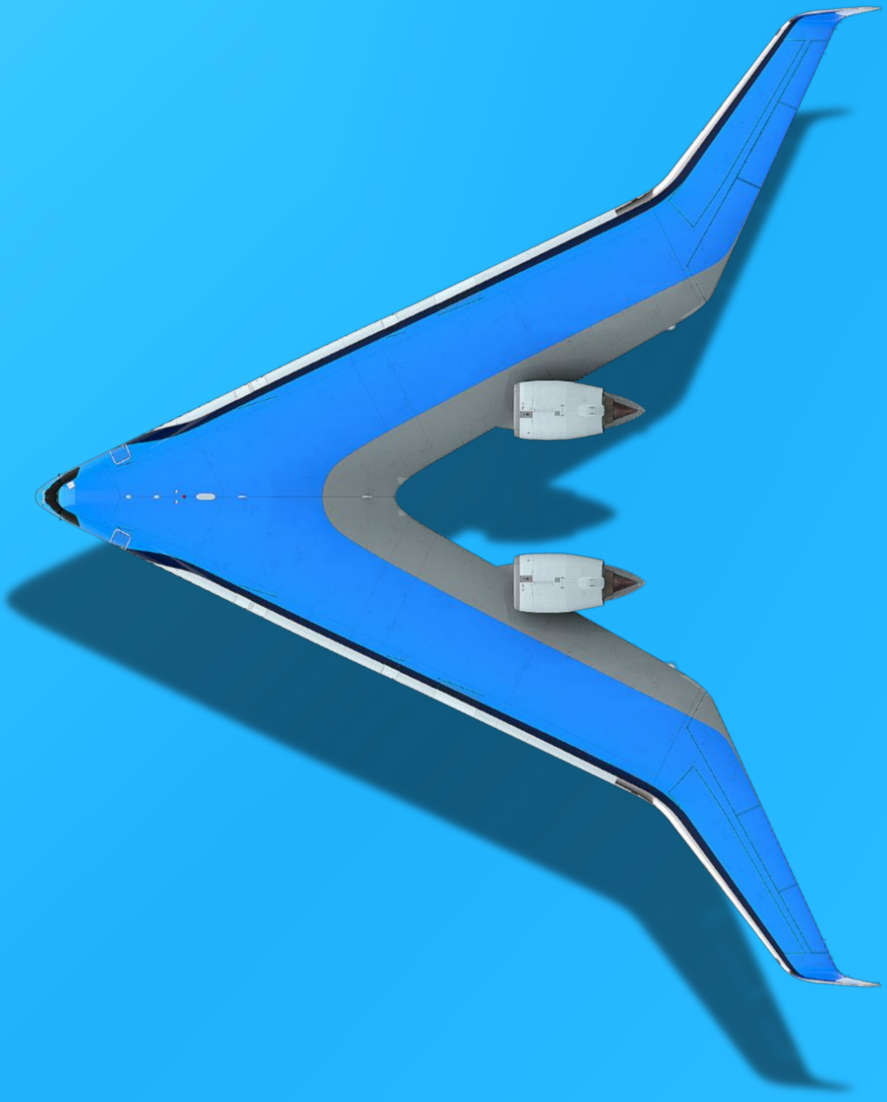
Piloted simulator evaluation of low speed handling qualities of the Flying-V

Riccardo Torelli



TU Delft

Thesis Report

Piloted simulator evaluation of low speed handling qualities of the Flying-V

by

Riccardo Torelli

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at the Delft University of Technology,
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Cover image source: https://www.tudelft.nl/lr/flying-v.

Preface

This report is divided in three parts. In Part I the Research Paper with the title ”Piloted simulator evaluation of low speed handling qualities of the Flying-V” is presented, containing all the main aspects and results of this research. Part II contains the Book of Appendices, which includes the data and appendices that are supplementary to the Research Paper. Finally, Part III consists in the Preliminary Thesis Report of this research, which has already been graded.

Ringraziamenti

Quest’ultimo anno all’Università di Delft è stato più difficile di quanto potessi immaginare, e concludere questo progetto segna la fine di un’avventura faticosa. Sono stato fortunato, però, perche persone indimenticabili mi hanno accompagnato durante questo periodo difficile. Vorrei dire grazie a tutti voi.

A Olaf, per essere stato il miglior supervisor che uno studente possa desiderare. Sei stato non solo una guida luminosa per tutti i capitoli di questo progetto, ma la tua gentilezza e la tua pazienza hanno anche fatto dei nostri (lunghi) ”Monday meeting” uno spazio sicuro e piacevole. Insieme a te, vorrei dire grazie a Max, per essere stato un mentore prezioso, e ai ragazzi del Giovedì, per essere stati compagni di squadra indispensabili.

Ai miei amici di ogni giorno, quelli di Palazzo Mare, perché immaginatevi se non ci fossimo mai conosciuti; a João, perché sei il mio sostenitore numero uno; a Rokas, perchè siamo ancora qui.

A tutta la mia famiglia, perchè siete la mia vita; ai miei genitori, perché semplicemente vi devo tutto; a mia sorella, perché sei così buona che è impossibile non volerti un bene dell’anima; a Pego, perché ti posso mettere nel paragrafo della famiglia; a Nonna Franca e Nonno Rocco, perchè mi avete fatto conoscere l’affetto infinito; a Nonno Nino, perché mi hai mostrato la via per la notte stellata.

A Nonna Teresa, perché mi hai insegnato a scrivere sulla sabbia, di fronte al mare.

Riccardo Torelli
Delft, Giugno 2022

Acknowledgements

This last year in TU Delft has been more difficult than I could ever expect, and concluding this project marks the end of a strenuous adventure. However, I was really lucky, because memorable people have accompanied me through this difficult time. I want to say thanks to all of you.

To Olaf, for being the best supervisor a student can ask for. You have not only been a brilliant guide throughout all the steps of this project, but your kindness and patience have also made every ”Monday meeting” into a safe and enjoyable (two-hours long) moment. I would also like to say thank you to Max, for your precious mentoring, and to the Thursday meeting guys, for being essential teammates.

To my everyday friends, the Palazzo Mare guys, because imagine if we never met; to João, for really being my number one supporter; and to Rokas, because we are still here.

To my entire family, because you are my life; to my parents, because I simply owe you everything; to my sister, because you are so loving that it’s impossible not to love you back; to Pego, because I can put you in the family paragraph; to Nonna Franca e Nonno Rocco, because you showed me what infinite love feels like; to Nonno Nino, because you pointed me to the starry night.

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Riccardo Torelli
Delft, June 2022

Part I - Research Paper

Piloted simulator evaluation of low speed handling qualities of the Flying-V

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***Abstract*—The Flying-V novel aircraft design aims at reducing fuel consumption by an innovative low-drag, fuselage-free geometry. However, possible issues related to certification requirements have been noted regarding longitudinal handling qualities at low speed, the pull-up manoeuver, and the flight path angle response. This study aims at investigating these issues by means of piloted simulations. 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 center of gravity position (forward, nominal, aft), approach speed (between 0.225 and 0.3 Mach), maximum deflection of the control surfaces (between 20 and 30 degrees), and flight control system (Direct Law or Pitch Rate Command). The piloted experiments, supported by the preliminary analytical assessment, show 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 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.**

I. INTRODUCTION

In the context of aircraft fuel efficiency, increasingly smaller reduction of fuel consumption has been achieved via subsystem optimization. ICAO has set the target reduction in fuel consumption for the next 20 years [19], but the most recent projections show that these goals are not expected to be met at the current pace of improvement [18].

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%[1]. 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[1]. Its geometry comes with the advantage of an improved lift-to-drag ratio compared to conventional aircraft [25], at the expense of a potentially unconventional maneuverability. In this regard, in June 2020 a scaled model flight test was conducted[1]. The Dutch-roll was found to be “wobbling”, and the longitudinal handling qualities at high angles of attack were considered questionable.

This research 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;
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 critically reviewed. By means of the off-line analysis, it is possible to determine how the aircraft is expected to respond during relevant maneuvers of longitudinal 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 prediction of the 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 accepted 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

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

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 [13] is used.

This paper is structured as follows. First, 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, which includes aircraft geometry and aerodynamic model generation. The flight control system is then introduced, which includes an explanation of the two control laws considered in this study – Direct Law and Pitch Rate Command. Control allocation and engine control are here explained as well. Next, a summary of the preliminary results follows from the off-line analysis of the Flying-V, which sets the basis for the discussion of the result of the experiments. Then the experiments are described, including a thorough description of setup and rationale and a presentation of the results. Finally, a discussion of the results and their significance for the Flying-V project is given, followed by some short conclusions.

II. BACKGROUND

A. The Flying-V

TU Delft, KLM and Airbus have been focusing on the realization of the Flying-V ([28], [30], [4], [24], [25], [32], [9]) since the first idea of Justus Benad in 2015 [3].

The aerodynamic model was first studied by Faggiano [9], 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 [28], who worked on aerodynamic model identification from wind tunnel experiments.

In collaboration with Airbus, Cappuyns [30] computed a range of locations for the center of gravity based on the longitudinal handling qualities which is narrower compared to a conventional aircraft.

Palermo [24] and Pascual [25] worked on a 4.6% scaled model of the Flying-V, with 3.06 m wing span, 2.76 m length and 22.5 kg 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 [31] did in his research on Flying-V system modelling and control.

Rob Viet [32] also worked on the 4.6% scaled model. He identified the optimal position of the center of gravity at 1.365 m behind the nose, stall speed of 14.8 m/s (again, for the 4.6% scale model) 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).

Pascual [25] 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. The position of the engines in the model used for this research 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 [6]. 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": (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 Mean of Compliance AMC-20" [2] and the corresponding FAA "Flight Test Guide for Certification of FAR-25 Airplanes" [8] 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 1.5 g and pushover to 0.5 g 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)

From this list, (1) and (2) (climb and pull-up performance) have been previously observed as critical by Cappuyns [30].

Maneuver (3) is relevant due to the outcome of the 2020 scaled model flight, where potentially poor handling qualities were observed and the landing failed.

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 optimal 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 C" by the American Department of Defense [5].

It is safe to assume that the Flying-V might 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). 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 [14], then revised in 1986 [13]. 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, [14], 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, [13], p. 1). Today, their work is commonly considered the state-of-the-art 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 [7], or Humphreys-Jennings, Lappas and Mihai Sovar [16]), 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 [11], Stoliker [29], Field and Rossitto [10]).

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 [16, 23, 15]
- Short period damping ratio [21, 16, 23, 15]
- Control Anticipation Parameter (CAP) [10, 21, 16, 23, 1]
- Bandwidth criteria [10, 21, 23]
- Gibson dropback criterion [10, 21, 23]

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

- trim conditions (elevons deflection and angle of attack);
- impact of the Pitch Rate Command controller on the handling qualities;
- compliance with the certification requirements;
- relevance of the preliminary analysis.

This preliminary assessment needs to be thereafter validated and expanded by human-in-the-loop simulations, in which pilots give specific feedback on the handling qualities according to their opinion. This feedback is normally collected in the form of rating, 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 [14, 13]. 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 sole aircraft.

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' research [30]. It is motivated by the findings summarized in the Background section, with the addition of the engines positioned as proposed by Pascual [25].

The configuration chosen for this research is shown in Figure 1; the control surfaces configuration is displayed in Figure 2; and the design parameters are given in Table I. 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 (see Figure 2), 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 $\tau_{act} = 0.1\,s$ and $\tau_{eng} = 5\,s$, respectively, and rate limiters equal to $l_{act} = 25\,deg/s$ and $l_{eng} = 38\,kN/s$, 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 [25]).

TABLE I
DESIGN PARAMETERS FOR FLYING-V CONCEPTUAL DESIGN.
FROM CAPPUYNS, (2019) [30]

Parameter	Value	Unit
Length	[redacted]	m
Wingspan	[redacted]	m
Height	[redacted]	m
Pax	[redacted]	-
Fuel Capacity	[redacted]	l
Cargo Capacity	[redacted]	m^3
Design Mach number	[redacted]	-
Cruise altitude	[redacted]	ft

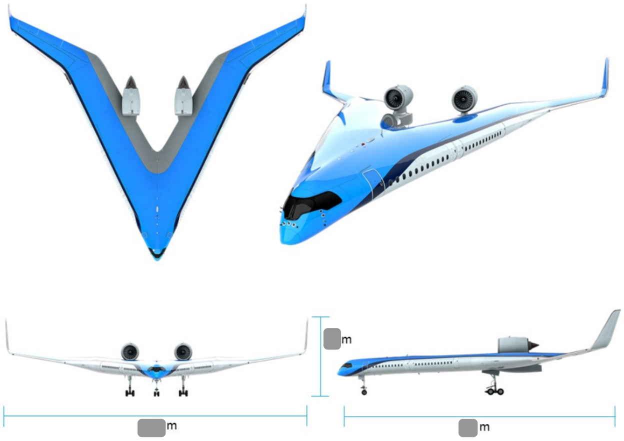

Fig. 1. Flying-V, three view renders adopted from TU Delft; "Flying-V, flying long distances energy-efficiently", https://www.tudelft.nl/en/ae/flying-v/

In order to focus only 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.

