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Piloted Simulator Evaluation of Low-Speed Handling Qualities of the Flying-V

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The Flying-V novel aircraft design aims at reducing fuel consumption by an innovative low-drag, fuselage-free geometry. Possible issues related to certification requirements have been noted, however, regarding longitudinal handling qualities at low speed, the pull-up manoeuver, and the flight-path-angle response. This study aims at investigating these issues through a pilot-in-the-loop experiment. Starting with a mathematical model of the Flying-V, based on the vortex lattice method, a preliminary off-line analysis of the handling qualities is conducted. A sensitivity analysis is considered over the proposed operational center-of-gravity range, approach speed (between 0.225 and 0.3 Mach, 149 and 198 knots indicated airspeed, respectively), maximum deflection of the control surfaces (between 20 and 30 degrees), and flight control system (Direct Law or Pitch-Rate Command). The pilot-in-the-loop experiment, its design guided by results from the analytical assessment, shows that the handling qualities provided by the current design of the Flying-V with Direct Law at 0.3 Mach are satisfactory with minor improvements related to aircraft responsiveness. For lower speeds (0.225 Mach), the handling qualities degrade due to a sluggish response, high compensation workload, insufficient control authority, insufficient sight angle, and tendency to pilot induced oscillations. Shifting the center of gravity away from the nose provides larger control authority at the expense of a minor reduction of responsiveness. Control augmentation proves to be very effective at improving the handling qualities. It is expected that the go-around certification standards will be satisfied, but approach speed will remain critical for controllability and safety.

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I. Introduction

In the context of aircraft fuel efficiency, increasingly smaller reduction of fuel consumption has been achieved via sub-system optimization. ICAO has set the target reduction in fuel consumption for the next 20 years [1], but the most recent projections show that these goals are not expected to be met at the current pace of improvement [2].

The Flying-V is a design for a fuel-efficient long-distance travelling aircraft that is predicted to improve the current fuel efficiency by 10-20%*. It is a flying-wing prototype with no fuselage, in which everything, from crew to fuel and payload, is stored in a single wing-shaped structure. Its geometry comes with the advantage of an improved lift-to-drag ratio compared to conventional aircraft [3], at the expense of a potentially unconventional maneuverability. In this regard, in June 2020 a scaled model flight test was conducted. The Dutch-roll was found to be "wobbling", and the longitudinal handling qualities at high angles of attack were considered questionable.

The current study focuses on the full-scale model, for which the small-scaled model analysis only provides approximate qualitative results. It aims at three main contributions to the Flying-V project:

1) analyse the handling qualities by means of off-line analytical assessment and piloted simulations;
2) verify the opportunity of improving the handling qualities by means of control augmentation; and
3) understand the potential of compliance with aircraft certification standards.

A preliminary analysis will be carried out to prepare useful experiments and make predictions. Normally, this is done by means of standardized handling qualities analysis criteria. However, the Flying-V might have unconventional characteristics, such that theory and relevance of the criteria should be reviewed critically. By means of the off-line analysis, it is possible to determine how the aircraft is expected to respond during relevant maneuvers of longitudinal

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*https://www.tudelft.nl/en/2020/tu-delft/successful-maiden-flight-for-the-tu-delft-flying-v, 2020. Accessed: 20-04-2022.

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flight, in particular pull-up and pitch tracking. The quality of the response can be categorized into handling quality levels, and the overall results of the analysis provide a picture of the predicted handling qualities.

A flight control system can have an impact on the handling qualities of an aircraft. To complete the study of the handling qualities of the Flying-V, augmentation should be considered in the analysis as well. In this respect, a custom flight control system is designed to deal with the possible issues that emerge from the off-line analysis.

Regarding airworthiness certification, the regulatory authorities demand compliance to a set of requirements that should be taken into consideration during the aircraft design iterations. As a consequence, understanding the relevant and critical requirements is key for planning useful experiments and contributing to the next steps of the design of the Flying-V. The relevant regulations and the acceptable means of compliance should be selected carefully, since it is unclear whether the Flying-V response can be classified as conventional.

Finally, piloted simulations complement and finalize this assessment. They are intended to investigate the handling qualities of the Flying-V, its compliance with the certification requirements, and the capabilities of a flight control system to improve its response. The flight task performed during the simulations should exhibit the critical characteristics of the Flying-V as they became apparent during the preliminary analysis. To perform pilot experiments on handling qualities, the Cooper-Harper approach [4] is used.

This paper is structured as follows. First, in Section II a review is given on the context of the Flying-V, of the Certification Requirements, and of the Evaluation of Handling Qualities by means of piloted evaluation. Then, the system modelling of the Flying-V is explained in Section III, which includes aircraft geometry and aerodynamic model generation. The flight control system is introduced in Section IV, which includes an explanation of the two control laws considered in this study – Direct Law and Pitch Rate Command – and discusses the control allocation and engine control. Section V summarizes the preliminary results of the off-line analysis, which sets the basis for discussing the experimental results. Section VI describes the pilot-in-the-loop experiment, including a description of its setup and rationale and followed by a presentation of the results in Section VII. Finally, a discussion of the results and their significance for the Flying-V project is given in Section VIII, followed by some conclusions, Section IX.

II. Background

A. The Flying-V

TU Delft, KLM and Airbus have been investigating the realization of the Flying-V ([5], [6], [7], [8], [3], [9], [10]) since the first idea of Justus Benad in 2015 [11]. The aerodynamic model was first studied by Faggiano [10], who analysed the first aerodynamic design and made the prediction of 25% higher fuel-efficiency compared to reference aircraft of the same class (e.g., A350); and by Garcia [5], who worked on aerodynamic model identification from wind tunnel experiments. In collaboration with Airbus, Cappuyns [6] computed a range of locations for the center of gravity based on the longitudinal handling qualities which is narrower compared to that of a conventional aircraft.

Palermo [8] worked on a 4.6% scaled model of the Flying-V, with 3.06m wing span, 2.76m length and 22.5kg weight. They provided an analysis of the longitudinal static stability and control characteristics of the airplane for a large range of angles of attack (-10 degrees to +35 degrees), and the data can be used as a first means of validation of the full aircraft model used in this research, as Overeem [12] did in his research on Flying-V system modelling and control. Using the same model, Viet [9] identified the optimal position of the center of gravity at 1.365 meters behind the nose, stall speed of 14.8 m/s at an angle of attack of 28.5 degrees and safe stall of 19.2 m/s at 15.9 degrees angle of attack. For the full model, the stall angle of attack is here assumed to be higher than 21 degrees. This assumption was used to limit the validity of the aerodynamic model up to 20 degrees of angle of attack (Section III), and in the experiments to tune the stick shaker (see Section VI).

Rubio Pascual [3] identified the optimal location of the engine to reduce the lift-to-drag ratio of 10%. Such location is the product of a compromise of controllability, structure and probability of impact upon disk failure. The position of the engines in the model used for this study comes from Pascual's work.

B. Certification Requirements

The reference regulations for the Airbus A350, to which the Flying-V is comparable in size, use and performance, are the CS-25 published by EASA [13]. The corresponding regulations by FAA are the PART-25. The overall CS-25 requirements on controllability are as follows:

- EASA CS 25.143: "Controllability and Manoeuvrability":

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(See AMC 25.143(a).) The aeroplane must be safely controllable and manoeuvrable during Climb, Level Flight, Descent and Landing.

To complement these requirements, the EASA "Acceptable Means of Compliance AMC-20" [14] and the corresponding FAA "Flight Test Guide for Certification of FAR-25 Airplanes" [15] provide operational procedures to demonstrate compliance with CS-25.

From the AMC-20 and CS-25 combined, a few maneuvers appear relevant based on the scope of this research and on previous results:

1) Reach 3.2% climb during approach in landing configuration (CS-25.119, AMC-20-6.5)
2) Pull-up to 1.5g and pushover to 0.5g in landing configuration (CS-25.143(j).1 and CS-25.143(j).2, AMC-20-6.9.2(c))
3) Conduct full approach and landing/go-around multiple times with different configurations (CS 25.143, AMC-20-6.9.2(e) to (h))
4) Show trim in a number of configurations (CS-25.161(c)(2), AMC-20-6.12.2)
5) Show static stability after achieving trim in a number of configurations (CS-25.175(a) through (d), AMC-20-6.14.2)

Maneuvers (1) and (2) (climb and pull-up performance) have been previously observed as critical by Cappuyns [6].

Maneuver (3) is relevant due to the outcome of the 2020 scaled model flight, where potentially poor handling qualities were observed and one of the early flights ended in a hard landing.

Tasks (4) and (5) can be tested off-line and then confirmed with piloted simulation, and relevant to confirm the viability of the considered design.

For all these tasks, the requirement is that the handling qualities are acceptable during all the maneuvers and the airplane must be safely controllable and maneuverable.

These regulations do not provide direct and measurable methods to predict the compliance of an aircraft. However, a so called "off-line" evaluation can be performed by analysing the response of the aircraft against criteria that can be found from sources such as the "MIL-Handbook-1797" by the American Department of Defense [16].

It is safe to assume that the Flying-V will use a certain level of control augmentation and a Fly-by-Wire system. The main consequence is that the regulatory authority might demand some handling qualities requirements for the most degraded control law as well, such as the Direct Law (or Mechanical Backup) modes. Piloted evaluations of the non-augmented Flying-V, as a consequence, are necessary to get the full picture of its airworthiness potential.

C. Piloted Simulation Evaluation of Handling Qualities

A pivotal point in the history of handling qualities is the publishing of a study carried out by George Cooper and Robert Harper in 1969 [17], then revised in 1986 [4]. In their work, handling qualities are defined as "*those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role*"(Cooper, Harper, 1969, [17], p. 31) and that they are "*characteristic of the combined performance of the pilot and vehicle acting together as a system in support of an aircraft role*"(Cooper, Harper, 1986, [4], p. 1). Today, their work is commonly considered the standard modus operandi for the evaluation of handling qualities with test pilots based on the concept of pilot workload.

Analytical and numerical methods are combined in order to predict the behaviour of an aircraft and assess its safety and maneuverability. The goal is to predict the opinion of a pilot regarding a vehicle by means of mathematical criteria.

In terms of the MIL-STD convention, the relevant off-line assessment methods for the Flying-V are those for Class III aircraft (large, heavy, low/medium manoeuvrability aircraft, see CS-25) in Category C phase (takeoff, catapult takeoff, landing, approach, aborted approach).

The Flying-V is a new prototype, and the criteria (such as the MIL-STD) designed for standard aircraft might not be suitable for the evaluation of its handling qualities. On this topic, some attempts have been made to link the most commonly used criteria to the handling qualities of a flying wing (e.g., Ehlers [18], or Humphreys-Jennings, Lappas and Mihai Sovar [19]), and more in general to specialize the criteria on the evaluation of handling qualities in final approach and landing (e.g., Frost, Franklin, and Hardy [20], Stoliker [21], Field and Rossitto [22]).

Since it is not known yet to which extent the response of the Flying-V is comparable to that of standard aircraft on which the criteria are normally applied, the criteria that involve fewer assumptions were preferred. A selection of these criteria is used to perform a preliminary assessment of the handling qualities in Section V:

- Phugoid damping ratio and time to double [19, 23, 24];
- Short period damping ratio [19, 23–25];

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- Control Anticipation Parameter (CAP) [19, 22, 23, 25, 26];
- Bandwidth criteria [22, 23, 25], and
- Gibson dropback criterion [22, 23, 25].

These are completed by a presentation of the preliminary expectations related to the following:

- Trim conditions (elevon deflections and angle of attack);
- Impact of the Pitch Rate Command controller on the handling qualities;
- Compliance with the certification requirements, and
- Relevance of the preliminary analysis.

This preliminary assessment was thereafter validated and expanded by human-in-the-loop simulations, in which pilots gave specific feedback on the handling qualities according to their opinion. This feedback is normally collected in the form of ratings, which are valuable to understand the quality of the response of the complex pilot-aircraft system. For this, the preferred rating scale is that of Cooper-Harper, a useful framework to give a quantitative form to the qualitative opinion of the pilots [4, 17]. It should be noted that the rating exists only as a specific evaluation of the HQ during a certain task, and not as an inherent characteristic of the aircraft in general.

III. System Modelling

A. Aircraft Geometry

In this project, the model used for analysis and simulation is based on the same design iteration of the Flying-V that was used for Cappuyns' [6] research. It is motivated by the findings summarized in the Background section, with the addition of the engines in the position proposed by Pascual [3].

The configuration chosen for this study is shown in Figure 1. Notice the three control surfaces on each wing: one is a vertical rudder-like surface which serves as a rudder (see Figure 1), while two surfaces serve both as elevators and ailerons, and are consequently called "elevons". In an attempt to increase the accuracy of this model, actuators and engines are modelled, in the form of first order lag transfer functions with time constants equal to $\tau_{act} = 0.1s$ and $\tau_{eng} = 5s$, respectively, and rate limiters equal to $l_{act} = 25deg/s$ and $l_{eng} = 38kN/s$, respectively. The limit for the deflection of the actuator is an independent variable of the experiments of this research (either 20 or 30 degrees, as explained later), and the thrust limit for the engine is 379 kN, according to previous Flying-V models (see Pascual [3]).

