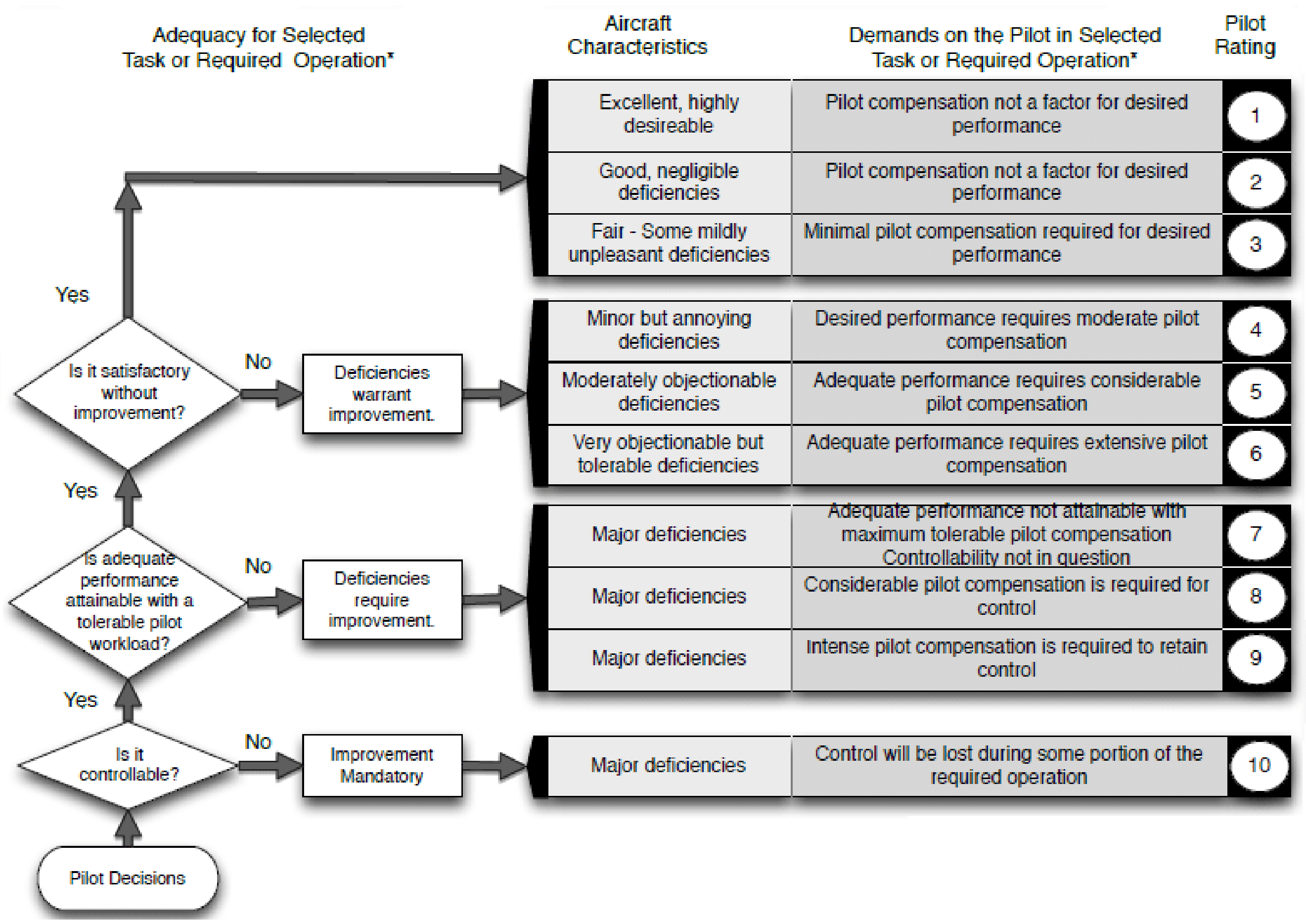

Figure 4. Cooper-Harper Handling Qualities Rating Scale [16].

The handling qualities of the Cooper-Harper Handling Qualities Rating Scale (CHRS) are subdivided in three categories, with the addition of a rating for an uncontrollable aircraft. The handling qualities scale is a subjective scale in which pilots give their rating of the handling qualities by following the flowchart shown in Figure 4. The questions on the flowchart always relate to the specific task performed.

The experiments are designed with this evaluation in mind. That means that the experiments are repeatable, and require the pilot to perform a task within desired- and adequate limits to specify the performance needed for Level 1 and Level 2.

III. EXPERIMENT DESIGN

The experiments performed will be derived from the Standard Evaluation Maneuver Set (STEMS) [5, 15], and are part of FAA's Advisory Circular [6]. The STEMS are created to help aircraft designers discover deficiencies in the handling of an aircraft. Simultaneously, these maneuvers will demonstrate the capabilities of the aircraft. The STEMS are to be used as a guideline in what type of maneuvers to test in order to demonstrate the handling qualities of the aircraft. The maneuvers are designed to demonstrate this in operationally representative scenarios. However, these maneuvers are designed for military aircraft, as are many handling qualities evaluation methods [4]. For this reason, the maneuvers are slightly adapted.

The maneuvers which are stated to accurately test the aircraft's handling qualities are the longitudinal fine tracking task and the longitudinal gross acquisition (STEM 2 and STEM 10 respectively). These maneuvers are performed at normal cruise angle of attack instead of the indicated high angle of attack. These tasks are chosen because they can easily be adapted to cruise operation of a commercial aircraft. Additionally, the STEMS maneuvers which generate handling qualities ratings by pilot opinion generally require acquisition or tracking tasks [21]. In order to benefit from both maneuvers, and generate a streamlined and easily trainable experiment for the pilots, both maneuvers are combined into one task. This task will consist of a forcing function which will follow both steps and ramps, for gross acquisition and fine tracking respectively. Combining these tasks results in an existing method used for evaluation of handling qualities for commercial aircraft [14], and part of FAA's Advisory Circular [6].

The experiment will be performed using a forcing function for the pitch angle which contains both steps and ramps. This signal will last for 100 seconds. The signal is randomly generated beforehand by letting the forcing function build up by first picking between using a ramp or a step. The size of the

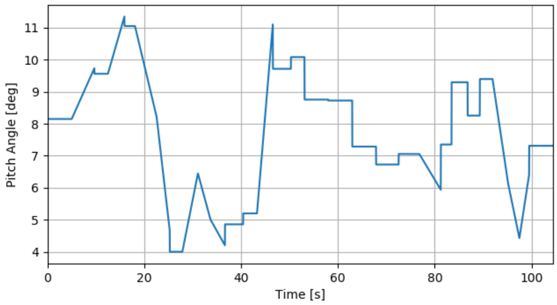

Figure 5. Forcing function of a pitch angle experiment.

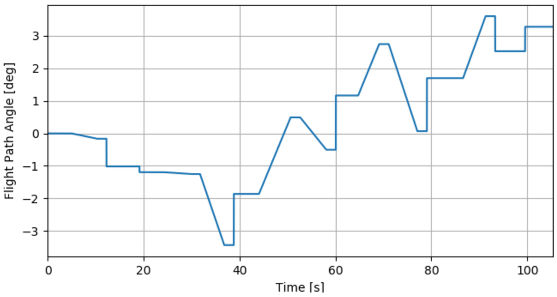

Figure 6. Forcing function of a flight path angle experiment.

step, or slope of a ramp, is then randomly chosen. The size of the step comes from a uniform distribution between negative two and two degrees. This step is held for a certain duration, which is picked from a uniform distribution between two and five seconds. A ramp will be generated in the same manner; a slope between negative two and two degrees per second, and a time between two and five seconds. The forcing function is always kept between negative four and four degrees from its starting point, which is where the aircraft is trimmed. An example forcing function is shown in Figure 5.

The pilot must match the pitch angle to this path with a set accuracy. The criterium for the STEM 2 tracking task is to be within ±0.28° for 50% of the time. The actual task will increase the desired performance window to ±0.5°. This window is similar to other handling qualities experiments [14]. However, this task is using a combination of pitch angle and roll angle targets at the same time. In order to compensate this, the desired performance mark is increased from 50% to 75%. The adequate performance for this task will be within ±1.0° for 75% of the time.

This pitch angle task is a well established way of testing handling qualities [4-6]. However, as stated in Section II the Flying V is prone to different behaviour compared to conventional aircraft due to its configuration. Therefore, a new type of experiment is needed to evaluate the flight path response of the Flying V. This new experiment will be similar to the pitch angle experiment to draw from the extensive experience in handling qualities experiments utilized in the design of this task.

Figure 7. Test setup in the SRS, photo: Frank Auperlé.

The flight path angle tracking task is an experiment where the pilot has to follow a forcing function for 100 seconds. The forcing function will start at zero degrees flight path angle, and move between negative four and four degrees. Because of the slower nature of the flight path angle compared to pitch angle, there is a limit on the rate it can take. This limit is set to 0.5 degrees per second. Additionally, when a ramp ends the forcing function will hold an angle for two seconds. This is incorporated to identify the behaviour of the aircraft when a flight path angle rate has to be stopped. The limit and hold time are set after testing and examining limited data from other evaluations involving flight path angle [22]. The steps have an amplitude between negative two and two degrees. In order to compensate this slower response, not only the maximum ramp rate is lowered, but the time the maneuvers take is also increased to four to eight seconds. The performance marks can still be kept at ± 0.5° for 75% of the time for desired performance, and ±1.0° for 75% of the time for adequate performance. An example flight path angle forcing function is shown in Figure 6.

IV. METHOD

A. Apparatus

1) Simona Research Simulator: The experiments will be performed at the Simona Research Simulator (SRS) at TU Delft. The simulator will move in 3-degrees of freedom, since the experiment is only for the longitudinal handling qualities. The pilot will sit in the right seat and use a sidestick with maximum deflection of 18° for the controls with a spring force gradient of 2.5 N/°. The outside visuals are displayed by FlightGear. The setup is shown in Figure 7.

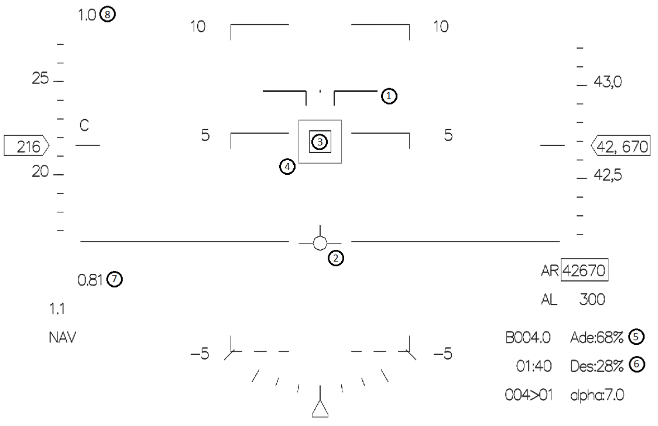

Figure 8. Display used during the experiments. ①: pitch angle, ②: Flight path angle, ③: desired performance target, ④: adequate performance target, ⑤: adequate performance score, ⑥: desired performance score, ⑦: mach number, ⑧: g-force

2) Flight Display: The display is created from an adapted F16 Head Up Display and shown on the primary flight display, see Figure 8. The display is kept as simple as possible. It shows the aircraft reference ① and the flight path angle ② on the pitch ladder. The aircraft reference is held at the same place on the display, while the pitch ladder moves behind it. In order to have the flight path angle consistently visible, the aircraft reference is placed at one third of the display height from the top. The target the pilot has to follow is also displayed on the pitch ladder.

The desired performance boundaries ③ are colored yellow and the adequate performance boundaries ④ are colored red when the controlled element is out of the boundaries. When the controlled element is within the limits, the squares turn green. This display has the option to show the scores in real time during an experiment, both adequate score ⑤ and desired score ⑥. These live scores can be used to speed up the training process by letting the pilot adjust their strategy as they are flying. The live score is only displayed during training runs. Some additional data are displayed on this screen like the Mach number ⑦ and the g-force the aircraft is experiencing ⑧. On the left hand side of the screen there is a speed indicator, and on the right hand side there is an altitude indicator.

B. Independent Variables

The independent variables are the control allocation (normal θ control allocation or new γ control allocation), the experiment types (θ or γ tracking), and the forcing functions.

Two control allocations were tested: the conventional control allocation, and the new flight path based control allocation. The conventional control allocation will also be tested in a pitch angle experiment. This yields three experiment blocks per pilot, where each pilot will perform two recorded runs.

C. Control Variables

The two different control allocations will both be tested on the same set of forcing functions. The aircraft starts in the same trimmed state at the same altitude for each task. The forcing functions have boundaries in step size and ramp steepness, as well as run-time and maximum deviation from trimmed value. Each pilot is given the same set of forcing functions in the same order during the experiment.

D. Participants & Instruction

TABLE II
EXPERIENCE OF THE PILOTS.

P1 Smaller jet aircraft	P2 USAF Test Pilot School
P3 commercial aircraft	P4 Commercial aircraft & smaller jet aircraft

Four pilots of varying experience participated, shown in Table II.

Before the experiment, the pilot received some information about the aircraft and the experiment. The briefing was sent beforehand and contains practical information, a safety video, and information about the experiment itself. The Flying V is very shortly introduced, and the general limits of the aerodynamic model are explained. The two different flight control allocations are mentioned, and the difference between the two is explained. The experiments are introduced and the limits of the forcing functions are mentioned as well as the time one forcing function takes. The separation between the training and recorded experiment runs is explained. It is followed by an explanation of the Cooper-Harper Handling Qualities Rating Scale. The experiment environment is explained, and the timetable of the experiment is shown as well as the display on which the experiment is done.

Before the experiment starts, the most important points of the briefing are repeated. This is done by following the order of the experiments, and the display. The pitch angle tracking experiment is explained, and the goal for the pilot is emphasized. The flight path angle experiment is explained, and the link to the first experiment is explained as a need for data on the behaviour between the pitch angle and the flight path angle. Finally, the new control mapping is explained. This is kept short to not bias the pilot for either system. The behaviour of the Flying V is not extensively explained. The pilot has the opportunity to ask some questions, but the answers might not be complete as to not bias the pilot.

E. Scenario

The experiment for each pilot is the same, with some minor differences in training time that was required. However, while the training time is kept flexible, the pilots will still train on identical forcing functions. Each experiment block structure is built up in the same fashion. The blocks are shown in Figure 9. Each block is estimated to take twenty minutes.

There is no block for a pitch angle task for the new flight path angle control allocation. This is because this control allocation focuses on the flight path angle. Performing a pitch angle task using this control allocation would not be relevant, as the pitch angle is used as a means to change the flight path angle for commercial aircraft.

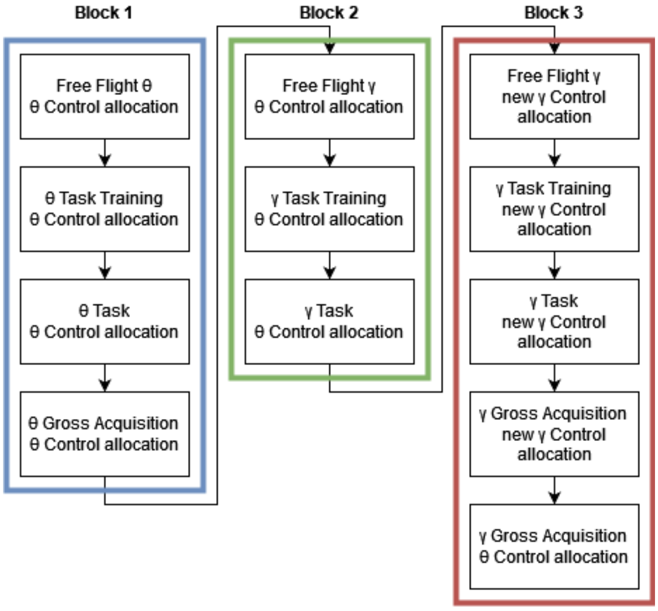

Figure 9. Block diagram of experiment timeline

The blocks are all similarly structured. The pilot is first given free flight time of 2 minutes to familiarize with the aircraft control system with the upcoming block in mind. During this free flight, the pilot is encouraged to perform gross acquisition tasks. When the pilot is done familiarizing, they are asked their first impression of the aircraft. This first impression can be used to set their initial strategy for the upcoming tasks.

After that, the pilot will perform a run with a forcing function. During this run, the pilot can see their score in real time. These training runs are done so that the pilot can set their strategy for the recorded runs. This is so that the pilot can focus on reaching the desired performance, and not more. Performing a task too aggressively can result in a different rating on the CHRS. The pilot is asked for first impressions of the task, to give a rating using the CHRS, and reason their decision. The pilot has the option to redo the same run if they think their performance could be improved opening the scale up to new ratings. The pilot is then given another forcing function, and asked the same evaluation. After this second training, given that the performance scores are on target and consistent, the pilot is asked if they are ready for a recorded run where the live score is turned off and is only shown after the experiment.

For the first recorded run of the new forcing function, the pilot has the option to redo the task without giving a rating. However, this is discouraged and only allowed if the pilot is close to a performance border, and intends to give a score for which this performance has to be met. The pilot is given two official runs, for which they give a score for each one individually. At the end of Block 1, the pilot is asked to perform some gross pitch angle acquisition tasks in normal operation with passenger comfort in mind.

After the last block, the pilot is asked to perform gross acquisition of the flight path angle using both control mappings. Again, the pilots' opinion on the behaviour of the aircraft are asked. Additionally, this also functions as a refresher for both systems in order to make the debriefing easier.

Each pilot is given the experiment in the same order by design. This is chosen because two completely new elements are introduced, which are both based upon existing elements. The flight path angle experiment is not something the pilots have done before, and neither have flown and aircraft by controlling the flight path angle. It is expected that the training time for Block 3 on itself will be long, since the pilot will have to get used to a new evaluation method and a new method of controlling an aircraft, in addition to the dynamics of the Flying V. The pilots are slowly introduced to these elements by keeping this order, and the total training time is minimized.

F. *Dependent Measures*

The pilot rating will be evaluated using the CHRS. The scale is given to the pilots to take with them in the cockpit so they can walk through the scale after every run. The pilot will indicate which rating fits best with the specific task. The pilot is asked to elaborate on their choices, and to think out loud while going through the flowchart. If the pilot is indicating a rating which mismatches with the performance, the experiment engineer will start a conversation about the rating to see if the view of the pilot lines up with the rating given. These comments the pilot makes are also recorded, as are the scores the pilot reaches. The time history of the experiment is saved so that afterwards these can be used to verify and explain the comments made.

After the experiment, the pilot is asked to give some last comments. The comments are about the capabilities of the aircraft, especially about both control mappings, and how it will fare in normal operation. The pilot is also asked how effective they think these experiments are in the evaluation of the handling qualities of the Flying V, especially the flight path angle task is spotlighted here.

G. *Hypotheses*

The expected outcome of the research can be divided in three parts. First, the longitudinal handling qualities of the Flying V in traditional sense; the pitch response. The expected result is Level 1 handling qualities, due to the good short period response. The pitch rate is not showing any undershoot, and responds quickly. Part two is the handling qualities in the flight path angle task. The expectation is that this task is more difficult, and will uncover the response shown in the offline research. The non-minimum phase response is expected to be visible in the time histories, and the pilots' comments. Due to these complications, the general outcome is expected to be Level 3. Part three concerns the handling qualities in the flight path angle task with the new γ control allocation. It is expected that this task is significantly better than the normal control allocation, and the handling qualities level will go up to Level 2, perhaps even Level 1.

V. RESULTS

The experiment was divided in three blocks, for which the results will be handled separately. The results presented here are the scores for desired performance, the Cooper-Harper ratings, and the comments made by the pilots during and after the runs. The ratings and scores are only shown for the measurement runs, but the comments made also include comments from the training and first impressions if those are relevant. Comments made outside of the specific task are highlighted by an asterisk. The experiments are identified by three symbols. The first symbol is the Control Allocation (CA) used: θ for pitch angle CA, and γ for flight path angle CA. The second symbol is for the task: θ for pitch angle task, and γ for flight path angle task. The last number is for the forcing function used. For instance, $\theta\gamma 2$ is flight path angle Task 2 using the pitch angle CA.

Note that there are some differences between the pilots. P1 was the first pilot to perform the full experiment. Afterwards, some improvements were made to the timeline and the flight path angle forcing functions. Because of this, P1 only performed one measurement run for the pitch experiment, and flew different forcing functions for Blocks 2 and 3. The "old" forcing functions for the flight path angle tasks had a higher maximum rate of change (1.0 degrees per second compared to 0.5 degrees per second). Incorporating this change meant that the forcing functions had to be regenerated for the other three pilots. Lastly, Pilot 3 accidentally did a measurement run on the wrong forcing function for a pitch task ($\theta\theta 5$ instead of $\theta\theta 3$).

A. Block 1: Pitch Angle

The percentage of time the pitch angle has been within the desired target, and the pilot ratings given based on the CHRS are shown in Table III.

TABLE III
PITCH ANGLE EXPERIMENT RESULTS

	Desired Score				Cooper-Harper Rating			
	P1	P2	P3	P4	P1	P2	P3	P4
$\theta\theta$ 3	76	89		91	1	3		1
$\theta\theta$ 4		95	94	96		2	3	1

From these results, two observations can be done: the desired score to be met is achieved by all pilots in all tasks, and the ratings they have given fall between 1 and 3. From these results alone, the handling qualities level of the Flying V for this block is Level 1. The comments the pilots made during and after the tasks are summarized below, to understand where the ratings come from. Comments Pilot 1:

- Flying more lazily than the previous run [$\theta\theta 2$],
- Flies beautifully, can play with the scores,
- Never have full deflections,

* Not an enormous short period,
* Easy to follow the target, and
* Performance of aircraft is nice, good to fly.

From these comments, it is clear to see why the rating of 1 was given. No objections about the handling qualities of the aircraft are being given.

Next are the comments of Pilot 2, who gave a rating of 3 and 2:

- Overall happy,
- Not great when the target reverses,
- Low workload, not gripping the stick too much,
- First stick position estimate for pitching down is difficult [to select pitch rate],
- Close to rating of 1 for the aircraft deficiencies,

* Can reach [pitch] rate limit, more stick gives very little extra pitch rate, and
* Can push through the rate limit found, but unhappy with deflections necessary for that.

These comments indicate that Pilot 2 also focused on how much the stick has to be deflected to achieve a desired pitch rate. They did not like to use all of the control authority available during the task. The latter two comments are an indication that Pilot 2 expected a relation between the stick position and the pitch rate. Additionally, the fact that the pilot was close to giving a rating of 1 for experiment $\theta\theta 4$ is useful for the full conclusion about these results.

Pilot 3 gave a rating of 3 for the measurement run. They mentioned during the experiment that the comments are the same as the previous task. Because of this, no comments from the actual experiment are in this list.

* Nothing unexpected at first glance,
* Little static stability in the pitch angle,
* Response is surprisingly quick,
* Was expecting more damping in the pitch angle, and
* *Comment from control room:* Looks like the pilot is experiencing some mild Pilot Induced Oscillations (PIO). Gets less with more training, but persists in the response.

Pilot 3 gave a rating slightly worse than the other pilots. This pilot also exhibited some PIO like oscillations when correcting overshoots. The behaviour of the pilot is illustrated in Figure 10 using the Mode Participation Factor (MPF). Here, the short period and flight path subsidence are oscillating. This is because the modes are starting and ending in quick succession due to stick inputs given by the pilot. This however got less prominent with more training.

This run can also be compared to P2. Especially since Pilot 2 mentioned the low workload, while Pilot 3 mentioned the need for more damping. This difference can also be seen in the MPF of P2, in Figure 11. This plot is smoother for both the short period MPF and the flight path subsidence MPF.

Lastly to Pilot 4, who gave a rating of 1 for both experiments:

- Good for the task,
- Overcontrolling when ramp down changes to ramp up,
- No problem, even with the ramp reversal a Level 1,
- Nothing in the behaviour the pilot would like to be changed,

* Very precise and stable, seems very clean,
* Very direct, feels like a fighter aircraft,
* Feels very crisp, but looks more direct because of relatively small pitch ladder range, and
* Very direct, very precise in pitch control.

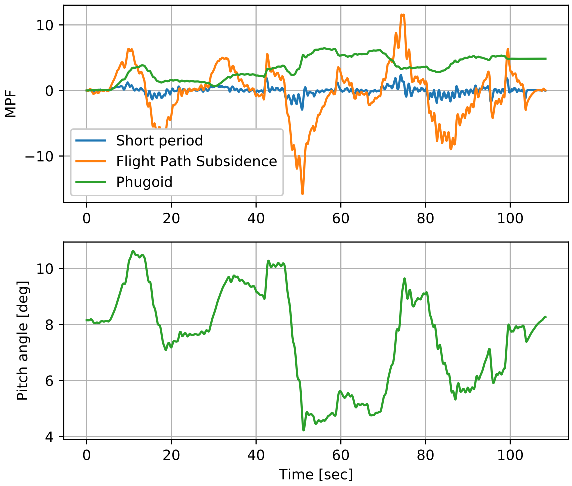

Figure 10. MPF and pitch angle of P3 during experiment $\theta\theta4$

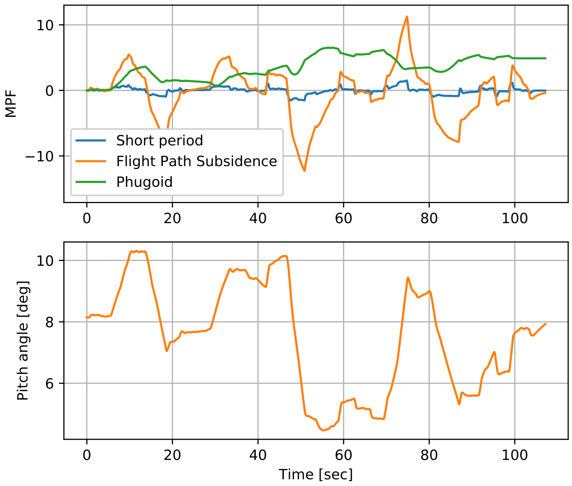

Figure 11. MPF and pitch angle of P2 in experiment $\theta\theta4$

Pilot 4 gave ratings of 1, which is in line with the positive comments that accompany the ratings given.

The conclusion which can be drawn from the results of Block 1 is that the Flying V will fall within Level 1 handling qualities for the pitch attitude control, with the conditions evaluated in this task.

B. Block 2: Flight Path Angle Normal Control Allocation

The percentage of time the flight path angle has been within the desired target, and the pilot ratings given based on the CHRS are shown in Table IV. The asterisk indicates that a different forcing function was used.

