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Simulator Evaluation of Flightpath-Oriented Control Allocation for the Flying-V

Gijs Vugts*, Olaf Stroosma†, Roelof Vos‡, and Max Mulder§
Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

A novel aircraft configuration, the tailless Flying-V, is examined for its longitudinal handling qualities in cruise by means of piloted simulations. The Flying-V is controlled by two aileron/elevator (elevon) surfaces on each side, and rudders on each wingtip. Two control allocation schemes were created: a conventional 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, allowing more direct control of the resulting flight path. The longitudinal handling qualities in cruise conditions were investigated by pilot opinion in a moving base simulator. Three experiments were conducted: a traditional pitch tracking experiment with the conventional control allocation, and a new flight-path-angle tracking experiment, using both the conventional and the flight-path-oriented control allocation. The pilots indicated the conventional pitch attitude control to have Level 1 handling qualities for the pitch control task, and Level 2 for the flight path control task. The flight-path-oriented control allocation improved the performance of the pilots during the flight-part tracking experiment, but the perceived control authority was considered too small for most pilots to consistently 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 constituted the first piloted simulator experiment with the Flying-V. This study investigates 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 [3, 8]. The non-minimum phase response warrants additional research. The handling qualities were assessed by testing with pilots, and included an assessment of the handling qualities in the flight path response.

The piloted experiment introduced 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 were 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

*MSc. student, Control & Simulation section, Faculty of Aerospace Engineering.
†Senior Researcher, Control & Simulation section, Faculty of Aerospace Engineering, Senior AIAA Member.
‡Assistant Professor, Flight Performance & Propulsion section, Faculty of Aerospace Engineering, AIAA Associate Fellow
§Professor, Control & Simulation section, Faculty of Aerospace Engineering.

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 were tested. One of the control allocations was designed to improve the flight path behavior 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 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 extends the legacy handling qualities experiments [4, 5]. The longitudinal handling qualities of the Flying-V in cruise conditions were 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 behavior, 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 experimental 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 reported, and recommendations for use of this research and future research are made. Conclusions are drawn in section VII.

II. Background

A. The Flying-V

First, the wing geometry of the Flying-V will be discussed to gain insight into how the aircraft will behave. The Flying-V model used for this study 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 nominal center of gravity of the Flying-V is 31.3 meters behind the nose (55% MAC), the nominal 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's elevator 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 behavior 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 MSc. 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 necessarily equilibrium conditions, as the angle of attack is always set to 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.

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 nominal centre of gravity is chosen, which is 55% MAC [3]. The force- and moment coefficients

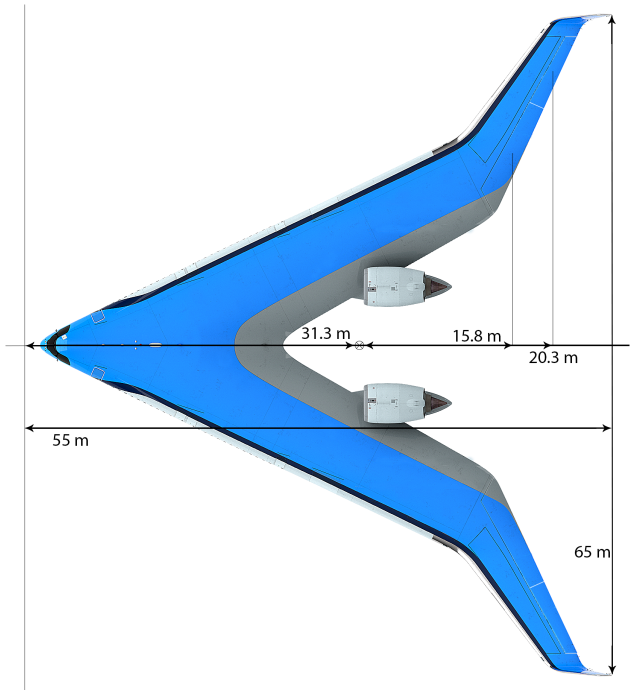

Fig. 1 Flying-V with inboard and outboard elevon location from the centre of gravity.