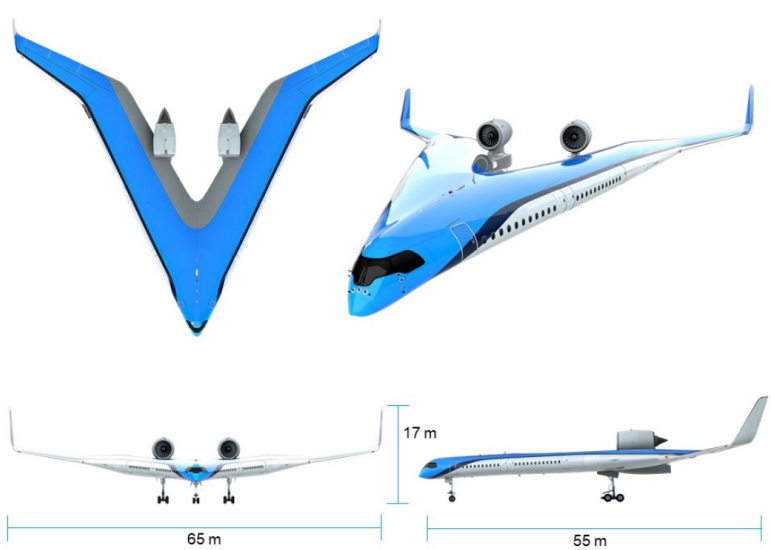

Fig. 1 Flying-V, three view renders adopted from TU Delft; "Flying-V, flying long distances energy-efficiently", https://www.tudelft.nl/en/ae/flying-v/

To focus on the longitudinal handling qualities, no lateral-directional motion is included in the model. This is accomplished by disconnecting the roll and yaw controls, which are lateral side-stick deflection and rudder pedals, respectively, so that no asymmetric deflection can be commanded to the control surfaces.

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B. Aerodynamics

In this section the generation and validity of the used aircraft model are discussed.

Airbus collaborates on the Flying-V project by providing essential tools and data, such as the model for this study. This aerodynamic model was generated through the ODILILA software (see, for example, Benad [11]), an Airbus proprietary tool for Computational Fluid Dynamics (CFD). The software is based on the Vortex Lattice Method [27]. Vortex Lattice CFD is particularly attractive for the first design iterations of an aircraft since it is light on a computational point of view, relatively easy to implement, and provides valuable insights on the dynamics of a body. However, it comes with limited validity due to the baseline assumptions:

- The flow is assumed to be **incompressible**.
  This is not a critical assumption, since in this study the speed range considered is between 0.2 and 0.3 Mach (landing speed is expected to be around 0.25 Mach), and, up to 0.3 Mach, a fluid can be accurately considered to have zero velocity divergence.
  In order to get more accurate results, a compressibility correction on the aerodynamic model data was applied by ODILILA in the form of Mach-dependent compressibility correction factors.
- The flow is also assumed to be **inviscid**.
  In a zero-viscosity fluid, boundary layer phenomena are non-existent and no stall behaviour can be modelled. This limits the validity of this study up to the stall angle of attack, which can be speculatively considered around 21 degrees by comparison with reference aircraft and previous studies on the Flying-V. In the future it will be necessary to study stall phenomena and re-define the validity of this research.
  Furthermore, in an inviscid fluid no friction is created with the lifting body. This has an impact on the drag coefficient, that in ODILILA is only computed in the form of lift-induced drag. In order to address this shortcoming, the model can be augmented by adding the drag coefficient measured during the scale model flight, $C_{d_0} = 0.039$. The validity of this augmentation is of course to be investigated, in particular by understanding how the small-scale model translates into full-model properties.
- Another assumption is that of **irrotational** fluid.
  It implies that no vorticity is present in the fluid. The regions where this assumption is not valid are not in the scope of this research. Since the flow is ideal and unspoiled, however, it should be remembered that this is a somewhat optimistic model.
- The method also assumes a **thin lifting body**.
  In this sense, the Flying-V is assumed to be represented by an infinitely thin sheet over which the panels are arranged in a lattice. As a result, the flow in the close proximity of the body is not realistic, and the method is not sensitive to form drag. This missing contribution to the drag, however, is not expected to significantly alter the outcome of this research, since the model is already based on more critical assumptions. Nonetheless, future studies should address these inaccuracies to confirm the results from the current study.
- Finally, the Vortex Lattice Method is based on the assumption of **small angles**.
  This assumption is only valid if side slip and angle of attack are small. In this study, side slip is set to zero and thus it can be of course considered small; however, the angle of attack is expected to be high in the part of the flight envelope that involves approach and landing. For this reason, the breakpoints of the model data are particularly dense between 15 and 20 degrees of angle of attack. The impact of this error on the results of this research is not known yet, and its assessment is left to future studies on more accurate aerodynamic models.

IV. Flight Control System

The aircraft response to pilot inputs can be manipulated through a Control Augmentation System (CAS), which improves the aircraft basic tracking and flying capabilities, addressing the *inner* loop. The pilot-in-the-loop experiment will also serve to explore the potential of augmentation system to improve the HQ of the Flying-V.

It is the inner-loop that mainly characterizes an aircraft, its response type and characteristics (granted that the outer-loop(s) is(are) properly designed and tuned). During the experiments of this research, an inner-loop augmentation system was tested to get some insights on the potential impact of the CAS on the HQ of the Flying-V. It is not in the scope of this research to further optimize the inner-loop, but rather to explore the possibility to design a control system that allows the current design of the Flying-V to meet the certification requirements. In the future, more complex approaches might be taken in consideration, such as [28], where a distributed genetic algorithm is used as an automatic and efficient way to design a Flight Control System for Flying Wings.

The next subsections explain the Control Allocation approach, the two designed control laws − Direct Law and

Pitch Rate Command − and the Auto-throttle system.

A. Control Allocation

The twofold action of the four elevons as both elevators and ailerons raises a control allocation question on how to optimize the use of control surfaces. In principle, one aims to regulate each actuator based on their control effectiveness either as elevators or as ailerons. However, this would involve the analysis of lateral-directional response of the aircraft, which is not in the scope of the current study; and accurate control surface models, which is not available for this Flying-V geometry since the size of the actuators is not defined yet.

To simplify this analysis and to study the full potential of the four elevons for longitudinal flight, control is equally allocated among the four surfaces. As a consequence, the four deflections can all be addressed with a single actuation angle, and pilot's longitudinal control (both with Direct Law and Pitch Rate Command) is mapped equally on all the four elevons. This controlled deflection is always symmetrical, which means that the four elevons are effectively used together as a single elevator and never for roll control.

B. Direct Law

The first controller is the Direct Law. When engaged, the pilot has direct control over the elevons, resembling the Mechanical Backup Law that Fly-by-Wire aircraft are equipped with in case of flight control system failure.

The side-stick input is simply scaled by a linear gain that yields proportional elevons deflection. Zero stick deflection corresponds to zero elevons deflection. The neutral (zero force) position of the stick is moved to the deflection needed for trim in each flight condition to mimic the functionality of trim tabs on the elevons. Full-forward side-stick deflection yields full pitch-down deflection of the elevons, and full-aft side-stick deflection yields full pitch-up deflection of the elevons. An advantage of this system is that elevon saturation is directly observable by the pilot through the side-stick reaching its endstops.

C. Pitch Rate Command

According to the preliminary analysis presented in Section V, Pitch Rate Command emerged as a viable control approach, since it should increase the controllable bandwidth range and improve the HQ by acting on the short period mode. Additionally, Pitch Rate Command is a rather standard response type and pilots are generally used to it.

The structure of this control system consists of a feedback of measured pitch rate over the elevons, through a PID controller and an allocation gain matrix. The pilot controls the aircraft pitch rate directly from the side-stick.

The PID was tuned to increase the short period frequency as much as possible without reducing damping. A number of tuning iteration were needed to make sure that the augmented system does not cause unrealistically jerky motion in the aircraft due to sudden extreme elevon deflection. The final result is a system that commands very large initial elevon deflection in order to cope with the slow short period, and then returns to lower deflection levels after the on-set pitch rate has been achieved. It consists of a considerable proportional gain (P = 17) that provides initial responsiveness, an equal integral gain (I = 17) that adjusts the steady state response to follow the input after the initial reaction, and a null derivative gain (D = 0), since it would fight against the proportional gain on the short period frequency.

D. Auto-throttle

As will be explained in more detail in Section V, the Flying V phugoid mode frequency was found to be unusually close to the slow short period frequency. To focus on the short period response, it was assumed that an auto-throttle system is available. Hence, an auto-throttle system was included in the flight control system of this experiment − measured airspeed is sent into a feedback loop over the engine throttle, with a Proportional controller ($P_{engine} = 100kN * s^2/m$) that provides constant airspeed within the physical limits of a realistic engine.

V. Handling Qualities Preliminary Analysis

The theory introduced in the Background Section II was applied to the model explained in the System Modelling Section III to predict the handling qualities of the Flying-V. The experiment is then designed based on this preliminary analysis, with the purpose of maximizing the value of the pilot-in-the-loop sessions for handling qualities research.

For the application of three criteria (Control Anticipation Parameter, Gibson Dropback and Gibson Flight Path Angle), a so-called "short period only" approximation was used. The dependency of the equation of motions on the

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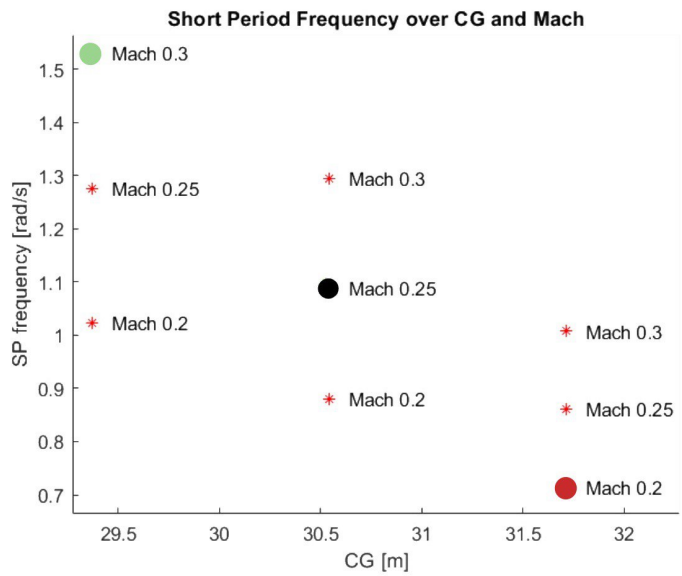

Fig. 2 Natural frequency of the short period of the Flying-V. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red).

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angle of attack was eliminated, cancelling the exchange between dynamic and potential energies which causes the phugoid eigenmode. This way, the phugoid mode was excluded from the response of the aircraft. The purpose of this approximation is to extract a clean representation of the short period mode, on which the mentioned criteria are based.

In the following subsections, the main findings of this preliminary analysis are presented.

A. Handling qualities assessment

1. Phugoid

Over the different configurations of CG positions and airspeed provided by the aerodynamic model, the phugoid resulted to be overall good and in the recommended limits (MIL-F-8785C: Phugoid damping ratio levels, Class III, CAT C). On average among the different aircraft configurations, the phugoid mode had a frequency $\omega_{ph} = 0.135 rad/s$, damping ratio $\zeta_{ph} = -8.92 \cdot 10^{-3}$ and time to double $-\frac{\ln 2}{\zeta_{ph}\omega_{ph}} = 575,6s$ which is Level 3 according to MIL-F-8785C, the "time to double" being positive yet very large. All the configurations fall into this Level based on this criterion.

2. Short period

The damping ratio of the short period mode is within the recommended limits, ranging between 0.58 (forward CG, 0.2 Mach) and 0.8 (aft CG, 0.3 Mach). MIL-F-8785C: Class III, CAT C places a short period damping of the range 0.35-1.30 into Level 1 handling qualities.

However, the short period frequency was found to be too slow in all the configurations, ranging from 0.72 rad/s (aft CG, 0.2 Mach) to 1.53 rad/s (forward CG, 0.3 Mach). An overview of the short period frequency as a function of CG and airspeed is shown in Figure 2.

This raises two main questions. The first one is what impact will the short period mode have on the handling qualities. On this regard, common handling qualities criteria such as the "short period thumbprint" (Roskam [29]) predict that the aircraft will exhibit a "very slow response, large control motion to maneuver, difficult to trim". This will be central to the piloted experiments.