Two observations can be made: pilots have more difficulty with the task, as the desired score is met only twice. The adequate score was met by all pilots. The task is also more difficult to fly, as the ratings are lower. The conclusion is that the handling qualities are of Level 2. Now it is important to look at the comments the pilots made during the runs. Note that P1's flight path angle experiments had different forcing functions where the maximum ramp steepness was higher. Therefore, the comments, ratings, and scores from P1 are discarded.

TABLE IV
FLIGHT PATH ANGLE EXPERIMENT WITH NORMAL CONTROL ALLOCATION RESULTS

	Desired Score				Cooper-Harper Rating			
	P1	P2	P3	P4	P1	P2	P3	P4
$\theta\gamma$ 3	71*	77	71	76	6*	5	6	4
$\theta\gamma$ 5	73*	68	67	74	6*	6	6	5

P2 gave a rating of 5 and 6. Note that due to an error in the simulator the scores were visible during the run for P2 in task 3.

- Unconsciously setting a θ angle and wait for the γ to catch up. A lot of anticipation because of this,
- Getting more used to this way of flying,
- Feels very sloppy and laggy,
- Bigger overshoots,

* Able to hit the scores, but do not like this way of flying,
* Harder to keep up with rates, and
* More workload.

These comments mention a higher workload, that the controls feel sloppy, and are lagging. The comment about larger overshoots indicate deficiencies in the aircraft response. These comments fit well with a rating of 5 and 6.

Pilot 3 gave a rating of 6 to both tasks. This pilot had difficulty adjusting to the new task, and therefore needed an extra forcing function to train on.

- Difficult due to task,
- Slow system,
- Flying with high gain and getting a lot of overshoot,
- Very difficult,

* Flight path angle is very slow in response to stick inputs,
* Very different from pitch angle response,
* Difficult, pitch angle necessary is very high,
* Response is slow, over-corrections,
* This task makes you over-correct, makes it almost feel unstable due to this, and
* *Comment from Control Room:* corrects late, which creates oscillation looking like PIO.

These comments indicate that the pilot was having difficulties with this block. The overshoots and over-corrections mentioned make the workload high. Desired performance was not met by this pilot in either run. This corroborates the score of 6, which is characterized by extensive pilot compensation, and very objectionable deficiencies. In addition, the pilot is correcting late which creates large overshoots which are then corrected late again. These oscillations look as if the pilot is experiencing PIO. The effect this has during task $\theta\gamma3$ is shown compared to P4, who gave a score of 4 for this task, in Figure 12.

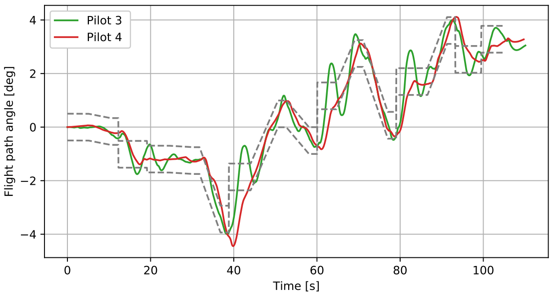

Figure 12. Results of P3 and P4 of task $\theta\gamma 3$. The gray dashed lines indicate the desired performance boundaries.

Pilot 4 gave a rating of 4 and 5 in this block, and was consistent in the desired scores for these tasks. Pilot 4 commented the following:

- When steps get bigger, the task gets harder,
- Task more difficult, anticipation needed is harder,
- Score of 4 or 5 for this task,
- Was flying less aggressively,
- Thought it went better than last time in $\theta\gamma 3$,
- Steps are difficult, ramps are easy. Still nice to fly aircraft,
- Could retry to get one percent extra, but it would not change the rating given,

* Expected more difficulty with this task,
* Need to know the change in flight path angle for the change in pitch angle,
* As expected a bit harder to control,
* Can be anticipated, but harder,
* More relevant task than pitch angle,
* Flight path angle can be precisely controlled, but it is more difficult,
* Has overshoot tendencies, and
* Larger flight path changes have more risk of overshooting.

Pilot 4 found this task easier compared to other pilots, which is also reflected in the comments and ratings. However, the pilot found the task is more difficult compared to Block 1. Pilot 4 commented during the test that it is more relevant than the pitch angle task from Block 1. They further commented that they were picking between a score of 4 and 5 for task $\theta\gamma 3$, and that a higher desired score in $\theta\gamma 5$ would not have changed the rating given.

The results of Block 2 are summarized by the following: The handling qualities of the Flying V in flight path angle control are of Level 2 for the conditions tested in the task. The experience from the pilots differs at times, some comments are about the overshoots the aircraft has in this mode while others are more focused on the workload that comes with it. However, no comments are made about the non-minimum phase response in the flight path angle, while it was present. The response is seen in the task shown in Figure 12 at the first input. This is zoomed in in Figure 13. The flight path angle is clearly rising after a positive input is given by both pilots at 12.5 seconds. It was more present for larger inputs, as given by Pilot 3.

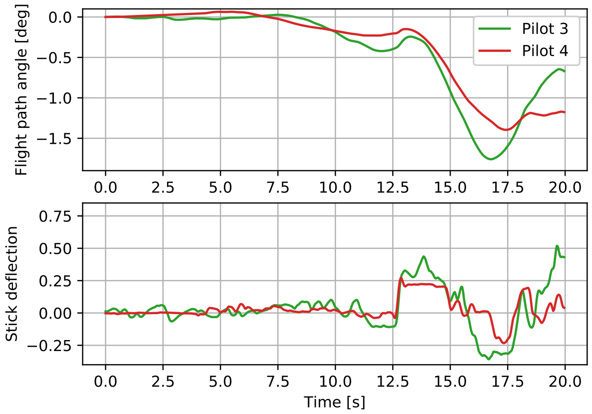

Figure 13. Results and input of P3 and P4 of the first 20 seconds of task $\theta\gamma 3$

C. Block 3: Flight Path Angle New Control Allocation

The percentage of time the flight path angle has been within the desired target, and the pilot ratings given based on the (CHRS) are shown in Table V. The asterisk indicates that a different forcing function was used.

TABLE V
FLIGHT PATH ANGLE EXPERIMENT WITH NEW CONTROL ALLOCATION RESULTS

	Desired Score				Cooper-Harper Rating			
	P1	P2	P3	P4	P1	P2	P3	P4
$\gamma\gamma$ 3	72*	78	89	80	6*	5	2	3
$\gamma\gamma$ 5	76*	70	82	81	4*	6	2	4

These results show more variations as compared to the previous two experiment blocks. This means that no direct conclusions can be derived from these results only. The only observation is that the pilots had higher desired scores for most runs compared to Block 2. The differences between the ratings can be found in the pilot comments to see why these scores were achieved. Therefore, the comments of the pilots will again be looked at. The comments, ratings, and scores from Pilot 1 are again discarded due to the different forcing functions flown.

Pilot 2 gave a rating of 5 and 6 for these tasks, while only reaching the target once. This pilot commented the following.

- *During the experiment:* “It is just hard.”,
- Difficult to get the closing rate,
- Initial guess of flight path rate always too low,
- *During the experiment:* “Do not like it.”,
- Even bigger deflections,
- Not able to catch up to the target and overshot,

* Deflections need to be even bigger for similar rates,
* Amplitude of overshoot has decreased,
* Tracking is easier, but deflections are more,
* Hit the forward [sidestick] stop when going nose down once,
* Captures not harder, closure rates smaller but makes deflections large, and

* Reached stop, is very objectionable deficiency.

Pilot 2 found the task easier, and the objections from the previous control allocation ——large overshoots, high amount of compensation needed—— are much less prominent. The pilot does have a clear aversion for the slower system. The fact that a forward stop (maximum push on the stick) was reached was very objectionable. This means that this pilot has a preference for a less damped but more maneuverable system. There are clear improvements to the task performance, but the slower system is strongly disliked.

Pilot 3 gave the rating of 2 for both tasks. The performance scores are also significantly higher compared to the normal control allocation tasks. The comments are as follows:

During $\gamma\gamma3$: “Steering nicely.”,
- Can give aggressive inputs because of the large damping,
- Nice to fly, relatively high damping during task. This gives confidence,
* First impression is much easier to control,
* More damped system,
* Better configuration,
* Can reach much higher scores, and
* More damping, less overshoot.

On first sight, these comments and scores seem to contradict P2. However, they are among similar lines upon further inspection. Pilot 3 also mentions the slower, more damped system, which is due to the lower overshoots. These comments reveal more about the personal preference of the pilot. Whereas Pilot 2 mentioned the high deflections as an objectionable deficiency, Pilot 3 does not mention it and gives the system a rating of 2 for both measurement runs. P3 clearly shows a strong preference for this system compared to Block 2.

Pilot 4 gave a rating 3 and a 4 while reaching the desired scores both times. The comments are as follows:

- Was more aggressive, less compensation compared to task $\gamma\gamma2$,
- Stops reached three times, an easy controller [during $\gamma\gamma3$],
- Full stick deflection for every step [during $\gamma\gamma5$],
- Feels like more control is needed,
- Not satisfactory anymore because the stop was hit,
- Catching the target is easy,
* A bit sluggish, need a lot of input to change flight path angle,
* Can see how this is easier,
* Easy to require a lot of stick input,
* Much more precise flight path angle control,
* Large pitch angle changes feels weird,
* Very good controller, pilot compensation is not a factor,
* A lot of input is required, using a lot of the input capacity,
* Aircraft highly desirable for this task, and
* Seems to lack authority for operation.

The last pilot is clear in one thing: the task is significantly easier with the γ control allocation compared to θ control allocation. Reaching the stop was also undesirable for this pilot.

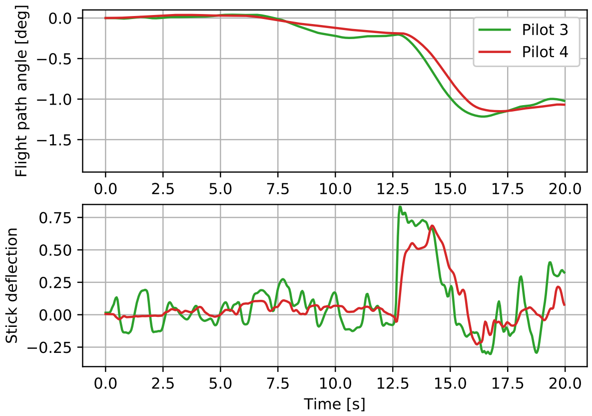

Figure 14. Results and input of P3 and P4 of the first 20 seconds of task $\gamma\gamma3$

The results of Pilot 3 and Pilot 4 are compared for the measurement run $\gamma\gamma3$ in order to see if the non-minimum phase response seen in Figure 13 is solved in the new control allocation. The results of the first 20 seconds for the new control allocation are shown in Figure 14. The dip indicating the non-minimum phase response is not present at 12.5 seconds into the run in this task.

The conclusion to be drawn for this block is more difficult. Personal preference of the pilots is more influential in this task. P3 for instance, who already gave relatively large inputs in the normal control allocation, rated this system higher compared to the other system, and other pilots. P2 on the other hand, had a flying style where the inputs were smaller. This resulted in lower ratings for this control allocation for Pilot 2. Overall, the new control allocation makes the task of following a flight path easier. However, the lower control authority is a problem for most pilots.

D. *Comments After Experimental Runs*

After the experimental runs, the pilots were asked questions about the overall handling qualities of the Flying V, and their opinion of the experiment to assess the handling qualities. The pilots were asked about the aircraft in normal operation, and the differences they found between the control allocations. They were asked about the suitability of the different tasks to assess the handling qualities.

Pilot 1 commented the following:

- Flight path control system (new control allocation) is a lot sloppier,
- Did not find too many differences between the control allocations,
- These tasks are not something which a pilot would do in normal operation. Level change would be more relevant,
- Pitch angle is more logical, flight path is more the outcome of the pitch attitude handling qualities, and
- Would be even more relevant if the flight path angle experiment would be flown on the rate of descend or rate of climb. This is how pilots usually fly their aircraft. Useful to consult a pilot with experience in flying on flight path indicator.

These comments indicate that there is not too much difference between both control allocations. This is also something which was seen in the results, and part of the reasons why the forcing function was changed for the other experiments. Additionally, the pilot mentions that the task of following a flight path angle is not relevant. Rather an experiment about the rate of climb or descend would be operationally relevant. However, both indicators are driven by the same dynamics, especially since the thrust is set in this experiment. Overall, the pilot was happy with the way the aircraft flies. Especially the pitch control was easy and highly rated by this pilot.

Pilot 2 commented the following:

- In normal operation, the normal control allocation is better,
- Normal control allocation is expected and much like a conventional aircraft. Nothing strange,
- Inexperienced pilots are able to fly the normal control allocation. The new control allocation would require extra training,
- Overshoot is something pilots are trained on. This is easy to overcome as pilot. A sluggish system, like the new control allocation, cannot be compensated by pilot inputs,
- Pitch angle experiment is only short period evaluation,
- Did not see too much difference for only flight path angle control for the normal control allocation, and
- Flight path angle task very useful tool for Flying V, not too much for conventional aircraft.

Pilot 2 mentions that the normal control allocation is better because of the training pilots get. They can compensate for overshoots, but cannot compensate for a system which is limited in its rate of change it can give. This pilot mentioned the task for the flight path angle tracking as being an asset for the evaluation of the Flying V.

Pilot 3 commented the following:

- Pitch angle control is fine, but lacking some damping,
- Flight path angle is not doable with the normal controller. Damping is lacking too much and task is challenging,
- New control allocation looks a lot like a real aircraft. Much more damping and can give much larger inputs, and
- Flight path angle tasks are very useful and reveals a lot about the handling of the aircraft, and show the difference between the systems very clearly.

Pilot 3 is clear in their preference for the new control allocation system. The pilot also mentions the flight path angle experiment as useful in identifying the handling qualities of the Flying V. It is interesting to note that this pilot found the new control allocation to be the most like a conventional aircraft, while the other pilots indicated the opposite.

Pilot 4 commented the following:

- If this is how the Flying V behaves, it is very pleasant,
- Very precise control in pitch angle, even better than some much smaller aircraft,
- Flight path angle needs more anticipation,
- The new control allocation is better for flight path angle control,
- Still prefers the normal control allocation,
- The flight path experiment is a useful addition,
- Task is on the limit of the aircraft, and
- Precise pitch angle control is also very useful to know.

Pilot 4 is positive about the handling of the aircraft. The pitch angle behaves favorably, while the flight path angle requires more pilot input. Interesting to see is that the pilot states that the flight path angle task is easier with the new control allocation, but they still prefer the normal control allocation. This again indicates that pilots rather have more control authority than higher damping.

All pilots gave comments along similar lines. They find the handling qualities assessment is improved by the flight path angle experiment, especially for the Flying V. The pilots also find the flight path angle task easier with the new control allocation, but most still prefer the normal control allocation.

All pilots were asked if they missed something during the evaluation. For instance some behaviour the aircraft exhibits was not reflected in the tasks, or some expected differences with conventional aircraft that were not highlighted by this experiment. All pilots commented that the tasks give a complete image of the longitudinal handling qualities of the Flying V in cruise conditions.

VI. DISCUSSION

This research investigates the longitudinal handling qualities of the Flying V aircraft in cruise condition. The hypothesis for this objective contained three parts.

A. *Part one: Traditional Handling Qualities*

Part one concerns the longitudinal handling qualities of the Flying V in traditional sense, the pitch response. The expected result is Level 1 handling qualities, due to the good short period response. The pitch rate is not showing any undershoot, and responds quickly.

All pilots rated the handling qualities of the aircraft during this experiment block within Level 1. Pilot 3 did indicate a lack of damping for the pitch angle, but still rated the aircraft in Level 1. Overall, no clear need for improvements to the aircraft characteristics were identified. This experiment already showed some differences between the pilots, as shown in Figure 11 and Figure 10. Pilot 3 is deflecting the stick in short increments which initiates and terminates the eigenmodes, especially the short period, repeatedly. Pilot 2 is deflecting the stick and trying to get a pitch rate to hold. Pilot 2 is correcting for this later. The strategy of Pilot 2 works better for this task, as shown by their respective scores and ratings in Table III.

B. *Part Two: Handling Qualities in the Flight Path Angle Task*

Part two considers the handling qualities in the flight path angle task. The expectation is that this task is more difficult, and will uncover the response shown in the offline research. The non-minimum phase response is expected to be visible in the time histories, and the pilots' comments. The general outcome is expected to be Level 3.

The results show something different. First, the pilots rated this system in Level 2 instead of Level 3. This means the deficiencies found in the offline analysis were not detrimental, and the pilot workload and performance were still tolerable and adequate. Second, the pilots did not notice the non-minimum phase response as much as was expected. As shown in Figure 13, the dip does exist but is more visible when the difference in input is large. This means it is seen when the input is reversed, like P3 does, instead of started, like P4 does. This will then be identified as an overshoot of the previous input instead of out of phase behaviour of the current input. As mentioned after the experiment by P2, pilots are taught how to deal with overshoots. The dip P4 generates here is also too short and low to notice next to all the other behaviour. Additionally, the pilots slowly increased their input most of the time in contrast to a sudden step input. This resulted in a much less prominent dip in the response.

The combination of these two factors result in the fact that the dip in the response was never mentioned by the pilots. This unexpected result also extends to the handling qualities level, which was rated in Level 2.

C. Part Three: Handling Qualities in the Flight Path Angle Task With New Control Allocation

Part three concerns the handling qualities in the flight path angle task with the new γ control allocation. It is expected that this task is significantly better than the normal control allocation, and the handling qualities level will go up to Level 2, perhaps even Level 1.

The expectations of the handling qualities of this task were correct. The control allocation was effective at changing the response to minimum phase. The dip indicating non-minimum phase response was seen in the normal control allocation in Figure 13, while it was not found while following at the same forcing function with the new control allocation in Figure 14.

While minimum phase response was achieved, making the response better and the task easier to follow, most pilots still preferred the normal control allocation. The interesting part is that most pilots gave similar ratings in Block 2 and Block 3, but for different reasons. Only Pilot 3 saw clear improvement from the new control allocation. The reasons for low ratings in Block 2 were the aircraft behaviour and the workload for the pilot. The reasons for low ratings in Block 3 were lowered control authority and the need to give maximum stick deflections. The difference between the deflections is also seen by comparing Figure 13 and Figure 14. The initial input given to decrease the flight path angle is around 2.5 times as high for the new control allocation compared to the normal control allocation. Therefore, the main downside of the new control allocation is the lowered control authority for the pilots. Most pilots still want to have more control over the aircraft attitude, even if that makes the response more difficult.

To summarize these results: the longitudinal handling qualities of the Flying V in cruise conditions warrant some improvement, but adequate performance is attainable with tolerable pilot workload with the normal control allocation. The new control allocation can improve slow flight path angle based tasks, but is overall not preferred by pilots because of the lowered control authority that comes with it.

However, the validity of these results depend greatly on the model used. As stated in Section II, the model is created at a non-trimmed state far from the operating states, especially the angle of attack. This questions whether the behaviour of the Flying V is comparable to the behaviour the pilots experienced during the experiments. Especially the reliance of the new control allocation experiments, which needed high deflections to be effective, is questionable. Effects like flow separation or extensive drag forces are expected to play a role in this control allocation, but are left out by the aerodynamic model used.

D. Recommendations

The initial recommendation is to use the base of the new control allocation to counteract the slow response of the flight path angle in a flight control system, while trying to increase the control authority.

More research is needed on the handling qualities of the Flying V. More flight conditions should be investigated, for instance the departure, climb, descend, approach, and landing. The handling qualities should also be extended to include all six degrees of freedom. Next, the aerodynamic model should be improved, and the high angle of attack in cruise flight should be investigated.

Last, a recommendation is to use the flight path angle experiment in more handling qualities evaluations. This new task for commercial aircraft is more relevant than the pitch angle tasks performed now, and can identify difficult to compensate aircraft behaviour which otherwise would be missed.

VII. CONCLUSIONS

Based on the current model, the longitudinal handling qualities of the Flying V in cruise conditions are expected to be Level 1 for pitch angle control, and Level 2 for flight path angle control. A new control allocation, where the control surfaces deflect in opposite directions to negate the flight path effect due to lift change at the control surfaces, can lower the pilot workload and increase performance for the flight path angle task. However, pilots still prefer the normal control allocation for its higher control authority in both pitch angle and flight path angle. It is recommended to use the techniques of the new control allocation for a flight control system.

The flight path angle control was tested by a novel task where the pilot had to follow a flight path angle tracking signal which moves by steps and ramps. This task was deemed a valuable asset in the evaluation of handling qualities of commercial aircraft for its increased operational relevance.

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II

Preliminary Thesis - This preliminary thesis has already been graded.

1

Introduction

The Flying V is a newly designed aircraft which has the potential to be aerodynamically 25 percent more efficient compared to conventional aircraft of similar passenger capacity [1]. This revolutionary new design is a flying wing, which means that the fuselage is incorporated in the wings of the aircraft. However, this new aircraft behaves differently from conventional aircraft in many aspects. Most notably, the aircraft does not have a tail, and thus no tail surfaces which can be used to control the Flying V. This affects the longitudinal handling qualities a lot, since that control is usually done from the horizontal tail surface. The Flying V has its longitudinal control surfaces (elevators) on the main wing, combined with the rolling control surfaces (ailerons). These elevons are very large relative to the elevators on a conventional aircraft, and the distance to the rotation point is roughly half as long (20m compared to 40m) [2, 3]. This means that the elevons have to create a much larger force to generate the same moment in order to achieve the same new pitch angle.

The main purpose of this research is to evaluate the longitudinal handling qualities in cruise condition of the Flying V aircraft. This report focuses on the analytical evaluation of the longitudinal handling qualities, and to prepare a plan for a test in a simulator to evaluate the handling qualities by pilot opinion. Herein, the model is analysed in its non-linear form. It is linearized, and the analytical handling qualities are determined using a very rudimentary flight control system and eigenmode analysis. The preparations for the experiment are made, and planned in broad lines.

This report will start with in introduction on the Flying V, and the work done so far in chapter 2. This is followed by chapter 3 where the aerodynamic model interpretation, where the use, limitations, and applicability of the aerodynamic model are discussed. This also includes a short introduction to the test environment, the Simona Research Simulator. In chapter 4, the model is linearized and the eigenmodes are investigated. chapter 5 explains the design of two flight control systems, and evaluates the open loop handling qualities of the Flying V. Finally, chapter 6 lays the experiment out in broad lines.

2

The Flying V

This chapter will focus on the Flying V aircraft, which is in development by TU Delft and Airbus. The first idea for this design was introduced by J. Benad at the Berlin University of Technology in collaboration with Airbus [1]. He first introduces the concept of merging two single isle aircraft fuselages together in a V shape. This design resulted in a ten percent increase in L/D, and a two percent weight decrease relative to the Airbus A350-900, and aircraft with similar passenger capabilities and an identical cruise speed. Benad also claims lower noise due to shielding of the engines towards the ground, and a simplicity of configuration as no high lift devices are needed. This promising design was later picked up by Delft University of Technology in collaboration with Airbus and KLM.

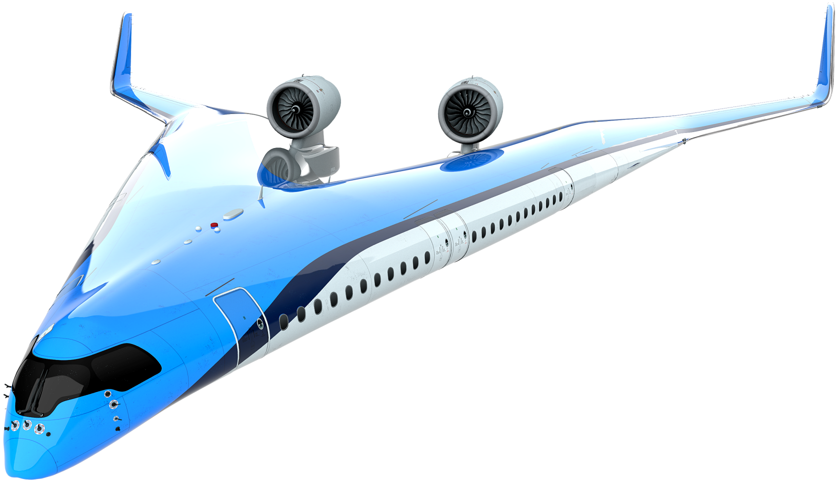


Figure 2.1: Flying V [4]

2.1. First Design Stages

In the first TU Delft study, the aerodynamic design of the Flying V has been further analysed, and it was concluded that an increase in L/D ratio relative to the reference aircraft of 25% could be achieved [5]. In order to optimize the cabin space available for payload, the concept of the dual-tube fuselage (where two cylindrical fuselages are arranged in a V shape) is replaces by an oval cabin concept [6]. In this oval, various constant-curvature arcs are adjoined. This structure is feasible and beneficial to cabin volume efficiency, as well as planform design flexibility. This structural concept was evaluated by performing a structural analysis and mass comparison to the reference aircraft (A350-900) [3]. This was performed to evaluate the feasibility of the Flying V aircraft by performing a mass estimation and structural sizing by making a comparison to the reference aircraft. The result is a structural model of the Flying V, and a mass estimation which indicates that aircraft will be lighter than its competitors. Additional research on the placement and influence of the engines was performed [7]. It was concluded that a misplaced engine could reduce the lift over drag ratio by up to 55%. The optimal position, a region behind the airframe's trailing edge, was found where the aerodynamic efficiency loss at 10%. In addition to that, this placement provides a minimum one-engine-inoperative yawing moment, and a small engine induced pitching moment. To quantify this, a scale model is used to evaluate the effect of the engine on the aerodynamic properties of the wing [8]. This is done with a 4.6% scale half model of the Flying V. The influence of the landing gear is researched by analysing two designs [9]. The first design has a landing gear of 5.5 meters. Because the aircraft is a flying wing, and thus has no lower fuselage part or dihedral, it has to have relatively high landing gears. This results in an increase of 20% in landing gear mass. The second design increases the dihedral of the aircraft to allow the landing gear to be as short as possible, resulting in a landing gear mass which is 4% lower compared to reference aircraft. The consequence of this is a significant increase in rolling moment due to sideslip, which impacts the dutch roll performance of the Flying V.