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 behavior 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 longitudinal 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 1. The eigenvectors are calculated with the velocities in meters per second, and the pitch- angle and rate in degrees and degrees per second.

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] of the equations of motion. The

Table 1 **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	[°]

absolute value of a modal state is the Mode Participation Factor (MPF), which shows how much that mode is active in a certain maneuver. The modal form can be constructed from a linear state space system in the following way,

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

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 inherent response from one eigenmode, only the Zero Input Response (ZIR) for the corresponding modal state is taken since no input is given to start the eigenmode. This equation shows that if the initial state ($x(0)$) 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.

The modal form can be used to isolate the eigenmodes in a specific response to a pilot input. By individually transforming the ZSR for each mode back to the physical state space, the contribution of each mode to the response can be identified. This is done for the three main eigenmodes −short period, flight path subsidence, and the oscillatory phugoid− in Figure 2. This plot shows how the pitch angle and flight-path angle are affected by each mode, while a 2 second longitudinal 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 similar in magnitude. 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's flight path, because the input will be out of phase with the aircraft response. Therefore, a new control allocation is created where this effect is mitigated. 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

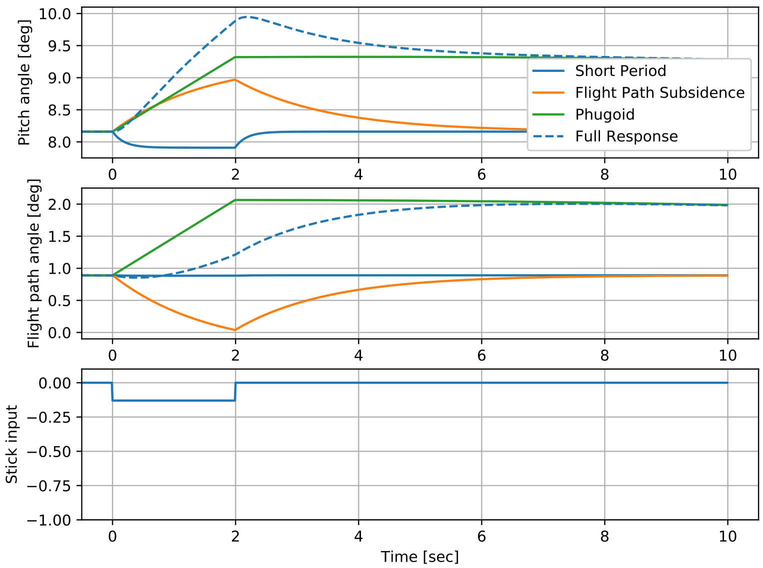

Fig. 2 Response of different eigenmodes to a step input using normal control allocation.

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 based on this analysis the pitch angle handling qualities will be within Level 1.

D. Control Allocation

In order to tackle the excessive 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 the bare airframe handling qualities.

The first control allocation has 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 pilot 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 behavior 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 on 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.

The new control allocation can be compared to the conventional 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

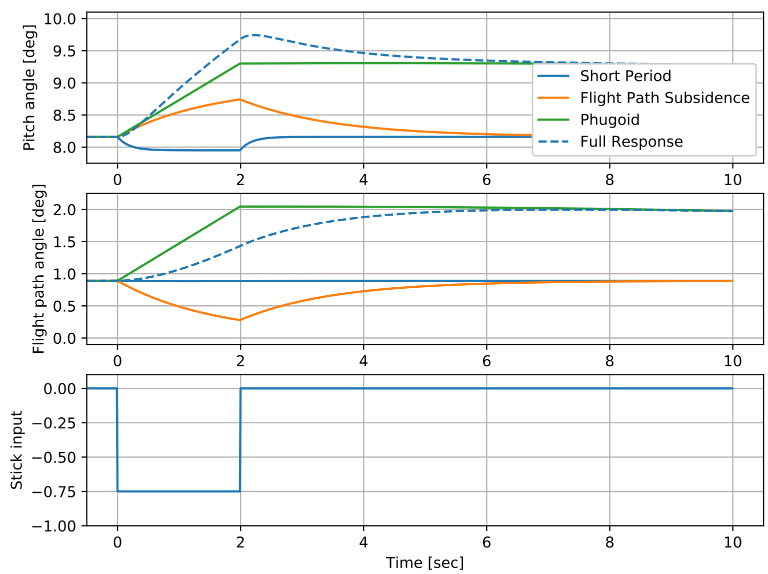

Fig. 3 Response of different eigenmodes to a step input using the new control allocation.