The second question is whether the short period is so slow that it would be affected by the phugoid in some relevant way. The preliminary analysis showed that, in particular at slower airspeed configurations, the phugoid gets in the way of the short period early in the initial response. To separate the two modes again, an auto-throttle can be used when assessing the short period behavior.

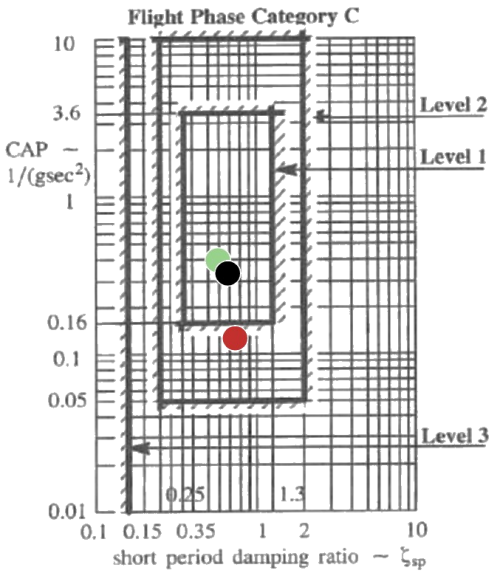

Fig. 3 Control Anticipation Parameter. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

3. Control Anticipation Parameter (CAP)

The CAP results for three configurations (forward CG = 29.371 and Mach = 0.3 (green); nominal CG = 30.540 and Mach = 0.25 (black); aft CG = 31.714 and Mach = 0.2 (red), corresponding to fastest, slowest and average short period frequency) is shown in Figure 3. Notice that this assessment is based on the short period model, as mentioned at the beginning of this section). The slower the short period frequency, the lower the HQ predicted with the CAP criterion. The fastest configurations fall well into the Level 1 boundaries, while slower configurations degrade into Level 2.

This confirms the interest in the pitch tracking piloted simulation task to investigate the degradation of the handling qualities in case of slower configurations. In particular, the focus is on understanding whether the pilot is able to comfortably interpret the response of the Flying-V from its first pitch acceleration in its slower configurations, since the interpretation of the CAP for the slower configurations suggests that this might be a source of poorer handling qualities.

Compared to the short period thumbprint, the Control Anticipation Parameter predicts overall better handling qualities. However, this has to be interpreted under two observations. First, the Control Anticipation in this case was computed on a short period only approximation, and the consequences of this approach are not clear. In this sense, the accuracy of this criteria should not be taken for granted. This is particularly true considering that the response of the Flying-V might not be accurately represented by this criterion, which has been tested on classical aircraft geometries. Second, on the other hand, it should be considered that the short period thumbprint is only an indication of the expected aircraft response − it does not provide handling qualities level expectations. This being said, the two criteria should be considered together, supporting the expectations of an overall sluggish aircraft (short period thumbprint) that should provide satisfactory handling qualities regarding the predictability of the response (Control Anticipation Parameter).

4. Bandwidth Criteria

The Flying-V shows Level 2 HQ according to the Bandwidth criterion, as shown in Figure 4, due to a limited control bandwidth with 45 phase margin limits. However, a feel system and more realistic actuator dynamics might have a negative impact on the real controllable bandwidth. More in-depth interpretation of this assessment is given in MIL-STD 1797.

5. Gibson Dropback criterion

According to the Dropback criterion (Figure 5), the CG position is expected to have a clear influence on the handling qualities, with the response of the aircraft changing from “sluggish” (aft CG) to “abrupt bobbling tendency” (forward CG), the nominal CG being the closest to the satisfactory area. However, the validity of this criterion depends on the

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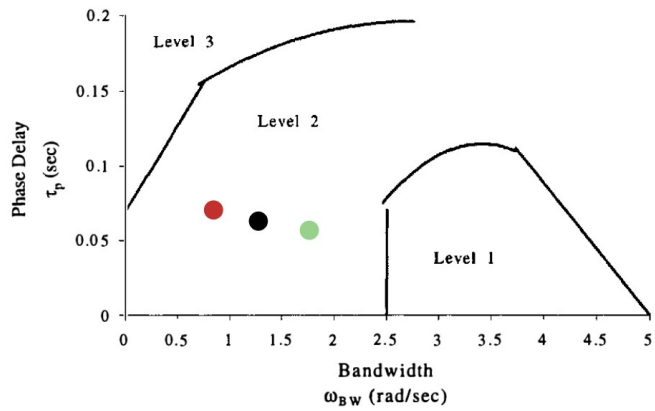

Fig. 4 Bandwidth criterion. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

short period frequency due to the way the dropback is computed, which is based on the difference from pitch attitude at the moment the stick is released and at steady state.

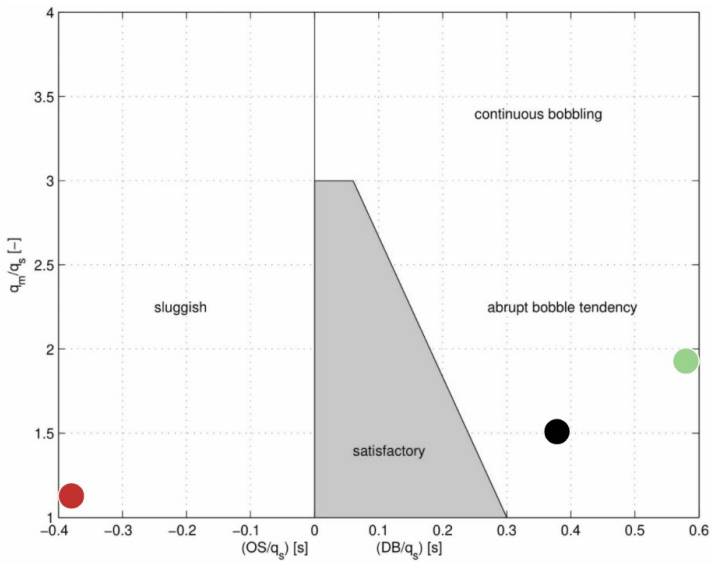

Fig. 5 Gibson dropback criterion. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red).

6. Trim

In general, the elevons deflection needed for trim is high and it reduces the pitch-up control authority. This is the case, in particular, for forward CG positions and slower airspeed configurations, for which safety and controllability is uncertain. In Table 1, the elevons deflection (Defl) and the angle of attack (AoA) at trim are shown for certain configurations (three CG positions, and speed ranging from 0.2 to 0.3 Mach).

At 0.2 Mach, in particular, the AoA is very close to the boundary of (assumed) validity of the aerodynamic model. The amount of elevon deflection with forward CG is very high (21.7 degrees), which would make part of the piloted

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experiments not viable with 20 degrees of maximum elevons deflection. Furthermore, 0.2 Mach airspeed, which corresponds to 133 knots, is expected to be quite lower than the design landing speed of the Flying-V. For these reasons, it was decided to not include the configurations with 0.2 Mach airspeed in this study, leaving it for future research when a more accurate aerodynamic model will be available together with more information on the final geometry of the Flying-V (including landing speed, elevon effectiveness, and any high-lift devices to be added to the design).

Table 1 Trim conditions – Elevons deflection and Angle of Attack

	Forward CG		Nominal CG		Aft CG	
Mach	Defl	AoA	Defl	AoA	Defl	AoA
0.200	21.7	20.1	13.2	18.6	4.6	17.1
0.225	16.5	15.7	9.7	14.5	3.0	13.4
0.250	12.9	12.6	7.4	11.7	1.9	10.7
0.275	10.3	10.3	5.7	9.6	1.2	8.8
0.300	8.3	8.6	4.6	8.0	0.8	7.4

For future control allocation design, it would be insightful to find the minimum control deflection needed for satisfactory handling qualities. It was then decided to explore the handling qualities for 20 degrees of maximum deflection, which is the minimum needed to trim all the configurations at Mach 0.225 (150 knots); and for 30 degrees, which is the realistic limit for control surface deflection, taking into account that part of the control authority must be left to the lateral-directional control channel. With 20 degrees of maximum deflection, control saturation issues are expected due to the limited control deflection left at 0.225 Mach and forward CG, which is 3.5 degrees.

B. Control augmentation

Due to the evident correlation between short period and predicted handling qualities, a Pitch Rate Command controller was tuned specifically to address the bad qualities of the short period mode. In Table 2 a comparison is shown between damping and frequency of the short period mode with Direct Law and Pitch Rate Command.

Table 2 Short period frequency (rad/s)
Direct Law (DL) vs Pitch Rate Command (PRC)

	Forward CG		Nominal CG		Aft CG	
Mach	DL	PRC	DL	PRC	DL	PRC
0.200	1.03	4.83	0.89	4.48	0.72	2.82[†]
0.225	1.17	5.91	0.99	5.60	0.80	5.27
0.250	1.29	6.80	1.10	6.46	0.87	6.13
0.275	1.42	7.64	1.20	7.27	0.93	6.89
0.300	1.55	8.44	1.31	8.05	1.02	7.64

Overall, it is predicted that the Pitch Rate Command mode will successfully improve the short period of the Flying-V, providing noticeable improvements in the handling qualities as well. In particular, all the configurations are expected to be improved up to the same level, in such a way that pilots might not be able to tell any two configurations apart.

C. Certification Requirements

According to the preliminary analysis, three main concerns can be raised regarding the certification requirements introduced in the Background section.

[†]Overdamped short period – two real poles with frequency wn1 = 2.82 rad/s and wn2 = 5.91 rad/s.

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First, it is unclear whether the Flying-V provides acceptable handling qualities and good maneuverability as per EASA CS 25.143 in all the configurations. In fact, some configurations are predicted to require a higher workload from the pilot, mainly due to the slow short period frequency.

Second, it is preferable for certification purposes to provide good handling qualities, or at least to guarantee controllability and safety also with low-augmentation control laws, such as the Direct Law. Based on the preliminary analysis, it is expected that the Pitch Rate Command will reduce the workload significantly, and it is to be confirmed whether this improvement is necessary for the pilots to safely control the Flying-V.

Finally, Cappuyns ([6]) identified some critical disadvantages of the Flying-V as compared to some analysis criteria and to EASA Certification Requirements. According to his work, the pull-up maneuver (CS-25.143) is critical for the Flying-V, since [6, p. 42] *"when elevons 1 and 2 were deflected to their maximum deflections in approach, the loss in lift was so significant that the aircraft could lose up to tens of meters of altitude and initially go significantly below 1 g."*. Based on the preliminary analysis here presented, however, no specific evidence was found of this unusual response of the Flying-V during a pull-up maneuver. Nevertheless, dedicated experiments will be part of the piloted tests, in order to further investigate Cappuyns' findings.

D. Relevance and validity of the preliminary analysis

It is important to note that the preliminary analysis so far discussed is based on a considerable number of assumptions. It is assumed that the response of the Flying-V is comparable to that of standard aircraft, and that the off-line analysis criteria, normally used on standard aircraft, are applicable on the Flying-V as well. In particular, most of the analysis criteria are based on a clear separation between phugoid and short period modes, which might not be the case for the Flying-V based on the current model.

These, together with all the assumptions and the inaccuracies of the aircraft model (explained in the System Modelling section), are reasons to consider the preliminary analysis limited both in relevance and validity. The goal of this analysis is to draw preliminary conclusions in order to design a meaningful piloted experiment, all in the perspective of providing design insights for the proceeding of the design process of the Flying-V. It should not be expected that the real aircraft will fly exactly as predicted here.

Additionally, it should be noted again that this study does not include roll control, neither in the preliminary analysis nor in the piloted experiments. This has two main implications. First, the overall workload for the pilots is lower than in real flight. In real operations, the workload might be higher due to possible lateral-longitudinal coupled dynamics [30], and to the necessity for the pilot to focus on both longitudinal and lateral motions. Second, the elevon deflection range is all available for longitudinal control. This has an influence on the interpretation of the results related to control authority, since in real operations part of the deflection range will not be available while used up for roll control purposes. Joosten et al. have investigated the lateral-directional handling qualities of the Flying-V and encountered both these issues [31].

VI. Experiment: Method

A. Objectives and hypotheses

The first objective of the experiment was to support and possibly expand the conclusions of the preliminary analysis. This was done according to the Cooper-Harper methodology for aircraft handling qualities research, explained in the Background Section II, the handling qualities were explored by means of piloted simulations, with pilot tasks specifically designed for this purpose.

Based on the observations of the preliminary analysis, it was expected that the aircraft response was overall sluggish, mostly due to the short period mode being slow and requiring considerable compensation.

The second objective was to investigate the potential of compliance with EASA certification standards by means of pilot-in-the-loop evaluations. In particular, according to previous results the critical requirements were those regarding the go-around scenario and the pull-up manoeuver performance in general.

As a hypothesis, it was expected that the Flying-V would comply with the standards on the pull-up performance, since the 3.2% rate of climb could always be achieved with ease, controllability was provided during the entire maneuver (including pull-up, climb, and level-off), and the lag between pitch angle and flight path angle was not excessive. The requirement on controllability over $\pm 0.5g$ pull-up and push-down was also expected to be satisfied.