2.2. First Testing Phase

The next step in the design of the aircraft is a scale model to perform aerodynamic testing. The 4.6% scale half model is created for the experimental aerodynamic analysis [10]. This analysis reveals the maximum lift coefficient. In addition to that, it is found that the model is statically unstable in its pitching at an angle of attack higher than 19 degrees. This experiment also revealed that the effectiveness of the control surfaces hardly deteriorate with increasing angle of attack. This research was verified, with some additional experiments [11]. This experiment verified the maximum angle of attack where the Flying V is still stable, as well as the maximum lift coefficient. Furthermore, it identified the stable range for the centre of gravity, as well as its optimal position at 13.65 meters behind the nose. In addition to this, the stall speed was identified. The aerodynamic model of the Flying V 4.6% scale half model is identified [12]. These models can be used to determine the aerodynamic forces on the Flying V at any flight condition, as long as it is within the scope of the model. With these models, an engine setting and trim routine was created for different flight path angles and flight speeds. This results in a safe flight envelope for the aircraft. In addition to that, the feasible range for the centre of gravity was calculated using the model to ensure stability and controllability. From this research, a non-linear model of these characteristics are developed using experimental data. This same 4.6% scale half model is used to evaluate the longitudinal static stability and control characteristics of the Flying V [13]. Here, the model is used to identify the pitching behaviour and effectiveness of the control surfaces for a large range of angles of attack. This analysis identified the first iteration of the flying and handling qualities, and prompted the need for further research in this area. The results of these models is what lead to the need for further research in the handling qualities of the Flying V.

2.3. Handling Qualities Evaluation

In collaboration with Airbus, a MSc thesis project on the handling qualities of the Flying V was performed [2]. Here, the handling qualities of the Flying V are evaluated numerically using a model generated from Airbus' in-house software 'Odilila'. These models have three different versions, which correspond to different CG positions. The CG was placed at the reference CG position (55% MAC), the most forward CG position (45% MAC), and the most aft CG position (57.5% MAC). The handling qualities are evaluated by using a state space model generated using this aerodynamic model to generate the forces and moments. The model will be introduced extensively in chapter 3. This aerodynamic model will be used in this thesis for all analysis and simulation. All these theses and performed research described above allow for the needed data to start the thesis. Of the research, the most usable result for this thesis is the aerodynamic model [2], and the structural design combined with the accurate engine placement [3, 8]. These both can be used to adapt the model to implement it into the Simona Research Simulator and evaluate the handling qualities using pilot evaluation.

3

Aerodynamic Model Interpretation

This chapter is about the setup of the experiment which is to be performed to determine the handling qualities of the Flying V aircraft using pilot evaluation. The model used for the simulation is discussed, and its uses and limitations are determined. The model used in the experiment is an aerodynamic model generated from a parametric model previously produced at Airbus [2]. First, the structure of this model is discussed. Next the application of this model is laid out by discussing the flight dynamics. This transforms the aerodynamic parameters into a usable aircraft model of the Flying V. Last, the trim point is calculated.

3.1. Odilila

The aerodynamic model is generated using in-house software created by Airbus, and delivered as a set of 132 aerodynamic coefficients for each of the 15 flight conditions evaluated. The 15 conditions are as follows: There are 3 different evaluations for the position of the centre of gravity; the (according to [2]) most forward and most rearward cg positions which still lie within the stability margin. In addition to these two limits, the optimal CG position was evaluated. These positions are shown in Table 3.1. Note that this is a purely aerodynamic model, and that the engine thrust is not a part of this model.

Table 3.1: CG positions in the parametric model.

CG position	Description
45% MAC	Most forward CG
55% MAC	Optimal CG position
57.5% MAC	Most rearward CG position

Each of these CG positions have been evaluated at 5 different flight velocities expressed in their mach number; 0.2M, 0.3M, 0.5M, 0.7M, and 0.8M. Of these, only the highest velocity will be used as the experiment takes place under cruise conditions. All these models are created with a set angle of attack. This angle of attack is at 2.5 degrees. The combination of the airspeed and angle of attack give the most important part of the linearization point.

The aerodynamic model consist of 132 coefficients. These coefficients can be distinguished in two ways; first by the dimensionless moment or force they contribute to. These 3 moments and 3 forces are all in the aerodynamic frame. The aerodynamic frame x-coordinate is in line with the airstream and points forwards. The y-coordinate points to the right of the aircraft, and the z-coordinate points upwards. These aerodynamic coefficients summed up, form the dimensionless force and moment coefficients of the Flying V acting in the center of gravity. This means that there are 22 coefficients per moment or force. These can then be divided in two parts since every coefficient has a cross-term with the angle of attack, α. This angle of attack is relative to its linearization point, which is 2.5 degrees. This leaves 11 different contributors to the aerodynamic coefficients. First is a zero coefficient, which gives the forces and moments generated around the linearization point. The next value is for the sideslip angle, β. The following influence is from the rotational velocities; p, q, and r. Lastly are the control surfaces. These are 6 surfaces; three on each side. There are inboard elevons, outboard elevons, and the rudders.

These aerodynamic coefficients are then multiplied with their relevant influence, and summed up to form the dimensionless force or moment coefficient. The structure of the coefficients is identical, only the full formula for C_X can be seen in Equation 3.1. Note that α here is meant as the change in angle of attack relative to the linearization point (2.5 degrees).

$$\begin{aligned} C_X =& C_{X_0} + C_{X_{0_\alpha}}\alpha + C_{X_\beta}\beta + C_{X_{\beta_\alpha}}\beta\alpha + C_{X_p}p + C_{X_{p_\alpha}}p\alpha + C_{X_q}q + C_{X_{q_\alpha}}q\alpha + C_{X_r}r + C_{X_{r_\alpha}}r\alpha + C_{X_{C1}}C1 \\ &+ C_{X_{C1_\alpha}}C1\alpha + C_{X_{C1001}}C1001 + C_{X_{C1001_\alpha}}C1001\alpha + C_{X_{C2}}C2 + C_{X_{C2_\alpha}}C2\alpha + C_{X_{C1002}}C1002 \\ &+ C_{X_{C1002_\alpha}}C1002\alpha + C_{X_{C3}}C3 + C_{X_{C3_\alpha}}C3\alpha + C_{X_{C1003}}C1003 + C_{X_{C1003_\alpha}}C1003\alpha \end{aligned} \tag{3.1}$$

Now that the dimensionless forces and moments are known, the actual forces and moments can be calculated. This is done according to Equation 3.2. There is one thing to note here; the moments are always multiplied with the mean cord ($\bar{c}$), while normal conventions call to multiply the C_L and C_N by half the span instead of the cord. However, because of the way the vortex lattice method is set up, this is all made dimensionless by the cord and never the span.

$$M_X = C_L\frac{1}{2}\rho V^2 S\bar{c} \tag{3.2a}$$

$$M_Y = C_M\frac{1}{2}\rho V^2 S\bar{c} \tag{3.2b}$$

$$M_Z = C_N\frac{1}{2}\rho V^2 S\bar{c} \tag{3.2c}$$

$$F_X = C_X\frac{1}{2}\rho V^2 S \tag{3.2d}$$

$$F_Y = C_Y\frac{1}{2}\rho V^2 S \tag{3.2e}$$

$$F_Z = -C_Z\frac{1}{2}\rho V^2 S \tag{3.2f}$$

Now that there is a method with which aerodynamic forces can be calculated according to the model generated using vortex lattice method. The next step is to use this in a flight model of the Flying V.

3.2. Application of Model using Flight Dynamics

The result of the previous subsection is a method with which aerodynamic forces on the aircraft can be calculated. These aerodynamic forces can then be used in a full flight model. This model will be created using a full 12 state system of equations of motion [14] shown in Equation 3.3. This system of equations calculates the derivative of: the position of the aircraft in three axes, the velocity of the aircraft in three axes, the rotational velocity around three axes, and the angles around three axes. All of this is in the body frame, except for the position.

$$\dot{X} = \Big(Ucos(\theta) + \big(Vsin(\phi) + Wcos(\phi)\big)sin(\theta)\Big)cos(\psi) - \big(Vcos(\phi) - Wsin(\phi)\big)sin(\psi) \tag{3.3a}$$

$$\dot{Y} = \Big(Ucos(\theta) + \big(Vsin(\phi) + Wcos(\phi)\big)sin(\theta)\Big)sin(\psi) + \big(Vcos(\phi) - Wsin(\phi)\big)cos(\psi) \tag{3.3b}$$

$$\dot{Z} = -Usin(\theta) + \big(Vsin(\phi) + Wcos(\phi)\big)cos(\theta) \tag{3.3c}$$

$$\dot{U} = Vr - Wq - gsin(\theta) + A_X \tag{3.3d}$$

$$\dot{V} = Wp - Ur + gsin(\phi)cos(\theta) + A_Y \tag{3.3e}$$

$$\dot{W} = Uq - Vp + gcos(\phi)cos(\theta) + A_Z \tag{3.3f}$$

$$\dot{p} = \frac{I_{zz}}{I^*}M_X + \frac{I_{xz}}{I^*}M_Z + \frac{(I_{xx} - I_{yy} + I_{zz})I_{xz}}{I^*}pq + \frac{\big((I_{yy} - I_{zz}) * I_{zz} - I_{xz}^2\big)}{I^*}qr \tag{3.3g}$$

$$\dot{q} = \frac{M_Y}{I_{yy}} + \frac{I_{xz}}{I_{yy}}(r^2 - p^2) + \frac{I_{zz} - I_{xx}}{I_{yy}} pr \tag{3.3h}$$

$$\dot{r} = \frac{I_{xz}}{I^*} M_X + \frac{I_{xx}}{I^*} M_Z + \frac{(I_{xx} - I_{yy}) I_{xx} + I_{xz}^2)}{I^*} pq + \frac{(-I_{xx} + I_{yy} - I_{zz}) I_{xz}}{I^*} qr \tag{3.3i}$$

$$\dot{\phi} = p + sin(\phi) tan(\theta) q + cos(\phi) tan(\theta) r \tag{3.3j}$$

$$\dot{\theta} = cos(\phi) q - sin(\phi) r \tag{3.3k}$$

$$\dot{\psi} = \frac{sin(\phi)}{cos(\theta)} q + \frac{cos(\phi)}{cos(\theta)} r \tag{3.3l}$$

These equations have a couple of notable inputs. First of all, there are the states themselves. These are received from mathematically integrating the derivatives one by one. Secondly are some moments of inertia. These are set constant and the assumption is made that the moment of inertia does not change during the flight test. Lastly are the inputs. These are the moments (M) and the specific forces (A). The moments are taken from the Odilila model and given dimension by Equation 3.2. The specific forces are taken from the Odilila model, given dimension by Equation 3.2, and divided by the mass to transform the force into a specific force. The mass and moment of ineria are taken from the model created by the MSc thesis of Cappuyns [2].

However, as stated before, the aerodynamic coefficients are calculated in the aerodynamic frame. The equations of motion, on the other hand, are expressed in the body frame. This means that the moments and specific forces have to be transformed into the right reference frame. This is done by the following set of equations in Equation 3.4.

$$F_X = F_{X_{ae}} cos(\alpha) cos(\beta) - F_{Y_{ae}} cos(\alpha) sin(\beta) - F_{Z_{ae}} sin(\alpha) \tag{3.4a}$$

$$F_Y = F_{X_{ae}} sin(\beta) + F_{Y_{ae}} cos(\beta) \tag{3.4b}$$

$$F_Z = F_{X_{ae}} sin(\alpha) cos(\beta) - F_{Y_{ae}} sin(\alpha) sin(\beta) + F_{Z_{ae}} cos(\alpha) \tag{3.4c}$$

3.3. Trim Point

This completes the equations of motion. However, a starting point has to be carefully chosen. Because the Odilila model for the forces and moments, and the equations of motion both use each other's output as an input. The starting point was chosen to take an actual trim point of the aircraft model. Since the model does not include trimming surfaces, the inboard elevons are used to trim the Flying V. This meant taking both models, finding a point where no changes happen. In order to do this, some assumptions about the trim point can be made. First of all, the position has no effect on the other states and can thus be left out for the calculation of the trim point. This leaves 9 equations. Next, the asymmetric parts of the aircraft's motion were left out. This means that the aircraft will be in level flight with no sideslip. This eliminates the equations for the sideways velocity ($\dot{V}$), the rolling velocity ($\dot{p}$), the yawing velocity ($\dot{r}$), the rolling angle ($\dot{\phi}$), and the yaw angle ($\dot{\psi}$). In addition to these equations being eliminated, the asymmetrical variables are also zero (V, p, r, ϕ, and ψ) This leaves four equations. As a last assumption the angular velocities are set to zero (p, q, and r). This eliminates the equation for the pitch angle ($\dot{\theta}$).

The equations which are left are $\dot{U}$, $\dot{W}$, and $\dot{q}$. These equations can now be simplified by leaving out the terms which are assumed to be zero as shown in Equation 3.5.

$$\dot{U} = -g sin(\theta) + A_X \tag{3.5a}$$

$$\dot{W} = +g cos(\theta) + A_Z \tag{3.5b}$$

$$\dot{q} = \frac{M_Y}{I_{yy}} \tag{3.5c}$$

These equations now hold θ, two specific forces, and a moment as their unknowns. These specific forces and moment have to be expanded first. The specific forces come from a force divided by the mass. Then the forces and moments have to be expanded from the change of reference frame as shown in Equation 3.4, the coefficients in Equation 3.2, and the aerodynamic coefficients in Equation 3.1. Because the aircraft is only trimming in symmetrical form, the coefficients for the left side and the right side are identical (i.e. $C_{X_{C1}} = C_{X_{C1001}}$. Similarly, the deflections left and right are the same ($C1 = C1001$). This all together results in Equation 3.6.

$$\begin{aligned} A_X =& \big(C_{X_0} + C_{X_{0_\alpha}}(\alpha-\alpha_0) + 2C_{X_{C1}}C1 + 2C_{X_{C1_\alpha}}C1(\alpha-\alpha_0)\big)\frac{\rho(U^2+W^2)S}{2mass}\sqrt{\frac{U^2}{U^2+W^2}} \\ &-\big(C_{Z_0} + C_{Z_{0_\alpha}}(\alpha-\alpha_0) + 2C_{Z_{C1}}C1 + 2C_{Z_{C1_\alpha}}C1(\alpha-\alpha_0)\big)\frac{\rho(U^2+W^2)S}{2mass}\sqrt{\frac{W^2}{U^2+W^2}} \end{aligned} \tag{3.6a}$$

$$\begin{aligned} A_Z =& -\big(C_{X_0} + C_{X_{0_\alpha}}(\alpha-\alpha_0) + 2C_{X_{C1}}C1 + 2C_{X_{C1_\alpha}}C1(\alpha-\alpha_0)\big)\frac{\rho(U^2+W^2)S}{2mass}\sqrt{\frac{W^2}{U^2+W^2}} \\ &-\big(C_{Z_0} + C_{Z_{0_\alpha}}(\alpha-\alpha_0) + 2C_{Z_{C1}}C1 + 2C_{Z_{C1_\alpha}}C1(\alpha-\alpha_0)\big)\frac{\rho(U^2+W^2)S}{2mass}\sqrt{\frac{U^2}{U^2+W^2}} \end{aligned} \tag{3.6b}$$

$$M_Y = \big(C_{M_0} + C_{M_{0)\alpha}}(\alpha-\alpha_0) + 2C_{M_{C1}}C1 + 2C_{M_{C1001_\alpha}}C1(\alpha-\alpha_0)\big)\frac{1}{2}\rho(U^2+W^2)Sc \tag{3.6c}$$

This expansions shows three extra values; α, α_0, and $C1$. However, since α is calculated using U and W, it is not a new variable. α_0 is the trim point of the aerodynamic model, and is equal to 2.5 degrees. This adds only the control surface deflection $C1$ to the set of variables. This means that there are now 4 variables (U, W, θ, and $C1$), but only three equations. The extra equation which is used to complete the set is the total airspeed, which is set at 0.8M (the airspeed at which the aerodynamic model was created).

Another point to note is the square root term at the end of the specific forces. This term is the worked out version of the change in reference frame. These are the sine or cosine of α expressed in U and W.

This all combined sets up the model in a realistic way, starting at a trim point. The derivatives of the states can be integrated every time step in order to run the simulation in the time domain.

4

Preliminary Model Analysis

Before predictions about the handling qualities of the Flying V can be made, some preliminary analysis can be done on the model itself. Traditionally, this analysis includes determining the eigenmodes, calculating the Control Anticipation Parameter (CAP), looking at the time response, and making a rudimentary controller to see what the pilot has to do. However, before the handling qualities can be estimated by these methods, the model has to be adapted. This is done by first linearizing the full aircraft model. This linearization is then verified, and lastly an eigenmode analysis is performed to be used in the evaluation of the handling qualities.

4.1. Linearization of Model

Before the model can be analysed, the model has to be linearized. The linearization will make it possible to perform an eigenmode analysis, which in turn is used to determine the handling qualities.

4.1.1. Method of Linearization

This is done using systems theory [15]. The model which is used, is the set of states shown in Equation 3.3. This has the form of a non-linear state space system.

$$\dot{x} = f(x,u), \tilde{x}(0) = \tilde{x}_0 \tag{4.1}$$

Here x are the states, and u are the inputs from the control surfaces. Now take a solution $\tilde{x}(t)$ with initial condition $\tilde{x}(0) = \tilde{x}_0$, and input $\tilde{u}(t)$. Then another solution is which a small distance away from the original solution and input. Call this $\tilde{x}(t) + z(t)$ which has initial condition $\tilde{x}_0 + z_0$ and input function $\tilde{u}(t) + v(t)$.

$$\frac{d}{dt}(\tilde{x} + z) = f(\tilde{x} + z, \tilde{u} + v) \tag{4.2}$$

In this context, $\tilde{x}$ and $\tilde{u}$ are the linearization point as seen in Equation 4.1. The second solution in Equation 4.2 is the point which will be calculated by use of linearization. The points z and v are assumed small such that the Taylor expansion will result in a good approximation using only the linear terms. This approximation, with higher order terms left out, is shown in Equation 4.3.

$$\frac{d}{dt}(\tilde{x} + z) = f(\tilde{x}, \tilde{u}) + \frac{df}{dx}(\tilde{x}, \tilde{u})z + \frac{df}{du}(\tilde{x}, \tilde{u})v \tag{4.3}$$

Here, $\frac{df}{dx}(\tilde{x}, \tilde{u})$ is a matrix of the partial derivatives with respect to x, and can be called A. z is a vector containing the difference in the states with respect to the linearization point $\tilde{x}$. $\frac{df}{du}(\tilde{x}, \tilde{u})$ is a matrix containing the partial derivatives with respect to u and can be called B. v is a vector containing the difference in input with respect to the linearization point $\tilde{u}$. In order to make this a usable state space system, Equation 4.1 is subtracted from Equation 4.3. This makes it a state space system for z as seen in Equation 4.4.

$$\dot{z} = Az + Bv \tag{4.4}$$

Since the output of this is the states themselves, it makes is unnecessary to elaborately construct a C and D matrix, as that would just be an identity matrix and zero matrix respectively. This is now already a linearized system, but it only shows the change relative to the starting point. This means that the new state space system does not accurately represent the aircraft on its own. However, the goal of this linearization is to perform an analysis to make prediction about the aircraft itself. This can be solved very simply. That is to take a trim state of the aircraft as the linearization point. In other words, $\tilde{x}$ and $\tilde{u}$ are chosen such that $\dot{\tilde{x}} = 0$ (except for X, Y, and Z). Now only the states have to be adjusted and the aircraft can be represented by the linearized system.

4.1.2. Linearization of the Flying V

Now that the basic theory for the linearization of the Flying V is established, the aircraft model of the Flying V can be linearized to prepare it for an analysis of handling qualities. The goal is to have a state space system in the form of Equation 4.5.

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx + Du \end{aligned} \tag{4.5}$$

This starts with the full system of non-linear equations. These are shown in Equation 3.3 in section 3.2. From this same set of equations, the same states can also be used for the linear system. The states are shown in Equation 4.6. The position states are not included in the linearized model since those states are not zero at the trim point.

$$z = \begin{bmatrix} \Delta u & \Delta v & \Delta w & \Delta p & \Delta q & \Delta r & \Delta\phi & \Delta\theta & \Delta\psi \end{bmatrix}^T \tag{4.6}$$

The next step is to find a trim setting of the Flying V which can be linearized. For this, the trim point from section 3.3 is used. Now in order to calculate the A matrix according to Equation 4.4, the partial derivatives are written out in Equation 4.7.

$$A = \begin{bmatrix}
\frac{\delta \dot{u}}{\delta u} & \frac{\delta \dot{u}}{\delta v} & \frac{\delta \dot{u}}{\delta w} & \frac{\delta \dot{u}}{\delta p} & \frac{\delta \dot{u}}{\delta q} & \frac{\delta \dot{u}}{\delta r} & \frac{\delta \dot{u}}{\delta \phi} & \frac{\delta \dot{u}}{\delta \theta} & \frac{\delta \dot{u}}{\delta \psi} \\
\frac{\delta \dot{v}}{\delta u} & \frac{\delta \dot{v}}{\delta v} & \frac{\delta \dot{v}}{\delta w} & \frac{\delta \dot{v}}{\delta p} & \frac{\delta \dot{v}}{\delta q} & \frac{\delta \dot{v}}{\delta r} & \frac{\delta \dot{v}}{\delta \phi} & \frac{\delta \dot{v}}{\delta \theta} & \frac{\delta \dot{v}}{\delta \psi} \\
\frac{\delta \dot{w}}{\delta u} & \frac{\delta \dot{w}}{\delta v} & \frac{\delta \dot{w}}{\delta w} & \frac{\delta \dot{w}}{\delta p} & \frac{\delta \dot{w}}{\delta q} & \frac{\delta \dot{w}}{\delta r} & \frac{\delta \dot{w}}{\delta \phi} & \frac{\delta \dot{w}}{\delta \theta} & \frac{\delta \dot{w}}{\delta \psi} \\
\frac{\delta \dot{p}}{\delta u} & \frac{\delta \dot{p}}{\delta v} & \frac{\delta \dot{p}}{\delta w} & \frac{\delta \dot{p}}{\delta p} & \frac{\delta \dot{p}}{\delta q} & \frac{\delta \dot{p}}{\delta r} & \frac{\delta \dot{p}}{\delta \phi} & \frac{\delta \dot{p}}{\delta \theta} & \frac{\delta \dot{p}}{\delta \psi} \\
\frac{\delta \dot{q}}{\delta u} & \frac{\delta \dot{q}}{\delta v} & \frac{\delta \dot{q}}{\delta w} & \frac{\delta \dot{q}}{\delta p} & \frac{\delta \dot{q}}{\delta q} & \frac{\delta \dot{q}}{\delta r} & \frac{\delta \dot{q}}{\delta \phi} & \frac{\delta \dot{q}}{\delta \theta} & \frac{\delta \dot{q}}{\delta \psi} \\
\frac{\delta \dot{r}}{\delta u} & \frac{\delta \dot{r}}{\delta v} & \frac{\delta \dot{r}}{\delta w} & \frac{\delta \dot{r}}{\delta p} & \frac{\delta \dot{r}}{\delta q} & \frac{\delta \dot{r}}{\delta r} & \frac{\delta \dot{r}}{\delta \phi} & \frac{\delta \dot{r}}{\delta \theta} & \frac{\delta \dot{r}}{\delta \psi} \\
\frac{\delta \dot{\phi}}{\delta u} & \frac{\delta \dot{\phi}}{\delta v} & \frac{\delta \dot{\phi}}{\delta w} & \frac{\delta \dot{\phi}}{\delta p} & \frac{\delta \dot{\phi}}{\delta q} & \frac{\delta \dot{\phi}}{\delta r} & \frac{\delta \dot{\phi}}{\delta \phi} & \frac{\delta \dot{\phi}}{\delta \theta} & \frac{\delta \dot{\phi}}{\delta \psi} \\
\frac{\delta \dot{\theta}}{\delta u} & \frac{\delta \dot{\theta}}{\delta v} & \frac{\delta \dot{\theta}}{\delta w} & \frac{\delta \dot{\theta}}{\delta p} & \frac{\delta \dot{\theta}}{\delta q} & \frac{\delta \dot{\theta}}{\delta r} & \frac{\delta \dot{\theta}}{\delta \phi} & \frac{\delta \dot{\theta}}{\delta \theta} & \frac{\delta \dot{\theta}}{\delta \psi} \\
\frac{\delta \dot{\psi}}{\delta u} & \frac{\delta \dot{\psi}}{\delta v} & \frac{\delta \dot{\psi}}{\delta w} & \frac{\delta \dot{\psi}}{\delta p} & \frac{\delta \dot{\psi}}{\delta q} & \frac{\delta \dot{\psi}}{\delta r} & \frac{\delta \dot{\psi}}{\delta \phi} & \frac{\delta \dot{\psi}}{\delta \theta} & \frac{\delta \dot{\psi}}{\delta \psi}
\end{bmatrix} \tag{4.7}$$

These partial derivatives are calculated analytically by extending the non-linear equation with the specific forces and moments, and with the angles from the aerodynamic model (α and β) written in their velocity components.

The input vector v is a little more complicated, since they are not in the equations shown in Equation 3.3. However, they are hidden in the aerodynamic model from Equation 3.1. The input vector is shown in Equation 4.8.

$$v = \begin{bmatrix} \Delta C1 & \Delta C1001 & \Delta C2 & \Delta C1002 & \Delta C3 & \Delta C1003 \end{bmatrix}^T \tag{4.8}$$

Lastly is the input matrix B. This matrix of partial derivatives of the input states is shown in Equation 4.9.

$$B = \begin{bmatrix}
\frac{\delta \dot{u}}{\delta C1} & \frac{\delta \dot{u}}{\delta C1001} & \frac{\delta \dot{u}}{\delta C2} & \frac{\delta \dot{u}}{\delta C1002} & \frac{\delta \dot{u}}{\delta C3} & \frac{\delta \dot{u}}{\delta C1003} \\
\frac{\delta \dot{v}}{\delta C1} & \frac{\delta \dot{v}}{\delta C1001} & \frac{\delta \dot{v}}{\delta C2} & \frac{\delta \dot{v}}{\delta C1002} & \frac{\delta \dot{v}}{\delta C3} & \frac{\delta \dot{v}}{\delta C1003} \\
\frac{\delta \dot{w}}{\delta C1} & \frac{\delta \dot{w}}{\delta C1001} & \frac{\delta \dot{w}}{\delta C2} & \frac{\delta \dot{w}}{\delta C1002} & \frac{\delta \dot{w}}{\delta C3} & \frac{\delta \dot{w}}{\delta C1003} \\
\frac{\delta \dot{p}}{\delta C1} & \frac{\delta \dot{p}}{\delta C1001} & \frac{\delta \dot{p}}{\delta C2} & \frac{\delta \dot{p}}{\delta C1002} & \frac{\delta \dot{p}}{\delta C3} & \frac{\delta \dot{p}}{\delta C1003} \\
\frac{\delta \dot{q}}{\delta C1} & \frac{\delta \dot{q}}{\delta C1001} & \frac{\delta \dot{q}}{\delta C2} & \frac{\delta \dot{q}}{\delta C1002} & \frac{\delta \dot{q}}{\delta C3} & \frac{\delta \dot{q}}{\delta C1003} \\
\frac{\delta \dot{r}}{\delta C1} & \frac{\delta \dot{r}}{\delta C1001} & \frac{\delta \dot{r}}{\delta C2} & \frac{\delta \dot{r}}{\delta C1002} & \frac{\delta \dot{r}}{\delta C3} & \frac{\delta \dot{r}}{\delta C1003} \\
\frac{\delta \dot{\phi}}{\delta C1} & \frac{\delta \dot{\phi}}{\delta C1001} & \frac{\delta \dot{\phi}}{\delta C2} & \frac{\delta \dot{\phi}}{\delta C1002} & \frac{\delta \dot{\phi}}{\delta C3} & \frac{\delta \dot{\phi}}{\delta C1003} \\
\frac{\delta \dot{\theta}}{\delta C1} & \frac{\delta \dot{\theta}}{\delta C1001} & \frac{\delta \dot{\theta}}{\delta C2} & \frac{\delta \dot{\theta}}{\delta C1002} & \frac{\delta \dot{\theta}}{\delta C3} & \frac{\delta \dot{\theta}}{\delta C1003} \\
\frac{\delta \dot{\psi}}{\delta C1} & \frac{\delta \dot{\psi}}{\delta C1001} & \frac{\delta \dot{\psi}}{\delta C2} & \frac{\delta \dot{\psi}}{\delta C1002} & \frac{\delta \dot{\psi}}{\delta C3} & \frac{\delta \dot{\psi}}{\delta C1003}
\end{bmatrix} \tag{4.9}$$

The C and D matrices represent what the state space system will give as a result. The output of the system are the states themselves, so the C matrix is a 9 by 9 identity matrix, and D is empty. This constructs the full model. In order to use this model, the integration of the values has to be done. This is done using the Runge-Kutta method [16].