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 in shape. 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 investigates whether the non-minimum phase response is degrading the handling qualities, and whether the new control allocation improves the flight path response of the Flying-V.

E. Cooper-Harper Pilot Rating Scale

The handling qualities have been evaluated using the Cooper-Harper Rating Scale [16, 19]. This widely used scale uses pilot opinion, and 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.

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

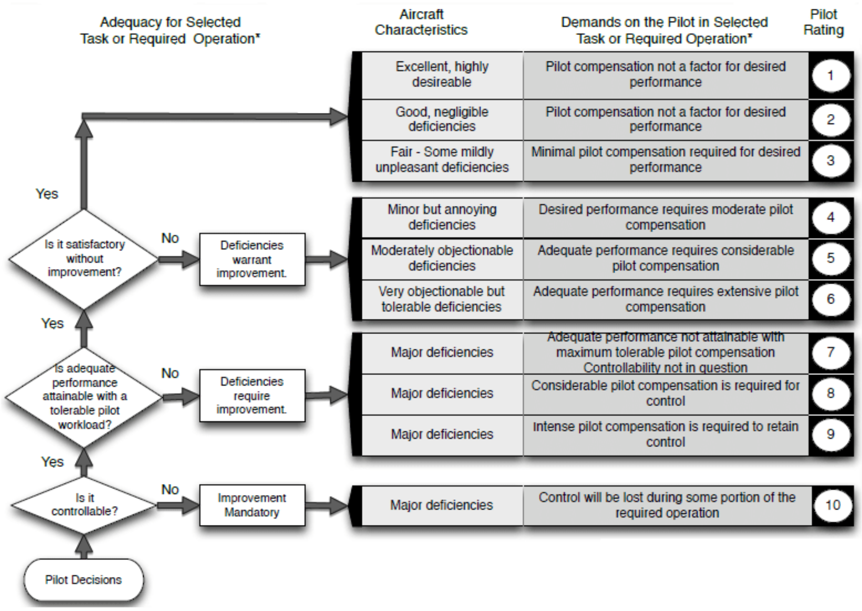

Fig. 4 Cooper-Harper Handling Qualities Rating Scale [16].

III. Experiment Design

The experiments performed have been 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 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 for this study.

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 used forcing functions for the pitch angle which contains both steps and ramps. This signal lasts for 100 seconds. All references signals were randomly generated beforehand by letting the forcing function build up by first picking between using a ramp or a step. The size of the 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 criterion for the STEM 2 tracking task is to be within $\pm 0.28°$for 50% of the time. The actual task will increase the desired performance window to $\pm 0.5°$. 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 $\pm 1.0°$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