B. Aerodynamics

In this section the generation and the 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 research. This aerodynamic model was generated through the ODILILA software (see, for example, J. Benad [3]), an Airbus proprietary tool for Computational Fluid Dynamics (CFD). The software is based on the Vortex Lattice Method [17].

The validity of this model should be hereby discussed. 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 research 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 research 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 properties translate into the 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 this research.
- 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 research, 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 response of an aircraft to pilot inputs can be manipulated by means of a Control Augmentation System (CAS), which enhances and improves tracking and flying capabilities of the aircraft. In this research, the piloted simulations will also serve to explore the potential of an augmentation system to improve the HQ of the Flying-V.

During the experiments of this research, a CAS was tested to get some insights on the potential impact on the HQ of the Flying-V. It is not in the scope of this research to optimize the control system, but rather to explore the possibility to

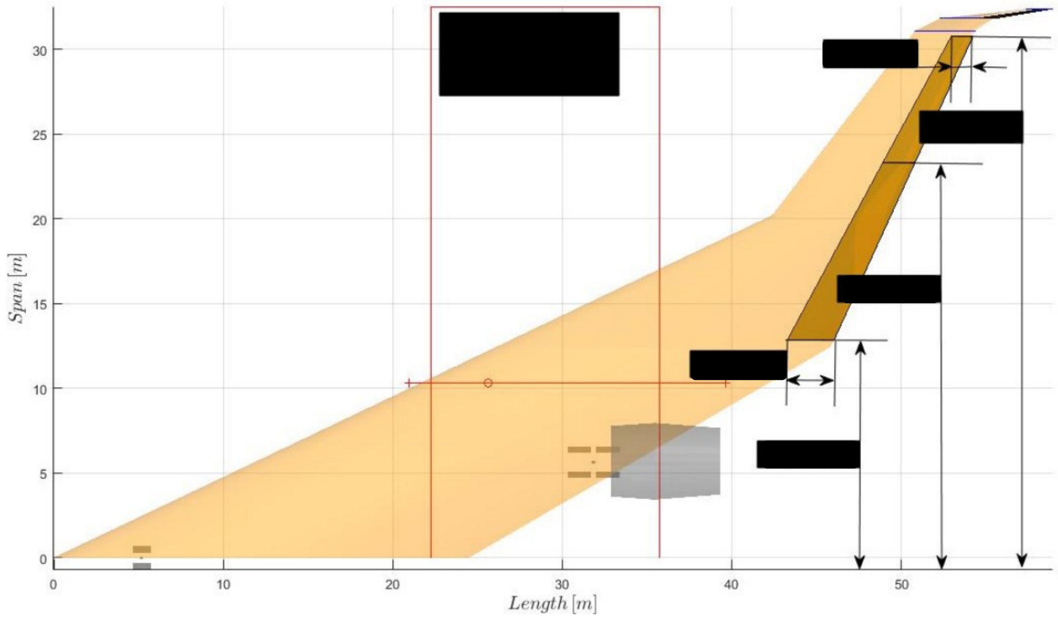

Fig. 2. Flying-V elevons dimensions. From Cappuyns, (2019) [30]

design a CAS 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 [33], where an automatic and efficient way to design a Flight Control System for Flying Wings is researched.

The next sections explains the Control Allocation approach, followed by the design of the two control laws that were studied for the experiments of this research – Direct Law and Pitch Rate Command – and an explanation of 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, the idea is 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 this research; 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 a simple Direct Law. With this mode 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 position of the stick is moved to the deflection needed for trim in each flight condition. 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.

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 control system and pilots are generally used to it.

The block diagram of the Pitch Rate Command is shown in Figure 3, which also includes the auto-throttle loop as explained in the next paragraph. It consists of a single feedback loop where the current pitch rate is subtracted to the commanded pitch rate and multiplied through a PID controller. The pilot commands a pitch rate directly from the side-stick, and the output of the PID controller is distributed to the elevons via an allocation matrix. The PID was tuned to increase the short period frequency as much as possible without reducing damping. A number of tuning iterations were needed to make sure that the augmented system does not cause jerky motion in the aircraft due to sudden extreme elevons deflection. The final result is a system that commands very large initial elevons 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 in a high 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. The elevons allocation matrix controls all the elevons symmetrically.

In general, for a control system a distinction can be made between inner and outer control loops. Assuming that the inner-loop is tuned properly, the outer-loop determines the handling qualities, since it regulates the response type of the augmented system. Notice that, for this prototype CAS, the Pitch Rate Command consists of one single feedback loop that works both as an inner-loop and an outer-loop – it controls the actuators to track the commanded input, and it determines the response type and the handling qualities.

D. *Auto-throttle*

As will be explained more in details in the Preliminary Analysis section, the phugoid mode frequency of the Flying-V was found to be unusually close to the slow short period frequency. In order to focus on the short period response, it was assumed that an auto-throttle system is available in operational scenarios. As a consequence, 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 ($P_{engine} = 100\,kN * s^2/m$) that provides constant airspeed within the physical limits of a realistic engine. The engines allocation matrix controls the two engines symmetrically, since only longitudinal dynamics are considered.

V. HANDLING QUALITIES PRELIMINARY ANALYSIS

The theory introduced in the Background section was applied to the model explained in the System Modelling section to predict the handling qualities of the Flying-V. The experiments were then designed based on this preliminary analysis, with the purpose of maximizing the value of the piloted simulations 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 angle of attack was eliminated, cancelling the exchange between dynamic and potential energies that 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 frequency

$$\omega_{ph} = 0.135\,rad/s,$$

damping ratio

$$\zeta_{ph} = -8.92e-03$$

and time to double

$$-\frac{\ln 2}{\zeta_{ph}\omega_{ph}} = 575,6\,s,$$

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 resulted 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 4.

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 [27]) predict that the aircraft will exhibit a “very slow response, large control motion to maneuver, difficult to trim”. This prediction 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. Auto-throttle effectively separates the two modes.

3) Control Anticipation Parameter: The Control Anticipation Parameter results for three configurations (forward CG and Mach = 0.3 (green); nominal CG and Mach = 0.25 (black); aft CG and Mach = 0.2 (red), corresponding to fastest, average and slowest short period frequency) is shown in Figure 5. Notice that this assessment is based on the short period only, 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,

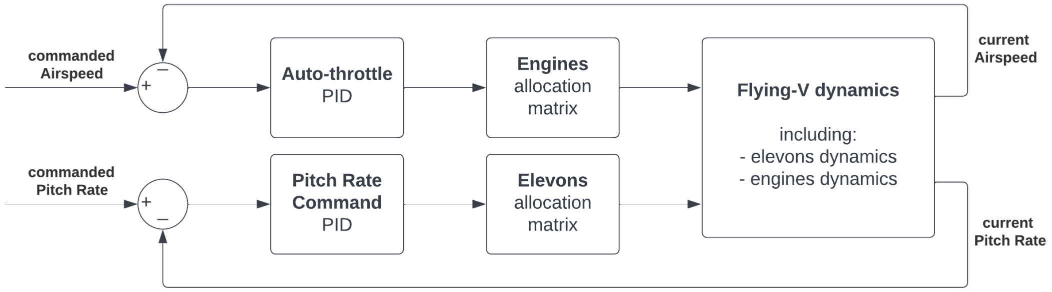

Fig. 3. Block diagram of the Control Augmentation System, including Auto-throttle (upper control loop) and Pitch Rate Command (lower control loop).

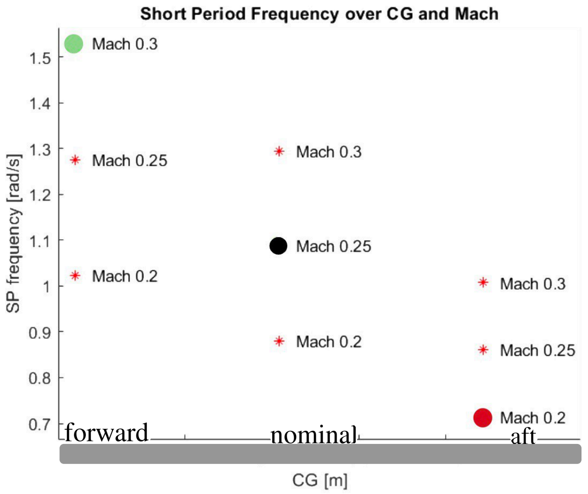

Fig. 4. Natural frequency of the short period of the Flying-V. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red).

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 Control Anticipation Parameter 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).

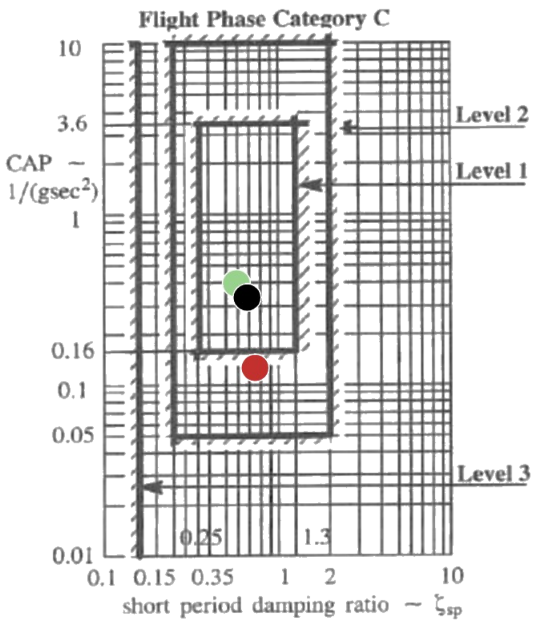

Fig. 5. Control Anticipation Parameter. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

4) Bandwidth Criteria: The Flying-V shows Level 2 HQ according to the Bandwidth criterion, as shown in Figure 6, 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 P.244.

5) Gibson Dropback criterion: According to the Dropback criterion (Figure 7), 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

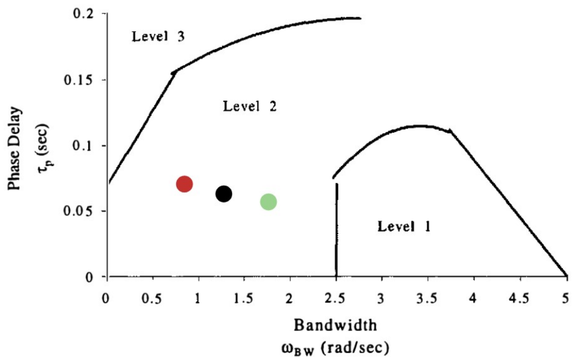

Fig. 6. Bandwidth criterion. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

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

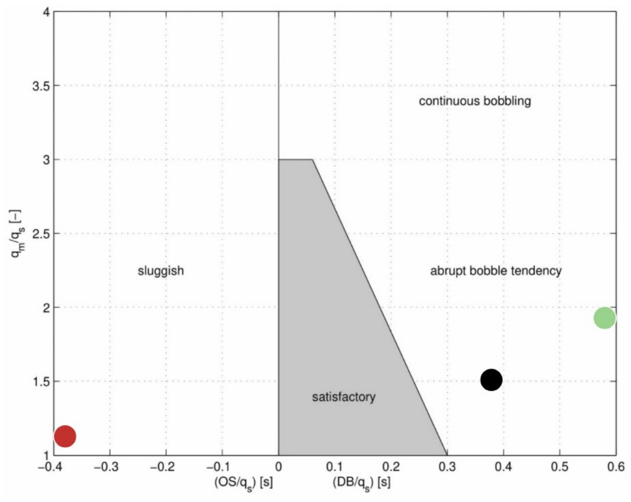

Fig. 7. Gibson dropback criterion. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red).

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 II, 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 experiments not viable with 20 degrees of maximum elevons deflection. Furthermore, 0.2 Mach airspeed, which corresponds to 133 kts, 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 and elevons effectiveness).

TABLE II
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 150 kts; 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 III a comparison is shown of damping and frequency of the short period mode between Direct Law and Pitch Rate Command.

TABLE III
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[2]
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

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

improved up to the same level, in such a way that pilots might not be able to tell two augmented configurations apart.

C. *Certification Requirements*

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

First, it is unclear whether the Flying-V provides acceptable handling qualities and good maneuverability as for EASA CS 25.143 in all the configurations. In fact, some configurations are predicted to require heavier workload from the pilot, mainly due to the bad 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 [30] 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 manoeuver (CS-25.143) is critical for the Flying-V, since [30, 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 notice that the preliminary analysis so far discussed is based on a considerable amount 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 meaningful piloted experiment, all in the perspective of providing 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 [20], and to the necessity for the pilot to focus on both longitudinal and lateral motions. Second, the elevons 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.

VI. EXPERIMENT

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 paragraph – 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.

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 $\pm 0.5\,g$ 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 sight angle from the cockpit would be a source of discomfort or danger according to the pilot.