4.2. Validation of Linearization

The linearized model is validated against the non-linear model from which it is constructed. This can be done by running both models with a variety of inputs and comparing the states afterwards. It is key to keep the goal of the model in mind, and reliably test its fidelity in the application range this research is conducted in. This means that the input for the test case should be a relevant movement. First, the generation of these inputs will be tackled. Secondly, the manoeuvre and its validation will be shown.

4.2.1. Input Generation

The input is generated for a set of tests the pilots will have to perform during the experiment. The setup for this generation is the linearized state space system with a simple PID controller to control one of the states using the inboard or the outboard elevons. This controller is roughly tuned to have the wanted motion within an acceptable time frame. The linearized state space equation from section 4.1 is put into a Simulink model to create the PID.

This model can iteratively be tuned until an acceptable response of the manoeuvre is achieved. Because the controller is very simple and only works on one state, only that state is looked at. The input of the system which is generated by this controller is then saved and exported to be the input of both the linearized and non-linear system to perform a comparison between the two systems. It should be noted that both systems will get the exact same control surface input in an open loop system, but this input is generated in a closed loop linearized system.

4.2.2. Pitch Angle Capture

The first manoeuvre to be evaluated is a pitch angle capture. This is a fundamental element of many longitudinal manoeuvres. It is also very operationally relevant [17]. During this manoeuvre the pilot starts from a stable flight path, tries to capture a target pitch angle as quickly as possible, and hold it for at least one second. The performance is desired if the aim point stays within approximately 2 degrees, and only has one overshoot. The pilot should perform multiple tests with intervals of 5 degrees. However, this manoeuvre was designed for fighter aircraft. In order to get a representative test here, the model should capture a five degree difference in pitch angle from the trim state. The four longitudinal states are then evaluated for both the full model, and the linearized model. The response is shown in Figure 4.1. The control surface deflection is shown in Figure 4.2.

There is a clear difference in the states visible in the pitch angle. Here, the linear model and the non-linear model do not converge to the same state. This is also visible in the pitch rate plot, where the linear model is reaching a value of zero, while the non-linear model is slightly lower, which results in the slope in the pitch angle state. This difference is still very small, and stems from the fact that the pitch angle of the linearized model is controlled, while the non-linear model is given the same input. This results in the small difference between the models when the target value is reached. Something to be noted is the difference in total airspeed. The difference between the two models stems from the fact that both the vertical velocity and forward velocity change, but both in different directions. This means that the total velocity changes relatively less,

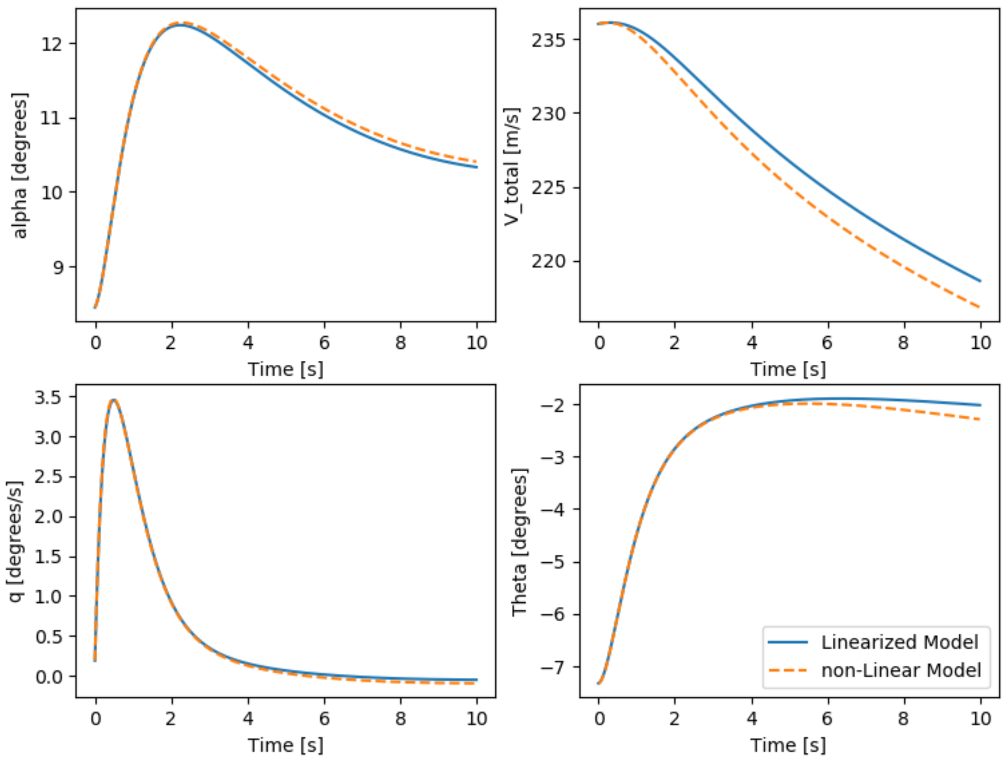


Figure 4.1: Longitudinal states response to a simulated pitch capture manoeuvre.

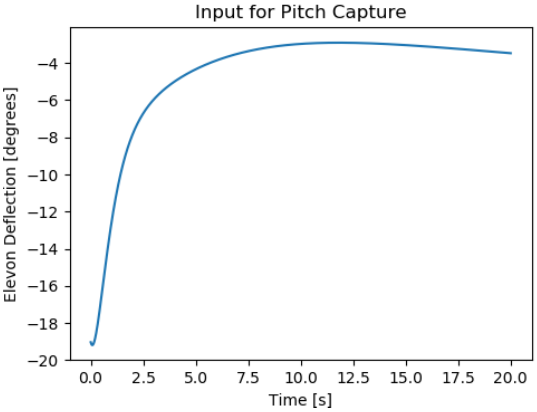


Figure 4.2: Inboard Elevon deflection used for the simulated pitch capture manoeuvre.

but the error for both is fully visible in this plot. Note that the aircraft starts in a dive, since the engine is not included in this model and thus the Flying V is in a gliding flight.

Even though this manoeuvre does give a difference between the two models, this difference is considered to be acceptable for the use of this model which is eigenmode analysis. This is also because the way the linear model will be used. The linearized model will be evaluated for its eigenmodes by using eigenshapes. In this case, the two longitudinal eigenmodes are of interest. This is the phugoid and especially the short period. The goal of this manoeuvre was to simulate the short period as clearly as possible. The clearest parts of the short period are the pitch rate, increase in angle of attack, and the increase in pitch angle itself. These parts are all very clear in the plots, and are where both models follow each other very closely.

4.3. Eigenmode Analysis

A proven way to analyse the stability and handling qualities of an aircraft, is by analyzing the eigenmodes. The eigenmodes determine how the aircraft reacts when stimulated in different directions, and different time frames. These eigenmodes are quantified by the eigenvalues and eigenvectors of the state equations. The analysis of the eigenmodes will give a static stability margin (positive or negative), a damping factor of the motions, and variables from these eigenmotions can be used to determine handling qualities by parameters such as the Control Anticipation Parameter (CAP) [18]. First the eigenvalues and eigenvectors of the linearized system are calculated. These eigenvalues are shown in Table 4.1, and the eigenvectors are shown in Table 4.2.

Table 4.1: Eigenvalues of the linearized system

λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_9
0	-4.73	-4.20	-0.32 + 0.55j	-0.32 - 0.55j	-0.53	-0.014	-0.0025 + 0.040j	-0.0025 - 0.040j

Table 4.2: Eigenvectors of the linearized system

	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9
u	0	-0.12	0.13	-5.2e-4 + 6.1e-4j	-5.2e-4 - 6.1e-4j	0.11	-0.045	-1.0 + 0j	-1.0 - 0j
v	0	0.60	0	1.0 + 0j	1.0 - 0j	0	-0.98	0 - 0j	0 + 0j
w	0	0.72	-0.99	0.0063 + 0.0032j	0.0063 - 0.0032j	0.99	0.0073	0.018 + 0.0092j	0.018 - 0.0092j
p	0	-0.32	0	-0.0015 - 9.8e-4j	-0.0015 + 9.8e-4j	0	5.7e-4	0 + 0j	0 - 0j
q	0	-0.015	0.018	-9.5e-6 + 1.4e-5j	-9.5e-6 - 1.4e-5j	-0.0011	2.0e-6	-1.6e-4 - 7.3e-6j	-1.6e-4 + 7.3e-6j
r	0	-0.038	0	0.0011 - 0.0025j	0.0011 + 0.0025j	0	-0.0026	0 - 0j	0 + 0j
ϕ	0	0.067464	0	3.8e-4 + 0.0027j	3.8e-4 - 0.0027j	0	-0.064	0 - 0j	0 + 0j
θ	0	0.0032	-0.00437	2.7e-5 + 1.3e-6j	2.7e-5 - 1.3e-6j	0.0020	-1.4e-4	7.0e-5 + 0.0040j	7.0e-5 - 0.0040j
ψ	1	0.0083	0	-0.0043 + 4.5e-4j	-0.0043 - 4.5e-4j	0	0.19	0 - 0j	0 + 0j

The eigenvectors in Table 4.2 show the relative contribution of each state to the eigenmode. The eigenmode is then again identified by the eigenvector. This way, the longitudinal motions, and their corresponding eigenshapes, can be isolated. This is done by taking the eigenmodes which are not influencing the asymmetric states (v, p, r, ϕ, ψ). These are eigenvectors v_3, v_6, v_8, and v_9. Then, the eigenvalues can be used to plot isolated responses of the eigenmotions. In a conventional aircraft, there are two longitudinal motions easily identified by the eigenshapes. These are the phugoid and the short period. Both are complex eigenvalues, with the phugoid a slow and low damped motion, while the shot period is fast and heavily damped. For the Flying V however, there is only one set of longitudinal complex eigenvalues which belongs to the phugoid.

4.3.1. Mode Participation Factor

Mode Participation Factor can be calculated from [19]. This shows how much of a certain eigenmode is present in a particular time response. In this case, it will be used the other way around where a response is designed in such a way that only a single eigenmode is present. This works by expressing the response in a different form, which shows the contributions from the inputs, states, and eigenvalues and eigenvectors.

$$\begin{aligned} r(t) &= \underbrace{e^{\Lambda t} V^{-1} x(0)}_{\text{ZIR}} + \underbrace{\int_0^t e^{\Lambda(t-\tau)} V^{-1} B u(\tau) d\tau}_{\text{ZSR}} \\ y(t) &= C V r(t) \end{aligned} \tag{4.10}$$

The first part of the equation for r is the Zero Input Response (ZIR). The second part is the Zero State Response (ZSR). The ZIR represents the response when the input is zero (or trim setting), and the states are different from the trim setting. The ZSR represents the response when the states start at trim, and an input is given.

This notation is used to see the isolated eigenmotions. This is done by using only the zero input response. Here, the starting state is multiplied by the inverse of the matrix of eigenvectors. If the starting state is chosen to be an eigenvector, the output of this part will be a vector of zeros, with a 1 at the location corresponding to the eigenvector. This means that the output of the ZIR will be the exponential of the eigenvalue.

The zero state response can be used to see which control surface affects which eigenmotion the most. Additionally, it can be calculated what the deflection has to be to perform an isolated eigenmotion using the control surfaces.

4.3.2. Phugoid Eigenshape

Of these eigenshapes, v_8, and v_9 are complex conjugates and correspond to the same eigenmotion; the phugoid. This is recognised because it is a very slow, and low damped motion (low magnitude of real and complex part of the eigenvalue). If the eigenvector is plotted to show the relative contribution, especially the phase is easily identified. This is shown in Figure 4.3. Here it is clear that u and q are in phase, with θ 90 degrees behind, and w about 180 degrees behind. From Table 4.2 the magnitudes can be seen where it is clear that u is the main contributor [20].

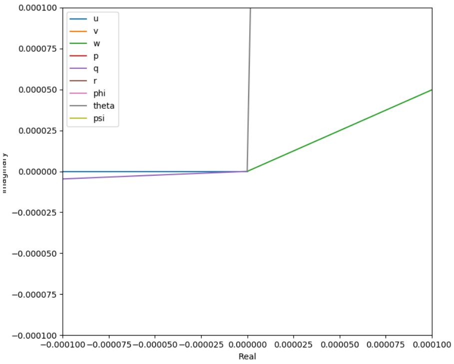


Figure 4.3: Eigenvector of the phugoid plotted

Using the isolated response following Equation 4.10, a time history can be plotted. This shows the contribution the phugoid has. This is shown in Figure 4.4. Note that this is generated by using the MPF to design a start position for the aircraft where it will only exhibit the behaviour of the phugoid.

4.3.3. Short Period Eigenshape

The identification of the short period is different. This is because the short period is not a complex set of eigenshapes for the Flying V. The eigenvalues belonging to the longitudinal motion are λ_3 and λ_6. In a conventional aircraft, these eigenvectors are a complex set representing a fast, heavily damped motion. In the

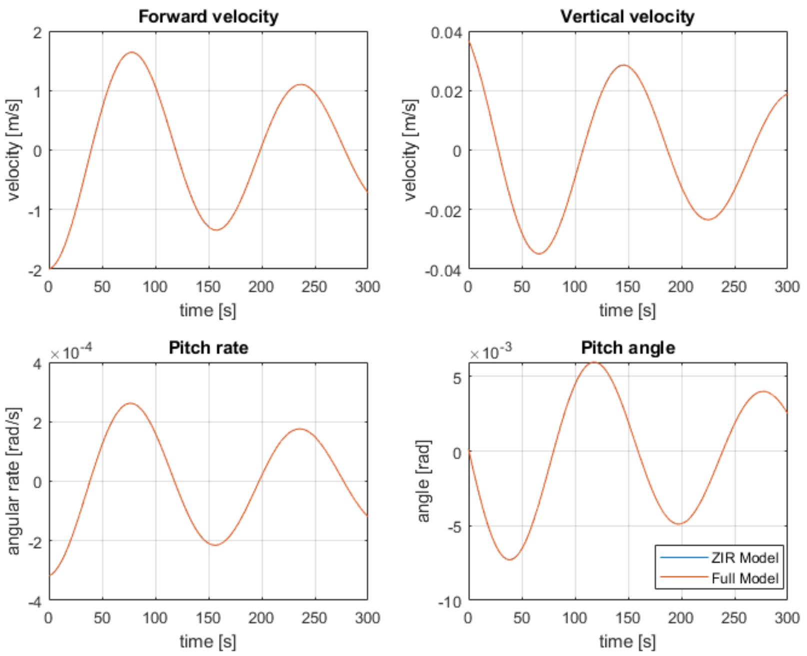
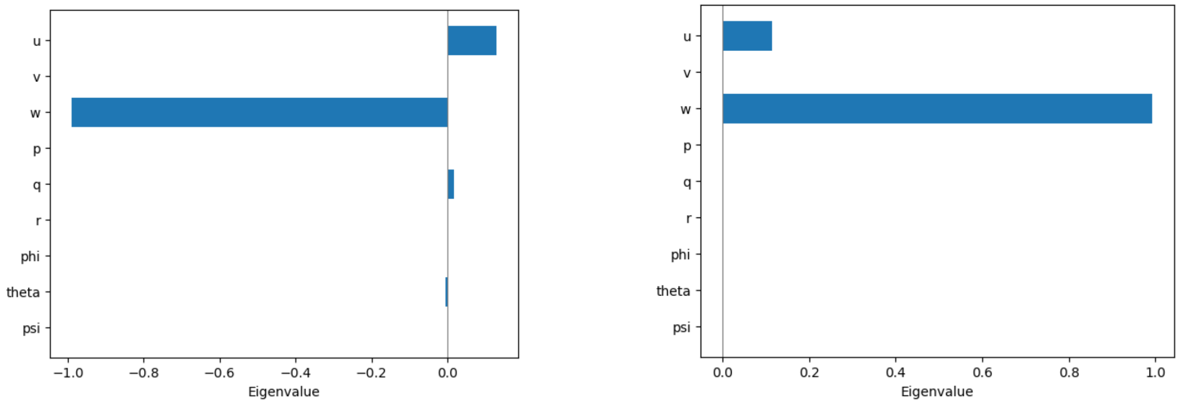


Figure 4.4: Response of the isolated phugoid motion.

Flying V, there are two real-valued eigenvalues. The eigenvalue λ_3 has a larger magnitude than λ_6. This means that the response which belongs to λ_3 much faster is compared to λ_6. This means that the motion of λ_6 will take about 10 times as long to reach its trimmed state compared to λ_3. The eigenvalues are negative, which indicates that the motion is stable.

Next is the values of the eigenvectors. The relative influence of the states on the eigenvectors are plotted in Figure 4.5. In a conventional aircraft, the contribution of w and θ is very similar in magnitude and phase, while the forward velocity barely changes. Instead there are two real eigenvectors. In order to determine what kind of motion belongs to these eigenshapes the same analysis is done as on the phugoid.



(a) Relative contributions of the states in Eigenvector v_3

(b) Relative contributions of the states in Eigenvector v_6

Figure 4.5: Relative contributions of the states in Eigenvector v_6

This motion relatively affects the pitch angle and pitch rate very little compared to the vertical velocity. So the aircraft is flying much more with direct lift control, than pitch angle control, like normal aircraft have. Because of this, the eigenmotions do not line up with the expected eigenmotions of a conventional aircraft. The motion this aircraft exhibits is much more like a heave motion found in helicopter dynamics [21]. Especially v_6 has a shape very similar to the heave subsidence of rotorcraft dynamics, as seen in Figure 4.6. The other eigenmode, which normally corresponds to the pitch subsidence, is not similar at all. This eigenmode still has a very large contribution to the vertical velocity, and the pitch and pitch rate are still very small.

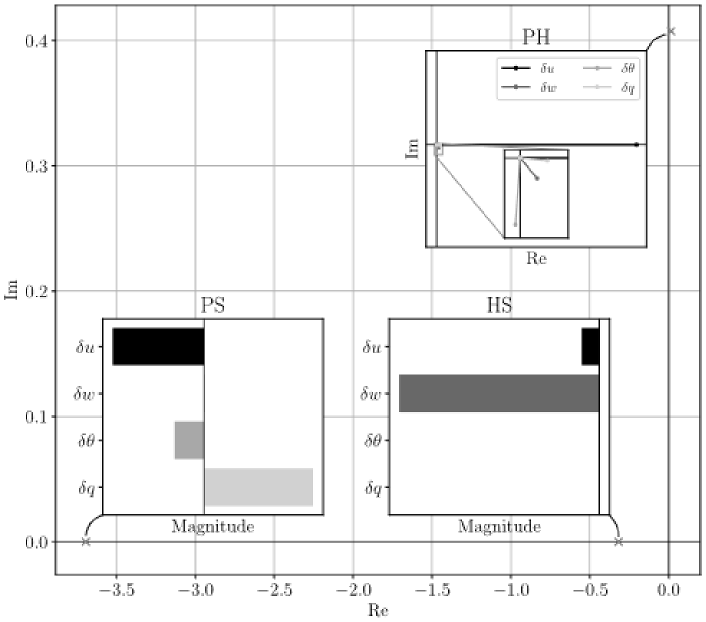


Figure 4.6: Eigenvectors and eigenvalues of longitudinal motion in a helicopter [21, Figure 5.1]

Now to the comparison of these eigenvalues to see what motion it should form. The largest influence is from the vertical velocity w. These are opposite in sign, and equal in magnitude. This means that the response will start at zero, and quickly rise (the fastest contribution is from λ_3 which will go to zero fastest), and go towards zero again. The pitch rate q has a much bigger contribution from λ_3, so this will start at a positive value, and go down into a negative value. After that it will rise towards zero again. The pitch angle will have a very similar effect, but in reverse sign. Lastly is the forward velocity, which is an odd one. Here, the signs are the same, and magnitudes are very similar. This means that it will start at a positive value, and go towards zero. This can all be seen in the response of the sum of these two eigenmotions in Figure 4.7.

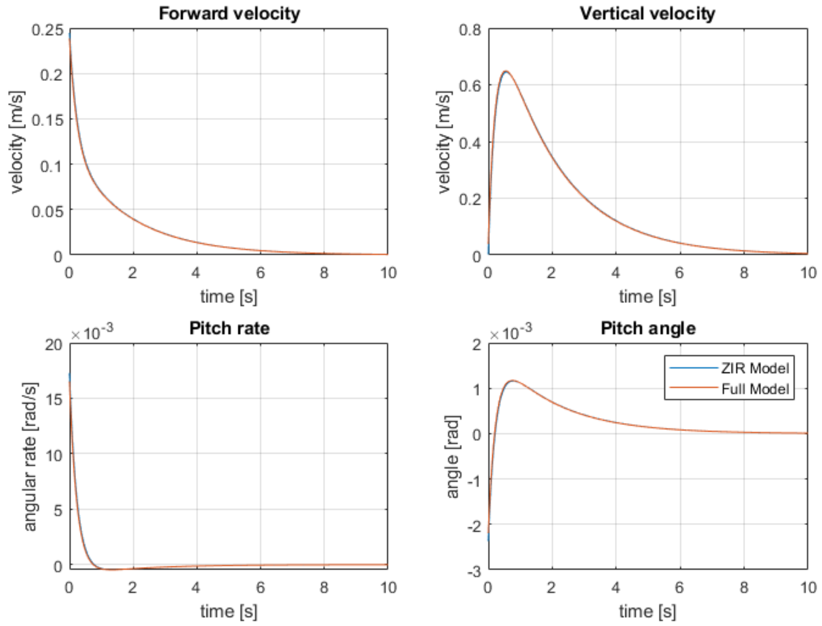


Figure 4.7: Sum of the isolated response of λ_3 and λ_6.

5

Flight Controls and Handling Qualities

In this chapter, the rudimentary flight control system in designed using the Zero State Response (ZSR) of the system using the Mode Participation Factor (MPF). With this control system, the handling qualities are then evaluated.

5.1. Flight Control System

The goal of this section is to design a flight control system where the different control surfaces are mapped. As stated before, the pitch control capabilities of the Flying V are low compared to conventional aircraft.

5.1.1. Control Surface Effectiveness

To design this control surface mapping, the effectiveness of the control surfaces is taken into account, as well as the Zero State Response. For the effectiveness of the control surfaces, an input is given to see what it changes in the states. In short, the Bu is calculated for certain inputs. First, the value is calculated for a symmetrical input using only the inner elevons. Since the goal of this is to see the relative influence on the states, the is shown relative to the influence on the forward velocity. This is shown for three longitudinal states in Table 5.1. The state for the pitch angle θ is left out, since it is not directly influenced by the control inputs, but rather indirectly by the pitch rate q.

Table 5.1: Relative influence the control surfaces have on the three longitudinal states.

Influence on:	u	w	q
Inner Elevon	1.0000	-4.2690	-0.5008
Outer Elevon	1.0000	-4.8241	-0.7757

Since these values correspond to only the derivative of the states, and the units of the states are not the same, only the difference between the inner and outer elevons should be looked at. From this difference, it can be noted that the inner and outer are relatively very similar in their effectiveness for forward velocity and pitch rate, while the vertical velocity is relatively affected much more by the inner elevons. This means that if the pilot wants to induce a pitch moment while retaining altitude, the outer elevons will be more effective. In addition to that, the outer elevons are smaller, and thus less effective, compared to the inner elevons.

5.1.2. Zero State Response

However, just looking at the input relation does not give a good image of the full response of the aircraft. This can be useful to see the relative effectiveness and should be taken into account when the flight system is designed. The next step is to look at the Zero State Response. The method introduced in subsection 4.3.1 is so far only used to isolate the response of the eigenmotions. However, it can also be used to see what modes are started when a certain input is given. This is done by looking at the Zero State Response (ZSR). Especially when looking at the term $V^{-1}Bu$, which indicates how much a given input u starts every eigenmode. This can be used to determine the relative influence the control surface deflection has on each eigenmode, or to cancel out eigenmodes in the response. It can also be used to see the relative influence the control surfaces have on the eigenmotions. This is visualized in Figure 5.1.

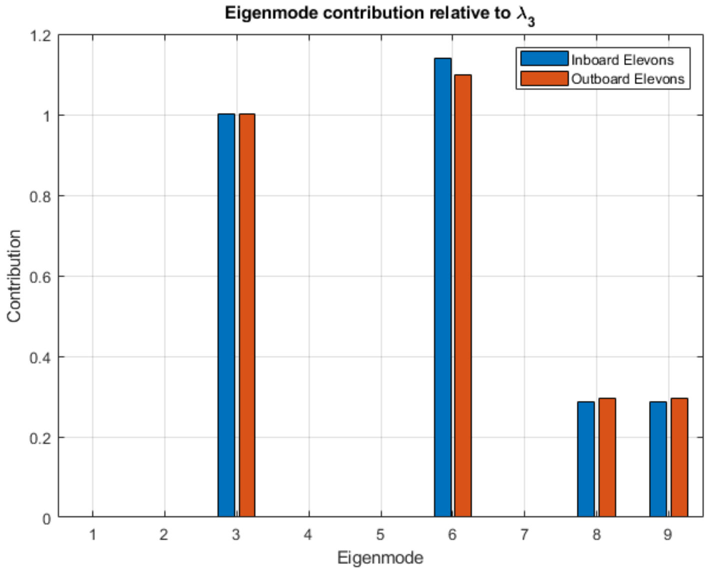


Figure 5.1: Effect inboard and outboard elevons have on eigenmotions from zero state response

From the figure it can be derived that the differences between the control surfaces are small. This means that the Zero State Response will not be used to create a control mapping.