However, it was predicted that in the slower scenarios the pilot might have limited pull-up control authority, which could result in reduced safety. Additionally, it was questioned whether the high pitch angle and the subsequent high

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sight angle from the cockpit would negatively impact the pilot's assessment of comfort or safety.

At the same time, another goal of this experiment was to provide insights for future design iterations on which configurations might be a source of issues for the compliance with certification standards on longitudinal maneuverability. In these regards, the experiment was intended to prove that, in general, the Flying-V is safe and maneuverable, with and without control augmentation. However, safety concerns are expected for those configurations in which sufficient control authority is not provided.

The third objective of the experiment was to study the sensitivity of the handling qualities on three design parameters: position of center of gravity, maximum deflection of the elevons, and approach/landing speed.

The preliminary analysis suggested that the forward center of gravity would be associated with better handling qualities, since it provides a faster short period frequency. However, it comes with reduced control authority and slightly lower damping. It was also noted that the short period for the aft center of gravity is associated with a slight overshoot to control input, whereas the forward center of gravity produces a stronger tendency to drop-back. As a consequence, another goal of the experiment was to identify the preferred trade-off of control authority, short period damping and frequency according to the pilots.

For the maximum deflection of the elevons, the objective was to prove that in some configurations 20 degrees are not sufficient to provide satisfactory control authority to the pilots, whereas 30 degrees are enough.

Regarding the approach/landing speed, the experiment is meant to prove that the handling qualities decrease significantly with speed, warranting a landing speed closer to 200 knots than it is to 150 knots.

Finally, the fourth goal of the experiment was to prove that the flight control system with the design that was explained in the Flight Control System paragraph can successfully improve the handling qualities of the Flying-V. The experiment was also intended to show that all the configurations are successfully improved by control augmentation.

B. Method

1. Subjects and Instructions

Subjects A, B and C participated in the experiment (Table 3). They were not compensated financially for their participation. They were all informed with an experiment briefing. This consisted in: a short introduction to this research and its context; a presentation of the main aspects of this design iteration of the Flying-V; a complete explanation of the apparatus (the SIMONA Research Simulator, as explained below), including the Main Instrument Panel (MIP) display; a detailed description of the simulation tasks.

Table 3 Experiment subjects information

Subject	Credentials
Pilot A	Flight Test Engineer, National Test Pilot School US
Pilot B	Technical pilot (airliner)
Pilot C	Research pilot (airliner/business jet), retired

2. Apparatus

The experiment was carried out in the SIMONA Research Simulator (SRS) [32]. The simulator is equipped with a six-degree-of-freedom motion system. Only the right seat was used. A light-weight outside world display system provides a collimated 180-degree horizontal by ±20-degree vertical field of view. Three DLP projectors project high-resolution computer-generated images onto a rear projection screen, which are then displayed on the large collimating mirror wrapped around the simulator.

Motion cueing was provided by filtering the virtual motion of the aircraft through a washout filter. The washout filter was based on an updated version of the filter developed in the context of handling qualities experiment in collaboration with Boeing (see Gouverneur, [33]). It included a low-pass filter for tilt-coordination, and it was tuned specifically for this experiment in order to optimize the use of motion space during the pitch-tracking tasks. The motion filter is tuned as in Table 4. Note that only the longitudinal degrees of freedom are included in the filter (x, z, θ). The reference point

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(a) Experiment setup inside (b) Outside impression

Fig. 6 SIMONA Research Simulator

for cueing was set at x = -26.26, y= 0, z = -1.2075 from the aircraft's center of gravity.

Table 4 SRS motion cueing filter settings[‡]

	High-pass filter					Low-pass filter		
DOF	Ord.	K	ω_n	ζ	ω_b	Ord.	ω_n	ζ
x	2nd	0.5	1.5	0.7	-	2nd	3.0	0.7
y	-	-	-	-	-	-	-	-
z	3rd	0.5	2.2	0.7	0.2			
ϕ	-	-	-	-	-			
θ	1st	0.5	1.4	0.7	-			
ψ	-	-	-	-	-			

A side-stick was available for longitudinal control only. The SRS is equipped with an electrically actuated side-stick that runs an admittance display (control-loading) simulating a mass-spring-damper system. For this experiment, in the case of Direct Law control (see the Flight Control System paragraph) the control-loading system responded as a single spring system with constant $k = 3N/deg$; with Pitch Rate Command control the control-loading system responded as a single break-out spring system with constant $k_{bo} = 50N/deg$ up to $3N$, and a single spring with constant $k = 3N/deg$ after. For both control laws the side-stick could be deflected up to 18 degrees forward and aft. For Direct Law the side-stick neutral position would change proportionally to the elevon deflections at trim and could be adjusted by the pilot; for Pitch Rate Command the side-stick neutral position would always be in the center, regardless of elevon deflections at trim. A stick-shaker with magnitude $A = 5N$ and frequency $\omega = 20Hz$ was included to communicate the hypothetical risk of stall above 21 degrees of angle of attack and prevent pilots from flying the aircraft outside of the validity boundaries of the aerodynamic model.

[†]DOF - Degree Of Freedom; Ord. - filter order; K - gain; ω_n - 2nd order natural frequency; ζ - damping; ω_β - 1st order break frequency.
[‡]DOF - Degree Of Freedom; Ord. - filter order; K - gain; ω_n - 2nd order natural frequency; ζ - damping; ω_β - 1st order break frequency.

Since auto-throttle was always engaged and lateral-directional motion was not included in this experiment, no additional control device was used such as throttle lever or rudder pedals.

A separate display was used to show task-specific data. For all the experiments, it had the following elements, displayed in Figure 7 with the relative letters in red:

- **A** - Load factor indicator (g)
- **B** - Airspeed indicator (kts)
- **C** - Airspeed indicator (Mach)
- **D** - Pitch ladder (deg)
- **E** - Pitch attitude marker
- **F** - Flight path marker
- **G** - Altitude indicator (ft)
- **H** - Additional information, including elevon saturation percentage ("Ele"), Pitch Tracking task adequate and desired scores ("Ade" and "Des"), and angle of attack ("AoA").

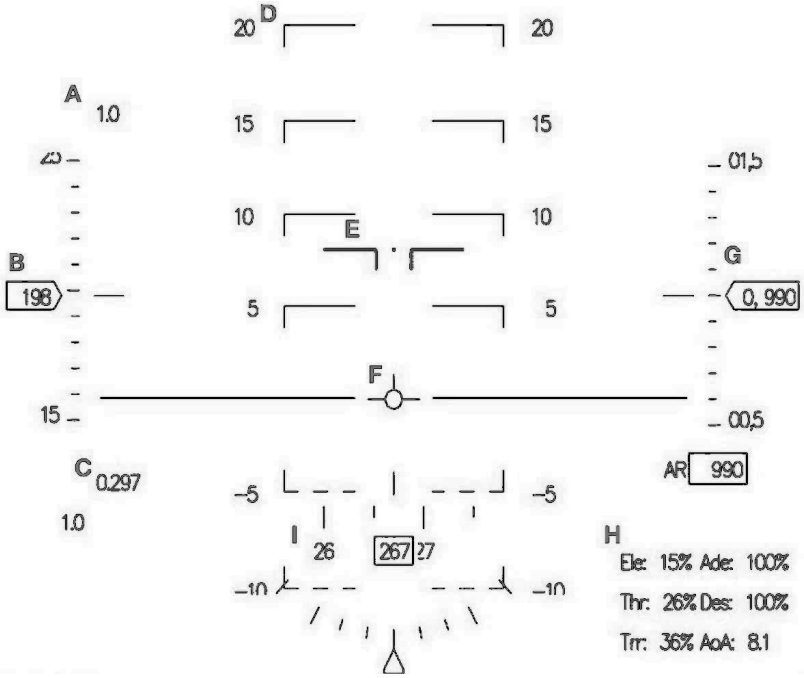

Fig. 7 Arrangement of information in the MIP.

3. Task Description

Pitch Tracking The first task was Pitch Tracking. Subjects were asked to use the side-stick to control the four elevons. The current pitch angle was shown on the MIP by means of a pitch angle indicator on the pitch ladder, and the desired pitch angle was shown by two squares, also on the pitch ladder, see Figure 8. One square, $2deg$ wide and red, represented the "Adequate" performance of $\pm 1deg$ error from the desired target pitch angle, which was in the center of the square. The other square, $1deg$ wide and yellow, represented the "Desired" performance of $\pm 0.5deg$ error from the desired target pitch, which was also in the center of the square. The subjects were instructed to use the sidestick to keep the current pitch angle inside the larger red square to turn it to green and raise the score in "Adequate" performance; and inside the smaller yellow square to turn it to green and raise the score in "Desired". The final performance metrics were the times spent within "Adequate" and "Desired" performance limits.

The target pitch angle was provided by a time-dependent signal made of a sequence of ramps and steps. Five different signals were designed: four for training purposes, one for measurement purposes. All the signals were designed so that they would include at least: a large pull-up ramp that resembles a rather aggressive go-around maneuver; a higher frequency series of captures and ramps that represents quick attitude corrections during approach and landing; a

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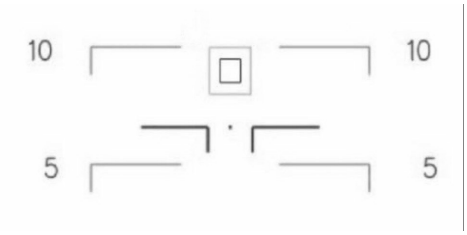

Fig. 8 MIP detail: Pitch tracking target. The larger square, yellow in the real MIP, corresponds to Adequate score; the smaller squares, red in the real MIP, corresponds to Desired score.

combination of large (8 deg) and small (2 deg) attitude changes, in an attempt to explore the handling qualities and the maneuverability of the aircraft as explained in the Objectives paragraph; maneuvers up to $\pm 0.5g$, inspired by the certification requirements on acceleration and controllability.

A score of 68% Adequate and Desired performance was communicated as a goal for the pilots. This percentage was chosen after preliminary tests, where the objective was to find a proper score that is both feasible and challenging enough for the pilots to actively enter the control loop during the experiments.

The two "Adequate" and "Desired" squares turned green when successfully tracked by the pilot, and the scores in both "Adequate" and "Desired" tracking were shown to the pilots during the training sessions as a real-time feedback of their performance. During the measurement run (after the training is done), the scores were only displayed at the end of the run, so that the pilots would fully focus on the tracking task. All the target signals (training and measurement) lasted 90 seconds each.

During the simulation, auto-throttle was activated, to have pilots focus on side-stick control.

In Figure 9 an example measurement run is given. For each configuration, this is the tracking task that was proposed to the pilot after completing the training run(s). The grey and black lines define the limits for "Desired" and "Adequate" performance respectively, while the dashed line represents the pitch angle of the aircraft as controlled by the pilot.

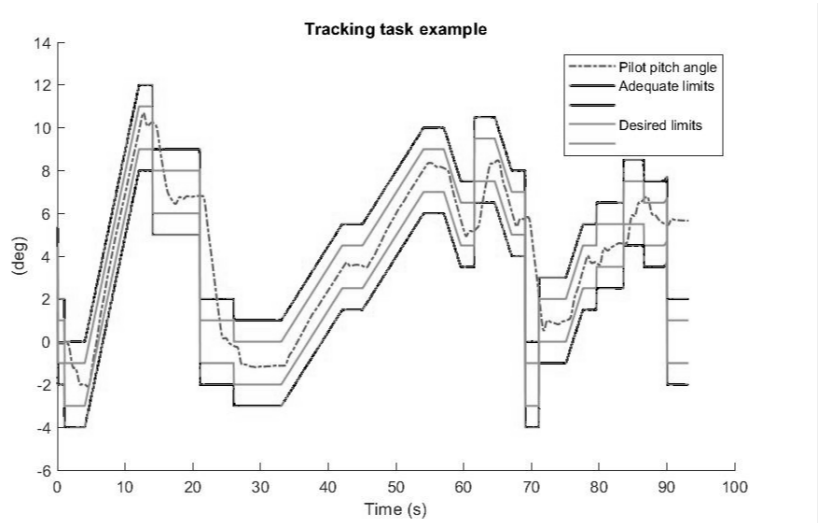

Fig. 9 Tracking task for the measurement run, delimited by the "Desired" performance limits (grey lines) and the "Adequate" performance limits (black lines). An example of pilot-controlled pitch angle is also given (dashed line).

Free Pitch Capturing Pitch tracking was followed by a session of free pitch capturing. During this part of the experiment, the pilots were requested to capture a succession of pitch angles, alternating between $+5deg$ and $-5deg$ capturing. This task was intended as an occasion for further discussions of the handling qualities of the Flying-V configuration, in order to confirm and integrate the results of the Pitch Tracking task. For this purpose, the tempo of capturing was left to the pilot, in the sense that the pilots were free to chose their pace for alternating between the two

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target pitch angles. This allowed for more freedom for the pilot to form an opinion on the handling qualities of the aircraft compared to the pitch tracking task. The task would be repeated for different configurations for about 30 seconds each in order to encourage comparative feedback between the handling qualities at different center of gravity position, speed, elevon limits and control augmentation.