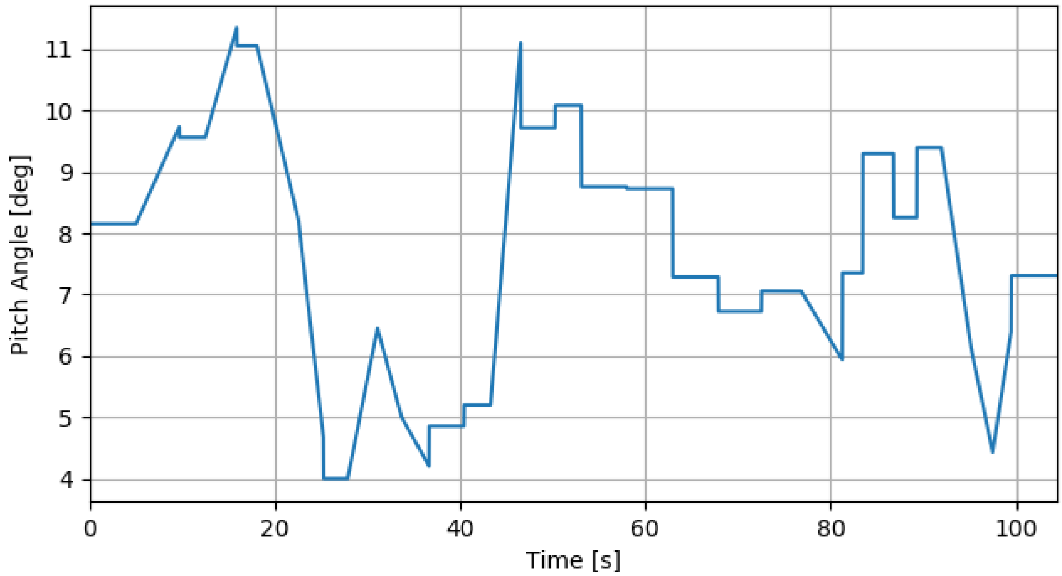

Fig. 5 Forcing function of a pitch angle experiment.

the Flying-V is prone to different behavior 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 is similar to the pitch angle experiment to draw from the extensive experience in handling qualities experiments utilized in the design of this task.

The flight-path-angle tracking task is an experiment where the pilot has to follow a forcing function for 100 seconds. The forcing function starts at zero degrees flight-path angle, and moves 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 behavior 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 were performed with the SIMONA Research Simulator (SRS) at TU Delft [23]. The simulator moved in 3 degrees of freedom, since the experiment only considers the longitudinal handling qualities. The pilot sat in the right seat and used a sidestick with maximum deflection of 18°for the controls with a spring force gradient of 2.5 N/°. The outside visuals were generated by FlightGear. The setup is shown in Figure 7.

2. Flight Display

The display was 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 marker 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

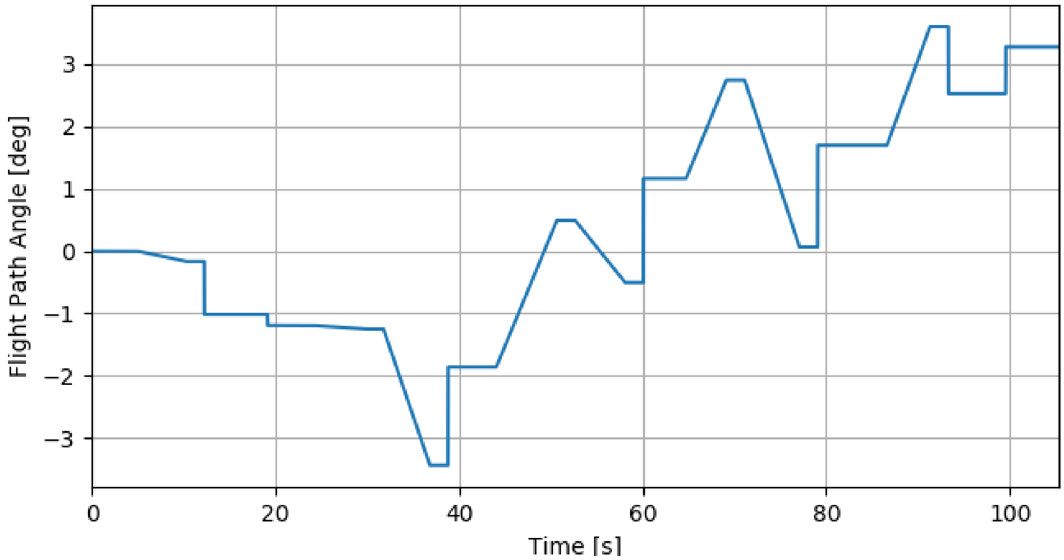

Fig. 6 Forcing function of a flight-path-angle experiment.