5.2. Control Mapping Options

For the control mapping, two simple options will be presented. The control mapping will be kept as simple as possible, to keep the test of the handling qualities of the bare aircraft. As seen from the control surface effectiveness, the two sets of control surfaces (inboard and outboard) can be used differently. The two options will be designed such that one mapping will be specialized to control the pitch attitude, and one will be specialized to control the vertical velocity.

5.2.1. Pitch Attitude Controller

The pitch attitude focused control mapping will deflect both surfaces in opposite directions in order to cancel as much of the influence on the vertical velocity as possible. The goal is to have the pitch control as close to a conventional aircraft as possible. In order to achieve this, the influence as seen in Table 5.1 is set such that the vertical velocity is cancelled out. The result of this is that the pitch rate is also partially cancelled out, but since the outboard elevons are more effective in generating a pitch moment, the aircraft will still pitch. This is summarized in Table 5.2 where the outer elevon has to be deflected almost 2 times as much in the opposite direction relative to the inner elevon. Since this is created using the linear model the control surfaces can linearly scale up using the same ratio. This is shown in Figure 5.2. These outputs will still create a vertical velocity, because the change in the other states will still affect the vertical velocity. In order to negate that, a full controller has to be designed (for instance a PID controller). Since that will adapt the handling qualities too much, this is not chosen as a control mapping for the Flying V in this project.

Table 5.2: Relative influence of the control surfaces when vertical velocity is cancelled out.

Influence on:	u	w	q
Inner elevon	-0.2343	1	0.1173
Outer elevon	0.2073	-1	-0.1608
Total effect	-0.0270	0	-0.0435

5.2.2. Vertical Velocity Controller

The vertical velocity controller will deflect both control surfaces in the same direction. The mapping will then be made in such a way that both surfaces are equally effective in vertical velocity control. Effectively, this will

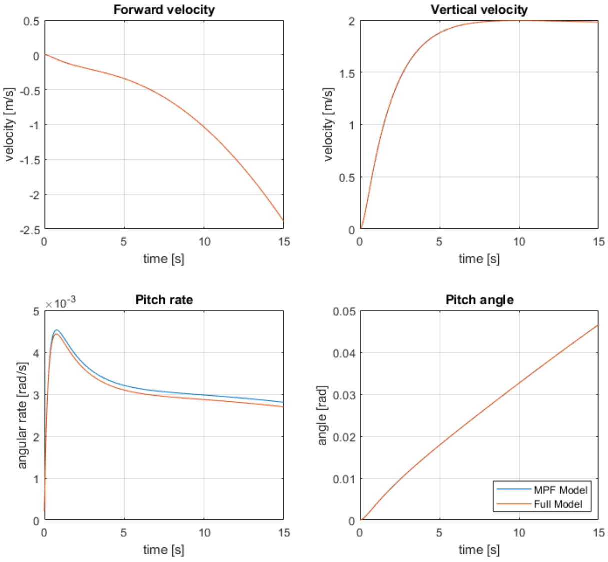


Figure 5.2: Response with a continuous step input using the mapping for pitch control. MPF model is the mode participation factor isolated model.

give the exact same ratio as the Pitch Attitude Controller, but the surfaces will move in the same direction for this situation. The response is shown in Figure 5.3.

5.3. Handling Qualities

In this section, the handling qualities will be evaluated analytically. A very common method to determine these handling qualities is to use the Control Anticipation Parameter (CAP). However, this parameter relies on the imaginary eigenvalue corresponding to the short period. This means that in order to accurately assess the handling qualities, the time domain has to be used. However, most of the evaluation methods for the handling qualities in the time domain rely on a constant steady state. The phugoid prevents this steady state to be visible. For that reason, the handling qualities are evaluated in the Zero Input Response which shows the isolated eigenmode corresponding to the short period. Because of the very slow response of the phugoid, this isolated short period response is actually very similar to the aircraft's response to an input. An alternative for this method is calculating the rise time, peak ratio, and effective delay. First, this is done for the pitch rate. After that, a similar analysis is done on the vertical velocity to assess handling qualities in that aspect to see how the different method of flight path control will score.

5.3.1. Pitch Rate Handling Qualities

As seen in the example plot, it is necessary to compute the pitch rate while it is heading for a steady state pitch rate. The problem with this is the phugoid which will influence the response before this steady state is reached. In order to filter out the phugoid, the influence the input has on all eigenmodes is calculated via the Zero State Response (ZSR) in subsection 4.3.1. The influence of the phugoid is then manually set to zero. The result is that only the short period response is shown, and the pitch rate will go towards a steady state. As seen in Figure 5.5, the results are very similar, especially at the start. This response will be used to evaluate the handling qualities according to Figure 5.4.

First, this evaluation is done on the pitch rate focused mapping. The pitch rate is shown in Figure 5.6. The deflection of the control surfaces is following the mapping as described in section 5.2. The maximum deflection chosen is 30 degrees. The plot, three points are highlighted. These points are used to compute the handling qualities. One thing should be noted. Since there is no second peak (Δq_2), the transient peak ratio is going to be zero. In addition to that, the deployment of the control surfaces is simulated by using a maximum rate of change of 40 degrees per second.

Using this time response, the handling qualities can be evaluated according to the level system which is common practice in handling qualities evaluation. The transient peak ratio will not be taken into account, since

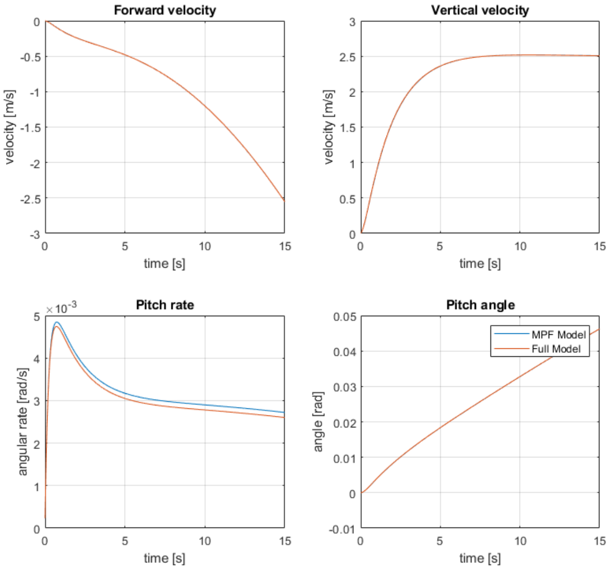


Figure 5.3: Response with a continuous step input using the mapping for vertical velocity control.

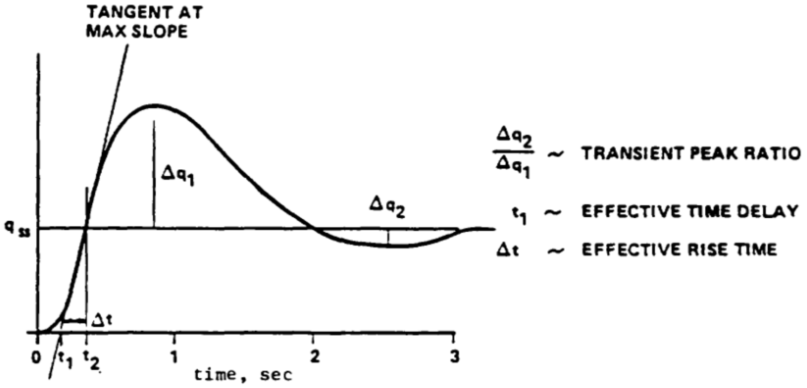


Figure 5.4: Handling qualities evaluation by pitch rate plot [18, Figure 49]

there is no second peak. The effective time delay requirement for level 2 is $t_1 <= 0.17s$. Since it is slightly higher than that, the effective time delay belongs in level 3 for both control mappings. The effective rise time handling qualities level depends on the true airspeed. It is level one if the rise time is between $29.5/V_T$ and $1640/V_T$. This means that the rise time should be between 0.125 seconds, and 6.9 seconds. This places the effective rise time for both control mappings in level 1.

Table 5.3: Results of the handling qualities.

	t_1 [s]	Level	Δt [s]	Level	Δq_1 [rad/s]	Level
Pitch rate mapping	0.18	level 3	0.5	level 1	0.00726	-
Vertical velocity mapping	0.18	level 3	0.45	level 1	0.054167	-

The levels for these different criteria can be used to predict what the aircraft will feel like to control. The level 3 for the effective time delay will mean that the aircraft will feel very slow to respond in pitch rate. The effective rise time indicates that the steady state pitch rate is achieved within a desirable time. The transient peak ratio can be seen as having a value of zero, since there is no second peak which goes under the steady state pitch rate. This is desirable since it will provide a faster response. However, the overall response is relatively slow, and the steady state pitch rate is very low. Especially considering that the deflections on the control surfaces are the maximum deflection.

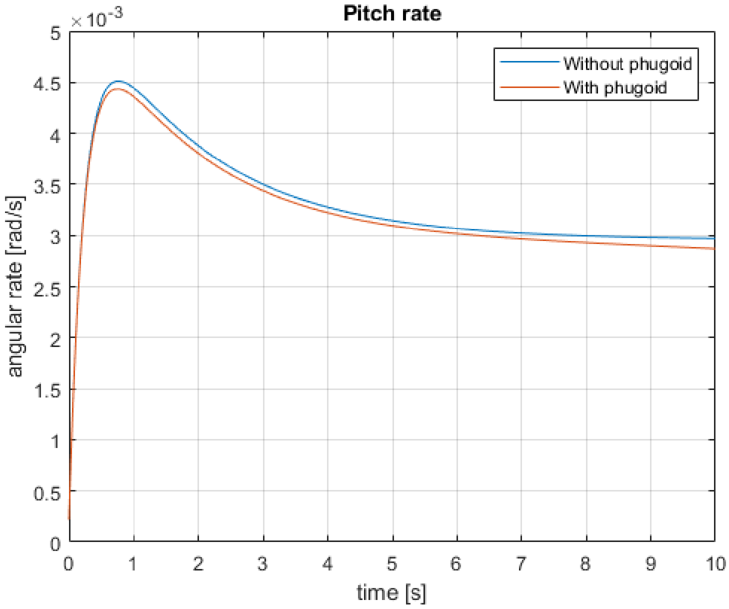


Figure 5.5: Pitch rate with and without the phugoid filtered out.

5.3.2. Vertical Velocity Handling Qualities

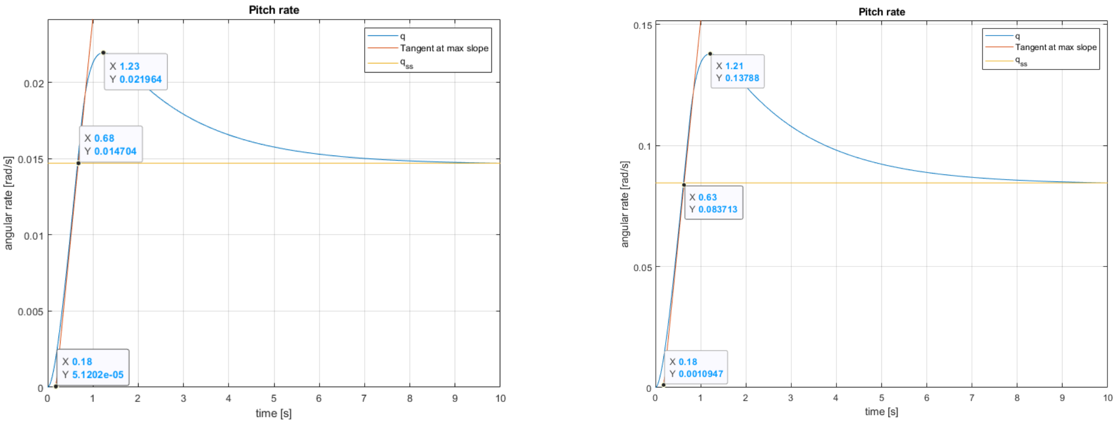
To also determine the handling qualities with the new response type a very similar quantification of the handling qualities is done using the vertical velocity. The same response as the previous subsection is used. Similarly to the last evaluation, the effective rise time and effective time delay are also investigated. The vertical velocity response is shown in Figure 5.7.

Using this time response, the handling qualities can be evaluated according to the level system as is common practice in handling qualities evaluation. The transient peak ratio will not be taken into account, since there is no overshoot. The effective time delay requirement for level 3 is $t_1 <= 0.21s$. Since it is higher than that, the effective time delay belongs outside level 3 for both control mappings. The effective rise time handling qualities level depends on the true airspeed. It is level one if the rise time is between $29.5/V_T$ and $1640/V_T$. This means that the rise time should be between 0.125 seconds, and 6.9 seconds. This places the effective rise time for both control mappings in level 1.

Table 5.4: Results of the handling qualities for vertical velocity.

	t_1 [s]	Level	Δt [s]	Level
Pitch rate mapping	0.5	outside level 3	2.68	level 1
Vertical velocity mapping	0.49	outside level 3	2.64	level 1

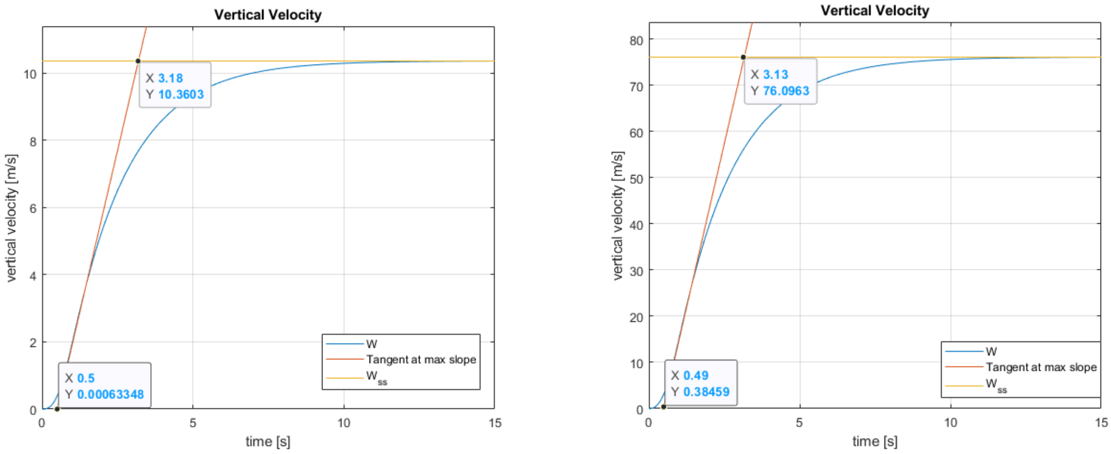
These levels will represent what the aircraft is like to fly for the pilots. The fact that the effective time delay is outside of level 3 means that it is very slow to respond. However, this requirement is very strict from the angular rate, where a sudden high angular acceleration is less of a discomfort than a sudden high acceleration. Additionally, the effective rise time is still within level 1. It should also be noted that the velocities achieved are (especially for the vertical velocity focused controller) are very high.



(a) Pitch rate response in pitch rate focused control mapping

(b) Pitch rate response in vertical velocity focused control mapping

Figure 5.6: Pitch rate plot to step response in both mappings of the control surfaces to evaluate the handling qualities.



(a) Vertical velocity response in pitch rate focused control mapping

(b) Vertical velocity response in vertical velocity focused control mapping

Figure 5.7: Vertical velocity plot to step response in both mappings of the control surfaces to evaluate the handling qualities.

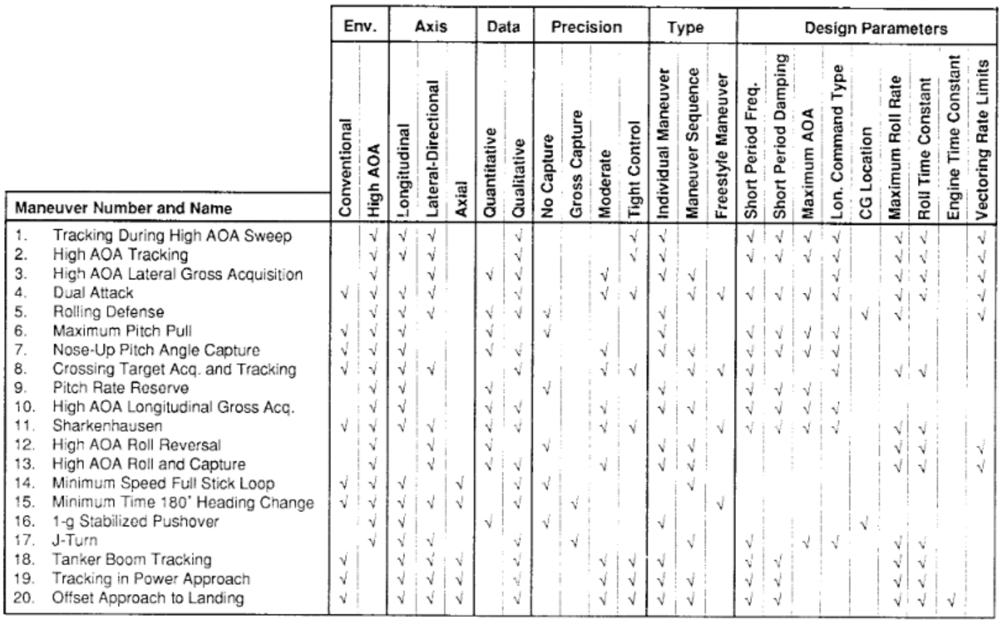
6

Experiment Preparation

In this chapter, the experiment is designed in broad lines. This means that the goal of the manoeuvres is designed, as well as some of the manoeuvres are picked. This will consist of two sets of tests. First the traditional longitudinal tests, which often focus on pitch attitude control. Secondly, an additional set of manoeuvres are to be performed to test the control of the vertical velocity. This can be seen as a more direct way to control the flight path of the aircraft.

6.1. Traditional Tests

Traditional flying and handling qualities tests are often used in military applications. Here, the agility of the aircraft is often very important, while for commercial, or smaller private aircraft, stability is a driving factor. Because of this, there are a few documents with guidelines on how to evaluate the handling qualities. First is a manoeuvre description and selection guide [17, 22]. This document defines Standard Evaluation Manoeuvre Set (STEMS). This is a set of twenty manoeuvres, which are designed to emulate the requirements in handling during operation. This set of manoeuvres is created to help during the designing process, as well as demonstrate what the aircraft can do. This set of manoeuvres focuses mostly on fighter aircraft. However, some of the longitudinal manoeuvres can still be used. The pitch angle capture, pitch tracking, and offset precision landing are still useful to evaluate the handling qualities of a civil aircraft [23]. The manoeuvres described in the document are summarized in Figure 6.1.



	Env.		Axis			Data		Precision				Type			Design Parameters								
Maneuver Number and Name	Conventional	High AOA	Longitudinal	Lateral-Directional	Axial	Quantitative	Qualitative	No Capture	Gross Capture	Moderate	Tight Control	Individual Maneuver	Maneuver Sequence	Freestyle Maneuver	Short Period Freq.	Short Period Damping	Maximum AOA	Lon. Command Type	CG Location	Maximum Roll Rate	Roll Time Constant	Engine Time Constant	Vectoring Rate Limits
1. Tracking During High AOA Sweep		√	√	√			√				√	√			√	√	√	√		√	√		√
2. High AOA Tracking		√	√	√			√				√	√			√	√	√	√		√	√		√
3. High AOA Lateral Gross Acquisition		√		√		√	√			√		√	√					√		√	√		√
4. Dual Attack	√	√	√	√			√			√	√		√	√	√	√	√	√		√	√		√
5. Rolling Defense		√	√	√		√	√	√				√							√	√			√
6. Maximum Pitch Pull	√	√	√			√		√				√			√	√	√	√					
7. Nose-Up Pitch Angle Capture	√	√	√			√	√			√		√	√		√	√	√	√					
8. Crossing Target Acq. and Tracking	√	√	√	√			√			√	√		√	√	√			√		√	√		
9. Pitch Rate Reserve		√	√			√		√				√			√	√	√						
10. High AOA Longitudinal Gross Acq.		√	√			√	√			√		√	√		√	√	√	√					
11. Sharkenhausen	√	√	√	√		√	√			√	√			√	√	√	√	√		√	√		
12. High AOA Roll Reversal		√		√		√		√				√	√							√	√		√
13. High AOA Roll and Capture		√		√		√	√			√		√	√							√	√		√
14. Minimum Speed Full Stick Loop	√	√	√		√		√	√					√										
15. Minimum Time 180° Heading Change	√	√	√	√	√		√		√					√									
16. 1-g Stabilized Pushover		√	√			√		√				√							√				
17. J-Turn		√	√	√			√		√				√		√		√	√		√	√		
18. Tanker Boom Tracking	√		√	√	√		√			√	√	√			√	√				√	√		
19. Tracking in Power Approach	√		√	√	√		√			√	√	√	√		√	√				√	√		
20. Offset Approach to Landing	√		√	√	√		√			√	√	√	√		√	√				√	√	√	

Figure 6.1: General Characteristics and Design Parameters Evaluated With the Initial STEMS Maneuvers [22, Figure 13]

From this figure, the manoeuvres which only the longitudinal axis is involved are selected. These are manoeuvre 6, 7, 9, 10, and 16; the maximum pitch pull, the nose-up pitch angle capture, the pitch rate reserve, the high AOA longitudinal gross acquisition, and the 1-g stabilized pushover. However, not all of these are useful for civil aviation passenger aircraft. For instance, the research on the longitudinal handling qualities of a business jet[23] only performs two tracking tasks, and a pitch angle capture. A further research on the usefulness in their evaluation of handling qualities of these manoeuvres is performed, which indicates that especially STEMS 2, 3, 4, 7, and 10 are important parts of flight testing [24]. A handling qualities analysis on the Eurofighter also mostly uses tracking and attitude captures to determine the handling qualities for the closed loop very similar to STEMS 7 and 10. Additionally some open loop manoeuvres, multi-axis tracking, and free manoeuvring is performed [25]. To determine which are useful for this research, the applicability of these STEMS to the longitudinal handling qualities of the Flying V are evaluated.

STEM 2 (high AOA tracking) is designed to isolate spot tracking and aim point correction characteristics, which indicates that this manoeuvre is mostly applicable for fighter aircraft. STEM 3 (high AOA lateral gross acquisition) is a lateral manoeuvre and is not applicable in this research. STEM 4 (Dual attack) is a multi-axis manoeuvre only applicable for fighter aircraft. STEMS 6 (maximum pitch pull) is an open loop manoeuvre in which the pilot pulls the stick fully aft until a maximum pitch rate is achieved. Since the experiment is done in a simulator, this quantitative data is already obtained without the pilot in the loop in subsection 5.3.1. STEMS 7 (nose-up pitch angle capture) is a manoeuvre in which the pilot has to capture a set pitch angle. The performance of this manoeuvre is difficult to quantify, because of the influence the skill of the pilot has on this STEM. However, it is very useful for generating pilot comments and determine the Cooper Harper Rating. STEM 9 (pitch rate reserve) is a manoeuvre in which the pilot pulls the stick fully back, and waits until the nose rate drops below the initial nose rate. This is also an open loop manoeuvre, and pilot comments are limited in the same way as STEM 6. STEM 10 (high AOA longitudinal gross acquisition) is a manoeuvre in which the pilot has to track a sequence of pitch attitudes. This is highly useful in generating pilot comments and Cooper Harper Ratings. STEM 16 (1-g stabilized pushover) is a manoeuvre in which the pilot starts at a high angle of attack, and pushes the stick fully forward until a set angle of attack is achieved. This manoeuvre is also open loop.

This concludes that the set of manoeuvres to be performed by test pilots in the full flight simulator should be derived from STEM 7 and STEM 10, adapted to be used for normal angle of attack ranges. The manoeuvres will be a pitch angle capture to different pitch angles (not necessarily nose up), and a set of pitch tracking tasks. This is to generate the pilot comments about the longitudinal handling qualities of the Flying V.

6.2. Direct Flight Path Tests

The goal of these direct flight path tests, or direct lift control tests, is to evaluate the handling qualities of the Flying V for a different control philosophy. Currently, the longitudinal flight control systems focus on pitch angle control in order to control the flight path of the aircraft. However, the Flying V is relatively inefficient in its pitch attitude control. On the other hand, the Flying V is very effective in vertical velocity control. This can also be seen as direct lift control which directly impacts the flight path angle. Seeing that the goal of pitch control in conventional aircraft is to determine the flight path angle, the Flying V can be much more efficient in this by directly controlling the vertical velocity.

In order to test this, and how this control philosophy would work in practice, some standard manoeuvres are designed. These manoeuvres will be based of the same STEMS from the traditional flight tests, but slightly changed to fit this goal.

As stated in section 6.1, the main manoeuvres should revolve around two different STEMS; a pitch angle capture, and a pitch tracking task. In order to alter these to a more direct version, they can be changed to a flight path capture, and a flight path tracking task. Alternatively, a more basic approach can be taken where the manoeuvres become a vertical velocity capture and a vertical velocity tracking task. The main goal of these manoeuvres still is to generate pilot opinions which can be used for the Cooper Harper Rating, especially to evaluate the different design philosophy of the control system using the vertical velocity as a driving factor. For this, especially the task derived from STEM 10 will be useful.

7

Conclusion and Recommendations

In the chapter, the results of the previous chapters are looked at and conclusions are drawn. From these conclusions, recommendations for further research can be made.

7.1. Conclusion

The longitudinal handling qualities of the Flying V aircraft are identified for two different control mappings, and following two different control philosophies; one mapping focused on pitch angle, and one focused on vertical velocity. The control philosophy also has one focusing on pitch control, and one on vertical velocity control. The preliminary analysis is done by a linearization of the aircraft model, followed by an extensive analysis using the eigenmodes.

First of all, is the absence of the eigenvalue which corresponds to the short period eigenmotion. In a conventional aircraft, this is a complex set of eigenvalues from which the Control Anticipation Parameter (CAP) can be calculated. In the case of the Flying V, however, this set of eigenvalues only has a real value. This composition of eigenvalues is very close to how helicopters behave at low speed. In the case of helicopters, there is no short period, but there is a heave subsidence and pitch subsidence. From the analysis of the eigenvalues, it seems that the Flying V does exhibit a heave subsidence eigenmotion. In the time domain, these motions of the eigenmodes combined look like an overdamped short period.

Since the CAP cannot be calculated from this model, alternative methods which rely on the time response are used. This is done by looking at the effective rise time, and effective time delay. It is concluded that the effective rise time is within level 1, so easy to control, for both control mappings, and both control philosophies. The effective time delay is in level 3 for the pitch angle focused control philosophy for both mappings, while the effective time delay for the vertical velocity focused control philosophy is outside level 3.