Go-Around The third task was the Go-Around. This task can be described in four steps. First, the aircraft was initialized in a $-3deg$ slope descent towards the runway, and the simulation was started in this trimmed condition at 500ft. In this phase, the pilots were simply asked to observe the flight states and focus on aspects such as the pitch angle and the sight angle to the runway during approach.

At 190ft the pilots were instructed to perform a go-around. The procedure consisted in a call from the pilot (that would verbally communicate the start of the go-around), followed by a pull-up to a target rate of climb of 3.2% (required by the EASA Certification Standards). As a reference for the pilot, a yellow dot in the center of a red square was displayed on the pitch ladder in the MIP, see Figure 10, to communicate the target flight path angle attitude. The dot and the square would turn green when the flight path angle would be higher than or equal to the target rate of climb of 3.2% (that corresponds to $2.4deg$).

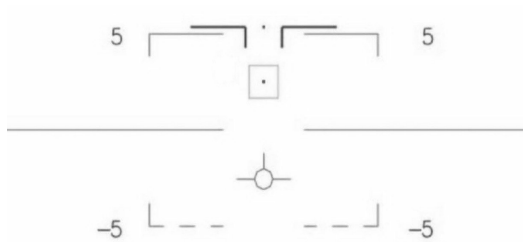

Fig. 10 MIP detail – Pull-up target. The dot in the center of the square, yellow in the real MIP, corresponds to a 3.2% **rate of climb.**

After the pull-up, pilots were instructed to climb up to 500 ft, keeping a rate of climb $\geq$ 3.2%.

Finally, the pilot was requested to level-off at 500 ft, bringing the flight path angle back to zero.

4. Independent Variables

Based on the experiment objectives, four independent variables were defined:

1) The center of gravity would span three positions, forward, nominal, and aft
2) the trim speed was set to two alternative values, namely:
   - 0.225 Mach (~150 kts, ~277 Km/h)
   - 0.3 Mach (~200 kts, ~370 Km/h)
3) the deflection limit of each of the four elevons was set to two alternative values, namely:
   - 20 deg
   - 30 deg
4) the Flight Control System provided two different laws, as explained in the Flight Control System Section IV:
   - Direct Law,
   - Pitch Rate Command.

5. Experiment Design and Procedure

A series of 24 aircraft configurations was considered by combining the four independent measures (3 center of gravity positions, 2 initial speeds, 2 maximum elevon deflections and 2 flight control laws).

For the pitch tracking task all 24 configurations were analysed. For each configuration, one training session was performed by default, and one additional training session per configuration could be requested by the pilot. The training sessions used a separate set of tracking references in a randomized order. After the training, the measurement run was carried out. One reference signal was used for all the measurement runs. Both training and measurement runs lasted 90 seconds each.

For the free pitch capturing task, all 24 configurations were analysed. For each configuration, no training was given and each run was aimed at lasting about 30 seconds.

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For the go-around task, only 6 configurations were taken into consideration based on the research questions. They consisted in the combination of the 3 center of gravity positions and the 2 initial speeds, the other parameters being fixed (20 degrees of maximum deflection and Direct Law flight control). Each run lasted about 60 seconds and was repeated once or twice based on pilot feedback.

Instead of short experiments with many different pilots, it is customary for handling qualities research purposes to prefer longer, more in-depth experiments with fewer pilots. This was also the adopted approach for this research – only three pilots were involved in the experiments. The presentation order of the conditions was determined before-hand and it was different for each pilot. However, the Pitch Rate Command was always simulated after the Direct Law, and the configurations with 30 degrees of maximum deflection were always presented after those with 20 degrees. The ordering criterion was to minimize the impact of learning effects, fatigue, and/or loss of concentration.

After each pitch tracking measurement run, and after each free pitch capturing and go-around run a number of questions were asked to the pilots, as explained below in the Dependent Measures paragraph. Additionally, the pilots were encouraged to give verbal feedback as often as they felt like, not only as a response to the questions.

Overall, each experiment lasted about 5.5 hours, approximately following the scheduling presented in Table 5.

Table 5 Experiment plan

Phase	Task	Duration
Reception and Briefing	-	45 min
Simulation block 1	Pitch tracking - Direct Law	90 min
Brake 1	-	15 min
Simulation block 2	Pitch tracking - Pitch Rate Control	90 min
Brake 2	-	15 min
Simulation block 3	Go-around and Pitch Capture	60 min
Debriefing	-	45 min

6. Aircraft Model

The aircraft model was specifically designed for this experiment; for the modelling approach, see Section III.

7. Dependent Measures

Pitch Tracking Two objective measures were recorded:

- Adequate score: the percentage of time that the pilot managed to keep the aircraft pitch attitude in between $\pm 1deg$ from the target pitch out of the 90 seconds of each run. 68% was considered sufficient, and the pilots were not encouraged to score higher. Adequate score is associated with a looser tracking activity that requires low to moderate precision from the pilot.
- Desired score: the percentage of time that the pilot managed to keep the aircraft pitch attitude in between the $\pm 0.5deg$ from the target pitch out of the 90 seconds of each run. 68% was considered sufficient, and the pilots were not encouraged to score higher. Desired score is associated with a higher gain tracking activity that requires moderate to high precision from the pilot.

Two subjective measures were recorded:

- Cooper-Harper scale rating: quantitative rating from the pilot on the handling qualities of the Flying-V relatively to the specific tracking task. In line with the Cooper-Harper approach to handling qualities, the rating was in the form of an integer number in a 1 to 10 scale, where 1, 2, 3 mean that the handling qualities are satisfactory without improvement (Level 1); 4, 5, 6 mean that the handling qualities are not satisfactory without improvement but adequate performance is attainable with a tolerable pilot workload (Level 2); 7, 8, 9 mean that the aircraft is controllable but adequate performance requires a non-tolerable pilot workload (Level 3); 10 means that the aircraft is not controllable. For further explanation on the scale, see [4].
- Pilot comments – qualitative assessment from the pilot on the handling qualities of the Flying-V configurations, relatively to the specific tracking task. This qualitative feedback is complementary to the analysis of the Cooper-Harper scale rating explained above.

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The feedback was provided during verbal discussions of the chosen Cooper-Harper rating. The comments from the pilots were noted down by the experiment operator, and later categorized in the following topics:
  - Sluggish response
  - Training
  - Control saturation
  - Airspeed
  - Pilot Induced Oscillations (PIO)
  - Elevon maximum deflections
  - Pitch Rate Command
  - CG position
  - Control strategy
  - Possible improvements

Go-around For the go-around, two dependent measures were considered:

- Pull-up performance: quantitative measure of the response of the aircraft during the go-around. After the call for go-around at 190ft, a measure was taken of the altitude loss during the pull-up and of the time required to take the flight path angle from the descent glide up to the target 3.2% rate of climb.
- Pilot comments: qualitative assessment of the handling qualities of the Flying-V for go-around operations. The pilot was guided through a discussion of the handling qualities by means of a list of open questions. These were:
  - Overall, what was the workload for performing the three sections of the task, namely
    * Pull-up,
    * Climb,
    * and Level off?
  - Did the sight angle have an impact on the task in terms of feasibility of the task, workload, and comfort?
  - Did the pitch angle have an impact on the task in terms of feasibility of the task, workload, and comfort?
  - Was the aircraft response too slow, sluggish?
  - Was the aircraft response too quick, abrupt?
  - Did you notice any unusual loss of altitude during the pull-up?

  The answers from the pilots were noted down by the experiment operator.

Free Pitch Capturing For this task, only qualitative feedback was recorded. The pilots were encouraged to elaborate on their opinion regarding the handling qualities. They were guided through the discussion by means of a list of observations, on which to express their level of agreement on a 5-points Likert scale:

- The aircraft was difficult to control.
- There is overshoot in the response of the aircraft.
- There is dropback in the response of the aircraft.
- At least sometimes, the aircraft response is too slow or sluggish.
- At least sometimes, the aircraft response is too quick or abrupt.
- The aircraft tends to pilot induced oscillations.
- There is enough control authority for pitch capturing.

8. Data Analysis

The Cooper-Harper scale ratings, the "Adequate" and "Desired" scores, and the qualitative assessments by the pilots were interpreted together to form an overall picture of the handling qualities of the Flying-V. The three pilots' different ratings and comments were analysed both separately and comparatively in order to highlight their sensitivity over the dependent variables, common trends and disagreements. When possible, the results were compared to the preliminary analysis.

Additionally, the following signals were logged at 25 Hz: time, aircraft position and linear velocity, attitude and rotational rates, angle of attack, flight path angle, pitch angle error (only for pitch tracking), side-stick deflection, elevons deflection, and engine thrust.

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VII. Experiment: Results

The results of the experiment are presented in this section. In the figures, the following terminology is used to refer to the different configurations:

- 150, or 200 − airspeed, in knots;
- f, n, or a − forward, nominal or aft position of CG;
- 20, or 30 − maximum deflection of the elevons, in degrees.

A. Pitch Tracking

1. Adequate score

The "Adequate" performance scores for the Pitch Tracking task are displayed in Figure 11 (Direct Law) and Figure 12 (Pitch Rate Command). At 150 knots, forward CG and 20 degrees of maximum deflection (first configuration in the figures), the scores were lower than the other configurations. For all the other configurations, the scores were between 75% and 89%. There was an improving trend going from 150 to 200 knots and changing the flight control system from Direct Law to Pitch Rate Command, but there were too few participants to rule out learning-curve effects.

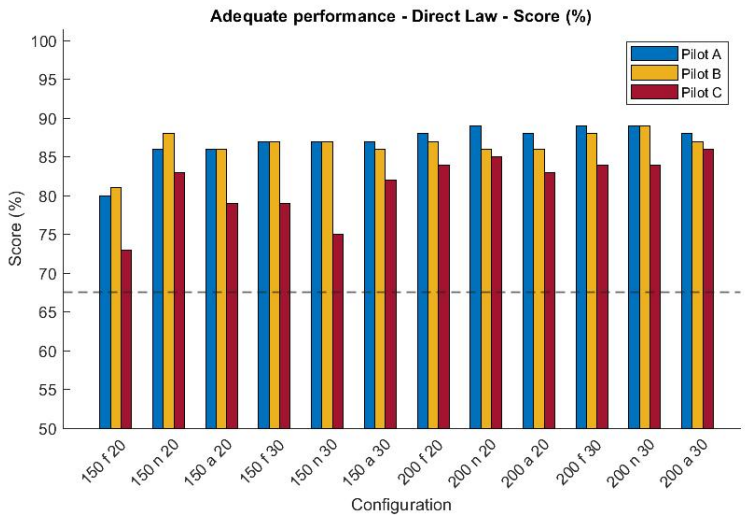

Fig. 11 Adequate performance score − Direct Law.

Overall, pilots could attain the adequate performance for all the configurations, suggesting that tracking maneuvers during approach and go-around are practicable at least down to $\pm 1deg$ precision. Pitch Rate Command was not essential to attain adequate performance, and it had a limited impact on the scores (particularly at 200 knots).

Other than at 150 knots and 20 degrees of maximum deflection, where the forward CG was associated with a lower score, no CG was found to have a remarkable impact on the performance.

2. Desired score

The "Desired" performance scores are displayed in Figure 13 (Direct Law) and Figure 14 (Pitch Rate Command). On average, desired performance scores were lower than adequate performance score by more than 12%. The score with Direct Law is considerably lower than with Pitch Rate Command, in particular at 150 knots.

With Direct Law, Pilot A always achieved a sufficient desired performance (> 68%); Pilot B failed 1 out of 12 configurations (150 knots, forward CG, 20 degrees of elevons maximum deflection); Pilot C failed 7/12 configurations (the six 150 knots configurations; and 200 knots, forward CG, 20 degrees of elevon maximum deflection). At 150 knots the variance among the pilot' performances was the highest − they performed the most differently. There was a clear improvement of performance and success rate at 200 knots compared to 150 knots.