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 kts than it is to 150 kts.

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 IV). 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 tasks.

TABLE IV
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) [12]. 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 shell around the simulator which functions as a collimating mirror.

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, [12]). It included a low-pass filter for tilt-coordination, and it was tuned specifically for these experiment in order to optimize the use of motion space during the pitch-tracking tasks. The motion filter is tuned as in Table V. Note that only the longitudinal degrees of freedom are included in the filter (x, z, θ). The reference point for cueing was set at x = -26.26 m, y= 0 m, z = -1.2075 m from the aircraft nose.

(a) Experiment setup inside SIMONA Research Simulator.

(b) Outside impression of SIMONA.

Fig. 8. SIMONA Research Simulator

A side-stick was available for longitudinal control only. The SRS is equipped with a fully electric side-stick that runs a control-loading admittance display as for 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 $k = 3\,N/deg$; with Pitch Rate Command control the control-loading system responded as a single break-out

[3] DOF - Degree Of Freedom; Ord. - filter order; K - gain; ω_n - 2^{nd} order natural frequency; ζ - damping; ω_b - 1^{st} order break frequency.

TABLE V
SRS MOTION CUEING FILTER SETTINGS[3]

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

spring system with constant $k_{bo} = 50\,N/deg$ up to $3\,N$, and a single spring with constant $k = 3\,N/deg$ 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 elevons deflection at trim; for Pitch Rate Command the side-stick neutral position would always be in the center, regardless of elevons deflection at trim. A stick-shaker with magnitude $A = 5\,N$ and frequency $\omega = 20\,Hz$ 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.

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 9 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”).

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 10. One square, $2\,deg$ wide and red, represented the “Adequate” performance of $\pm 1\,deg$ error from the desired target pitch angle, which was in the center of the square. The other square, $1\,deg$ wide and yellow, represented the “Desired” performance of $\pm 0.5\,deg$ 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”.

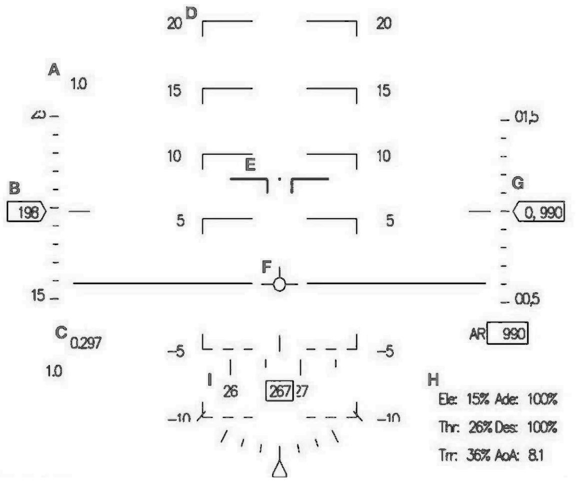

Fig. 9. Arrangement of information in the MIP.

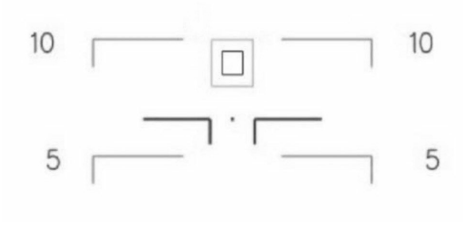

Fig. 10. MIP detail — Pitch tracking target. The larger square, yellow in the real MIP, corresponds to Adequate score; the smaller squares, red in the real MIP, corresponds to Desired score.

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, and 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 combination of large ($\sim 8\,deg$) and small ($\sim 2\,deg$) 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 $\pm 0.5\,g$, 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. Each target signals (training and measurement) lasted 90 seconds.

During the entire simulation, auto-throttle would always be engaged to let the pilots focus solely on side-stick control.

In Figure 11 an example of the 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 red and green lines define the limits for “Desired” and “Adequate” performance respectively, while the blue line represents the pitch angle of the aircraft as controlled by the pilot.

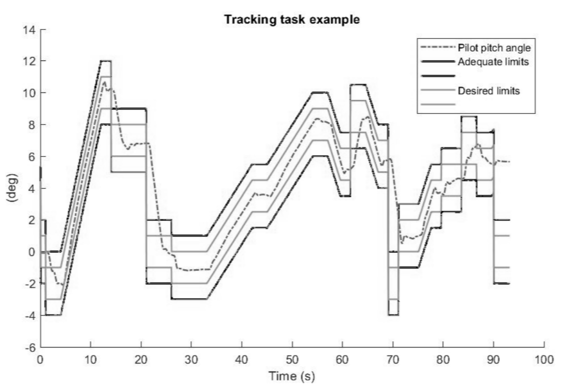

Fig. 11. Tracking task for the measurement run, delimited by the “Desired” performance limits (grey lines) and the “Adequate” performance limits (black lines). An example of pilot-controlled pitch angle is also given (dashed line).

Go-Around - The third task was the Go-Around. This task can be described in four different steps.

First, the aircraft was initialized in a $-3\,deg$ slope descent towards the runway, and the simulation was started in this trimmed conditions at 500 ft. In this phase, the pilots were simply asked to observe the flight conditions and focus on aspects such as pitch angle and sight angle during approach.

At 190 ft 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 12, 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 $2.4\,deg$).

After the pull-up, the pilots were instructed to climb up to 500 ft, keeping a rate of climb higher than or equal to 3.2%.

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

During the entire simulation, auto-throttle would always be engaged to let the pilots focus solely on side-stick control.

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 $+5\,deg$ and $-5\,deg$ capturing. This task was intended as an occasion for further discussions of the handling qualities of the Flying-V, in order to confirm and integrate the results of the Pitch Tracking task. For this purpose, the tempo of capturing was free, in the sense that the pilots were free to chose their pace for the alternation between the two target pitch angles. This allowed for more freedom for the pilot to form his opinion on the handling qualities of the aircraft compared to the pitch tracking task. The task would be repeated for different configurations for about just 30 seconds each in order to encourage comparative feedback between the handling qualities at different center of gravity position, speed, maximum elevons deflection and control augmentation.

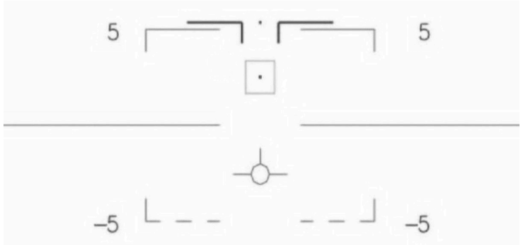

Fig. 12. MIP detail – Pull-up target. The dot in the center of the square, yellow in the real MIP, corresponds to a 3.2% rate of climb.

4) Independent Variables: Following the objectives of this experiment, the independent variables were four:

- The center of gravity would span three positions, namely forward, nominal, and aft;
- 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)
- the deflection limit of each of the four elevons was set to two alternative values, namely:
  - 20 deg
  - 30 deg
- 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 aircraft configurations was considered by combining the four independent measures just introduced (3 center of gravity positions, 2 initial speeds, 2 maximum elevons deflection and 2 flight control laws), yielding 24 different configurations.

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

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 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 VI.

TABLE VI
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 used was specifically designed for this experiment. The modelling approach was as explained in Section III.

7) Dependent Measures: **Pitch Tracking -** Three objective measures were recorded for the pitch tracking task:

- Adequate score – the percentage of time that the pilot managed to keep the aircraft pitch attitude between $\pm 1\,deg$ from the target pitch out of the 90 seconds of each run. It was considered sufficient to score 68%, and the pilots were not encouraged to score higher.
  Adequate score is associated with a looser tracking activity, requiring 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 $\pm 0.5\,deg$ from the target pitch out of the 90 seconds of each run. It was considered sufficient to score68%, and the pilots were not encouraged to score higher.
  Desired score is associated with a higher gain tracking activity, requiring moderate to high precision from the pilot.
- Side-stick and elevons saturation – the number of times and the amount of time the pilot hits the side-stick stops (two separate measures). This was measured in order to investigate which configurations are more prone to providing insufficient control authority, and to validate the comments of the pilots regarding control saturation.

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 [13].
- Pilot comments – qualitative assessment from the pilot on the handling qualities of the Flying-V relatively to the specific tracking task. This qualitative feedback is complementary to the analysis of the Cooper-Harper scale rating explained above.
  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)
  - Elevons maximum deflection
  - 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 190 ft, 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 is 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 altogether to form a synthetic 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.

VII. RESULTS

The results of the experiments 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 elevons deflection, in degrees;
- DL (Direct Law), PRC (Pith Rate Command).

A. Pitch Tracking

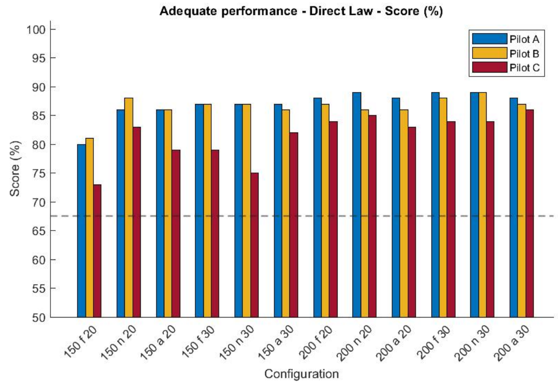

Fig. 13. Adequate performance score – Direct Law.

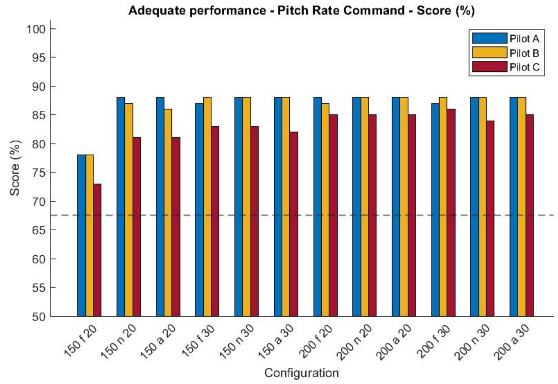

Fig. 14. Desired performance score – Pitch Rate Command.

1) Adequate score: The “Adequate” performance scores for the Pitch Tracking task are displayed in Figure 13 (Direct Law) and Figure 14 (Pitch Rate Command).

At 150 kts, 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 kts and changing the flight control system from Direct Law to Pitch Rate Command, however there were too few participants to exclude learning-curve effects.

Overall, the 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 $\pm 1\,deg$ precision. Pitch Rate Command was not essential to attain adequate performance, and it had a limited impact on the scores (particularly at 200 kts).

Other than at 150 kts 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.

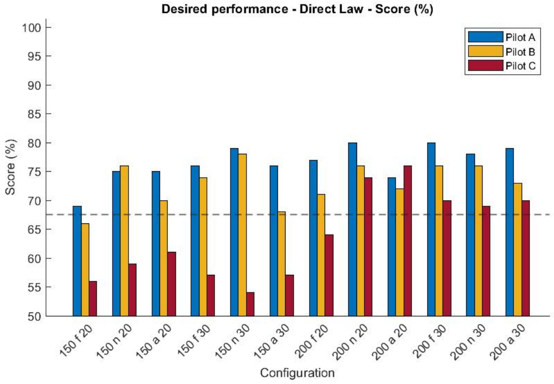

Fig. 15. Adequate performance score − Direct Law.

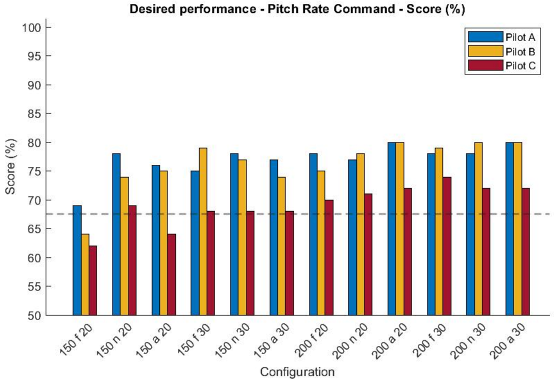

Fig. 16. Desired performance score − Pitch Rate Command.

2) Desired score: The "Desired" performance scores are displayed in Figure 15 (Direct Law) and Figure 16 (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 kts.

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

With Pitch Rate Command, Pilot A passed all the configurations; Pilot B failed 1 out of 12 configurations (again 150 kts, forward CG, 20 degrees of elevons maximum deflection); Pilot C failed 2 out of 12 configurations (150 kts, forward CG, 20 degrees of elevons maximum deflection; and 150 kts, aft CG, 20 degrees of elevons maximum deflection). The improvement identified at 200 kts compared to 150 kts 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, the pilots seemed to struggle significantly more to achieve a satisfactory score in the Desired Performance compared to the Adequate Performance − controlling the aircraft with a precision down to $\pm 0.5\,deg$ was more challenging than $\pm 1\,deg$.

3) Side-stick saturation: The number of times and the amount of time the pilots hit the side-stick stops are shown in Table VII. The amount of time is given as a percentage of the task time (90 seconds). The configurations are listed according to the same symbology used for the figures. Note that, at 150 kts with forward CG, Pilot C hit the side-stick stops both with 20 and 30 degrees of maximum elevons deflection, but the saturation time in the latter case was almost half of the former case.