Based on these levels, it can be concluded that the response of the aircraft when the pitch rates are achieved is desirable. However, the bad result in effective time delay indicates that the aircraft may behave sluggish. These findings will have to be tested by pilots to be confirmed.

7.2. Recommendations

This section will address the research necessary to confirm investigate the gaps in knowledge so far. This should be done using a pilot in the loop experiment. During this experiment, the focus should be on the different control mappings, and the new control philosophy where the flight path is controlled via the vertical velocity instead of the pitch angle. This need comes from the eigenmode analysis and the analytical evaluation of the longitudinal handling qualities.

What can be taken away from this, is that the Flying V behaves differently compared to conventional aircraft. It is still unclear if this different behaviour is in any way better or worse when it comes to the controllability. In order to determine that, a experiment has to be conducted where two different control mappings are tested.

The pilots should also be instructed to look at the controllability from a more direct angle, which is flight path control.

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III

Appendices

A

Briefing

Experiment Briefing

Content:

-
- About the Flying V/introduction
- Flight Control Mapping
- Experiments
- Experiment evaluation
- Experiment Environment
- Layout of Experiment

Practical Information

The experiment is in the Simona Research Simulator. This section contains safety information about the simulator itself, and some Covid rules in the facility.

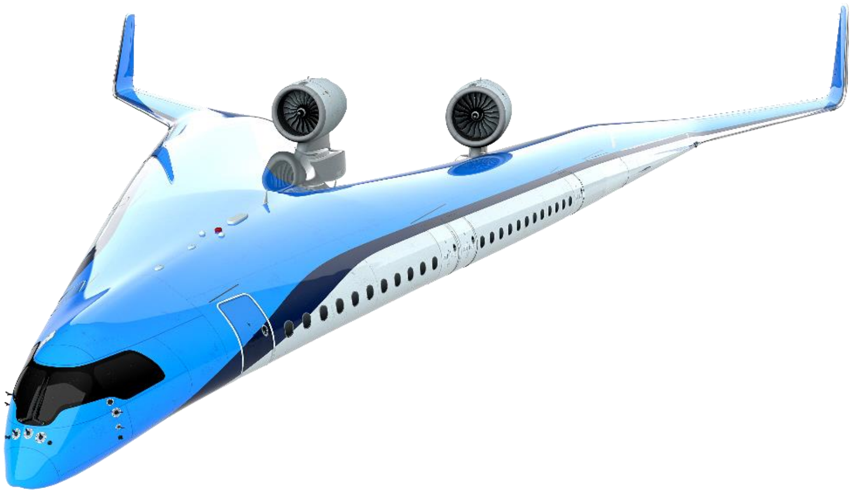
The main instructions and safety features are explained in this video: https://youtu.be/PXijsyJ3hro. They most important parts of this will be repeated before the experiment.

There are some additional Covid rules still in play at the faculty when it comes to participants before and after experiments. The most important measure is that a valid QR code has to be shown in the CoronaCheck app. Apart from that, standard rules apply which include keeping distance, not shaking hands, and cleaning equipment.

About the Flying V

General

This research is to test the handling qualities of the Flying V. The Flying V is a new aircraft using a novel configuration being developed here at TU Delft. This is the first handling qualities experiment performed on the Flying V. This experiment will only evaluate the longitudinal handing qualities. This means we will look at the pitch and flight path response.



Aerodynamic Model
The simulation runs on a very early aerodynamic model of the Flying V. This means the aerodynamics are linearized, and no stall or high angle of attack behaviour is included in this model. The aerodynamic model is used to generate the forces and moments on the Flying V, which are then used in the full aircraft model.

The model which is used is a bare airframe model. This means that no control or stability augmentation systems are present, and you will be controlling the elevons (almost) directly. More on that later in the Control mapping section.

The Flying V has three control surfaces on each wing. A rudder (which is not used in this experiment), An inboard elevon, and an outboard elevon. By using the stick, both inboard and outboard elevons will deflect.

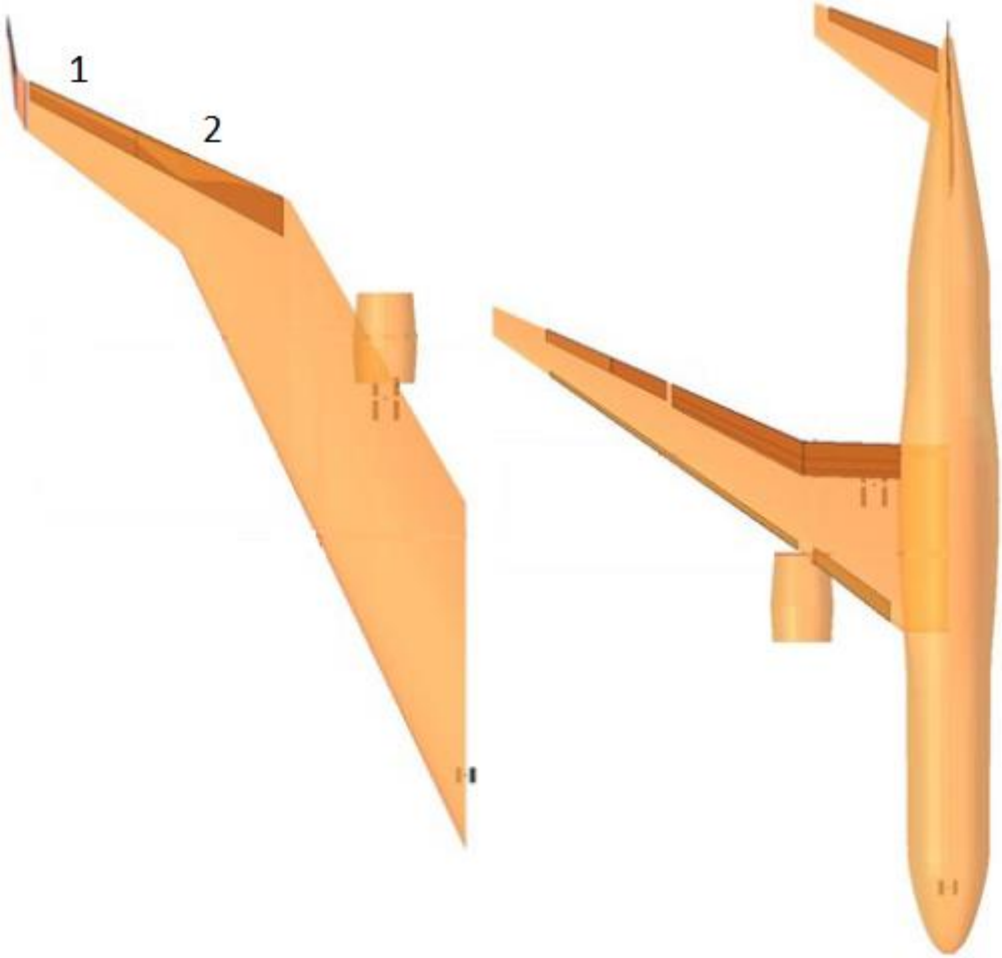
Flight Control Mapping

During the experiment, two different flight control mappings will be used. This control mapping determines how much both inboard and outboard elevons (control surface used for rolling and pitching) will deflect when an input to the stick is given. Two different mappings will be used during the experiment.

The first one will be traditional, where the elevons will both move in the same direction. This will result in a response which will affect the pitch angle the most.

The second one will be a new system in which the inboard and outboard elevon will move in different directions, thereby cancelling the change in pitch angle due to deflection of the control surfaces. This mapping will influence the flight path angle more directly.

Both these mappings will be tested in the experiments in the simulator.



Side by side comparison of Flying V and normal aircraft. 1: outboard elevon, 2: inboard elevon.

Experiments

There will be 3 experiments; Pitch angle tracking normal control mapping, Flight path tracking pitch angle control mapping, and Flight path tracking flight path control mapping.

Pitch angle tracking is a well-established traditional method of determining the handling qualities. In this experiment, the pilot will follow a target for approximately 100 seconds in which the target will move in steps or ramps between 4 and 12 degrees pitch angle. The goal of the pilot is to be within +-0.5 degrees for 75% of the time for a desired performance. Alternatively, if this cannot be reached, the goal is to be within +-1 degree for 75% of the time for adequate performance. After the task, the pilot can give an indication of the handling qualities by the reached performance and the amount of compensation necessary during the task.

Flight path angle tracking is a more operationally relevant method of testing the handling qualities for passenger/transport aircraft. The layout of the experiment is very similar to the pitch angle tracking experiment, only here the evaluation is the flight path angle instead of the pitch angle. The flight path angle tracking experiment will be performed with both control mappings.

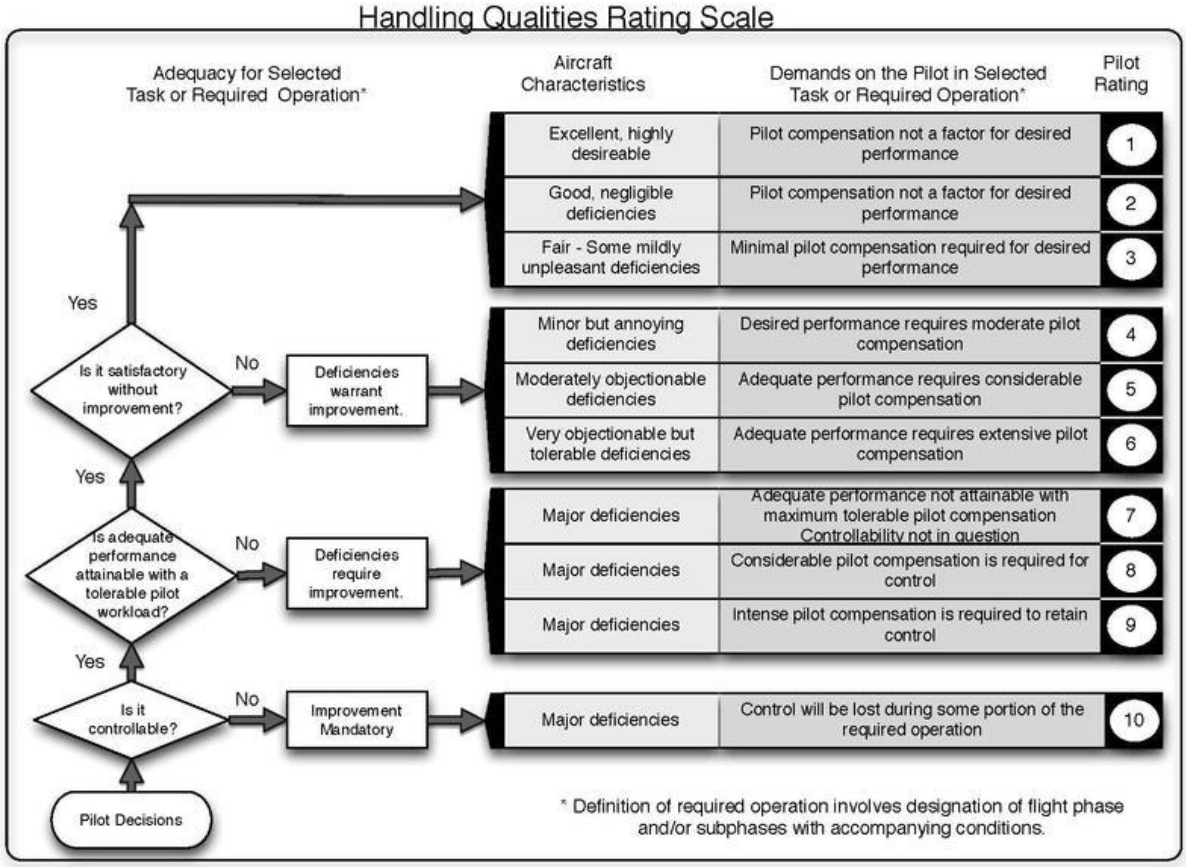
These experiments will be performed 2 or 3 times, and the pilot is asked every time to give a handling qualities rating using the Cooper Harper Scale.

Training

Before each experiment, the pilot will get ample time to train the task in a very similar setup. The task will be performed using a different tracking signal but using the same limits and performance boundaries. The pilot is able to see their score in real time. After the pilot has a consistent score in the task and is able to replicate this performance, the pilot will perform the recorded experiment.

Handling Qualities Evaluation

The pilot will evaluate the experiment after each run using the Cooper Harper Rating Scale:



The pilot will give a rating after each run to indicate the handling qualities. Note that a certain performance has to be obtained in order to give certain ratings. It will also be asked to give a very short explanation as to why a certain rating is given to verify the pilot's opinion.

During the first run, the pilot will get the option to repeat the experiment without giving a rating. The pilot can request to try again if they are not fully satisfied.

Experiment Environment

The experiment will be done in the Simona Research Simulator. This is a full flight simulator. The motion will be used during the experiment. The pilot will use a side stick to control the aircraft. Since the evaluation is only for the longitudinal handing qualities, the stick will be restrained to only move forwards and aft. Sideways motions are not possible. The stick can deflect 18 degrees in both directions.

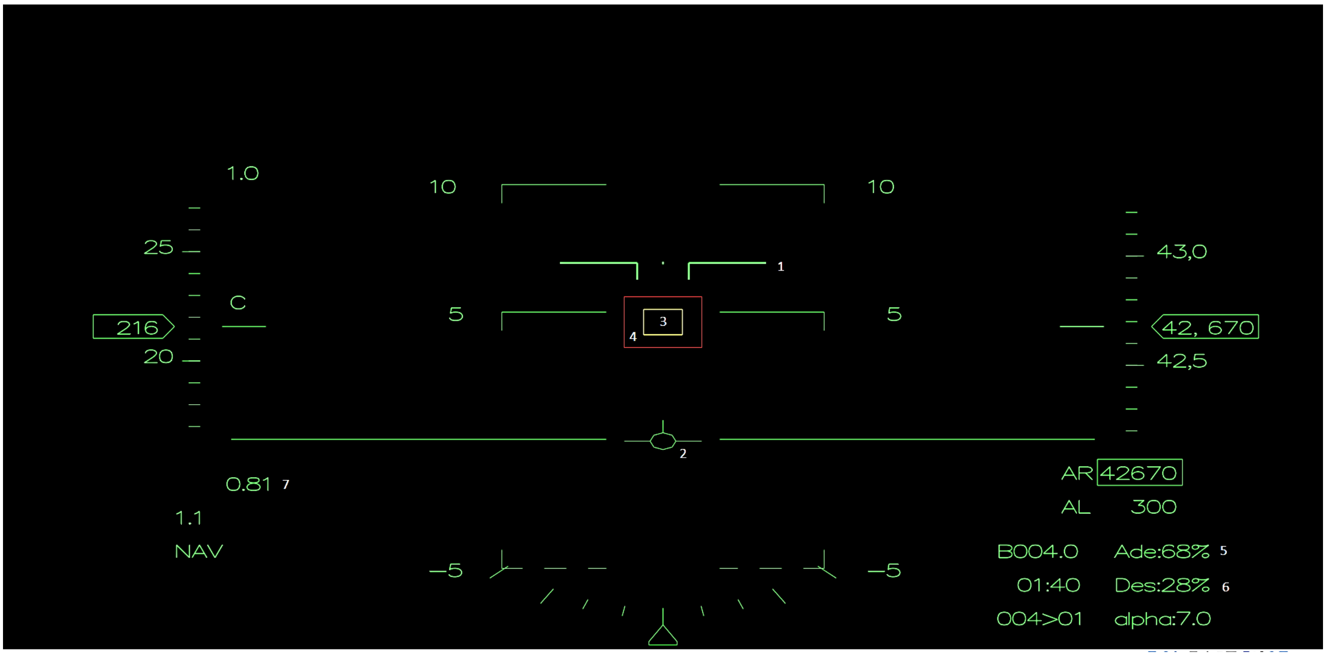
During the experiment, the pilot is expected to follow a target. This target, the pitch angle, and flight path angle are displayed on the PFC screen. An example is shown at the end of the document.

Experiment Timetable

The experiments will take a total of around 1 hour. First the pitch angle tracking will be performed, for which the pilot will get the training time needed to obtain a consistent performance. This is approximated at about 10-15 minutes. The experiment itself will then take about 5-10 minutes.

The next experiment will be flight path tracking using the traditional control mapping. For this, the pilot will also train until a consistent score is reached. This is approximated at about 10-15 minutes. The experiment itself will then take about 5-10 minutes.

The last experiment will be flight path tracking using the new control mapping. For this, the pilot will also train until a consistent score is reached. This is approximated at about 10-15 minutes. The experiment itself will then take about 5-10 minutes.



1: pitch angle, 2: Flight path angle, 3: desired performance target, 4: adequate performance target, 5: adequate performance score, 6: desired performance score, 7: mach number.

B

Comments on Experiment Cards

B.1. P1

Start Time: 11:52 Pilot ID:_P1_______________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__Free_	☐ Gamma ____	V Training
Run:_1___	Des Performance:___________	Ade Performance:___________	
Pilot Rating:			
Pilot Comments:			
Flight path angle dip is not noticable			
“nice” Steering nicely			
No enormous short period			
Stopping input too early			

Start Time:_11:57_________ Pilot ID:__P1_____________ Motion Parameter Set:________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__1____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__85______	Ade Performance:__95______	
Pilot Rating: 2			
Pilot Comments:			
Strange steering task, would never do this in operation			
Good to follow			
Am doing something			
Performance of the aircraft is nice			

Start Time:__12:04________ Pilot ID:_P1________________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch_2____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__89______	Ade Performance:_95_______	
Pilot Rating: 1			
Pilot Comments:			
Task is easier			
Flying aircraft with the same ease			
Good to fly aircraft			

Start Time:___12:12______ Pilot ID:_P1_____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__3____	☐ Gamma ____	☐ Training
Run:_1___	Des Performance:___76_____	Ade Performance:__96______	
Pilot Rating: 1			
Pilot Comments:			
Flying more lazy, thinking about passenger comfort			
Beautiful to fly, can play with the numbers			
No full deflections, task is a bit weird			

Start Time:__12:15________ Pilot ID:__P1___________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma free	V Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
G between 0.9 and 1.1			
Steering on g forces			
Good to fly			

Start Time:_12:22________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _1__	V Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
Was too lazy, is doing the same task again.			

Start Time:_12:24________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _1__	V Training
Run:_2___	Des Performance:_78______		Ade Performance:__________
Pilot Rating: 4			
Pilot Comments:			
No passenger comfort			
Hard counter-steering to compensate			
How much effort? More than moderate			
Giving a 4 because target was met			
Want faster flight path angle control, damping is the problem			
Task is strange for passenger aircraft			

Start Time:_12:31________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _3__	Training
Run:_1___	Des Performance:__71______		Ade Performance:_92______
Pilot Rating:6			
Pilot Comments:			
Can try more, but will never reach target			
Not very objectionable deficiencies, but not what you want			

Start Time:_12:34________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _5__	Training
Run:_1___	Des Performance:__73______		Ade Performance:_88______
Pilot Rating:6			
Pilot Comments:			
Really hard work to reach 75%			
Not noticing the dip in the flight path angle			

Start Time:_12:38_______ Pilot ID:__P1___________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma free_	V Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
Better damped but is still drifting			
Is drifting, but fine for this task			
Stopping a degree before the end with inputs			

Start Time:__12:45_________ Pilot ID:__P1____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 1__	V Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
Simona Crashed			

Start Time:__12:55_________ Pilot ID:__P1____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 1__	V Training
Run:_2___	Des Performance:__76______	Ade Performance:__92______	
Pilot Rating: 4			
Pilot Comments:			
Full deflection, between 6 and 7 for rating, but got the score			
Too slow, not responsive enough			
Overshoot still there, extensive pilot compensation			

Start Time:_12:59__________ Pilot ID:__P1____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 3__	☐ Training
Run:_1___	Des Performance:_72______	Ade Performance:_87______	
Pilot Rating: 6			
Pilot Comments:			
Task strange, sometimes slow and then its fine. Big steps are the most difficult			
Once or twice could not keep up with the rate			
Releasing the stick margin is oke			

Start Time:_13:03__________ Pilot ID:__P1____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 5__	☐ Training
Run:_1___	Des Performance:_76______	Ade Performance:_87______	
Pilot Rating: 4			
Pilot Comments:			
Sometimes task is natural and easy to follow			
Steps are tricky with full deflection			
Easier than previous			

Comments after experiment:

Overall handling qualities:

Flight path angle control mapping is much sloppier and slower
Not too much difference between control mappings

The experiments:

Not a task I would do, level change would be better
flight path more a result,, pitch angle is leading
Pitch angle is more logical
Not sure if this is realistic, rate of climb or rate of descend would make more sense. Ask a pilot who has flown on flight path marker.

B.2. P2

Start Time: 10:58 Pilot ID:_P2______________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__Free_	☐ Gamma ____	V Training
Run:_1___	Des Performance:___________	Ade Performance:___________	
Pilot Rating:			
Pilot Comments:			
Pilot does some pitch captures			

Start Time:_11:02_________ Pilot ID:__P2____________ Motion Parameter Set:________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__1____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__90______	Ade Performance:__97______	
Pilot Rating: 3			
Pilot Comments:			
Not too bad			
Reaching the pitch rate limit			
Found saturation → more stick input does not give more pitch rate			

Start Time:__11:07________ Pilot ID:_P2________________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch_2____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__92______	Ade Performance:_96_______	
Pilot Rating: 3			
Pilot Comments:			
Comment from control room: Flying very high gain			
Anticipates early on rates stopping			
Gain was higher due to pitch captures			
Level of compensation was double			

Start Time:__11:11________ Pilot ID:_P2_______________ Motion Parameter Set:_________

Control Mapping:		V Pitch	□ Gamma
Experiment Type:	V Pitch_2____	□ Gamma ____	V Training
Run:_2___	Des Performance:__81______	Ade Performance:_93_______	
Pilot Rating: 5			
Pilot Comments:			
Redid same run, told to fly more relaxed to be closer to desired performance limit and lower			
Workload, mentioned passenger comfort			
Started noticing the rate limit and can push through.			
Not happy with these deflections			
It warrants deficiencies			
Focussing more on comfort, very high deflection			
Double step inputs			
Hard to estimate stick position for desired rate.			

Start Time:___11:15______ Pilot ID:_P2_____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	□ Gamma
Experiment Type:	V Pitch__3____	□ Gamma ____	□ Training
Run:_1___	Des Performance:___89_____	Ade Performance:__96______	
Pilot Rating: 3			
Pilot Comments:			
Overall happy			
Not great when target reverses			

Start Time:__11:19________ Pilot ID:__P2___________ Motion Parameter Set:_________

Control Mapping:		V Pitch	□ Gamma
Experiment Type:	V Pitch__4____	□ Gamma ____	□ Training
Run:_1___	Des Performance:___95_____	Ade Performance:__99______	
Pilot Rating: 2			
Pilot Comments:			
Comment from control room: scores are visible in real time; bug in simulator program.			
Low workload, not gripping the stick too much			
First estimate is difficult for pitching down			
Close to level 1 for some deficiencies.			

Start Time:_11:23________ Pilot ID:_P2____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__aqui__	☐ Gamma ___	☐ Training
Run:_1___	Des Performance:___________	Ade Performance:___________	
Pilot Rating:3			
Pilot Comments:			
High g-forces			
Very low compensation, not to very little overshoot			
More bothered by the untrimmed state			

Start Time:_11:28________ Pilot ID:_P2____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _free_	V Training
Run:_1___	Des Performance:___________	Ade Performance:___________	
Pilot Rating:			
Pilot Comments:			
Happy, different way of flying			
Need a base line, some thinking going on.			

Start Time:_11:31________ Pilot ID:_P2____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _1__	V Training
Run:_1___	Des Performance:_81______	Ade Performance:___93_____	
Pilot Rating: 5			
Pilot Comments:			
“I do not like it”			
Able to hit the scores, but I do not like it.			
Moderate because scores are fine			

Start Time:_11:34________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _2__	V Training
Run:_1___	Des Performance:__79______	Ade Performance:_94______	
Pilot Rating:6			
Pilot Comments:			
Harder to keep up with the rates			
Like this even less than the previous one			
More workload, is moving head forwards			

Start Time:_11:37________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _3__	Training
Run:_1___	Des Performance:__77______	Ade Performance:_91______	
Pilot Rating:5			
Pilot Comments:			
Unconsciously sets a pitch angle and waits for the flight path angle to catch up			
Anticipating a lot because of this			
Better than the last one			
Getting more used to this way of flying			

Start Time:_11:41________ Pilot ID:_P1____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _5__	Training
Run:_1___	Des Performance:__68______	Ade Performance:_82______	
Pilot Rating:6			
Pilot Comments:			
Feels very sloppy and laggy			
Bigger overshoots			
If gains are realistic on the pilot’s side, the pilot does not like it.			

Start Time:_11:45_______ Pilot ID:__P2___________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma free_	V Training
Run:_1___	Des Performance:__________		Ade Performance:__________
Pilot Rating:			
Pilot Comments:			
Deflections need to be bigger for a similar rate			
Feels more sloppy in pitch rate			

Start Time:__11:48_________ Pilot ID:__P2____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 1__	V Training
Run:_1___	Des Performance:__88______		Ade Performance:___93_____
Pilot Rating:5			
Pilot Comments:			
Deflections have increased			
Amplitude of overshoots has decreased			
Tracking is easier, but more deflections compared to previous controller			
Rating of 5 due to large deflections			

Start Time:__11:51_________ Pilot ID:__P2____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 2__	V Training
Run:_1___	Des Performance:__86______		Ade Performance:__98______
Pilot Rating: 6			
Pilot Comments:			
Hit the forward stop when going nose down			
Captures not harder, closure rates smaller but makes deflections rates very large			
Reached the stop, so very objectionable.			

Start Time:_11:55___________ Pilot ID:__P2_____________ Motion Parameter Set:________

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch________	V Gamma 3__	☐ Training
Run:_1___	Des Performance:_78______	Ade Performance:_91______	
Pilot Rating: 5			
Pilot Comments:			
“It is just hard”			
Bothering to get the closure rate, initial guess is always too low			
Did not reach a stop			

Start Time:_11:59___________ Pilot ID:__P2_____________ Motion Parameter Set:________

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch________	V Gamma 5__	☐ Training
Run:_1___	Des Performance:_70______	Ade Performance:_84______	
Pilot Rating: 6			
Pilot Comments:			
“Do not like it”			
Even bigger deflections, did not reach a stop			
Got used to flying flight path angle			
Not able to catch up with target and overshot			

Start Time:_12:03___________ Pilot ID:__P2_____________ Motion Parameter Set:________

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch________	V Gamma acqui	☐ Training
Run:_1___	Des Performance:_ _______	Ade Performance:_ _______	
Pilot Rating:			
Pilot Comments:			
Not sure anymore			
Flight path angle changes for a smaller time			

Start Time:_12:06__________ Pilot ID:__P2____________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma acqui	☐ Training
Run:_1___	Des Performance:_ _______	Ade Performance:_ _______	
Pilot Rating:			
Pilot Comments:			
So much more pleasant			
Confirms less drift in the gamma controller			
Feels conventional, more direct.			