With Pitch Rate Command, Pilot A passed all the configurations; Pilot B failed 1 out of 12 configurations (again 150 knots, forward CG, 20 degrees of elevons maximum deflection); Pilot C failed 2 out of 12 configurations (150 knots, forward CG, 20 degrees of elevons maximum deflection; and 150 knots, aft CG, 20 degrees of elevons maximum

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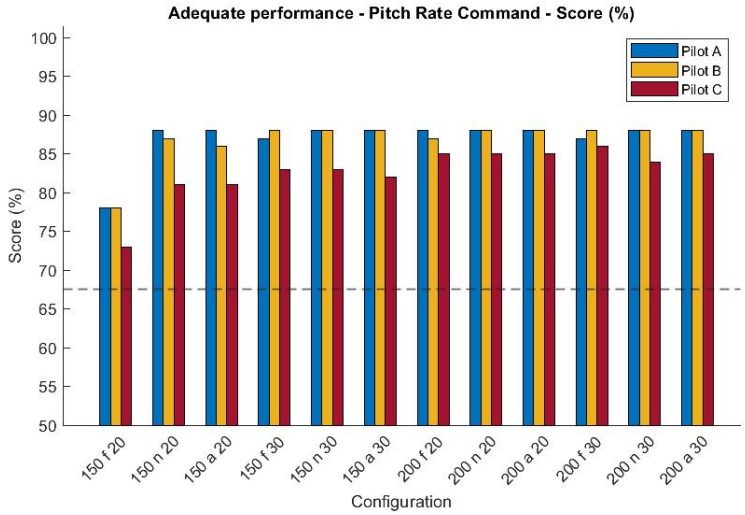

Fig. 12 Adequate performance score – Pitch Rate Command.

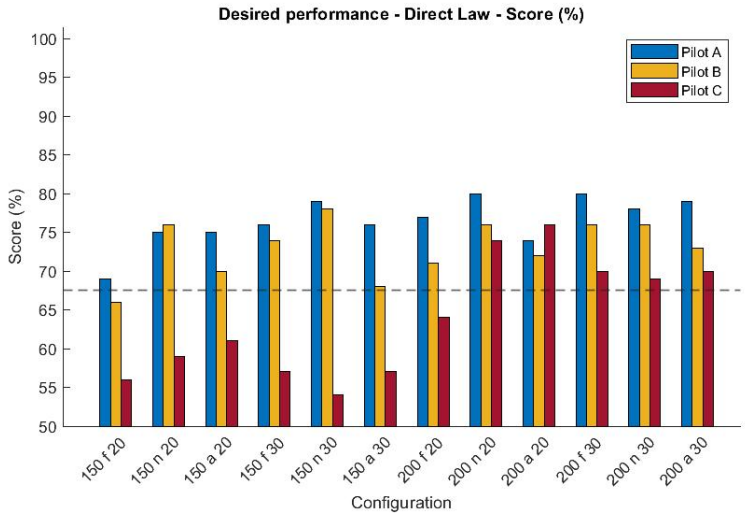

Fig. 13 Desired performance score – Direct Law.

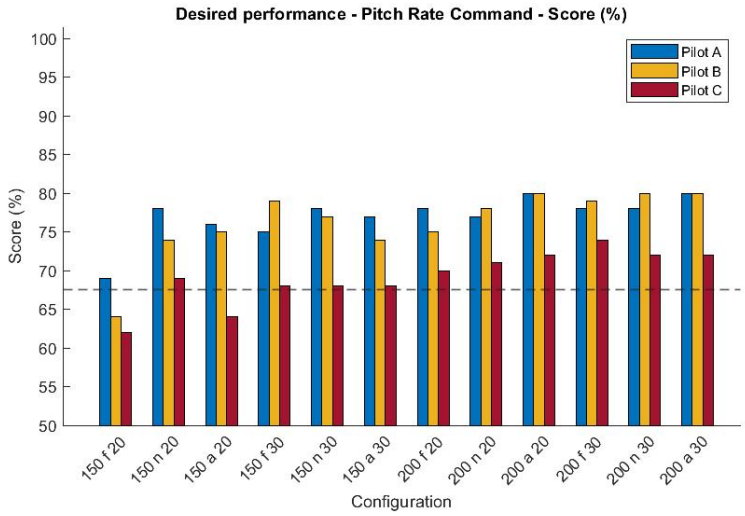

Fig. 14 Desired performance score − Pitch Rate Command.

deflection). The improvement identified at 200 knots compared to 150 knots is also apparent with Pitch Rate Command, but the impact of speed was smaller in comparison to that with Direct Law. The same can be noted regarding the position of the CG − the score difference among the different CG positions was less than with Direct Control.

Overall, pilots struggled significantly more to achieve a satisfactory score in the Desired Performance compared to the Adequate Performance − controlling the aircraft with a precision down to (±0.5 deg) was more challenging than (±1 deg).

3. Cooper-Harper scale rating

The Cooper-Harper scale rating is shown in Figure 15 (Direct Law) and Figure 16 (Pitch Rate Command), again for the three pilots and for all the configurations. With Direct Law, the pilots gave quite different ratings. Pilot A considered the Direct Law at 150 knots to be overall not satisfactory without improvement, while at 200 knots the handling qualities got an overall satisfactory rating; Pilot B deemed the first configuration to require non-tolerable pilot workload (150 knots, forward CG, 20 degrees maximum elevon deflection), but called satisfactory without improvement most of the other configurations (9/12 configurations), those at 200 knots being considered the best; Pilot C considered the Direct Law handling qualities of the Flying-V to be not satisfactory overall, requiring intolerable workload at 150 knots and warranting improvements at 200 knots.

The CG position didn't have a consistent effect on the handling qualities rating with Direct Law. The pilots disagreed on the best CG, each of them essentially giving a higher rating to a different CG position. Pilots B and C, however, agreed that the workload is intolerable at 150 knots with forward CG and 20 degrees of maximum elevon deflection, and Pilot A did not rate this configuration better than the other configurations.

With Pitch Rate Command (Figure 16), ratings were better overall. All pilots agreed that the first configuration (150 knots, forward CG, 20 degrees maximum elevon deflection) was not satisfactory without improvement, and Pilot B considered the task to require intolerable pilot compensation. Pilot C gave a rating of 4 to the two next configurations as well (150 knots, nominal and aft CG, 20 degrees maximum elevon deflection). All other configurations, instead, were called satisfactory without improvement by all pilots. All configurations at 200 knots were given a rating of 2 by all pilots.

The CG position had an even smaller impact on the handling qualities than with Direct Law − other than the first configuration (150 knots, forward CG, 20 degrees maximum elevon deflection), in fact, the CG did not have a clear impact on the handling qualities with the Pitch Rate Command system.

The maximum deflection of the elevons only had an impact at low speed, where the rating were overall better at 30 degrees of maximum deflection. On the contrary, no correlation with the handling qualities was identified at 200 knots.

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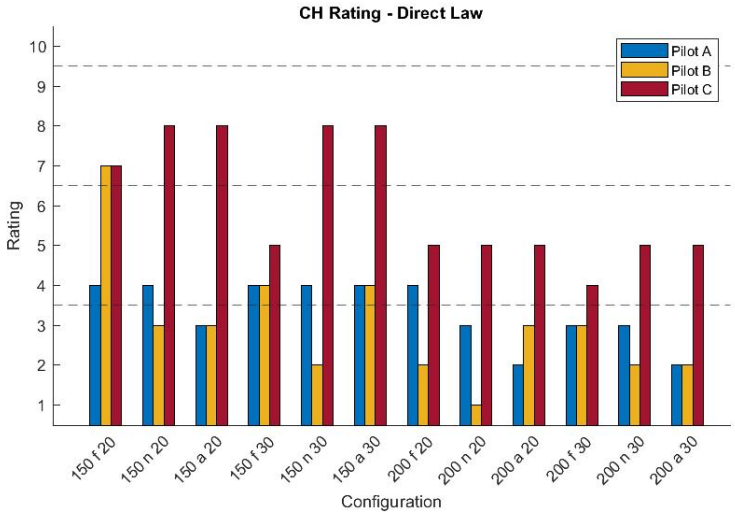

Fig. 15 Handling Qualities Rating – Direct Law.

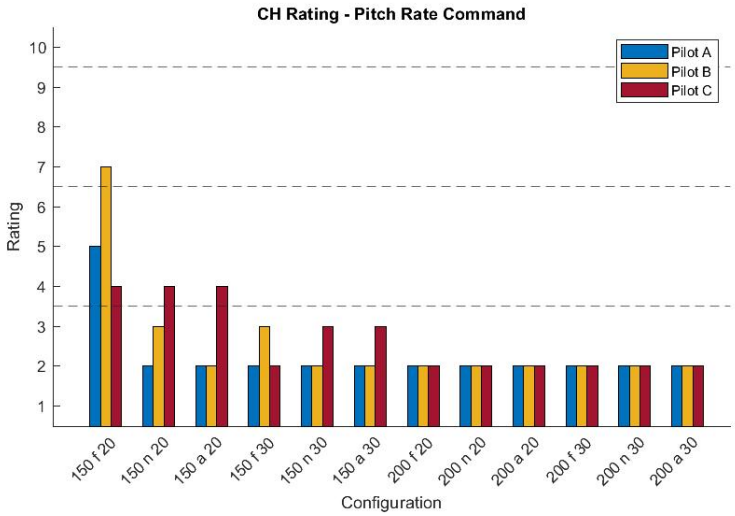

Fig. 16 Handling Qualities Rating – Pitch Rate Command.

4. Pilot comments

After each run, the pilots would explain their Cooper-Harper rating with verbal feedback. The main points are summarized in the following list:

- **Sluggish response -** With Direct Law, the aircraft is sluggish − it requires large initial inputs and active pilot compensation to perform any task. Pilots A and B considered the aircraft to be acceptably sluggish, since the workload related to compensation for slow response is not excessive. Pilot C, however, stated that the aircraft responds too sluggishly; he would not feel comfortable flying it without extensive training or good augmentation.
- **Training -** All pilots agreed that training will be helpful, since it is necessary to understand the sluggish response in order to compensate correctly. However, Pilots A and B did not consider it to be mandatory in order to fly the aircraft safely, while Pilot C stated that training is mandatory and that, without training, pilots might struggle to adapt to the sluggish response of the aircraft.
- **Control saturation -** The first configuration (150 knots, forward CG, 20 degrees maximum elevon deflection) received the worst rating overall. All pilots agreed that the reason is the lack of control authority. They had the feeling that they were lacking pitch-up capability, which comes with a series of inconveniences − impossibility to pull-up safely in case of emergency, unsafe maneuverability in case of turbulence, uncomfortable feeling of hitting the side-stick deflection limits (with Direct Law), higher workload required to complete the pitch tracking task. This control authority issue was identified both with Direct Law and Pitch Rate Command.
- **Airspeed -** All the pilots agreed that the handling qualities are significantly better at 200 knots compared to 150 knots. The pilots used expressions such as "everything speeds up nicely" to indicate that, together with airspeed, also the pitch angle gets more responsive. This impact of speed on the handling qualities was identified clearly with Direct Law, and just mildly with Pitch Rate Command. In fact, the Pitch Rate Command benefits from airspeed less than the Direct Law does.
- **PIO -** Pilot A did not find any tendency to PIO. Pilot B only suggested that this aircraft might have a tendency to PIO due to the sluggish response, but did not feel any PIO himself. Pilot C identified a significant tendency to PIO, particularly at 150 knots and with Direct Law.
- **Elevon maximum deflection -** As mentioned, 20 degrees of elevon maximum deflection were not considered enough for 150 knots and forward CG by any of the pilots, independently of the control law. However, in all the other configurations the pilots all mentioned that they would like more control authority in order to feel more safe and obtain better handling qualities, but none of them said that 20 degrees were insufficient. In this sense, again excluding the configuration at 150 knots and forward CG, 30 degrees were appreciated for the increased authority but they were not considered necessary. In fact, with Direct Law at 200 knots Pilots A and C stated that 30 degrees of max. deflections are too much and that it actually increased the workload (Pilot A) and the tendency to PIO (Pilot C). This is most likely due to the way the side-stick deflection is mapped into elevon deflections with Direct Law − a scaling is used which is proportional to the maximum allowed deflection. Any amount of side-stick input commands 50% larger elevon deflections when the maximum is 30 degrees compared to 20 degrees, increasing the apparent control sensitivity.
- **Pitch Rate Command -** All the pilots gave very positive feedback regarding the Pitch Rate Command. They mentioned that it "makes it much easier to track and hold", "helps fighting the slow short period" and "solves all the problems". With Pitch Rate Command, they stated that they would not be able to tell the difference between the configurations anymore − they all felt the same. The pilots all agreed that they would like more control authority and possibly a faster response.
- **CG position -** The three pilots disagreed on the impact of the position of the center of gravity on the handling qualities. Overall, pilot A preferred the aft CG, pilot B preferred the nominal CG, and pilot C preferred the forward CG. Pilot A believed that he was mainly fighting against dropback, and had a feeling that the aft CG generated the smallest dropback. Pilot B found the forward CG to be difficult to predict, and the aft CG to be too slow, hence preferring the nominal CG. Pilot C stated that the short period felt better damped and faster with the forward CG. Despite these preferences, however, they all commented that the impact of the CG position on the handling qualities was not pronounced.
- **Control strategy -** Pilot A stated that the aircraft requires some compensation after releasing the stick. However, as the CG shifted from forward to nominal and then to aft, he would notice that a different control strategy was viable − to "smoothly release the stick before capturing". He commented that he prefers this second control approach, and that it was easiest to apply it with aft CG and not really feasible with forward CG. Pilot B said that he applied the same approach to all the configurations − he applied two side-stick corrections after each capture at 150 knots, and only one correction at 200 knots. Pilot C described his approach as more "impulse-like", made of

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many full-stick inputs. He believed that the aft CG made it more difficult for him to use this approach, whereas 200 knots made it easier. With Pitch Rate Command, all the pilots said that compensation was minimal and that their approach essentially consisted in releasing the stick just before reaching the target attitude, hence correcting for the baseline sluggishness of the aircraft.