TABLE VII
SIDE-STICK SATURATION
NUMBER OF STOP-HITS (n) AND SATURATION TIME PERCENTAGE (%)

	Pilot A		Pilot B		Pilot C	
	n	%	n	%	n	%
DL 150 f 20	9	15.3	10	14.5	24	19.0
DL 150 f 30	0	0	0	0	10	10
DL 150 n 20	0	0	0	0	7	2.6
PRC 150 f 20	1	0.4	7	10.3	3	6.8
other configs.	≤ 3	≤ 1	≤ 3	≤ 1	≤ 3	≤ 1

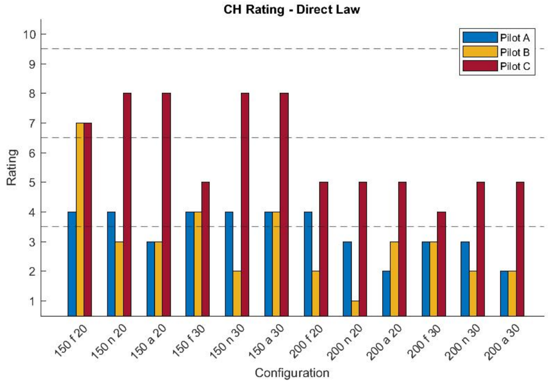

Fig. 17. Handling Qualities Rating − Direct Law.

4) Cooper-Harper scale rating: The Cooper-Harper scale rating is shown in Figure 17 (Direct Law) and Figure 18 (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 kts to be overall

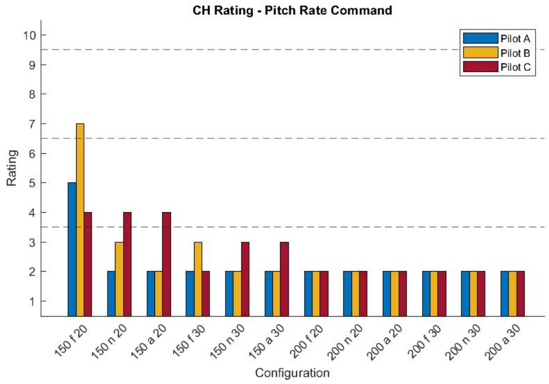

Fig. 18. Handling Qualities Rating – Pitch Rate Command.

not satisfactory without improvement, while at 200 kts the handling qualities got an overall satisfactory rating; Pilot B deemed the first configuration to require non-tolerable pilot workload (150 kts, forward CG, 20 degrees maximum elevons deflection), but called satisfactory without improvement most of the other configurations (9/12 configurations), those at 200 kts being considered the best; Pilot C considered the Direct Law handling qualities of the Flying-V to be not satisfactory overall, requiring un-tolerable workload at 150 kts and warranting improvements at 200 kts.

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 kts with forward CG and 20 degrees of maximum elevons deflection, and Pilot A did not rate this configuration better than the other configurations.

With Pitch Rate Command, the ratings were better overall. All the pilots agreed that the first configuration (150 kts, forward CG, 20 degrees maximum elevons 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 kts, nominal and aft CG, 20 degrees maximum elevons deflection). All the other configurations, instead, were called satisfactory without improvement by all the three pilots. All the configurations at 200 kts were given a rating of 2 by all the pilots.

The CG position had an even smaller impact on the handling qualities than with Direct Law – other than the first configuration (150 kts, forward CG, 20 degrees maximum elevons deflection), in fact, the CG did not have a clear impact on the handling qualities.

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 kts.

5) 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 is actually too sluggish, and that 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 kts, forward CG, 20 degrees maximum elevons deflection) received the worst rating overall. All pilots agreed that the reason for such rating 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 kts compared to 150 kts. 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 kts and with Direct Law.
- **Elevons maximum deflection -** As mentioned, 20 degrees of elevons maximum deflection were not considered enough for 150 kts 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 kts and forward CG, 30

degrees were appreciated for the increased authority but they were not considered necessary. In fact, with Direct Law at 200 kts Pilots A and C stated that 30 degrees of maximum 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 elevons deflection with Direct Law – a scaling is used which is proportional to the maximum allowed deflection. In other words, any amount of side-stick input commands 50% larger elevons deflection when the maximum is 30 degrees compared to 20 degrees.

- **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 a possibly 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 kts, and only one correction at 200 kts.

  Pilot C described his approach as more "impulse-like", made of many full-stick inputs. He believed that the aft CG made it more difficult for him to use this approach, and 200 kts 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 Cooper-Harper scale (as they did, in particular, for Pitch Rate Command at 200 kts), they all 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.

6) Time logs: All the data from the runs have been stored in time logs, as explained in Section VI. For discussion purposes, it turns 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 20, the time history of Pilot C pitch angle is displayed for the same configuration (nominal CG, 20 degrees of maximum deflection, 150 kts) and the two different control laws, Direct Law (blue line) and Pitch Rate Command (purple line). It can be seen that augmentation reduced the tendency to oscillations and their amplitude.

Figure 19 shows flight path angle and pitch angle during a tracking task (Pilot A, 150 kts, forward CG, 20 degrees of maximum elevons deflection). 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.

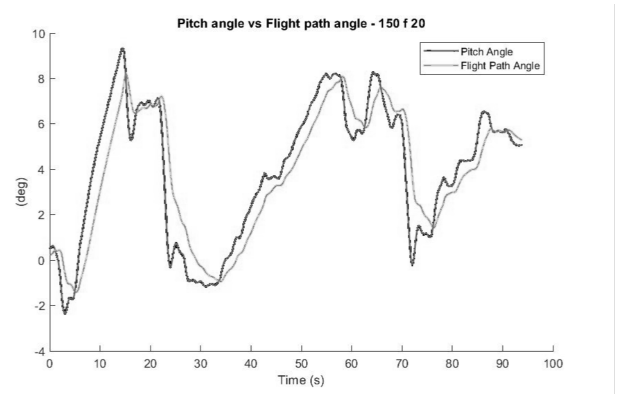

Fig. 19. Flight path angle (grey) lag behind Pitch angle (black). Tracking task. 150 kts, forward CG, 20 degrees of maximum deflection.

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 21; the time between the "go-around" call and the instant when the climb rate is above 3.2% is shown in Figure 22. Notice that the configurations considered for the go-around maneuver were all with Direct Law and 20 degrees of maximum elevons deflection, 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

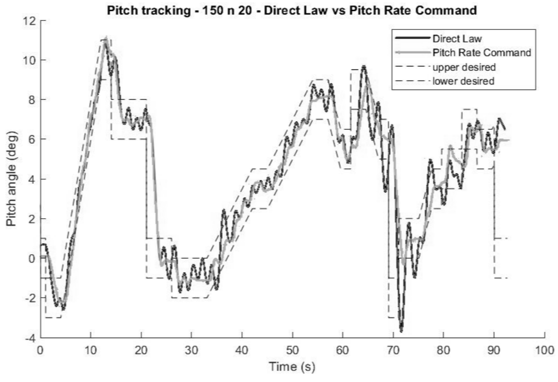

Fig. 20. PIO tendency comparison: Direct Law (black) and Pitch Rate Command (grey). Tracking task. 150 kts, nominal CG, 20 degrees of maximum deflection.

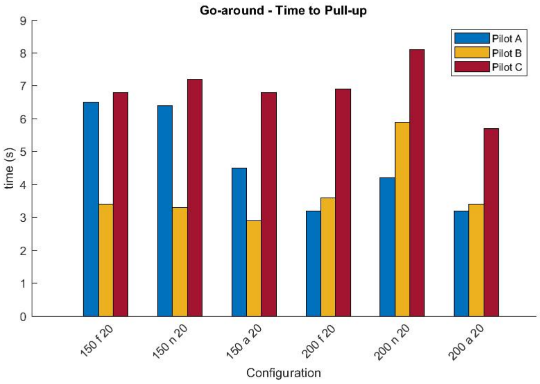

Fig. 22. Go-around - Time to achieve 3.2% rate of climb.

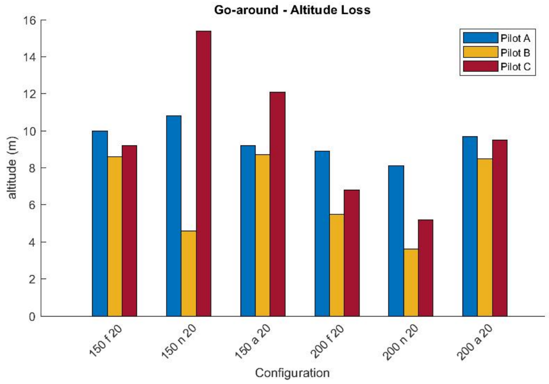

Fig. 21. Go-around — Altitude Loss.

maximum of 8.1 s. It was not possible to identify trends in 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 were 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 degrees 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 standard 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 potential 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 kts, 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 unusual.
- **Control saturation -** The control saturation issue that was evident in the pitch tracking task, in particular for the configuration with 150 kts, forward CG, 20 degrees maximum elevons deflection, 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, 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 instrumental landing might be required, since it is too difficult to control the vertical velocity of the aircraft based on 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 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 kts, the handling qualities resulted 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 kts). 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. Despite the sluggishness, in fact, 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 kts range. This research 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 kts range (closer to 200 kts than it is to 150).

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

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-A6). 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 kts with forward CG, where 20 degrees of deflection were considered insufficient by all pilots. In this configuration, the side-stick stops were hit the most times and the longest time by all pilots, both with Direct Law and Pitch Rate Command. 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 kts, since at 200 kts the elevons were never saturated; or by avoiding more forward positions of the CG, since with aft CG the elevons were never saturated.

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 [26] 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 kts in order to collect insights for future design iterations. This speed was decided in comparison with reference aircraft, such as the A350[4] for which the landing speed is 155 kts, 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 elevons deflection is 30 compared to 20 degrees. At faster configurations in particular, but not only, 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 elevons deflection and with optimal control allocation.

B. Control Augmentation

Control augmentation proved very effective in improving the handling qualities. All the configurations received a higher 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 at fighting PIO tendencies, reducing the workload needed to hold on the target attitude. For example, the smaller tendency to PIO is visible in Figure 20, Section VII. 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 [22].

On the other hand, the main shortcoming of the Pitch Rate Control law were 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 20 again, that Direct Law allowed for larger pitch rate commands. In fact, the limit to the pitch rate controller were 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. 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 researched 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 kts. 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

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

runway, and it is difficult to determine the current attitude of the aircraft based on the visuals. The issues arises 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 kts the sight angle was better than at 150 kts; pilots reported that it was still 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 15.4 m) and flight path angle does not lag behind pitch angle in an unusual way, as was shown in Figure 19 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 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/forward range, since this grants larger control authority and better sight angle at the expense of minor handling qualities deterioration;
- the design landing speed will be in the range of 175 to 200 kts;
- larger control effectiveness will be granted with better control surfaces.

Alternatively, in case these recommendations are not followed, most of the problems might be addressed with adjustments, such as unconventional cockpits to improve the sight angle; high-lift devices to improve C_{l_α}, 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 [30]. The risk of 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 part 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 in consideration that more aft CG positions provide slightly worse handling qualities, but that they come with significant improvements in terms of sight angle and control authority.

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

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 can be difficult 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 PIO tendency. It is recommended that in future works specific approaches to PIO assessment are considered.

Finally, it should be noted that the phugoid mode was essentially excluded by this analysis. The phugoid should not be a source of issues since the damping 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.

IX. CONCLUSIONS

The piloted simulations, supported by the analytical preliminary assessment, showed 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 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. 20 degrees of deflection proved sufficient, but 30 degrees were required for safe maneuvering at slow speed with forward CG. The Pitch Rate Command controller proved very effective at improving the handling qualities overall, but it does not solve the control saturation problem. The certification requirements related to the go-around performance should be satisfied, but, considering that the landing speed is expected to be lower than 0.3 Mach, new concerns related to controllability and safety emerged. In the future, a more accurate aircraft model should be used to confirm these results.

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Part II - Book of Appendices

Contents

A

Model Implementation

The implementation of the raw aerodynamic JSON file into viable data for the simulations is explained in this appendix.

Airbus provided the aerodynamic model data in a JSON file structure. This was first analysed, and minor asymmetrical anomalies were corrected. Then, the model was improved with the zero-lift drag coefficient explained before.

In order to read the data and implement them in the equations of motion of the aircraft, a JSON interpreter was used to convert the JSON structure into an array of numbers. Then, a custom interpolator was design, based on a bilinear interpolation method.

The full implementation of the equation of motions follows these steps:

1. First, a section of the JSON file is selected based on the chosen center of gravity (CG) position, and turned into an array of numbers.

2. At each time step, a request is made by the simulation software to the interpolation algorithm to return the aerodynamic coefficients based on the current state of the aircraft (angle of attack, airspeed, pitch rate, ...).