Comments after experiment:

Overall handling qualities:

Normal operation:

- first controller is better.
- Second controller is more sloppy

Inexperienced pilots will be able to fly the pitch angle system.
Overshoot is what they train on, can compensate an overshoot.
Rather an overshooting aircraft than a sloppy aircraft.

The experiments:

All tasks are about the short period.
Did not see difference too much for only flight path angle control
Liked the gamma experiment
Gamma very useful tool for the Flying V, not for conventional aircraft.
Was focussing on a high score, but got brought back to the goal of the experiment
Silences after a comment make the pilot doubt their judgement.

B.3. P3

Start Time: 13:19 Pilot ID:_P3______________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__Free_	☐ Gamma ____	V Training
Run:_1___	Des Performance:___________	Ade Performance:___________	
Pilot Rating:			
Pilot Comments:			
Nothing special			

Start Time:_13:24_________ Pilot ID:__P3____________ Motion Parameter Set:________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__1____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__72______	Ade Performance:__92______	
Pilot Rating:			
Pilot Comments:			
Not too many comments, did not fully understand the targets. Will redo.			

Start Time:_13:29_________ Pilot ID:__P3____________ Motion Parameter Set:________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__1____	☐ Gamma ____	V Training
Run:_2___	Des Performance:__80______	Ade Performance:__97______	
Pilot Rating: 4			
Pilot Comments:			
Low static stability at different pitch angles.			
Response is surprisingly quick			
4 → wants more pitch damping			
Compares it to plane flown in operation			
Swinging around the target			

Start Time:__13:32________ Pilot ID:_P3_______________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch_2____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__88______	Ade Performance:_95_______	
Pilot Rating: 4			
Pilot Comments:			
Comment from control room: looks like PIO			
Stays the same, little pitch angle damping			
Became more aggressive			

Start Time:__13:35________ Pilot ID:_P3_______________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch_5____	☐ Gamma ____	V Training
Run:_2___	Des Performance:__88______	Ade Performance:_95_______	
Pilot Rating: 4			
Pilot Comments:			
Extra training task, looks less like PIO			
Same comments as before			

Start Time:___13:39______ Pilot ID:_P3_____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__3____	☐ Gamma ____	☐ Training
Run:_1___	Des Performance:___90_____	Ade Performance:__95______	
Pilot Rating: 3			
Pilot Comments:			
Note: this was mistakenly given forcing function 5			
Same as before			
Rating of 3 due to getting used to the task			

Start Time:__13:42________ Pilot ID:__P3___________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__4____	☐ Gamma ____	☐ Training
Run:_1___	Des Performance:___94_____	Ade Performance:__99______	
Pilot Rating: 3			
Pilot Comments:			
Same comments as before			

Start Time:_13:45________ Pilot ID:_P3_____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__aqui__	☐ Gamma ___	☐ Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
Steering force stability almost zero. Put pitch to 10 degrees and can almost release the stick.			

Start Time:_13:50________ Pilot ID:_P3_____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _free_	V Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
“This is something else”			
Gamma is very slow on stick inputs			
Flying at very high pitch angle.			
Gamma response is very different from pitch angle response.			

Start Time:_13:54________ Pilot ID:_P3____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _1__	V Training
Run:_1___	Des Performance:_69______	Ade Performance:___93_____	
Pilot Rating:			
Pilot Comments:			
Control room: PIO!!			
Difficult, pitch angle needed is very high			
Response is slow, makes overcorrections			

Start Time:_13:58________ Pilot ID:_P3____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _1__	V Training
Run:_2___	Des Performance:__81______	Ade Performance:_92______	
Pilot Rating:			
Pilot Comments:			
Much more difficult than pitch angle experiment			
Are overcorrecting			
Almost unstable due to overcorrections [from control room: this is an indication of PIO]			
“I should steer calmer”			

Start Time:_14:01________ Pilot ID:_P3____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _2__	V Training
Run:_1___	Des Performance:__77______	Ade Performance:_91______	
Pilot Rating:5			
Pilot Comments:			
Comment from control room: correcting late which creates oscillations			
Same as last run, steering gamma is slower, you have to keep that in mind.			
Difficult due to large input			
Not steering too aggressively helps			

Start Time:_14:04________ Pilot ID:_P3____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _4__	V Training
Run:_1___	Des Performance:__71______	Ade Performance:_90______	
Pilot Rating:5			
Pilot Comments:			
Same opinion, mistakes were bigger			
Steering more calmly than before			
Anticipating on overshoots			

Start Time:_14:07_______ Pilot ID:__P3___________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma 3_	☐ Training
Run:_1___	Des Performance:__71______	Ade Performance:___90_____	
Pilot Rating:6			
Pilot Comments:			
Flying at very high gain, a lot of overshoot			
More difficult than before, overshooting			
Very difficult			

Start Time:_14:10_______ Pilot ID:__P3___________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma 5_	☐ Training
Run:_1___	Des Performance:__67______	Ade Performance:___84_____	
Pilot Rating:6			
Pilot Comments:			
Difficult due to task. Slow system.			

Start Time:__14:13_________ Pilot ID:__P3_____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma free__	V Training
Run:_1___	Des Performance:__ _______	Ade Performance:___ ______	
Pilot Rating:			
Pilot Comments:			
Pilot is calling the control allocation direct lift.			
Already easier than the first system			
More stable system			
Smaller pitch angles			
Better configuration			

Start Time:__14:17_________ Pilot ID:__P3_____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 1__	V Training
Run:_1___	Des Performance:__92______	Ade Performance:___96_____	
Pilot Rating:2			
Pilot Comments:			
Much nicer			
More damping, can reach much higher scores			
Much more pleasant			

Start Time:__14:20_________ Pilot ID:__P3_____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 2__	V Training
Run:_1___	Des Performance:__92______	Ade Performance:__99______	
Pilot Rating: 2			
Pilot Comments:			
Same opinion again			
More damping, little overshoot			
More like a conventional aircraft			

Start Time:_14:23___________ Pilot ID:__P3_____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 3__	☐ Training
Run:_1___	Des Performance:_89______		Ade Performance:_94______
Pilot Rating: 2			
Pilot Comments:			
“Is steering nicely”			
Can give aggressive inputs because of the high damping			

Start Time:_14:26___________ Pilot ID:__P3_____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 5__	☐ Training
Run:_1___	Des Performance:_82______		Ade Performance:_88______
Pilot Rating: 2			
Pilot Comments:			
Nice flying			
Considerate damping in task.			
Gives trust in the system			

Start Time:_14:29___________ Pilot ID:__P3_____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma acqui	☐ Training
Run:_1___	Des Performance:_ _______		Ade Performance:_ _______
Pilot Rating:			
Pilot Comments:			
Little effort, overshooting a little bit			
Very pleasant and good.			

Start Time:_14:33__________ Pilot ID:__P3____________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma acqui	☐ Training
Run:_1___	Des Performance:_ _______	Ade Performance:_ _______	
Pilot Rating:			
Pilot Comments:			
“Passengers will not like it due to high pitch angle change”			
Have to look out for overshoots			
A bit difficult, has a time delay			
More difficult than the previous one			

Comments after experiment:

Overall handling qualities:

Ptich angle is oke, a little low damping.
Flight path angle is not really doable with the pitch controller
Can imagine approach will be very difficult
Gamma-Gamma feels like a conventional aircraft, very high damping. Can give much larger inputs.
Just good, would be able to do an approach with the gamma system.

The experiments:

Flight path is very useful to have on the display.
Flight path angle tasks reveal a lot about the aircraft. Also shows the difference between both systems very well.

B.4. P4

Start Time: 13:29 Pilot ID:_P4______________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__Free_	☐ Gamma ____	V Training
Run:_1___	Des Performance:___________	Ade Performance:___________	
Pilot Rating:			
Pilot Comments:			
Flies at high AoA. Very high, higher than used to.			
Very precise and stable pitch attitude. Looks easy to control			
Seems very clean. Deceleration and acceleration is slow but to be expected			

Start Time:_13:34_________ Pilot ID:__P4____________ Motion Parameter Set:________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__1____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__82______	Ade Performance:__95______	
Pilot Rating: 2			
Pilot Comments:			
Expected steep ramps, less steps. Needs to get used to it.			
Very direct, feels like a fighter			
Unexpectedly crisp, look better because the pitch ladder is zoomed in.			
Minimal pilot compensation,1 or 2 for A/C deficiencies.			
Pretty good			

Start Time:__13:32________ Pilot ID:_P4_______________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch_2____	☐ Gamma ____	V Training
Run:_1___	Des Performance:__86______	Ade Performance:_94_______	
Pilot Rating: 1			
Pilot Comments:			
More aggressive due to task. Steering is more aggressive			
Very direct in pitch. Very precise control			
Pitch rate could be higher, but fine with passenger aircraft. Somewhere in rating 1 or 2			

Start Time:___13:44______ Pilot ID:_P4_____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__3____	☐ Gamma ____	☐ Training
Run:_1___	Des Performance:___91_____	Ade Performance:__97______	
Pilot Rating: 1			
Pilot Comments:			
More aggressive than would be wanted with passengers, but good for the task			
Overcontrolling when ramp reverses			
No problem, still rating of 1			

Start Time:__13:50________ Pilot ID:__P4___________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__4____	☐ Gamma ____	☐ Training
Run:_1___	Des Performance:___96_____	Ade Performance:__99______	
Pilot Rating: 1			
Pilot Comments:			
Again rating of 1. Nothing in the behaviour the pilot would want to change.			

Start Time:_13:52________ Pilot ID:_P4____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	V Pitch__aqui__	☐ Gamma ___	☐ Training
Run:_1___	Des Performance:__________	Ade Performance:__________	
Pilot Rating:			
Pilot Comments:			
Told about load factor after first 5 to 10 degree acquisition.			
Now is keeping it between 0.9 and 1.1			
“Doing some extremes”			
Zoomed in pitch ladder. Judge maneuvering by how fast you climb the ladder.			
Feels like very precise pitch control. Assumes automation or no pitch forces.			
“I like it.”			

Start Time:_13:55________ Pilot ID:_P4____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _free_	V Training
Run:_1___		Des Performance:___________	Ade Performance:___________
Pilot Rating:			
Pilot Comments:			
“This is going to be interesting”			
How to show descends on this display			
Need to find out the gamma change with the pitch angle change			
Expected more difficulty for this task			

Start Time:_13:59________ Pilot ID:_P4____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _1__	V Training
Run:_1___		Des Performance:_78______	Ade Performance:___91_____
Pilot Rating: 3			
Pilot Comments:			
As expected, a bit harder to control			
One step away from what you are controlling			
Can be anticipated, but harder			
More relevant task			
Very nicely precisely to control flight path angle, but it is harder			
Still satisfactory			
Very good but gamma more difficult. Overshoot tendencies			
Rating 2 or 3, some pilot compensation			

Start Time:_14:04________ Pilot ID:_P4____________ Motion Parameter Set:_________

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma _2__	V Training
Run:_1___		Des Performance:__87______	Ade Performance:_98______
Pilot Rating:3			
Pilot Comments:			
Same as before, easy to control small gamma changes			
Very stable			
Larger path changes has more risk of overshooting			
Do need to compensate for larger changes			

Start Time:_14:08_______ Pilot ID:__P4___________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma 3_	☐ Training
Run:_1___	Des Performance:__76______	Ade Performance:___91_____	
Pilot Rating:4			
Pilot Comments:			
When steps get bigger, it gets harder			
Task more difficult. Anticipation is larger			
Definitely rating of 4 or 5 for this task. Hard for steps.			

Start Time:_14:13_______ Pilot ID:__P4___________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma 5_	☐ Training
Run:_1___	Des Performance:__74______	Ade Performance:___88_____	
Pilot Rating:5			
Pilot Comments:			
From control room: Flies much more aggressively			
“thought it went better than last time.”			
Was flying less aggressively			
Steps are difficult, ramps are easy. Still nice aircraft			
Getting 1 percent higher score would not change the rating, so no retry necessary.			

Start Time:__14:18_________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma free__	V Training
Run:_1___	Des Performance:__ ______	Ade Performance:___ _____	
Pilot Rating:			
Pilot Comments:			
More damped. Almost sluggish. Deadbeat in pitch angle.			
Very stable. No short period or phugoid effects. Feels like not enough control. Not too happy with			
this controller.			
Very slow gamma drift.			
Was looking mainly at pitch angle, will redo this free flying.			

Start Time:__14:23_________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma free__	V Training
Run:_2___	Des Performance:__ ______		Ade Performance:___ _____
Pilot Rating:			
Pilot Comments:			
Now looking at gamma.			
Still sluggish. A lot of input to change the gamma.			
Allows very accurate gamma control			
See how this might be easier			
Easy to require a lot of stick input			

Start Time:__14:26_________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 1__	V Training
Run:_1___	Des Performance:__91______		Ade Performance:___96_____
Pilot Rating:1			
Pilot Comments:			
As expected much more precise gamma control			
Feels weird to have large pitch angles changes			
Easy task			
High pitch angle changes, same or better than previous controller			
“very good controller” pilot not a factor			
Maybe once or twice full deflection			

Start Time:__14:30_________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 2__	V Training
Run:_1___	Des Performance:__95______		Ade Performance:__98______
Pilot Rating: 2			
Pilot Comments:			
A lot of input required, using a lot of input capacity. Stop was hit once.			
Absolutely desired. A/C highly desirable for this task.			
Seems to lack authority for operation			
Rating of 2 since the stop was reached.			

Start Time:_14:35__________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 3__	☐ Training
Run:_1___	Des Performance:_80______	Ade Performance:_94______	
Pilot Rating: 3			
Pilot Comments:			
Control room: overshot			
More aggressive, les compensating			
Stop reached three times. Still desired, easy controller			
Stops make it unpleasant deficiencies.			

Start Time:_14:39__________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma 5__	☐ Training
Run:_1___	Des Performance:_81______	Ade Performance:_88______	
Pilot Rating: 4			
Pilot Comments:			
Was not so happy. Full deflection for every step.			
Feels like the pilot needs more control than is available.			
It is not satisfactory. Rating of 4 because of the stops hit.			
Catching the target is easy			

Start Time:_14:45__________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		☐ Pitch	V Gamma
Experiment Type:	☐ Pitch_______	V Gamma acqui	☐ Training
Run:_1___	Des Performance:_ ______	Ade Performance:_ ______	
Pilot Rating:			
Pilot Comments:			
“Forgot passengers in the beginning”			
Pretty precise. Was mimicking climb and level off.			
Precise flight path control.			

Start Time:_14:50__________ Pilot ID:__P4____________ Motion Parameter Set:_______

Control Mapping:		V Pitch	☐ Gamma
Experiment Type:	☐ Pitch_______	V Gamma acqui	☐ Training
Run:_1___	Des Performance:_ _______	Ade Performance:_ _______	
Pilot Rating:			
Pilot Comments:			
Last controller is more like an aircraft.			
Gamma controller is easier in the gamma task, but pitch angle is just as well to do.			
Feels like more direct smoother control.			
Prefers the normal control allocation.			

Comments after experiment:

Overall handling qualities:

If this is the aircraft, it is very pleasant.
Precise control, better than much smaller aircraft.
Precise pitch angle control in the first control allocation.
Have to anticipate the gamma more.
Second control allocation is easier for gamma control.
Prefer the first control allocation. Flying is more than just gamma control.

The experiments:

Flight path task is a useful addition.
Well defined definition of goals for the task.
On the limit of the aircraft.
Precise pitch angle control is useful to know. First experiment still important!
Pretty deadbeat pitch angle control.

C

Complete Experiment Results

C.1. Ratings and Scores

Table C.1: Ratings and Scores of all Runs Including Training

	Desired Score				Given Rating			
	P1	P2	P3	P4	P1	P2	P3	P4
$\theta\theta$ 1	85	90	80	82	2	3	4	2
$\theta\theta$ 2	89	81	88	86	1	5	4	1
$\theta\theta$ 3	76	89		91	1	3		1
$\theta\theta$ 4		95	94	96		2	3	1
$\theta\theta$ 5			90				3	
$\theta\gamma$ 1	78	81	81	78	4	5		3
$\theta\gamma$ 2		79	81	87		6	5	3
$\theta\gamma$ 3	71	77	71	76	6	5	6	4
$\theta\gamma$ 4			68				5	
$\theta\gamma$ 5	73	68	67	74	6	6	6	5
$\gamma\gamma$ 1	76	88	92	91	4	5	2	1
$\gamma\gamma$ 2		86	92	95		6	2	2
$\gamma\gamma$ 3	72	78	89	80	6	5	2	3
$\gamma\gamma$ 4								
$\gamma\gamma$ 5	76	70	82	81	4	6	2	4