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

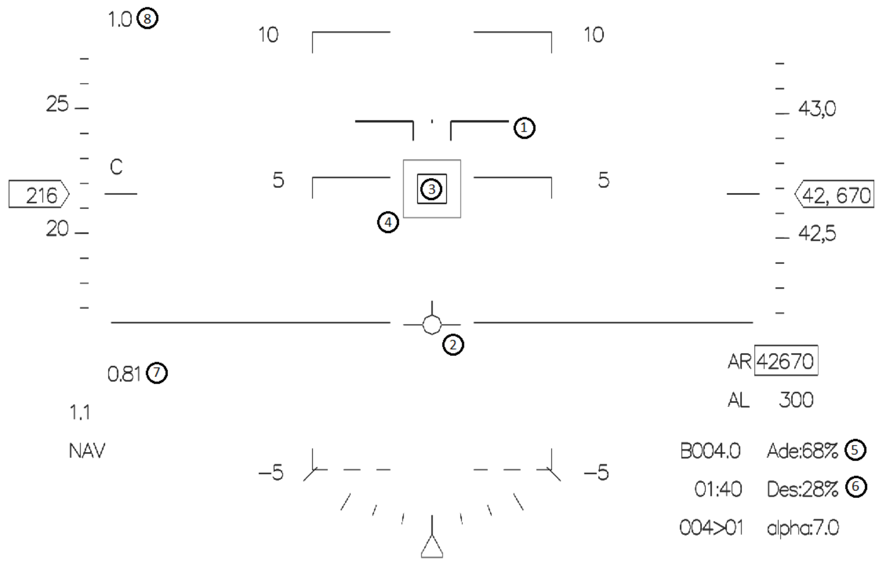

Fig. 8 Display used during the experiments. ①: pitch angle, ②: Flight path angle, ③: desired performance target, ④: adequate performance target, ⑤: adequate performance score, ⑥: desired performance score, ⑦: mach number, ⑧: load factor

have the flight path marker 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 respective boundary. When the controlled element is within the limits, the square turns green. This display has the option to show the scores, i.e. the relative time spent within each boundary, 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 current load factor 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 (conventional pitch, θ control allocation or new flight path, γ control allocation), the experiment types (pitch, θ or flight path, γ tracking), and the forcing functions.

Two control allocations were tested with the flight path tracking task: the conventional control allocation, and the new flight path based control allocation. The conventional control allocation was also tested with a pitch tracking task. This yields three experiment blocks per pilot, where each pilot performed two measurement runs.

C. Control Variables

The two different control allocations were both tested on the same set of forcing functions. The aircraft starts in the same trimmed (cruise) 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

Four pilots of varying experience participated, shown in Table 2.

Before the experiment, the pilot received some information about the aircraft and the experiment. The briefing was sent beforehand and contains practical information, a simulator safety video, and information about the experiment itself. The Flying-V is very briefly 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

Table 2 Experience of the pilots.