3. Each aerodynamic coefficient is obtained as the weighted sum of the coefficient derivatives. To compute these derivatives, an algorithm selects the two set-points in the array that are closest to the current state of the aircraft, in terms of airspeed and angle of attack (e.g., for the lift coefficient derivative over pitch rate (q), $C_{l_q}(V_0, \alpha_0)$, where α_0 is current pitch rate and V_0 is current airspeed, the algorithm selects the four points $C_{l_q}(V_1, \alpha_1)$, $C_{l_q}(V_1, \alpha_2)$, $C_{l_q}(V_2, \alpha_1)$, $C_{l_q}(V_2, \alpha_2)$, where V_1, V_2 and α_1, α_2 are the two nearest known data set-points to V_0 and α. When the current airspeed or angle of attack fall out of the limits of the aerodynamic data ([-5,20] degrees for the angle of attack, [0.2,0.3] mach for airspeed), the interpolation set-points are extrapolated from the available data.

4. A bilinear interpolation is carried out, according to the following formula:

   $$f(V,\alpha) = \frac{1}{(V_2-V_1)(\alpha_2-\alpha_1)} \begin{bmatrix} V_2 - V & V - V_1 \end{bmatrix} * \begin{bmatrix} f(Q_{11}) & f(Q_{12}) \\ f(Q_{21}) & f(Q_{22}) \end{bmatrix} \begin{bmatrix} \alpha_2 - \alpha \\ \alpha - \alpha_1 \end{bmatrix} \tag{A.1}$$

   where $f(V,\alpha)$ is the coefficient derivative, V is airspeed, α is angle of attack, and Q_{ij} are the coefficient derivatives at the nearest V_1, V_2 and α_1, α_2 set-points.

5. The six aerodynamic coefficient are computed as a weighted sum of the derivatives multiplied by their derivative variable. C_l, for instance, is computed as follows:

$$\begin{aligned} C_l = C_{l_0}(\alpha, V) + \beta * C_{l_\beta}(\alpha, V) + \ldots \\ p^* * C_{l_{p^*}}(\alpha, V) + q^* * C_{l_{q^*}}(\alpha, V) + \ldots \\ r^* * C_{l_{r^*}}(\alpha, V) + \delta_{c1} * C_{l_{\delta_{c1}}}(\alpha, V) + \ldots \\ \delta_{c2} * C_{l_{\delta_{c2}}}(\alpha, V) + \delta_{c3} * C_{l_{\delta_{c3}}}(\alpha, V) + \ldots \\ \delta_{c4} * C_{l_{\delta_{c4}}}(\alpha, V) + \delta_{c5} * C_{l_{\delta_{c5}}}(\alpha, V) + \ldots \\ \delta_{c6} * C_{l_{\delta_{c6}}}(\alpha, V). \end{aligned} \tag{A.2}$$

where $alpha$ is angle of attack, V is airspeed, β is side slip, p^* is normalized roll rate, q^* is normalized pitch rate, r^* is normalized yaw rate, δ_{cn} is deflection angle of the control surface number n, according to the geometry explained before.

6. Finally, the coefficient were used to write the conventional equations of motion of the aircraft.

In DUECA (Delft University Environment for Communication and Activation), the procedure to run a simulation using this interpolation method is the following one:

1. First, the desired aircraft configuration is selected from the ECI (Experiment Control Interface), which is the interface generated by the ECI module;
2. the ECI sends the configuration selection to the Vehicle Dynamics module;
3. this creates an instance of a RigidBody object with the selected configuration;
4. at initialization, the RigidBody object calls the JSON reader script to create a fast interpolation matrix from the aerodynamic data - this matrix is specific for the flight condition, so that only the necessary data are scanned through during the interpolation, and computation time is reduced;
5. then, during run time, at each simulation time step the Vehicle Dynamics module reads the pilot commanded inputs and processes them through the RigidBody object, which calls the interpolation method described before onto the interpolation matrix generated during initialization;
6. finally, with the interpolated data, the RigidBody object advances the equations of motion and return the new aircraft state for the Vehicle Dynamics module.

B

Trim states

In this appendix, the complete tables with the states of the aircraft in trimmed level flight and approach (-3 degrees glide slope) are presented.

B.1. Level flight

Level Flight @ 0.2 Mach	forward CG	nominal CG	aft CG
U (m/s^2)	64.4109	65.0057	65.5573
W (m/s^2)	23.6050	21.9140	20.2041
theta (deg)	20.1266	18.6294	17.1288
deflection (deg)	-21.6891	-13.2167	-4.6463
thrust (N)	1.035e+05	1.034e+05	1.025e+05

Level Flight @ 0.225 Mach	forward CG	nominal CG	aft CG
U (m/s^2)	74.2970	74.7050	75.0833
W (m/s^2)	20.8791	19.3684	17.8461
theta (deg)	15.6966	14.5348	13.3702
deflection (deg)	-16.4717	-9.7471	-2.9516
thrust (N)	1.053e+05	1.053e+05	1.025e+05

Level Flight @ 0.25 Mach	forward CG	nominal CG	aft CG
U (m/s^2)	83.6875	83.9794	84.2512
W (m/s^2)	18.6940	17.3355	15.9624
theta (deg)	12.5919	11.6635	10.7282
deflection (deg)	-12.8805	-7.4141	-1.8899
thrust (N)	1.124e+05	1.123e+05	1.025e+05

Level Flight @ 0.275 Mach	forward CG	nominal CG	aft CG
U (m/s^2)	92.7969	93.0135	93.2126
W (m/s^2)	16.9097	15.6747	14.4435
theta (deg)	10.3273	9.5656	8.8080
deflection (deg)	-10.2587	-5.7497	-1.2321
thrust (N)	1.232e+05	1.232e+05	1.025e+05

Level Flight @ 0.3 Mach		**forward CG**	**nominal CG**	**aft CG**
	U (m/s^2)	101.7361	101.9003	102.0533
	W (m/s^2)	15.4329	14.3087	13.1735
	theta (deg)	8.6258	7.9931	7.3553
	deflection (deg)	-8.3479	-4.5762	-0.7656
	thrust (N)	1.387e+05	1.386e+05	1.025e+05

B.2. Approach

Approach @ 0.2 Mach		**forward CG**	**nominal CG**	**aft CG**
	U (m/s^2)	64.2758	64.9026	65.4820
	W (m/s^2)	23.9706	22.2177	20.4469
	theta (deg)	17.4522	15.8973	14.3411
	deflection (deg)	-21.8106	-13.1601	-4.4383
	thrust (N)	4.768e+04	4.804e+04	4.737e+04

Approach @ 0.225 Mach		**forward CG**	**nominal CG**	**aft CG**
	U (m/s^2)	74.2321	74.6569	75.0482
	W (m/s^2)	21.1090	19.5536	17.9931
	theta (deg)	12.8739	11.6768	10.4824
	deflection (deg)	-16.4742	-9.6413	-2.7590
	thrust (N)	5.012e+04	5.027e+04	4.979e+04

Approach @ 0.25 Mach		**forward CG**	**nominal CG**	**aft CG**
	U (m/s^2)	83.6542	83.9552	84.2341
	W (m/s^2)	18.8431	17.4528	16.0528
	theta (deg)	9.6940	8.7435	7.7897
	deflection (deg)	-12.8330	-7.3000	-1.7212
	thrust (N)	5.756e+04	5.754e+04	5.678e+04

Approach @ 0.275 Mach		**forward CG**	**nominal CG**	**aft CG**
	U (m/s^2)	92.7793	93.0019	93.2044
	W (m/s^2)	17.0069	15.7483	14.4974
	theta (deg)	7.3873	6.6109	5.8412
	deflection (deg)	-10.1922	-5.6373	-1.0835
	thrust (N)	6.850e+04	6.843e+04	6.856e+04

Approach @ 0.3 Mach		**forward CG**	**nominal CG**	**aft CG**
	U (m/s^2)	101.7274	101.8939	102.0493
	W (m/s^2)	15.4954	14.3551	13.2049
	theta (deg)	5.6609	5.0192	4.3730
	deflection (deg)	-8.2736	-4.4732	-0.6378
	thrust (N)	8.396e+04	8.389e+04	8.316e+04

C

Motion Cueing

This appendix contains an explanation of the procedure used to tune the SIMONA Research Simulator (SRS) motion cueing filter. For the details on how motion cueing is implemented on the SRS one should refer to ”The SIMONA Research Simulator’s Motion Software”, by ir. O. Stroosma.

For this research, a washout motion filter was used to compute the motion of the simulator from the simulated aircraft motion. The filter was based on an updated version of the filter developed in the context of handling qualities experiment in collaboration with Boeing (see Gouverneur, [13]), and it includes a low-pass filter for tilt-coordination. It require simulation-specific tuning for the parameters of Table C.1, where the following terms are used:

- DOF - Degree Of Freedom;
- Ord. - filter order;
- K - gain;
- ω_n - 2^{nd} order natural frequency;
- ζ - damping;
- ω_β - 1^{st} order break frequency.

Table C.1: SRS motion cueing filter settings.

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

First, certain parameters can be set to zero:

- all the parameters related to lateral directional motion (y, ϕ, ψ), since this study only includes longitudinal motion;
- ω_b for all filters other than z, since this is the only 3^{rd} order filter;
- ω_n and ζ for all the low-pass filters other than x, since this is the only tilt-coordination filter used.

Based on previous experience using the SRS, the following assumptions are made:

- the x and θ filters should be tuned similarly;
- the z natural frequency ω_n should be about 2.0 rad/s;
- all the damping ratios ζ should be set to 0.7;
- the break frequency ω_b of the z high pass filter should be set to 0.2;
- frequency of the tilt-coordination low-pass filter ω_n should be twice $2 * \omega_n$.

Four parameters remain to be tuned: the x gain K and natural frequency ω_n, and the z gain K and ω_n. The criterion for tuning is to obtain motion cues which resemble as closely as possible the real cues. For this, the gain should be as close to 1 as possible, and the high-pass filter should be set as low as possible to capture more motion. The constraint are the physical limits of the simulator - exceeding the motion space of the simulator should be avoided for obvious reasons. For optimal tuning in this sense, the Gouverneur approach proposes to evaluate different filter tuning on a number of flight profiles. This was performed as in the following procedure:

1. Six flight profiles were generated, representing different pitch tracking tasks and pilot aggressiveness. Both Direct Law and Pitch Rate Command were used.
2. The washout filter was applied to each flight profile iteratively, changing the four filter parameters at each iteration.
3. The generated motion based displacement was compared to the available motion space, in order to generate six figures, such as Figure C.1, where the filters that result in a motion within the motion space limits are separated from those that exceed the limits. Every dot in the figure represents a different filter, located at the corresponding gain and phase shift for 1 rad/s motions that result from applying that filter. In this figure, moving right in the plot the dots represent filters with higher x gain, while moving up in the plot the dots represent filter with higher x natural frequencies. The z parameters in this case are set to $K = 0.5$ and $\omega_n = 2.2$, which were computed following the same procedure.
4. Over-imposing the outcome for the six flight profiles, Figure C.2 is obtained, where the lines separate the acceptable filters from those that exceed the motion space.
5. Based on Figure C.2, it was chosen to proceed considering only the filters that fall on the left of the lines, focusing in particular on those more to the down-right part of the figure which represent more realistic filters (higher gain and higher bandwidth).

This procedure yielded a selected number of parameters. These were tested manually on the simulation software, checking that the motion space would not be exceeded during any maneuver. Since the maneuvers performed in this study involve high pitch-up motions and vertical accelerations, it was eventually decided to tune the filter with the configuration shown in red in Figure C.2, which corresponds to the parameters of Table C.1. Note that, after testing, it was considered viable to lower the θ natural frequency to $\omega_n = 1.4 rad/s$.