- **Possible improvements -** When asked to explain why they would give a rating of 2 in the CH scale (as they did, in particular, for Pitch Rate Command at 200 knots), all pilots stated that the aircraft is almost perfect as it is but that, in order to give it a score of 1, they would require a more responsive short period and faster dynamics overall.

5. Time logs

All the data from the runs have been stored in time logs, as explained in Section VI. For discussion purposes, it is useful to consider two visualizations: a comparison between Direct Law and Pitch Rate Command for the same configuration, and a comparison between Pitch Angle and Flight Path Angle for the same run.

In Figure 17, the time history of Pilot C pitch angle is displayed for the same configuration (nominal CG, 20 degrees of maximum deflection, 150 knots) and the two different control laws, Direct Law (black line) and Pitch Rate Command (grey line). It can be seen that augmentation reduced the tendency towards oscillations and their amplitude.

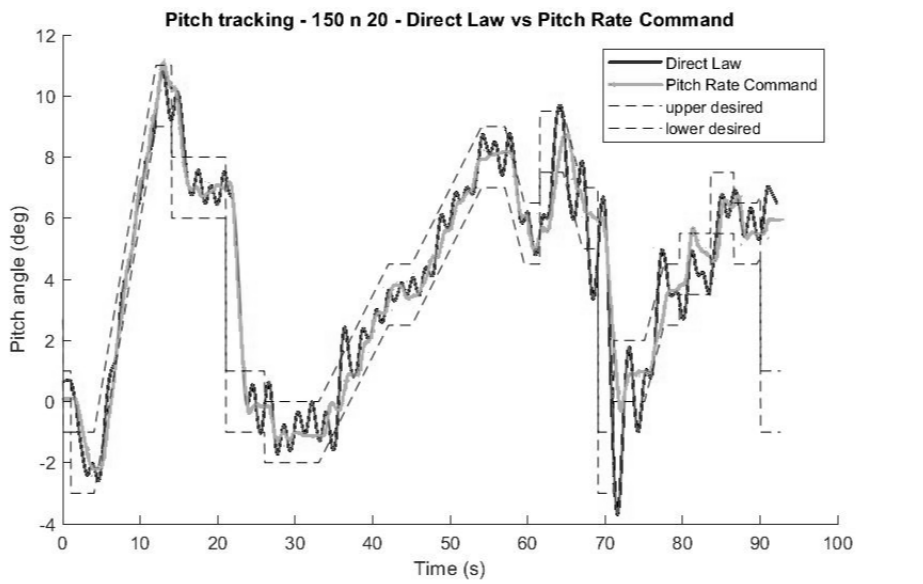

Fig. 17 PIO tendency comparison: Direct Law (black) and Pitch Rate Command (grey). Tracking task, 150 knots, nominal CG, 20 degrees of maximum deflection.

Figure 18 shows flight path angle and pitch angle during a tracking task (Pilot A, 150 knots, forward CG, 20 degrees of maximum elevon deflections). There is no particular evidence of unusual lag during high frequency sections nor during slower sections of the task. Note that this configuration has limited control authority − other configurations have even less lag between flight path angle and pitch angle.

B. Go-around

1. Pull-up performance

Regarding the go-around maneuver, the approximate altitude loss after the "go-around" call is shown in Figure 19, while the time between the "go-around" call and the instant when the climb rate is above 3.2% is shown in Figure 20. Notice that the configurations considered for the go-around maneuver were all with Direct Law and 20 degrees of maximum elevon deflections, so the only two changing parameters were speed and CG position.

The mean altitude loss was 8.6 m, with a minimum of 3.6 m and a maximum of 15.4 m. The mean time to achieve 3.2% rate of climb was 5.1 s, with a minimum of 2.9 s and a maximum of 8.1 s. It was not possible to identify trends in

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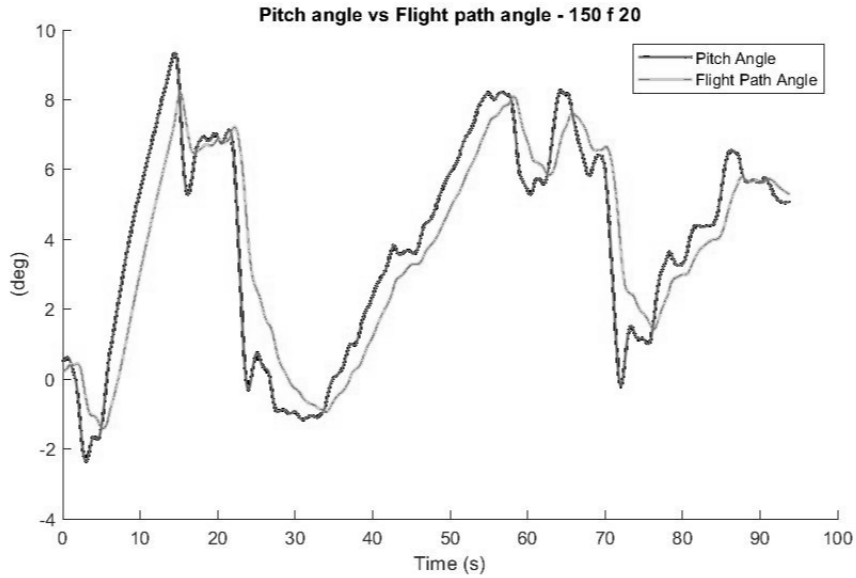

Fig. 18 Flight path angle (grey) lag behind Pitch angle (black). Tracking task. 150 knots, forward CG, 20 degrees of maximum deflection.

the correlation between configurations and aircraft performance − in all the configurations, altitude loss and time to pull-up were limited and essentially only dependent on the reaction-time of the pilot after the "go-around" call.

2. Pilot comments

After each Go-Around run, the comments from the pilots on every configuration was collected and the main points are summarized in the following list:

- **Workload -** All the pilots agreed that the workload was really low during all the phases of the task. Performing the pull-up to reach 3.2% rate of climb was easy and only required some compensation to avoid overshooting due to the sluggish response of the aircraft. Maintaining a rate of climb equal or higher than 3.2% during the climb phase was also very low-workload. In fact, it was easy to understand how to hold the target climb rate. Capturing 500 ft was also considered easy, although the workload was a bit higher due to the necessity of controlling the flight path angle into a precise target (0 in this case). In any case, all the pilots stated that the flight path angle lagged behind the pitch angle just as it does in conventional aircraft. When asked about their workload expectations in case of manual throttle and more realistic go-around scenarios, all the pilots agreed that they do not expect real operations to be significantly more demanding than the simulations of this experiment, supporting the validity of these results.
- **Sight angle -** Regarding the unusual sight angle (due to the exceptionally high angle of attack during landing), the three pilots raised different concerns. Pilot A stated that he struggled to see the horizon and that, in general, having such a limited sight angle made him feel very uncomfortable. He mentioned that he would not like to fly like that. Pilot B was very concerned with potentially conflicting air traffic, since the limited sight angle made him feel unsafe and not fully aware of the surroundings. Pilot C explained that he was concerned for not being able to predict when the landing gear would touch the runway, since he was not used to the unusual sight angle. Additionally, the three pilots agreed that the unusual pitch angle made it difficult to understand when the capturing at 500 ft had been executed correctly, and that being so tilted in the air was "annoying but not unacceptable". All the concerns were significantly lowered at 200 knots, although the pilots stated that they would still prefer to have a better sight angle.
- **Responsiveness -** The pilots confirmed that the aircraft responds in a rather sluggish way. They commented that the aircraft is easy to maneuver for operational tasks such as the go-around simulated in this experiment, but concerns remained related to emergency scenarios, where the handling qualities might be closer to those found in the pitch tracking experiment.
- **Loss of altitude -** None of the pilots considered the loss of altitude after the "go-around" call to be concerning or

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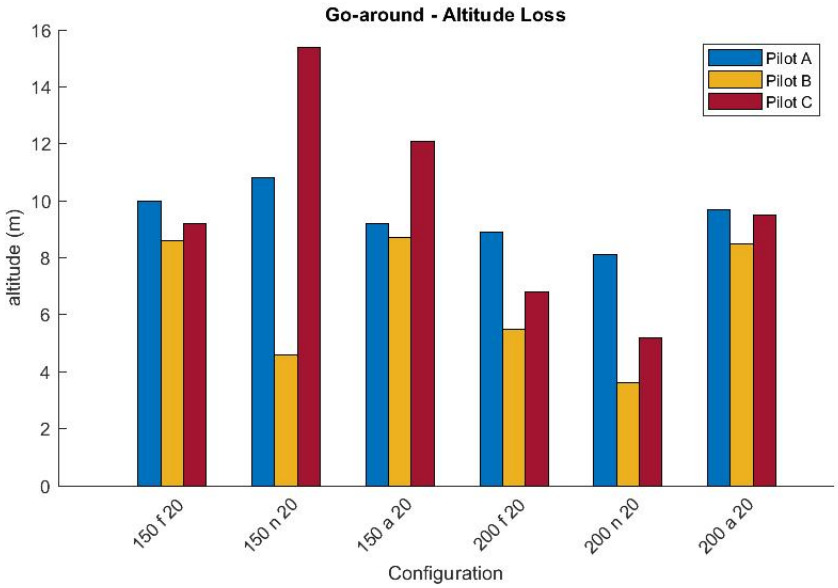

Fig. 19 Go-around – Altitude Loss.

unusual.

- **Control saturation -** The control saturation issue that was evident in the pitch tracking task, in particular for the configuration with 150 knots, forward CG, 20 degrees maximum elevon deflections, was identified during the go-around task as well. However, in this case Pilots A and C commented that they were only "annoyed" by the limited control authority. According to them, they could easily perform the go-around task regardless of the limited pitch-up authority, and they did not expect that real operations would be hindered by the control authority. Pilot B, instead, found the limited control authority to be a real danger, since he believed that the go-around with that control authority would not be possible in case of any turbulence.
- **Training -** According to pilots A and B, training will help to understand how much to pull-up in terms of pitch angle during the go-around, and how to capture the target altitude in a cleaner way. Pilot C, instead, considered training mandatory to fly this aircraft in approach, since the unusual sight angle and pitch angle require specific training and knowledge. In particular, he stated that instrument landing might be required, since it is too difficult to control the vertical velocity of the aircraft based on direct observation of visuals and pitch angle.

C. Free Pitch Capturing

Free pitch capturing was useful to confirm the results of the pitch tracking task. No new information was collected during the experiment that was not already mentioned in the pitch tracking section. In particular, pilots' feedback on the correlation between CG position and handling qualities was confirmed, and the short period frequency and damping were confirmed to be the main source of handling qualities issues together with the limited control authority.

VIII. Discussion

A. Handling qualities assessment

1. Short period and airspeed

The pitch tracking experiment supports the findings of the preliminary analysis regarding the correlation between short period and handling qualities. Most of the negative comments of the pilots, in fact, were related to the slow short-term response of the aircraft, and the higher frequency associated with higher airspeed had a clearly positive impact on the results of the experiment in terms of rating, scores and comments.

As predicted based on the short period frequency, all the configurations (regardless of speed and CG) are overall

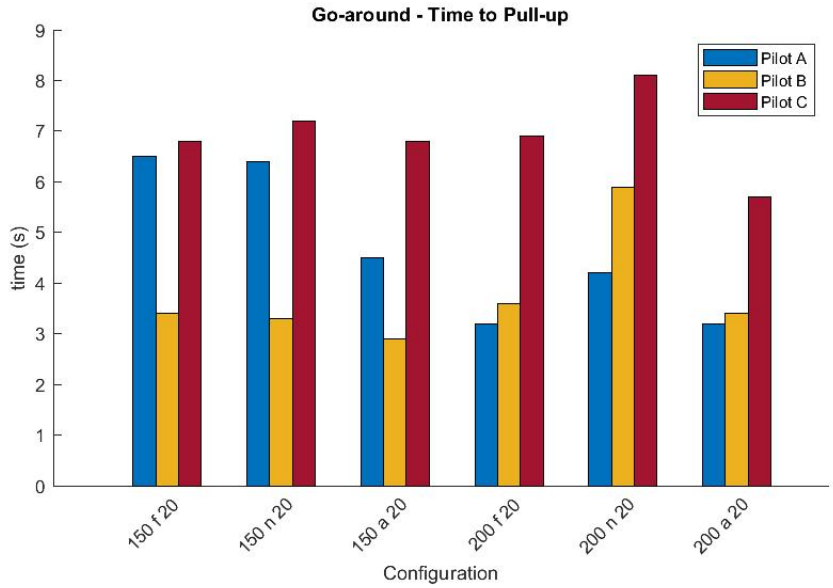

Fig. 20 Go-around – Time achieve 3.2% **rate of climb.**

negatively impacted by the sluggishness of the aircraft. This had been estimated by means of the "short period thumbprint" and of the Bandwidth criterion (Section V). In fact, even at 200 knots, where the handling qualities were considered acceptable (on average) with Direct Law, all the pilots would still complain that they would prefer a faster response to side-stick input, and one pilot even stated that he did not find the short period satisfactory without improvement.