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

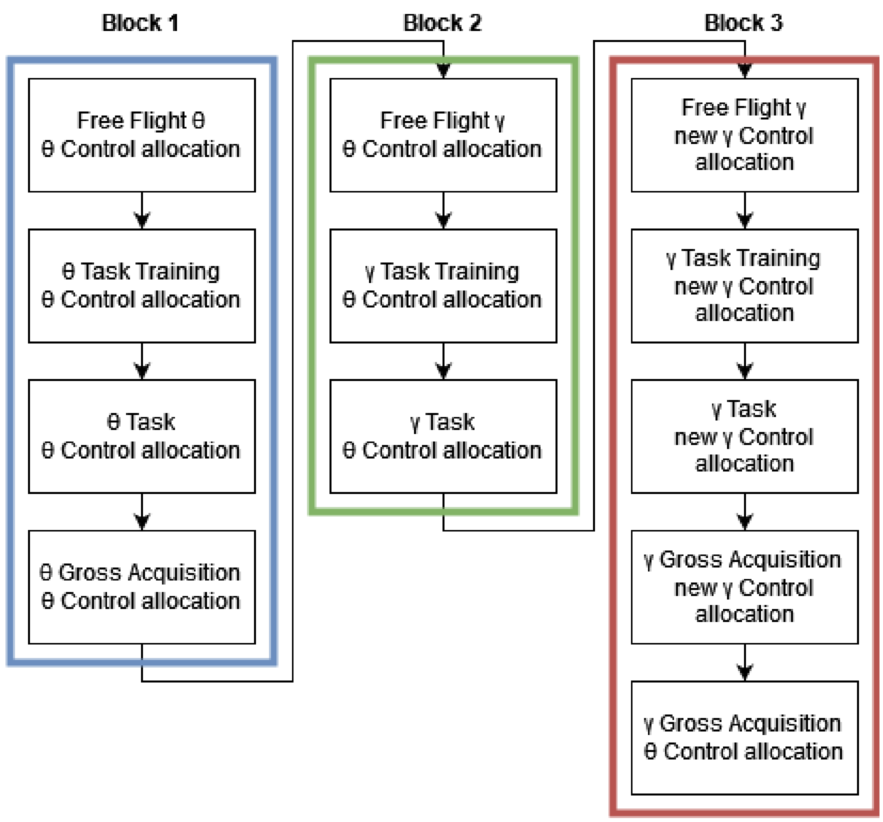

Fig. 9 Block diagram of experiment timeline

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 behavior 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 toward either system. The behavior of the Flying-V is not extensively explained, but left for the pilot to discover themselves. 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 nominally took 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 just used as a means to change the flight-path angle.

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 performs 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 behavior 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 was expected that the training time for Block 3 on itself would be long, since the pilot would 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 was 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 indicated 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 would 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 tracking 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 the 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 tracking task. The expectation is that this task is more difficult, and will uncover the unfavorable 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 conventional control allocation, and the handling qualities level would 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, $\theta\gamma2$ 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 ($\theta\theta5$ instead of $\theta\theta3$).

A. Block 1: Pitch Angle Tracking

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 3.

Table 3 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 made: 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 [$\theta\theta2$],
- 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 $\theta\theta4$ is useful for the full conclusion about these results.

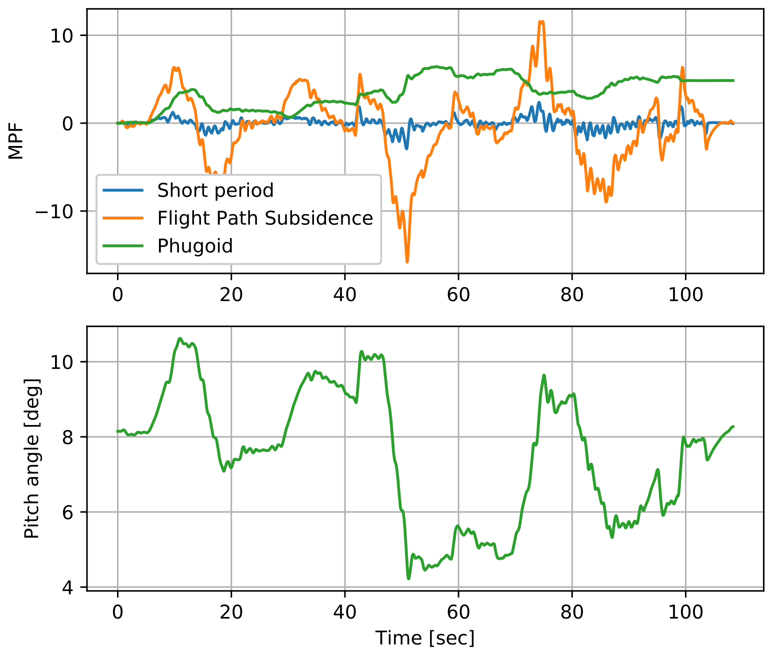

Fig. 10 MPF and pitch angle of P3 during experiment $\theta\theta 4$

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 behavior 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.

Finally, the comments of 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 behavior 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.

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.