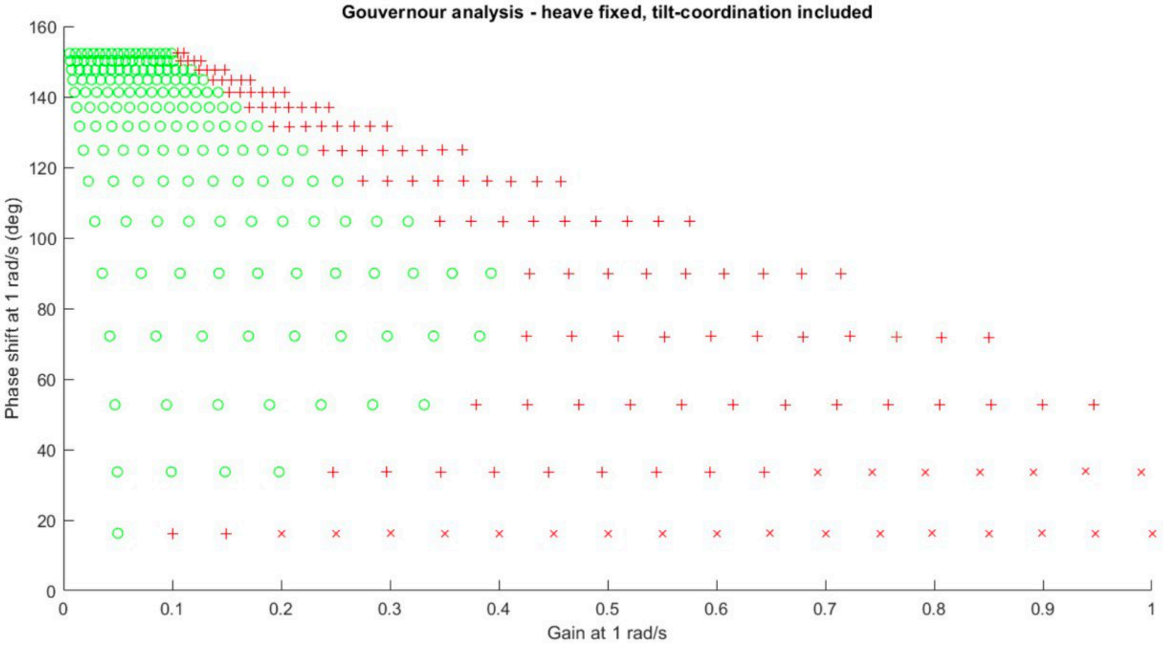


Figure C.1: Example of Gouverneur evaluation of one flight profile. Green circles correspond to acceptable filters; red '+' to filters that exceed the displacement limits; ref 'x' to filters that exceed the speed limits.

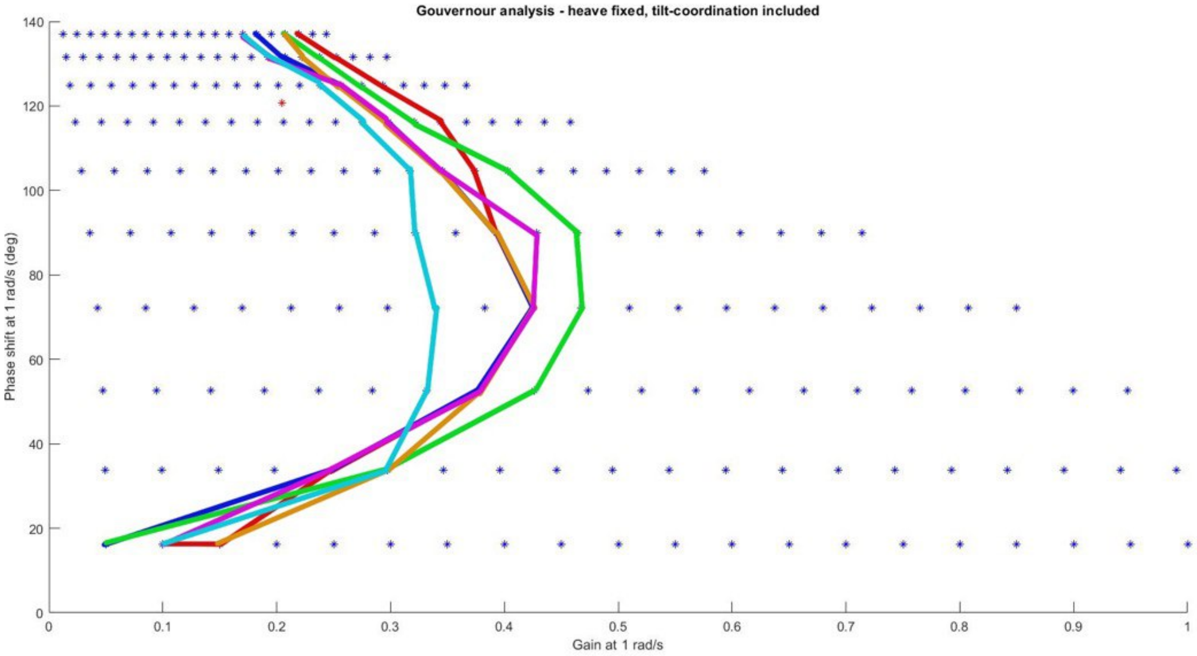


Figure C.2: Result of the six flight profiles evaluations. The red dot corresponds to the filter of Table C.1.

D

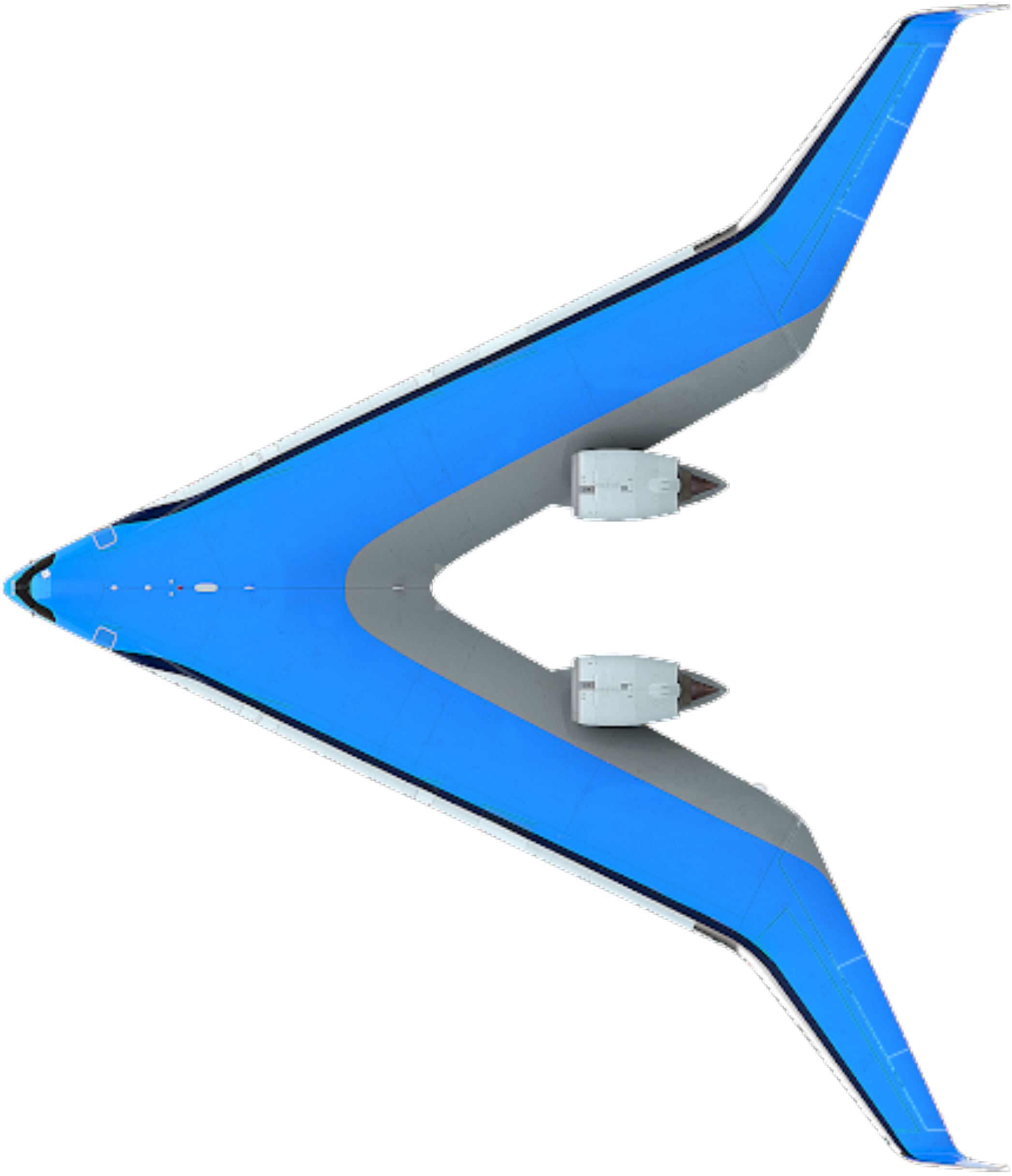
Pilot Briefing

A ”Pilot Briefing” document was prepared to introduce the pilots to this research and to the piloted experiments. It includes a short presentation of the context of the Flying-V project, an overview of goals and tasks of the experiment, a presentation of the SIMONA Research Simulator and some useful information. A copy of the Cooper-Harper handling qualities rating scale is also attached to the document. The Pilot Briefing is included in the following pages.

Pilot evaluation of low-speed longitudinal handling qualities of the Flying-V

Experiment Briefing

Riccardo Torelli, March 2022



1 The Flying-V

1.1 Introduction

The Flying-V is a design for a highly energy-efficient long-distance airplane. It integrates the passenger cabin, the cargo hold and the fuel tanks in the wings. It is shorter than an Airbus A350, but it has the same wingspan. Compared to the A350, its improved aerodynamic shape and reduced weight are expected to reduce fuel consumption by up to 20%.

According to earlier theoretical assessments, the longitudinal handling qualities of this v-shaped aircraft might differ from conventional aircraft.

Pilot-in-the-loop evaluations are essential to the study of handling qualities due to their subjective nature and to the complexity of the pilot-aircraft combined system. The experiments presented in this briefing are part of an on-going research on the longitudinal low speed handling qualities of the Flying-V by means of piloted simulations.

1.2 Research context

In 2015 Benad proposed the first concept of the Flying-V. The aircraft design was subject to a number of iterations, which lead to the geometry analyzed by Cappuyns in 2019. Based on this geometry, Airbus provided a new, more detailed aerodynamic model, which is used for the current research iteration and for these experiments.

With this model, an off-line preliminary analysis of the handling qualities was performed, which guided the preparation of the experiments presented here. Additionally, a flight control system prototype was designed based on this analysis.

Then, the SIMONA Research Simulator of TU-Delft was integrated with the software necessary to carry out the experiments related to this research.

The next step is that of pilot evaluations, which will complete the handling qualities research cycle on this aerodynamic model.

1.3 Flying-V model

For these experiments, the Flying-V will be simulated using an aerodynamic model of the **full scale** aircraft. In particular, the Computational Fluid Dynamics data of the Flying-V dynamics have been generated with the Vortex Lattice Method (VLM) approach, which only provides estimates of lift and lift-induced drag for the given aircraft design. As a consequence, it was necessary to integrate the VLM model with an additional zero-lift drag coefficient, computed during the first small scale model flight of July 2020.

The properties and the geometry of the Flying-V used in these experiments are summed up in Table 1 and Table 2; Figure 1 and Figure 2 show the most recent render and the dimensions.

Table 1: Geometric properties of the Flying-V

Property	**Description**	**Value**	**Unit**
T_{dy}	Engine y location w.r.t. centre line	[redacted]	m
T_{dz}	Engine z location w.r.t. centre line	[redacted]	m
S	Wing area	[redacted]	m^2
c/MAC	Wing Mean Aerodynamic Chord	[redacted]	m
b	Wing span	[redacted]	m
L	Length	[redacted]	m
$CG_{fowrard}$	Center of gravity - forward limit for stability	[redacted]	$\%MAC$
CG_{aft}	Center of gravity - aft limit for stability	[redacted]	$\%MAC$

Table 2: Inertial properties of the Flying-V

Property	**Description**	**Value**	**Unit**
MLW	Maximum Landing Weight	[redacted]	kg
$I_{xx_{MLW}}$	MLW Mass Moment of Inertia around X axis	[redacted]	$10^7 kgm^2$
$I_{yy_{MLW}}$	MLW Mass Moment of Inertia around Y axis	[redacted]	$10^7 kgm^2$
$I_{zz_{MLW}}$	MLW Mass Moment of Inertia around Z axis	[redacted]	$10^7 kgm^2$
$I_{xz_{MLW}}$	MLW Mass Moment of Inertia Cross Product around X and Z axes	[redacted]	$10^7 kgm^2$

Figure 1: Flying-V side view render and dimensions.