C.2. P1 Time Histories

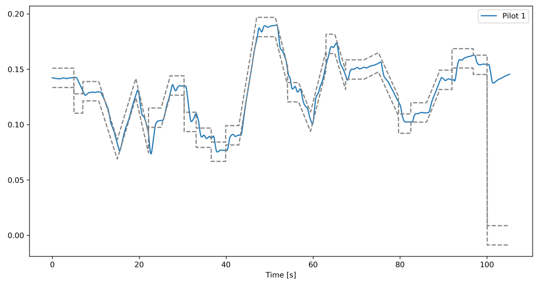


Figure C.1: P1 $\theta\theta 1$

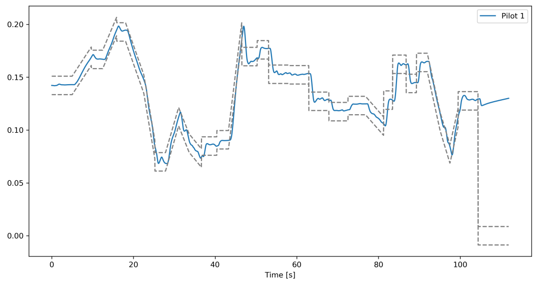


Figure C.2: P1 $\theta\theta 2$

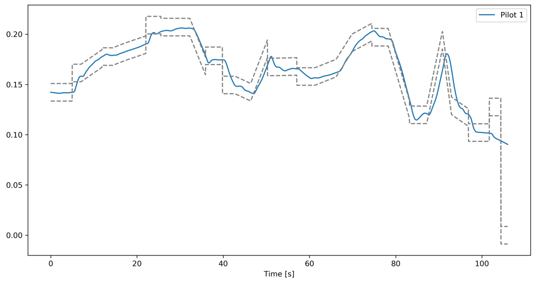


Figure C.3: P1 $\theta\theta3$

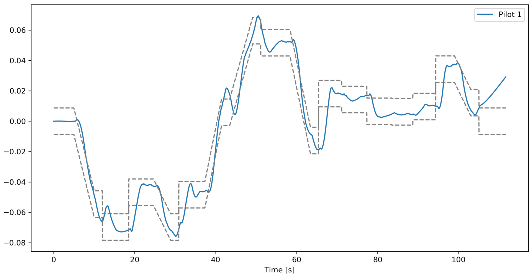


Figure C.4: P1 $\theta\gamma1$

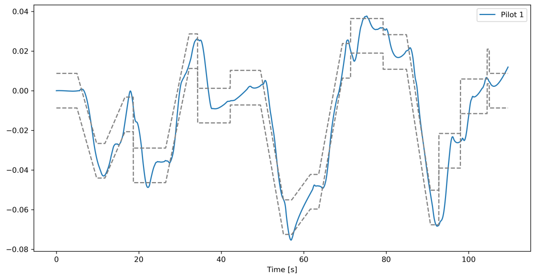


Figure C.5: P1 $\theta\gamma3$

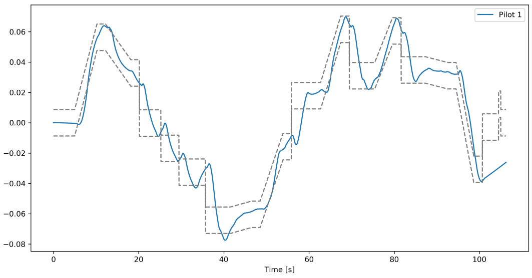


Figure C.6: P1 $\theta\gamma5$

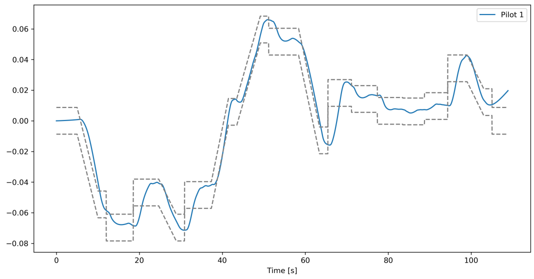


Figure C.7: P1 $\gamma\gamma1$

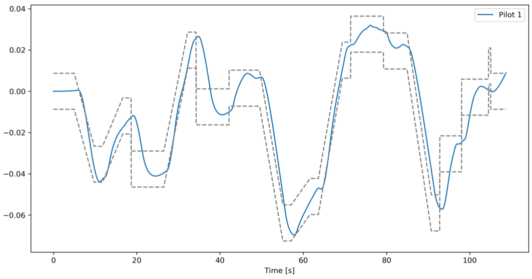


Figure C.8: P1 $\gamma\gamma3$

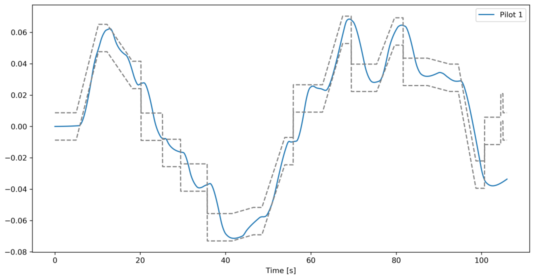


Figure C.9: P1 $\gamma\gamma5$

C.3. P2 Time Histories

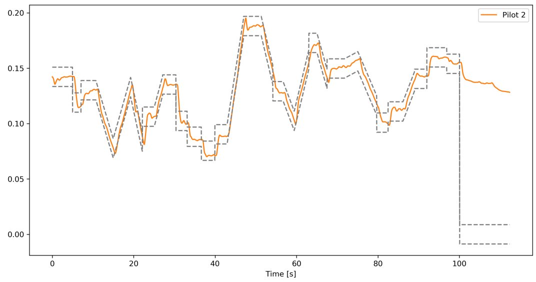


Figure C.10: P2 $\theta\theta 1$

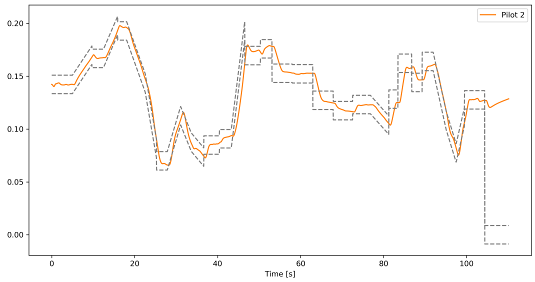


Figure C.11: P2 $\theta\theta 2$

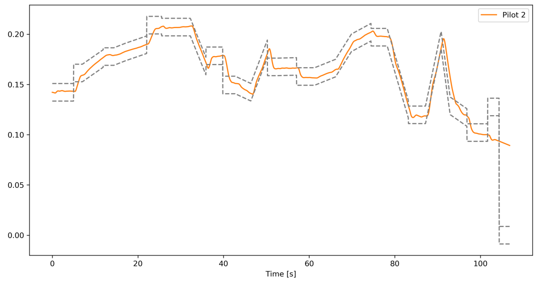


Figure C.12: P2 $\theta\theta 3$

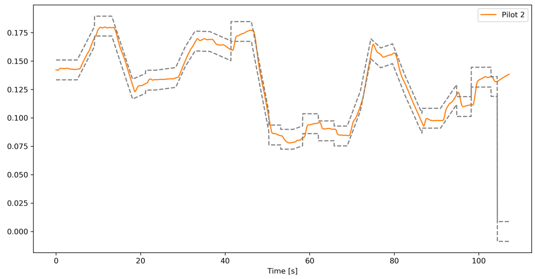


Figure C.13: P2 $\theta\theta 4$

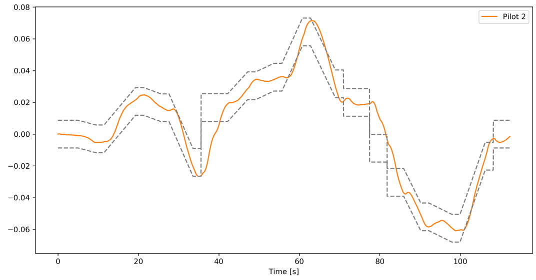


Figure C.14: P2 $\theta\gamma 1$

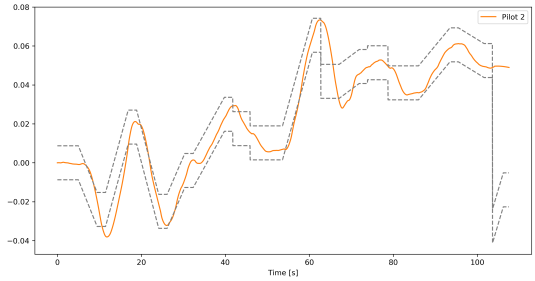


Figure C.15: P2 $\theta\gamma 2$

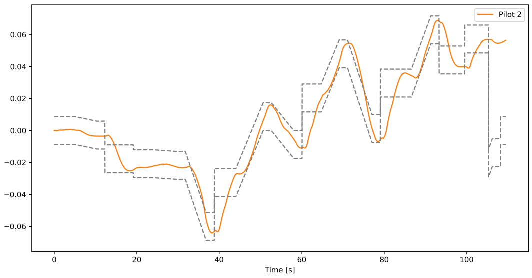


Figure C.16: P2 $\theta\gamma3$

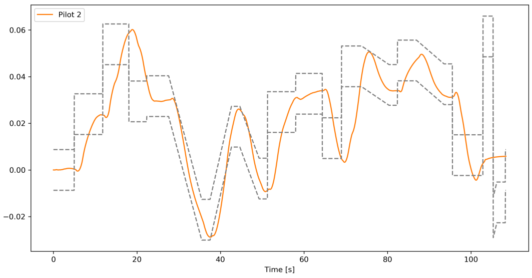


Figure C.17: P2 $\theta\gamma5$

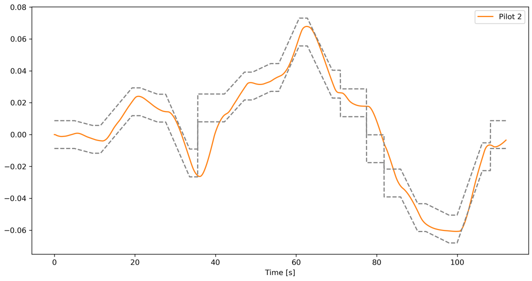


Figure C.18: P2 $\gamma\gamma1$

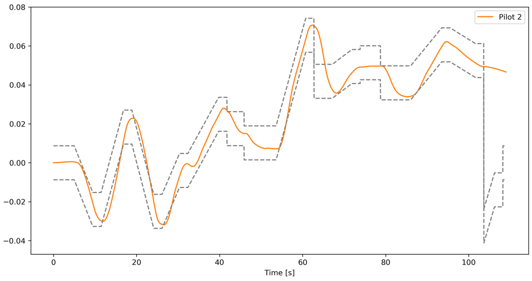


Figure C.19: P2 $\gamma\gamma2$

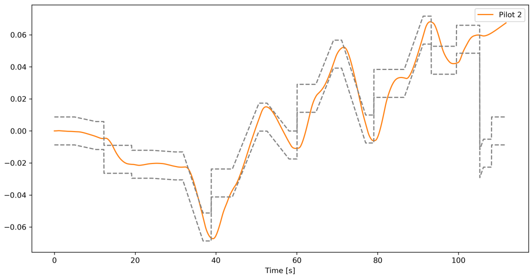


Figure C.20: P2 $\gamma\gamma3$

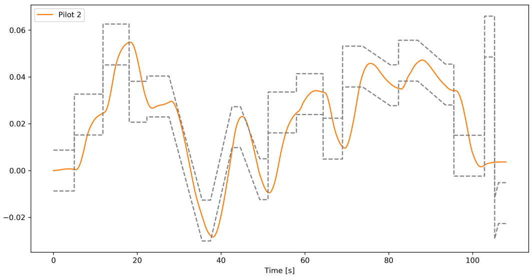


Figure C.21: P2 $\gamma\gamma5$

C.4. P3 Time Histories

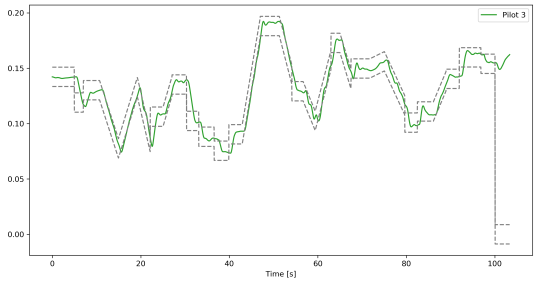


Figure C.22: P3 $\theta\theta 1$

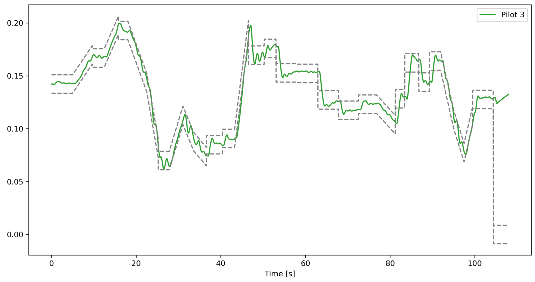


Figure C.23: P3 $\theta\theta 2$

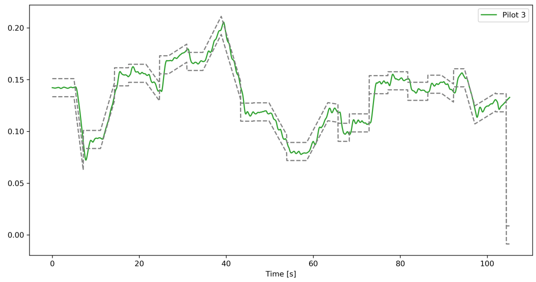


Figure C.24: P3 $\theta\theta 5$

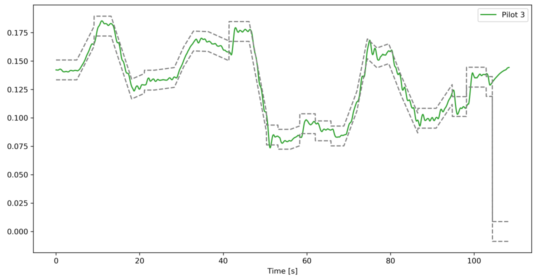


Figure C.25: P3 $\theta\theta 4$

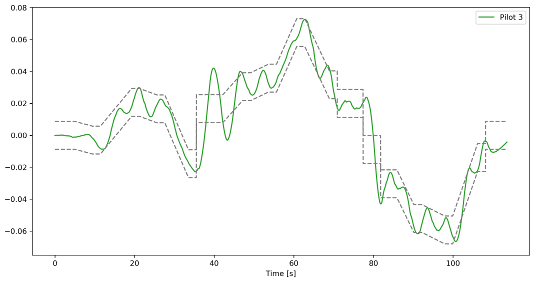


Figure C.26: P3 $\theta\gamma 1$

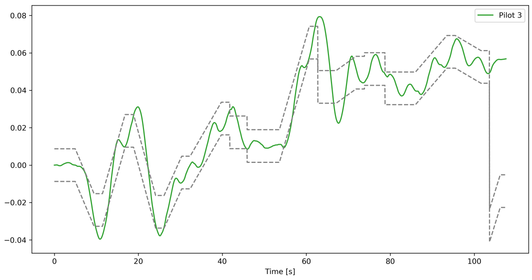


Figure C.27: P3 $\theta\gamma 2$

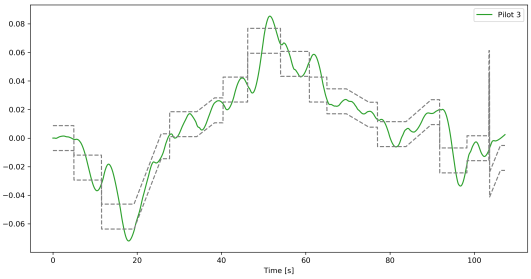


Figure C.28: P3 $\theta\gamma4$

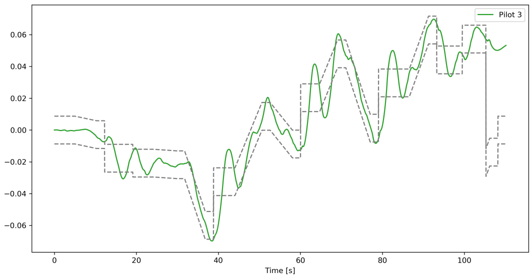


Figure C.29: P3 $\theta\gamma3$

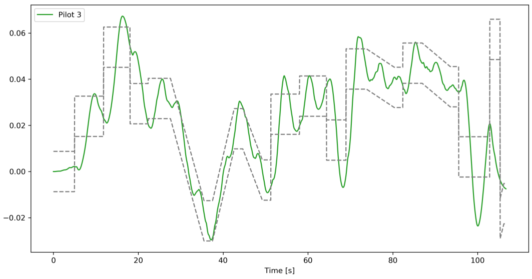


Figure C.30: P3 $\theta\gamma5$

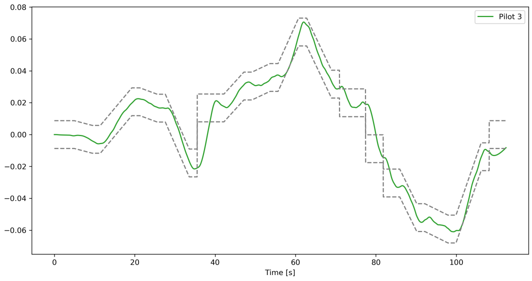


Figure C.31: P3 $\gamma\gamma1$

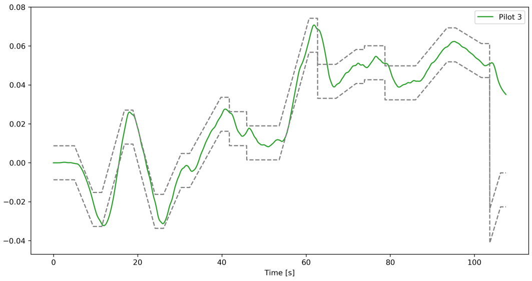


Figure C.32: P3 $\gamma\gamma2$

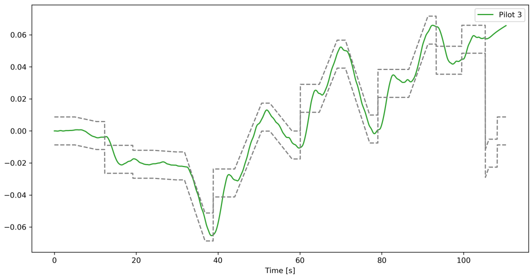


Figure C.33: P3 $\gamma\gamma3$

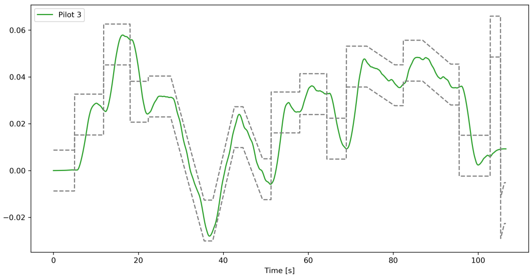
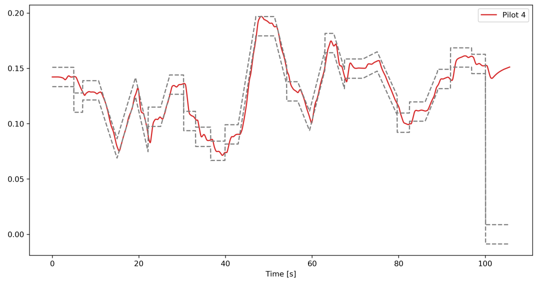


Figure C.34: P3 $\gamma\gamma5$

C.5. P4 Time Histories



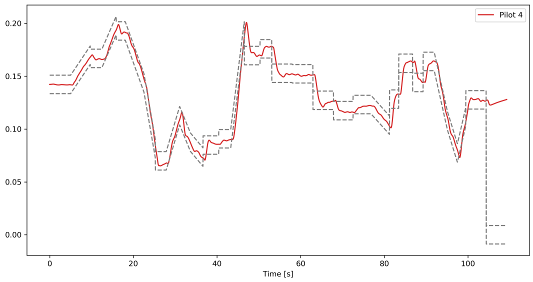
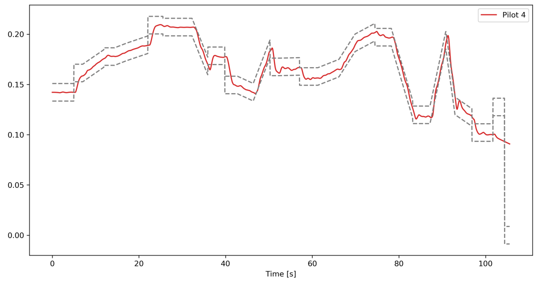


Figure C.35: P4 $\theta\theta 1$

Figure C.36: P4 $\theta\theta 2$



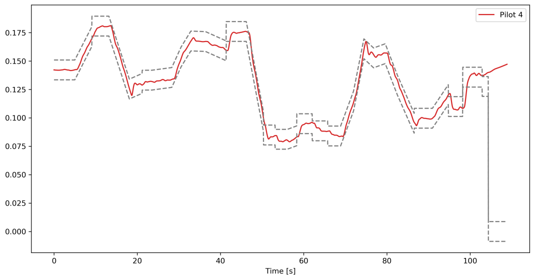
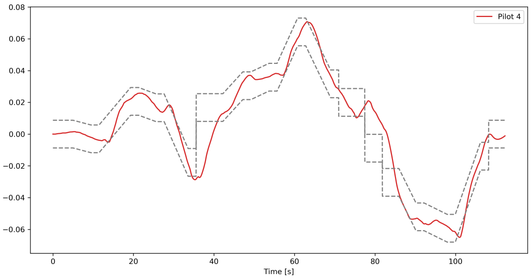


Figure C.37: P4 $\theta\theta 3$

Figure C.38: P4 $\theta\theta 4$



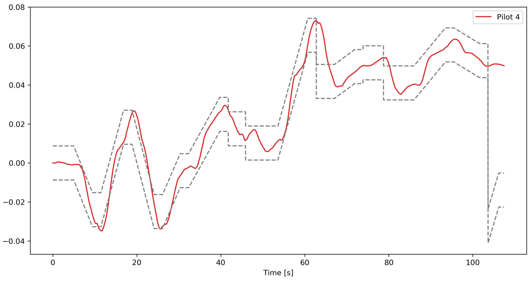


Figure C.39: P4 $\theta\gamma 1$

Figure C.40: P4 $\theta\gamma 2$

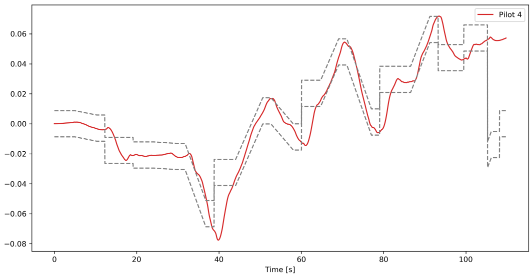


Figure C.41: P4 $\theta\gamma 3$

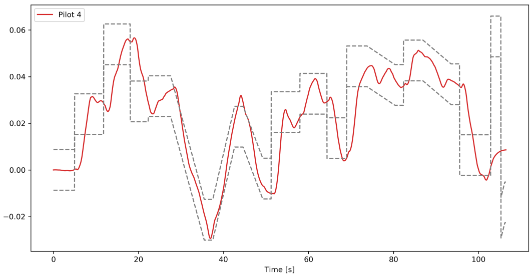


Figure C.42: P4 $\theta\gamma 5$

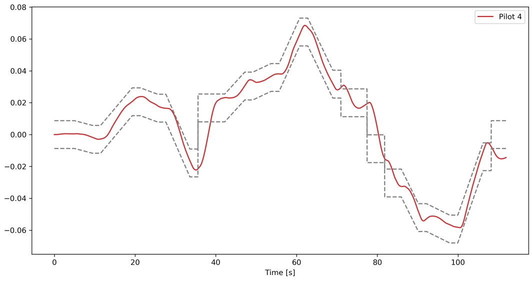


Figure C.43: P4 $\gamma\gamma 1$

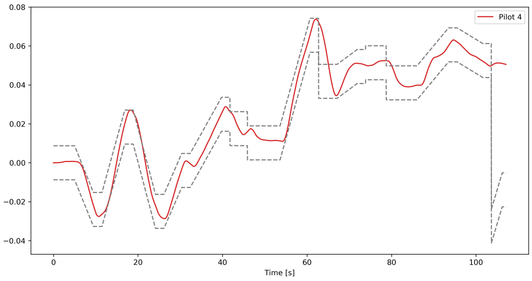


Figure C.44: P4 $\gamma\gamma 2$

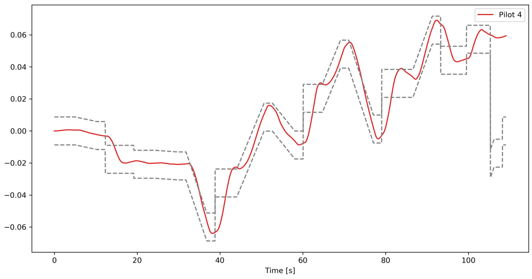


Figure C.45: P4 $\gamma\gamma 3$

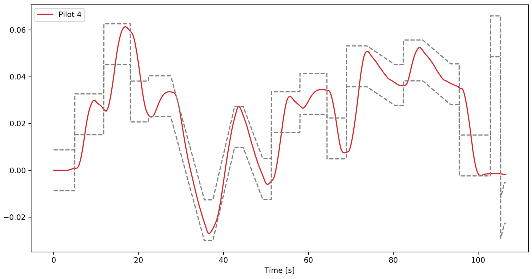


Figure C.46: P4 $\gamma\gamma 5$

D

Motion Filter Setup

The motion of the Simona Research Simulator (SRS) is linked to the aircraft model via a classical washout filter. The SRS also shows outside visuals which are generated from the position of the aircraft, and the attitude angles as input.

The specific forces, rotation rates, and rotation accelerations are the input for the motion. The classical washout filter then converts these to the motion of the SRS. The washout filter settings can be altered to fit the movements of the aircraft. These values are shown below in Table D.1.

Table D.1: Washout filter settings

tilt_coordination_method	1
surge_gain	0.4
surge_hp_wn	1.0
surge_hp_wb	0.0
surge_lp_wn	2.0
heave_gain	0.3
heave_hp_wn	2.0
heave_hp_wb	0.2
pitch_gain	1.0
pitch_hp_wn	0.0
pitch_hp_wb	1.0
sway_selection_gain	0.0
roll_selection_gain	0.0
yaw_selection_gain	0.0
surge_tilt_gain	1.0
tilt_rate_limit	3.0
ac_ref_pos_x	-26.26
ac_ref_pos_y	0.0
ac_ref_pos_z	-1.2075
filt_ref_pos_x	0.0
filt_ref_pos_y	0.0
filt_ref_pos_z	-1.2075

The tilt coordination method is set to 1, which stands for straight differentiation to generate the tilt needed to simulate the accelerations. The surge gain and break frequencies are set with a second order high pass filter, and a low pass filter. The first order is set to zero to keep the high pass filter at second order. The gain is set to 0.4 after some testing.

The heave settings were tuned using the Gouverneur Tuning Approach. The filter was tuned by flying two different forcing functions ($\theta\gamma 2$ and $\theta\gamma 4$). The result of both forcing functions is shown in Table D.2. The forcing function is indicated, and colored either red or green. Red indicates that a limit on the motion system is reached, and thus that this setting cannot be used during the experiment. Green indicates that no limit was reached. If both experiments result in a green run, the setup is viable. This test is done for the heave gain, and heave second order break frequency of the high pass filter. This gain and break frequency limited the motion the most.

The pitch gain is set to 1, and the first order break frequency is set at 1 rad/sec. The selection gains for sway, roll, and yaw are set to zero. This makes sure the simulator will stay at three degrees of freedom. The surge tilt gain is set to 1, so the surge tilt coordination is turned on. The tilt rate limit it set to three degrees per second. The aircraft reference position, and the filter reference position are set here. The aircraft reference position is the position where the motion should be calculated, in this case the cockpit of the aircraft, relative to where the forces are calculated, in case the center of gravity (c.g.). This includes some guessing, since the vertical center of gravity is not known for the Flying V. Therefore, the pilot position is estimated to be five meters behind the nose, and the vertical c.g. is on the floor. The reference position is thus 26 meters in front of the c.g., and 1.2 meters upwards at Design Eye Reference Point (DERP). The filter position is set at the DERP in the simulator, so 1.2 meters above the gimbal point in the simulator.

Table D.2: Gouverneur Tuning results

		Gain								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Frequency	2.8	🟩	🟩	🟩	🟩	🟩	🟩 $\theta\gamma4$	🟥 $\theta\gamma4$	🟩 $\theta\gamma2$	🟥 $\theta\gamma2$
	2.6	🟩	🟩	🟩	🟩	🟩 $\theta\gamma4$	🟩 $\theta\gamma2$ 🟥 $\theta\gamma4$	🟩 $\theta\gamma2$	🟥 $\theta\gamma2$	🟥
	2.4	🟩	🟩	🟩	🟩	🟥 $\theta\gamma4$	🟥 $\theta\gamma2$	🟥	🟥	🟥
	2.2	🟩	🟩	🟩	🟩 $\theta\gamma4$	🟩 $\theta\gamma2$ 🟥 $\theta\gamma4$	🟥 $\theta\gamma2$	🟥	🟥	🟥
	2.0	🟩	🟩	🟩 $\theta\gamma4$	🟩 $\theta\gamma2$ 🟥 $\theta\gamma4$	🟥 $\theta\gamma2$	🟥 $\theta\gamma2$	🟥	🟥	🟥
	1.8	🟩	🟩 $\theta\gamma4$	🟩 $\theta\gamma2$ 🟥 $\theta\gamma4$	🟥 $\theta\gamma2$	🟥 $\theta\gamma2$	🟥	🟥	🟥	🟥
	1.6	🟩	🟩 $\theta\gamma2$ 🟩 $\theta\gamma4$	🟥 $\theta\gamma2$	🟥 $\theta\gamma2$	🟥	🟥	🟥	🟥	🟥
	1.4	🟩 $\theta\gamma4$	🟥 $\theta\gamma2$ 🟥 $\theta\gamma4$	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	1.2	🟩 $\theta\gamma2$ 🟩 $\theta\gamma4$	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	1.0	🟩 $\theta\gamma2$ 🟩 $\theta\gamma4$	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	0.8	🟥 $\theta\gamma2$ 🟥 $\theta\gamma4$	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

E

Transfer Functions

Three transfer functions are shown here, one for each of the experiment blocks. The poles are the eigenmodes of the system, and independent from the input, or output shown. The poles of the system are shown in Table E.1.

Table E.1: Poles of the system.

-5.23
-0.654
-5.88
-0.000181 + 0.0465i
-0.000181 - 0.0465i
-0.3462 + 0.539i
-0.346 - 0.539i
-0.00333
0.0

The poles and zeros are calculated from the state space system of the form:

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx + Du \end{aligned} \tag{E.1}$$

The B-matrix is adapted to the control allocation by reducing the inputs from six $--1$ input for each control surface$--$ to one, which drives the control surfaces on both wings following the control allocation. This means both allocations have a different B-matrix. The proper transfer functions are chosen by picking C. For the pitch angle, the position corresponding to the pitch angle can be set to 1. For the flight path angle, the angle of attack is needed. In order to calculate the angle of attack from the state space system, the system is put into Simulink where the angle of attack is calculated. This system is then and linearized to estimate state space system. The C matrix from this system can be used to see the linearized relative portions of the forward velocity U and upward velocity W. This system is shown in Figure E.1.

E.1. Elevon - Pitch Angle

The transfer function $\frac{\theta(s)}{\delta_e(s)}$ is:

$$\frac{\theta(s)}{\delta_e(s)} = \frac{-0.02847s^6 - 0.1956s^5 - 0.1876s^4 - 0.1101s^3 - 0.02238s^2 - 0.000287s - 7.08e-07}{s^8 + 12.46s^7 + 46.62s^6 + 51.48s^5 + 29.84s^4 + 8.483s^3 + 0.09483s^2 + 0.01811s + 5.947e-05} \tag{E.2}$$

The zeros which belong to this transfer function are shown in Table E.2. There are no zeros in the right hand plane.

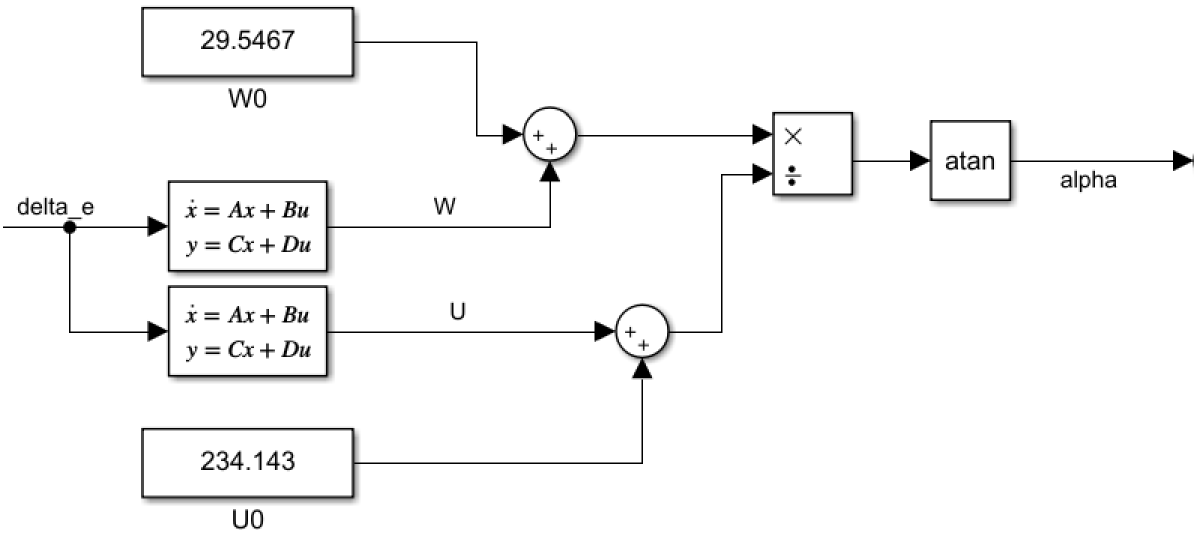


Figure E.1: Simulink model used to calculate α

Table E.2: Zeros of the normal θ control allocation system from elevon deflection to pitch angle.

-5.85
-0.349 + 0.538i
-0.349 - 0.538i
-0.305
-0.0102
-0.00331
0.0

E.2. Elevon - Flight Path Angle Pitch Control Allocation

The transfer function for the normal allocation system for $\frac{\gamma(s)}{\delta_e(s)}$ is:

$$\frac{\gamma(s)}{\delta_e(s)} = \frac{0.0008649s^7 + 0.006917s^6 + 0.003048s^5 - 0.0515s^4 - 0.03772s^3 - 0.02182s^2 - 4.76e-05s + 7.994e-08}{s^8 + 12.46s^7 + 46.62s^6 + 51.48s^5 + 29.84s^4 + 8.483s^3 + 0.09483s^2 + 0.01811s + 5.947e-05} \tag{E.3}$$

The zeros belonging to the system using the normal control allocation are shown in Table E.3. There are two zeros in the right hand plane. These zeros indicate the non-minimum phase response.

Table E.3: Zeros of the normal θ control allocation system from elevon deflection to flight path angle.

-5.85
-4.03
2.59
-0.3495 + 0.538i
-0.349 - 0.538i
0.00111
-0.00331
0.0

E.3. Elevon - Flight Path Angle Flight Path Angle Control Allocation

The transfer function for the new control allocation system for $\frac{\gamma(s)}{\delta_e(s)}$ is:

$$\frac{\gamma(s)}{\delta_e(s)} = \frac{-5.638e-06s^7 - 0.0005885s^6 - 0.005176s^5 - 0.01261s^4 - 0.008356s^3 - 0.00375s^2 - 1.597e-05s - 9.618e-09}{s^8 + 12.46s^7 + 46.62s^6 + 51.48s^5 + 29.84s^4 + 8.483s^3 + 0.09483s^2 + 0.01811s + 5.947e-05} \tag{E.4}$$

The zeros belonging to the system using the new control allocation are shown in Table E.4. The zeros which were in the right hand plane for the normal control allocation are now moved to the left hand plane. This proves there is no non-minimum phase response anymore.

Table E.4: Zeros of the new γ control allocation system from elevon deflection to flight path angle.

-94.9
-5.84
-2.88
-0.352 + 0.538i
-0.352 - 0.538i
-0.000725
-0.00357
0.0