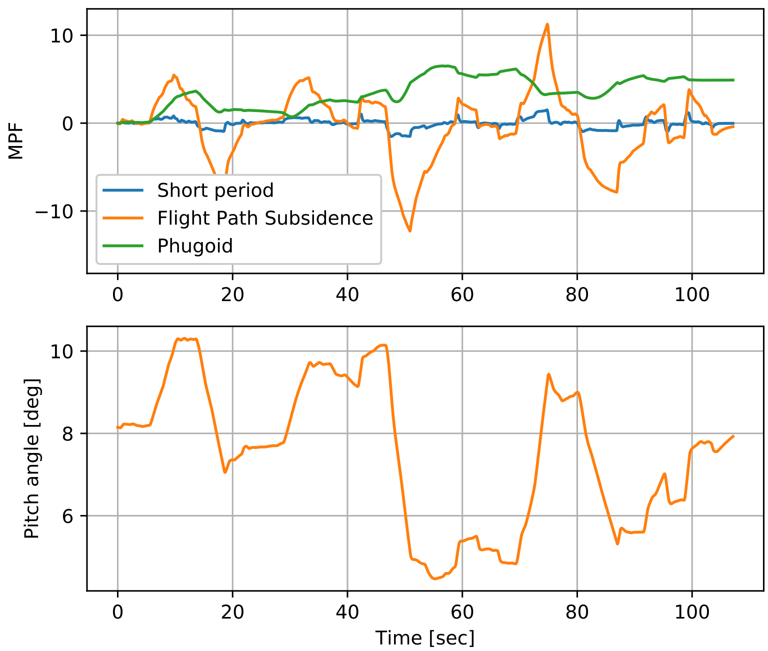

Fig. 11 MPF and pitch angle of P2 in experiment $\theta\theta 4$

B. Block 2: Flight Path Angle Tracking with Conventional 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 4. The asterisk indicates that a different forcing function was used.

Table 4 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

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.

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

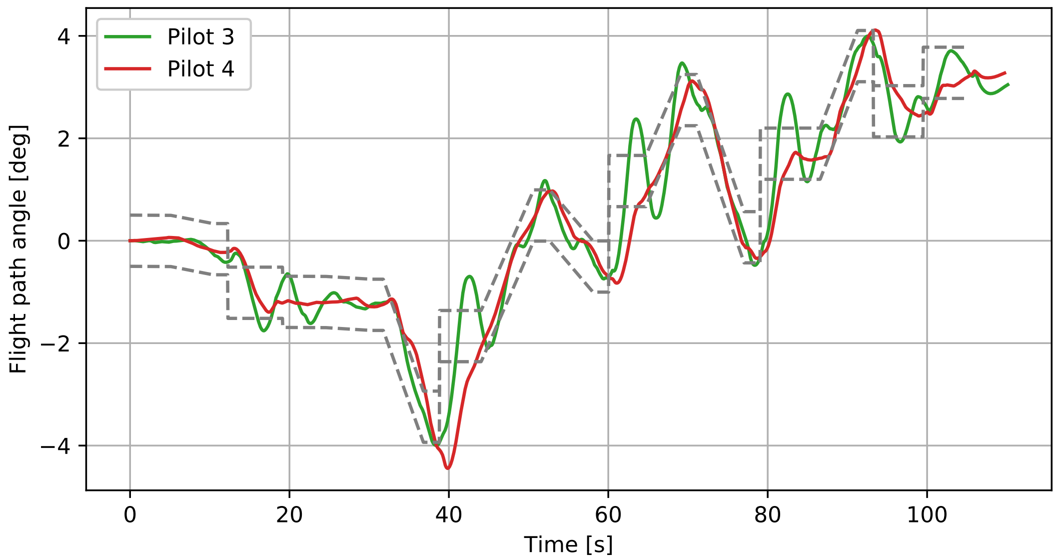

Fig. 12 Results of P3 and P4 of task $\theta\gamma3$. The gray dashed lines indicate the desired performance boundaries.

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.

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 $\theta\gamma3$,
- 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,