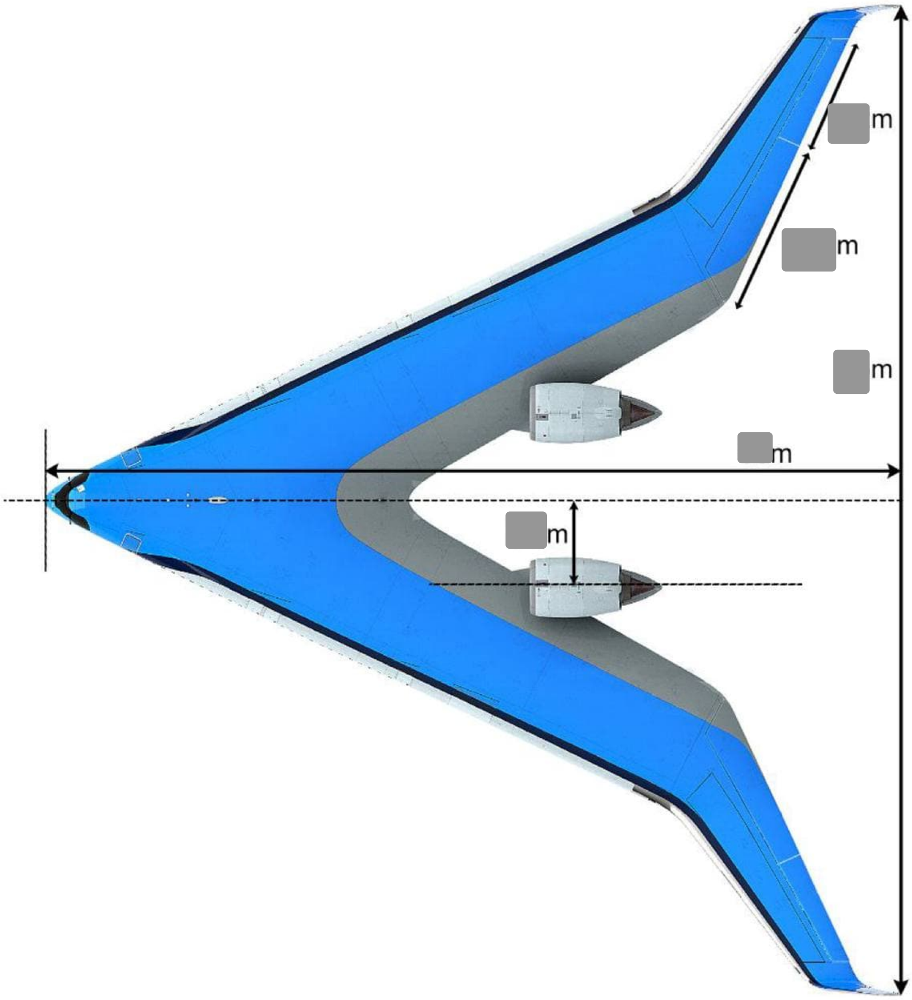


Figure 2: Flying-V top view render and dimensions.

The model includes data for the deflection of six independent control surfaces: two rudders (left and right), and four elevons (left and right inboard, which are [redacted]m long in Figure 2; and left and right outboard, which are [redacted]m long in Figure 2). The two rudders will not be used during these experiments, since they do not have a significant impact on the longitudinal handling qualities. The four elevons, so called since they provide control authority both as elevators (for pitch) and as ailerons (for roll), are all connected to a single control channel. In this sense, differential control of the four elevons is not part of this research, and all side-stick inputs will control the elevons uniformly.

2 Standards and Regulations

One of the main interests of this research is to investigate the potential compliance with safety regulations and standards. Following earlier results, this research focuses on:

1. go-around and aborted landing,
2. pull-up in approach and landing configurations,
3. trim and control authority in approach and landing configurations.

On these maneuvers, the following relevant standard as required by EASA (CS-25) should be considered:

- EASA CS 25.143: “Controllability and Manoeuvrability”:

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

The EASA “Acceptable Mean of Compliance AMC-20” (or the corresponding FAA “Flight Test Guide for Certification of FAR-25 Airplanes”) expands the requirement above by providing operational procedures to demonstrate compliance. By a combination of standard requirements and means of compliance, the following set of maneuvers was chosen as critical for the Flying-V:

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).

3 Experiment overview

3.1 Experiment goals

The experiments are intended to:

- Assess the longitudinal low speed handling qualities of the Flying-V with pilot-in-the-loop simulations.
- Investigate the impact of different aircraft configurations on the handling qualities according to pilots, focusing on:
  - the position of the center of gravity,
  - the speed of the aircraft,
  - the deflection limits of the elevons.
- Collect quantitative measures and qualitative feedback from the pilots on safety requirements related to:
  - handling qualities during approach and landing,
  - go-around,
  - trim.
- Investigate the potential need of flight control augmentation and quantify the improvement in terms of handling qualities.
- Collect qualitative feedback from the pilots on the go-around, focusing on:
  - high pitch angle during approach,
  - reduced sight angle on runway.
- Complete and integrate the off-line analysis of the longitudinal low speed handling qualities of the Flying-V.

3.2 Aircraft configuration setup

The experiments will be conducted in the SIMONA Research Simulator. The simulation model of the Flying-V will be setup to explore different conditions and configurations.

1. The center of gravity will span three positions, as in Table 3:

Table 3: Center of Gravity position

CG position [%MAC]	**CG position [m]**
Forward Limit ([redacted] MAC)	[redacted]
Backward Limit ([redacted]% MAC)	[redacted]
Middle ([redacted]% MAC)	[redacted]

2. the trim speed will be 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 will be set to two alternative values, namely:
    - 20 deg
    - 30 deg
4. the Flight Control System will provide two different laws:
    - a Direct Law, in which the pilot has direct control of the four elevons. Side-stick input will be converted linearly in a single commanded deflection angle for the four elevons, which will deflect according to their rate and deflection limits.
    - a Pitch Rate Controller, in which the pilot controls the pitch rate of the aircraft.
5. Auto-throttle will always be engaged during the simulations.
6. The roll and yaw control channels will be turned off, hence no lateral-directional control will be possible.

3.3 Experiment Tasks

By combining the EASA Certification Standards and Acceptable Means of Compliance (CS-25, CS-25 AMC), the results of the preliminary analysis, and the Handling Qualities evaluation guidelines of FAA (AC 25-7D), it was decided to run three simulation tasks, which will be presented in the following subsections.

3.3.1 Pitch Tracking

The aircraft will be trimmed in level flight. A 90-seconds-long pitch angle reference signal will be displayed on the HUD, which should be to tracked as accurately as possible. The goal is to achieve a minimum score of 68% in both adequate and desired performance. That means, to track the reference pitch angle within ±1 degrees for at least 68% of the task (adequate performance), and to track the reference pitch angle within ±0.5 degrees for at least 68% of the task (desired performance).

During this task, auto-throttle will always be on, in order to focus on side-stick control.

The task will be repeated for all the configurations presented in the previous section, in a predetermined order. **Each configuration will be simulated up to three times - one or two (if needed) for training, and one for the actual score measurement.** The procedure will be repeated identically for the two laws of the Flight Control System, which are Direct Law and Pitch Rate Control.

At the end of each run, an objective score will be determined based on the pilot's performance in the tracking task, and subjective feedback will be asked based on the Cooper-Harper scale, which is attached at the end of this document as a reference. On top of the usual Cooper-Harper questions, specific questions will be asked regarding:

- control strategy and compensation,
- noticeable sluggish or abrupt response,
- tendency to pilot induced oscillations,
- noticeable dropback or overshoot.

3.3.2 Free Pitch Capture

The aircraft will be trimmed in level flight. The pilot is asked to "capture" pitch angles in steps of ±5 degrees, for a total of 30 seconds per run. During this task, the pilot should try to capture the target pitch angle as stably and accurately as possible. Since this is a "free" capturing task, the pilot can choose the capturing pace, meaning that there is no minimum number of captures to be achieved in the 30 seconds limit.

During this task, auto-throttle will always be on, in order to focus on side-stick control.

The task will be repeated for all the configurations presented in the previous section, in a predetermined order. **Each configuration will be simulated only once**, meaning that each 30 seconds run also includes a short time for the pilot to adjust to the new configuration. The procedure will be repeated identically for the two laws of the Flight Control System, which are Direct Law and Pitch Rate Control.

At the end of each run, a number of questions will be asked to the pilot on their perception of the aircraft response. In particular, a five steps scale (Strongly disagree, Disagree, Neutral, Agree, Strongly agree) should be used to comment on the following sentences:

- 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.

3.3.3 Pull-up and go-around

At the beginning of the task, the aircraft will be trimmed in a 3 degrees glide slope, 500 ft above the runway of AMS airport.

The pilot will be asked to perform a pull-up and go-around starting 190ft above the runway. During the maneuver, the pilot should:

- Pull-up to a 3.2% Rate of Climb (which will be displayed to the pilot as a reference for the flight path angle)
- Maintain a Rate of Climb not lower than 3.2% and climb up to 500ft;
- Level off and capture 500ft.

During this task, auto-throttle will always be on, in order to focus on side-stick control.

The whole maneuver is expected to take around 60 seconds. During the task, the amount of altitude loss for the maneuver and the time needed to achieve the 3.2% climb of rate after initiating the go-around will be measured and displayed on the HUD.

The task will be repeated for a number of relevant configurations, always in Direct Law. **Each configuration will be simulated once or twice, based on pilot's feedback.**

At the end of each run, a number of questions will be asked to the pilot, in particular:

- 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?

3.4 Experiment plan

The proposed plan for the experiment session is as in Table 4. The expected duration includes the time to discuss the task and the related questions.

Table 4: Experiment plan

Phase	**Task**	**Duration**
Reception and Briefing	-	60 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	30 min
Debriefing	-	60 min

4 The SIMONA Research Simulator

4.1 Cockpit set-up

In Figure 3, the cockpit of the SIMONA Research Simulator is shown, with the following legend:

1. Outside view
2. Throttle levers
3. Emergency button (push in case of emergency - shuts down simulator motion and flight controls)
4. HUD display
5. Rudder pedals (not used in this research)
6. Side-stick

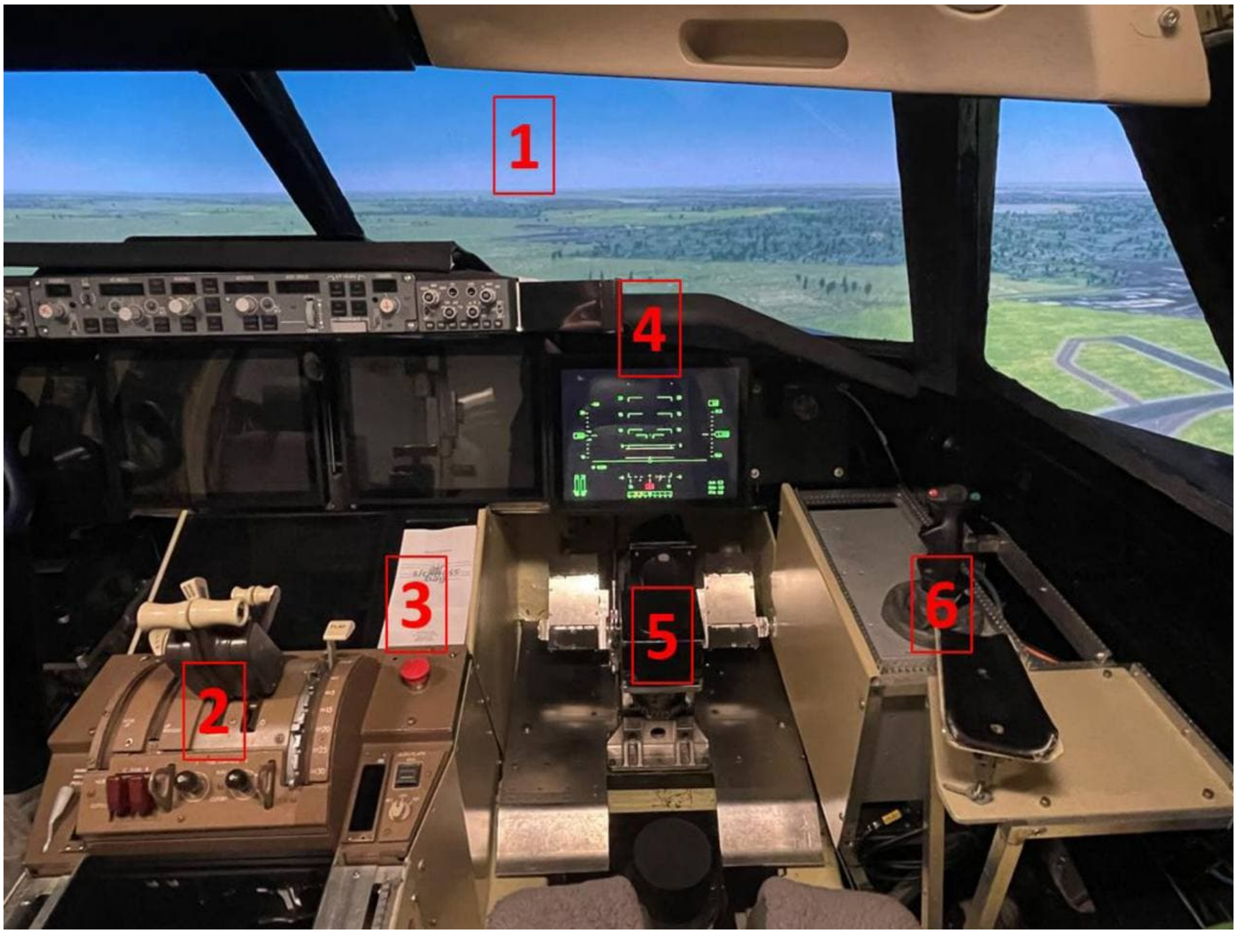


Figure 3: SIMONA Research Simulator cockpit.

4.2 HUD set-up

The HUD (number 4 in Figure 3) presents some minor differences based on the task to be simulated, as explained in the following subsections.