It should also be noticed that the short period frequency difference between the configurations did not have a considerable impact on the handling qualities – the whole range falls into the same "sluggish" response, even for the fastest configurations (forward CG, 200 knots). However, compared to the expectations, airspeed has a larger impact on the handling qualities level.

The experiment supports the preliminary analysis also in terms of handling qualities level. In fact, despite the sluggishness, short period damping, control anticipation parameter and phugoid frequencies all suggested that the handling qualities would be between level 1 and 2, which they approximately did.

The design landing speed so far has been estimated in the 130-200 knots range. This study has proven that the handling qualities, at least according to this aerodynamic model, benefit from higher speed in terms of aircraft responsiveness (short period response) and control authority (see Control Saturation section below). As a consequence, it is recommended that future designs will take into account the degradation of the handling qualities into Level 2 or even 3 when speed is reduced, and, with this aircraft design and these control surfaces, the design landing speed should be preferred to be in the 175-200 knots range.

2. CG preference and Gibson criterion

The main mismatch between preliminary analysis and experiment results is related to the sensitivity of the handling qualities over the position of the CG. According to the preliminary analysis, and in particular to the Gibson Dropback criterion, it was expected that pilots would be able to perceive a different response (dropback or overshoot) based on the position of the CG (forward or aft, respectively). However, this was not the case, and not even the Free Pitch Capture activity helped at proving this prediction. Moreover, it was also expected that the pilots would have a preference for the forward CG, since according to the Gibson criterion a more dropback-prone CG, in this case the forward one, can provide better handling qualities compared to an overshoot-prone CG. However, this expectation was not confirmed either, since each pilot preferred a different CG position, for different reasons, and with low confidence.

It is difficult to identify the exact reason of this mismatch. The most probable explanation, however, is that the low short period frequency of the Flying-V reaches its steady state quite slower than usual aircraft (up to 8-9 seconds). Since Gibson intends the dropback as a difference between the pitch angle when the stick is released, and when it reaches its

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steady state, it is debatable whether this criterion is actually applicable to this slow aircraft configuration.

3. Control saturation and PIO

Based on this model, the effectiveness of the control surfaces is sufficient in most configurations. However, the preliminary analysis predicted that the control authority might not be enough for safe longitudinal maneuvering in the slower configurations with more forward CG positions and 20 degrees of maximum deflection (Section V.A.6). During the piloted experiments, then, it was noted that a limited control authority had a consistent, negative impact on the handling qualities evaluation. It made the tracking task difficult, since it required shorter reaction times to follow the larger pitch-up ramps, or otherwise the target attitude would be missed for the whole duration of the ramp. On top of this, the pilots had a feeling of discomfort related to the side-stick end stop, and concerns related to the capabilities of the aircraft in case of turbulence and emergency pitch-up maneuvers. They confirmed the expectations of the preliminary assessment − the limitations in control authority are most concerning at 150 knots with forward CG, where 20 degrees of deflection were considered insufficient by all pilots. This can be addressed either by improving the effectiveness of the control surfaces, by studying an optimal control allocation strategy, by limiting the minimum airspeed of the aircraft to more than 150 knots, or by avoiding more forward positions of the CG.

Regarding this control saturation problem, some additional observations should be made. First, it should be noted that the sizing of the control surfaces included in the aerodynamic model is not final, since no dedicated studies have been done on this topic yet. Together with the sizing, also the validity of the aerodynamics around the control surfaces is debatable. In fact, the data are only available for 1 degree of deflection of each elevon, and the effectiveness for larger deflections is extrapolated linearly. However, it is known ([34]) that non-linear phenomena can take place around the elevons, in particular at higher angles of deflection. As a consequence, the effectiveness of the elevons should be further investigated. Finally, it should be remembered that the approach airspeed was here set at 150 knots in order to collect insights for future design iterations. This speed was decided in comparison with reference aircraft, such as the A350[§] for which the landing speed is 155 knots, but it is not definitive for the Flying-V.

On the other hand, a PIO tendency issue arises with larger control deflections. As explained in Section IV, in fact, stick sensitivity is raised by 50% when the maximum elevon deflections are 30 compared to 20 degrees. At faster configurations in particular, but not exclusively, it appeared that this increased limit was excessive according to the pilots, with one pilot even stating that the aircraft has evident tendencies to PIO. However, it is uncertain whether this was due to the increase stick sensitivity, or to the experiment sequence − in fact, all the configurations with 30 degrees of maximum deflection were simulated after the respective version with 20 degrees of deflection.

In any case, it is safe to assume that this issue can be solved with optimal mapping of control input onto elevon deflections and with optimal control allocation.

B. Control Augmentation

Control augmentation proved very effective in improving the handling qualities. All the configurations received a better rating and more positive comments with the Pitch Rate Command compared to the Direct Law, with the only exception of those with insufficient control authority mentioned above.

The Pitch Rate Command controller was tuned precisely to improve the short period characteristics. Cooper Harper rating, pilots feedback, and simulation logs all prove that this goal was achieved. The rating changed drastically from Direct Law to Pitch Rate Command, and the improvement was consistent for all the pilots. The reasons behind this improvement, according to the pilots, is that the short period feels more responsive with Pitch Rate Command. Additionally, as pilots confirm, this control law helps fighting PIO tendencies, reducing the workload needed to hold on the target attitude. For example, in Figure 17, Section VII, the smaller tendency to PIO is visible. Anyway, it is important to remember that this study was not aimed at neither searching nor proving PIO proneness. The conclusions related to PIO should be interpreted as advice for future research and design, rather than technical claims that would require specific experiments [35].

On the other hand, the main shortcoming of the Pitch Rate Control law was clear. The pilots complained that they would appreciate to be able to command a faster pitch rate. And it can be seen, for example in Figure 17 again, that Direct Law allowed for larger pitch-rate commands. In fact, the limit to the pitch rate controller was chosen in the design phase, when it was noticed that higher gains would cause abrupt accelerations, which caused discomfort.

Furthermore, a certain level of sluggishness was perceived by the pilots also with Pitch Rate Command engaged.

[§] https://skybrary.aero/aircraft/a359

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Despite the good improvements on the short period achieved with augmentation, it was still possible to identify the inherently slow characteristics of the Flying-V.

Based on this experience, control augmentation should be considered as an effective way to improve the handling qualities of this aircraft. It is recommended that the flight control system is tuned to speed up the short period, and that optimal mapping is investigated to make full use of the control effectiveness of the elevons without causing the discomfort connected with the mentioned abrupt accelerations. Linear mapping was found sub-optimal for this purpose, and a better system should map larger accelerations to larger side-stick deflections.

C. Certification requirements

In order to meet the certification standards, some criticalities were identified related to the requirements on landing, approach and go-around.

Good handling qualities have to be proven during these phases. According to what has been discussed in the previous two sections, most of the related requirements should be achieved with Pitch Rate Command, and with Direct Law at 200 knots. In this sense, EASA requirements CS- 25.161(c)(2), AMC-20-6.12.2 (on trim demonstration), CS-25.175(a) through (d), AMC-20-6.14.2 (on stability), CS-25.143(j).1 and CS-25.143(j).2, AMC-20-6.9.2(c) (on acceleration capability) and CS 25.143, AMC 25.143(a) (on controllability and manoeuvrability) are expected to be satisfied.

Some concerns were noted related to the limited sight angle. The very high pitch angle limits the view of air traffic and runway, and it is difficult to determine the current attitude of the aircraft based on the visuals. The issues arise from the unusually large angle of attack required at low speed, caused by the relatively low C_{l_α}. If not with high lift devices, this can again be solved by raising the minimum design landing speed. In fact, at 200 knots the sight angle was better than at 150 knots; pilots reported that it was unusual but safer.

Regarding the go-around maneuver, most of the concerns raised in previous research were not applicable to this newer model. In particular, pulling up does not cause significant loss of altitude (during the simulation the largest loss was 15.4m) and flight path angle does not lag behind pitch angle in an unusual way, as was shown in Figure 18 Section VII. For these reasons, CS-25.119, AMC-20-6.5 (on climb rate), and CS 25.143, AMC-20-6.9.2(e) to (h) (on performing approach and go-around) are expected to be satisfied.

On the other hand, some potential operational issues were identified. The already discussed control saturation issue makes it difficult to get certification against EASA CS 25.143 ("Controllability and Maneuverability"), and so does the necessity of augmentation to obtain satisfactory handling qualities.

All considered, it can be expected that the certification requirements will be easier to meet if:

- the CG position will be in the nominal/aft range, since this grants larger control authority and better sight angle at the expense of minor handling qualities deterioration;
- the design landing speed would be in the range of 175-200 knots, operational considerations permitting;
- larger control effectiveness will be granted with better control surfaces.

Alternatively, in case these recommendations cannot be followed, most of the problems might be addressed with adjustments, such as unconventional cockpits to improve the sight angle; high-lift devices to improve the usable $C_{L_{\max}}$, allow for slower landing speeds, and reduce the required angle of attack; unconventional control systems to make optimal use of the available control authority.

The findings of this study are in agreement with many of the results of precious research, in particular Cappuyns [6], The potential for handling qualities degradation due to high angles of attack at low speed was already known, and the previously suggested CG limits are confirmed by this study. However, more aft CG positions are here recommended compared to the past, and more attention should be given to problems related to control authority rather than the flight path angle, in particular for certification purposes.

D. Future work

The aerodynamic model is a critical point of this research, since it is based on a CFD method that does not guarantee accuracy for high angles of attack. For this reason, this analysis should be repeated focusing on the risk of stall and, more in general, on the effects of flow separation on handling qualities and performance of the Flying-V. The aerodynamic model should be more accurate for the control surfaces as well. This will allow for further studies on control allocation, and more relevant research on the lack of control authority that was evident throughout this research.

For future design iterations of the Flying-V, it should be taken into consideration that aft CG provides slightly worse handling qualities, but that it comes with significant improvements in terms of sight angle and control authority.

A better flight control system should be designed, possibly following the insights obtained from this research.

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Further analysis is required on allocation, control mapping, and alternative control architectures that were not considered here. The goal should remain that of speeding up the short period, while providing smooth control (as opposed to abrupt response) and exploiting the entire available control deflection.

According to this research, the Direct Law does not provide sufficient handling qualities overall. In the future, it should be made clear to what extent the Flying-V can rely on augmentation to meet the handling qualities certification requirements.

Pilot Induced Oscillations are a difficult topic in handling qualities assessment. It might be complicated to identify PIO and prove that an aircraft is PIO-prone. Specific techniques exist for PIO identification, which however were not used during this study. In fact, during the preliminary analysis there was basically no evidence of any PIO tendency. It is recommended that in future works specific approaches to PIO assessment are used, in order to clarify this tendency for design purposes.

Finally, it should be noted that the phugoid mode was essentially excluded in this analysis through the use of short period models for the HQ predictions and the application of an auto-throttle in the experiment. The phugoid should not be a source of issues since the time to double is expected to be very high and the mode itself to provide acceptable handling qualities. Additionally, the auto-throttle proved effective at cancelling the phugoid motion, and it is expected that an auto-throttle mode will be available on the Flying-V. In any case, a more accurate analysis, should be carried out when more realistic engines will be included in the simulation model.

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IX. Conclusions

The pilot-in-the-loop experiment – supported by a preliminary analytical assessment – shows that at 0.3 Mach approach speed the longitudinal handling qualities of the Flying-V are overall satisfactory with minimum improvements needed, mostly related to the short period mode. For lower approach speeds (0.225 Mach) the handling qualities degrade due to a sluggish aircraft response, limited control authority, insufficient sight angle, and a tendency to PIO. More aft positions of the center of gravity, instead, provide better sight angle, better control authority, and only minimally reduced handling qualities. Twenty degrees of elevon deflection proved sufficient, but 30 degrees were required for safe maneuvering at slow speed with a forward CG. The Pitch Rate Command controller proved effective at improving the handling qualities overall, but did not solve the control authority problem. The certification requirements related to the go-around performance could be satisfied, but, considering that the Flying-V landing speed is expected to be lower than Mach 0.3, new concerns related to controllability and safety emerge. In the future, a more accurate aircraft model should be used to further elaborate the results found in this study.

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