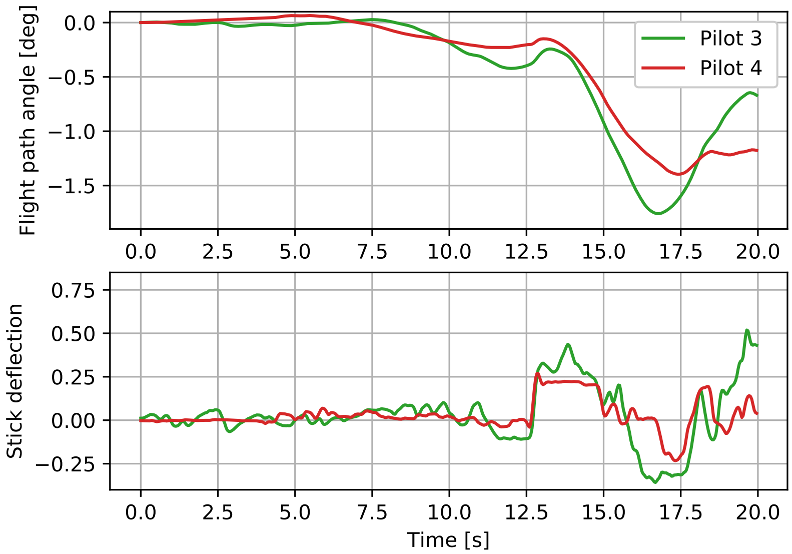

Fig. 13 Results and input of P3 and P4 of the first 20 seconds of task $\theta\gamma 3$

* 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, even though 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.

C. Block 3: Flight Path Angle Tracking with 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 5. The asterisk indicates that a different forcing function was used.

Table 5 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

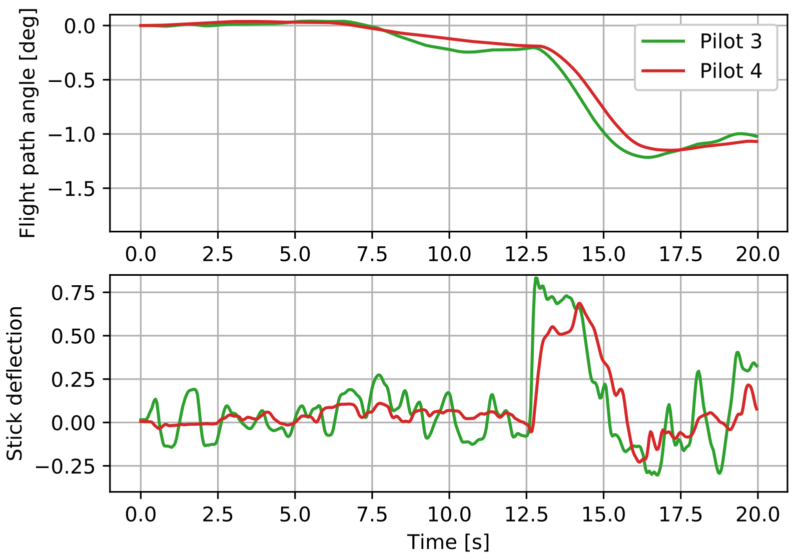

Fig. 14 Results and input of P3 and P4 of the first 20 seconds of task $\gamma\gamma3$

allocation. Reaching the stop was also undesirable for this pilot.

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.

Drawing conclusions from this block's results 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 in this flight condition, 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 conventional control allocation is better,
- Conventional control allocation is expected and much like a conventional aircraft. Nothing strange,
- Inexperienced pilots are able to fly the conventional 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 conventional 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 conventional 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 conventional 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 conventional control allocation.

All pilots were asked if they missed something during the evaluation. For instance some behavior 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 study investigates the longitudinal handling qualities of the Flying-V aircraft in cruise condition, and how flight path control could be improved with a special control allocation scheme. 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 3.

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

Part two considers the handling qualities in the flight path angle tracking task. The expectation is that this task is more difficult, and will uncover the undesirable response shown in the theoretical analysis. The non-minimum phase response was expected to be visible in the time histories, and the pilots' comments. The general outcome was 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 theoretical analysis were not as 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 in flight path angle 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 behavior 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 small to notice next to all the other behavior. 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 flight path response was never mentioned by the pilots. This unexpected result is also reflected in the reported handling qualities, which was rated in Level 2.

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

Part three concerns the handling qualities in the flight path angle tracking task with the new γ control allocation. It was expected that this task is significantly better than the conventional 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 conventional 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 conventional 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 behavior 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 conventional 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 control of the flight path 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 conventional control allocation. The flight-path-oriented 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 behavior of the Flying-V is comparable to the behavior 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 not included in the used aerodynamic model.

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. Initial progress in these areas has already been made [24, 25]. 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 behavior 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 adverse flight path effect due to lift change at the control surfaces, can lower the pilot workload and increase performance for the flight path angle tracking task. However, pilots still prefer the conventional control allocation for its higher control authority in both pitch angle and flight path angle. It is recommended to further improve 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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