4.2.1 HUD components

For all the experiments, the HUD will have the following elements, displayed in Figure 4 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 (see below)

In the bottom right corner of the HUD (letter **H**), additional information are give to the pilot. Different information will be displayed depending on the task. The following abbreviations are used:

- **Ele** - Elevon deflection saturation (%), turns yellow when deflection rate limit is reached, turns red when deflection limit is reached
- **Thr** - Current throttle setting (%)
- **Trr** - Required throttle setting for trim (%)
- **Ade** - Adequate performance score (%)
- **Des** - Desired performance score (%)
- **Loss** - Altitude loss during go-around (m)
- **Time** - Elapsed time from initiating pull-up to reaching target climb-rate (s)
- **AoA** - Angle of Attack (deg)

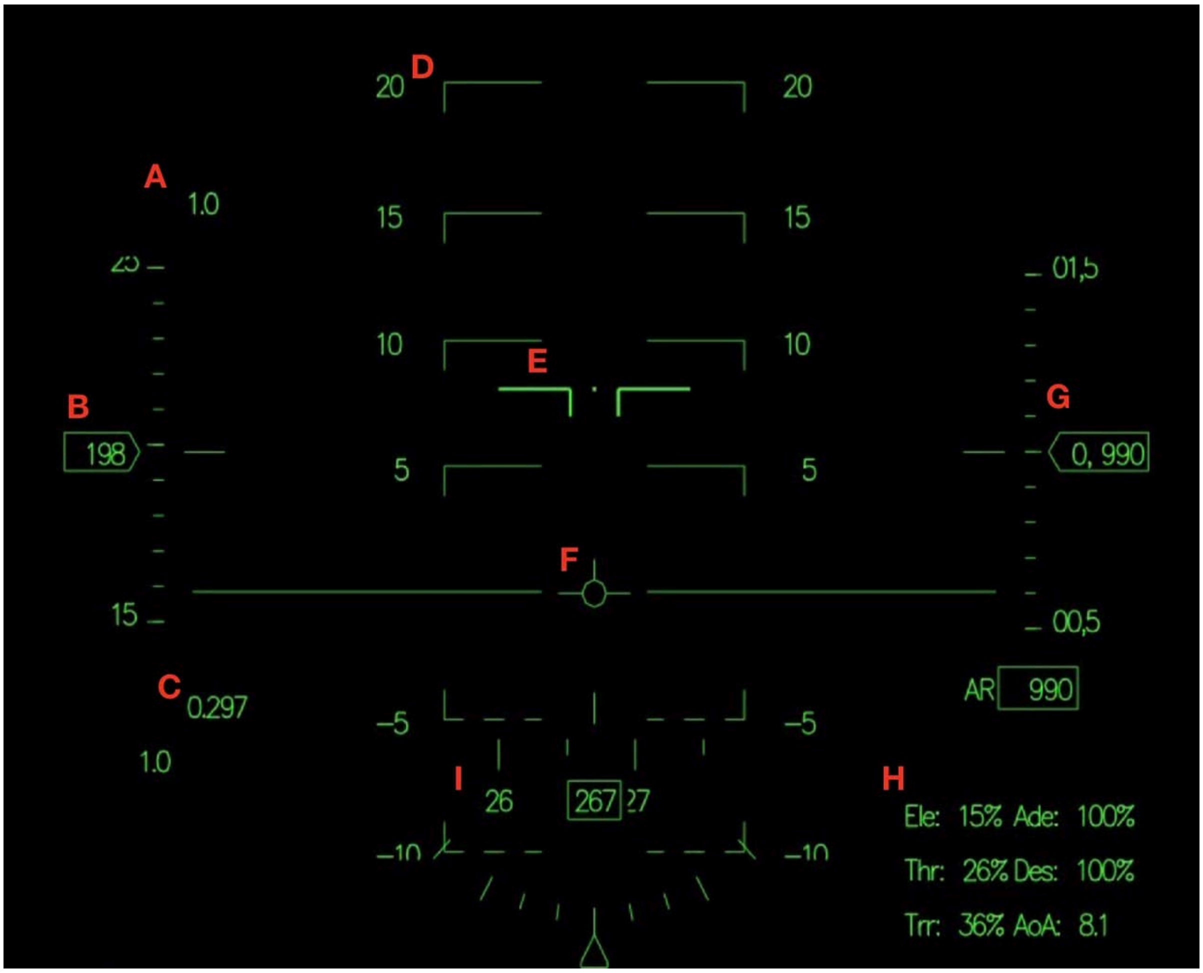


Figure 4: General HUD setup.

4.2.2 Pitch Tracking

During pitch tracking the HUD will look like in Figure 5. The target pitch angle for the tracking will be displayed with two moving squares (letter **J**) - the outer one, in color red, shows the ±1 deg limits for the Adequate performance; while the inner square, in color yellow, shows the ±0.5 deg limits for the Desired performance. Both squares turn green when tracked.

In the right bottom corner (letter **H**), the "Ade" (adequate performance) and "Des" (desired performance) indicators will show the real-time score. This will be visible during the two training runs of each configuration, but it will be hidden until the end of the task during the third run (see section 3.3.1).

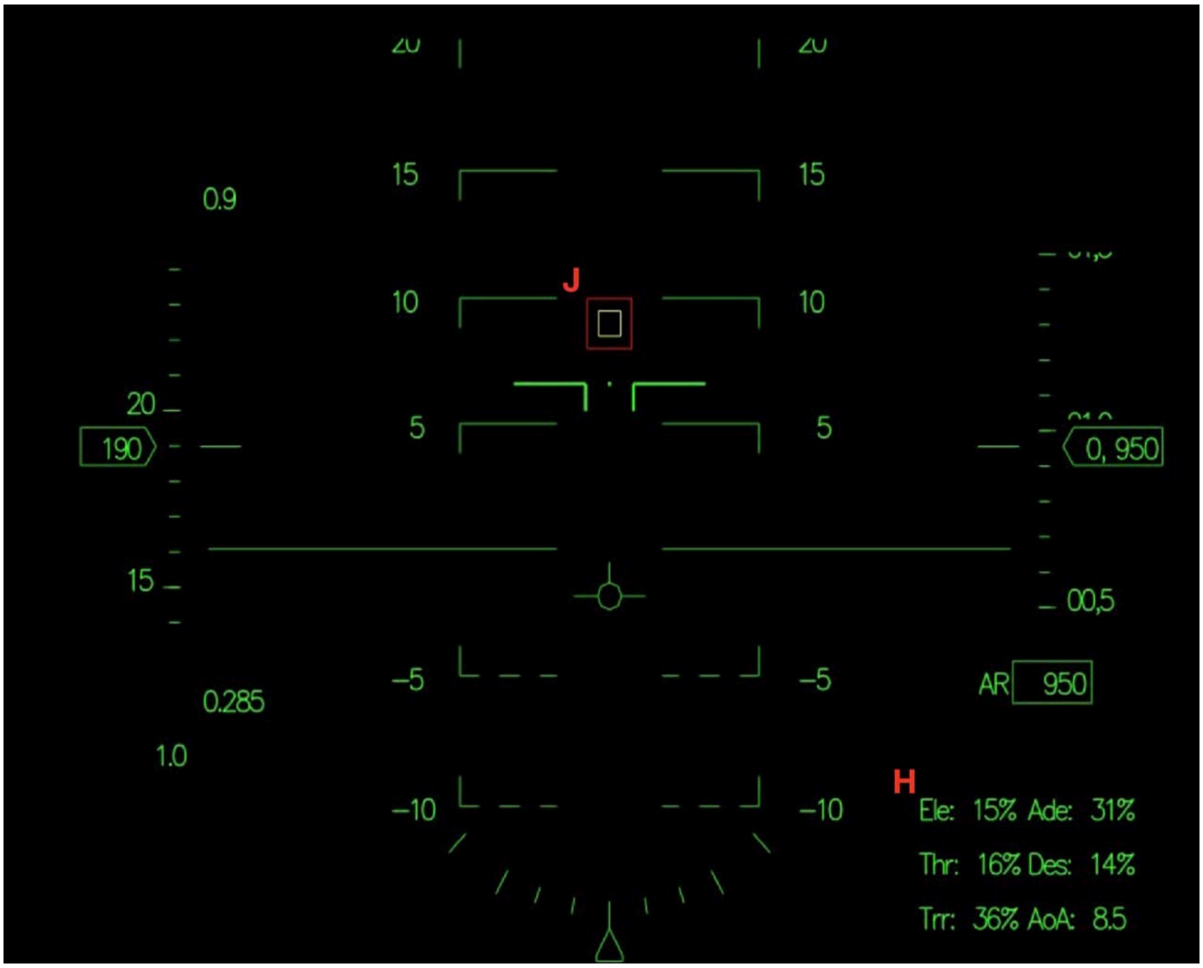


Figure 5: Pitch tracking HUD.

4.2.3 Free Pitch Capture

The Free Pitch Capture task does not require task-specific indicators on the HUD, hence it will look just like in Figure 4.

4.2.4 Go-around

During the Go-around task, a target Flight Path indicator will be displayed as in Figure 6, letter **K**, with a red square and a yellow dot which will both turn green when the target climb rate is achieved. Notice that this is a target reference indicator for Flight Path angle and NOT for Pitch angle.

In the right bottom corner (letter **H**), the "Loss" and "Time" indicators will show, respectively, the altitude loss after Decision Height, and the elapsed time between crossing Decision Height and achieving the target climb rate.

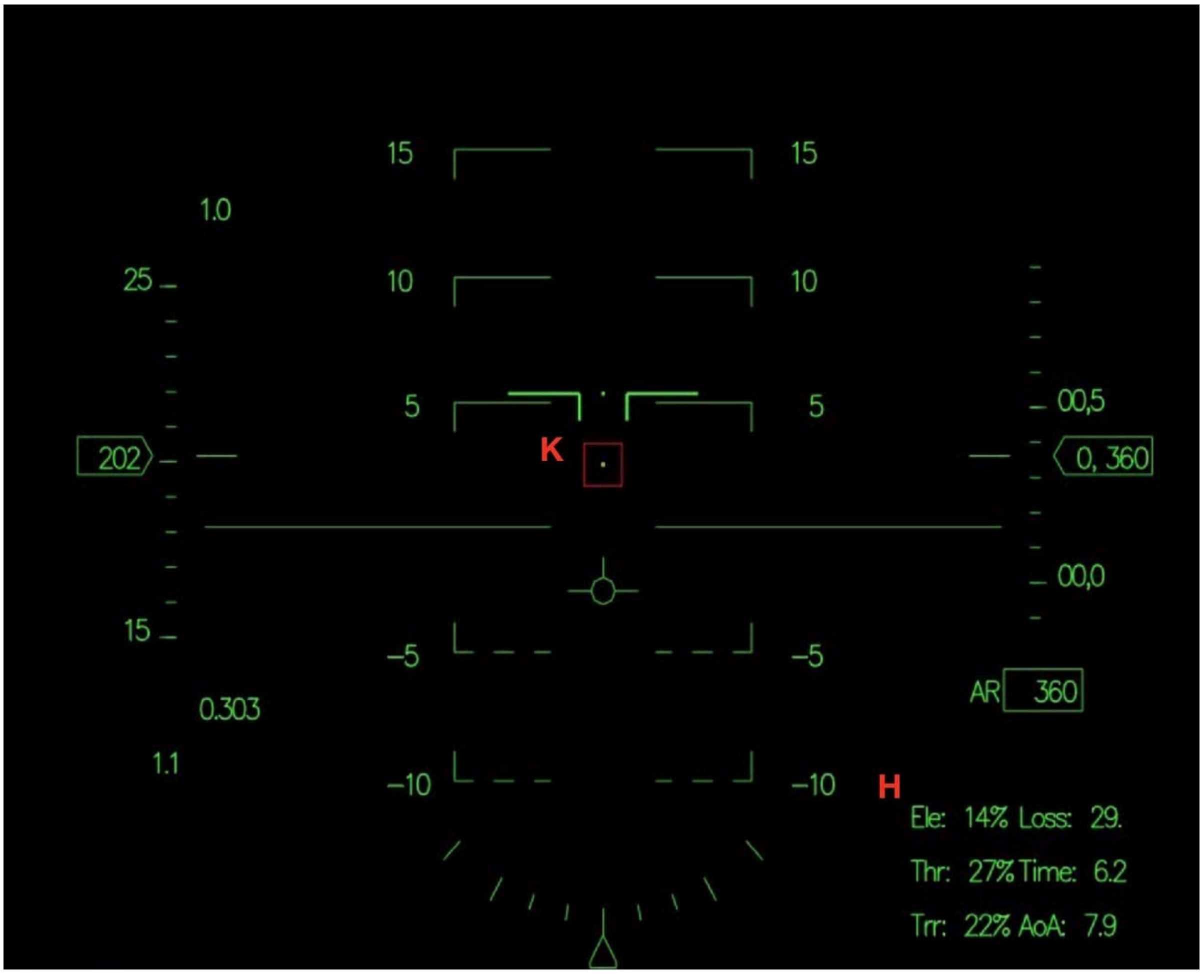
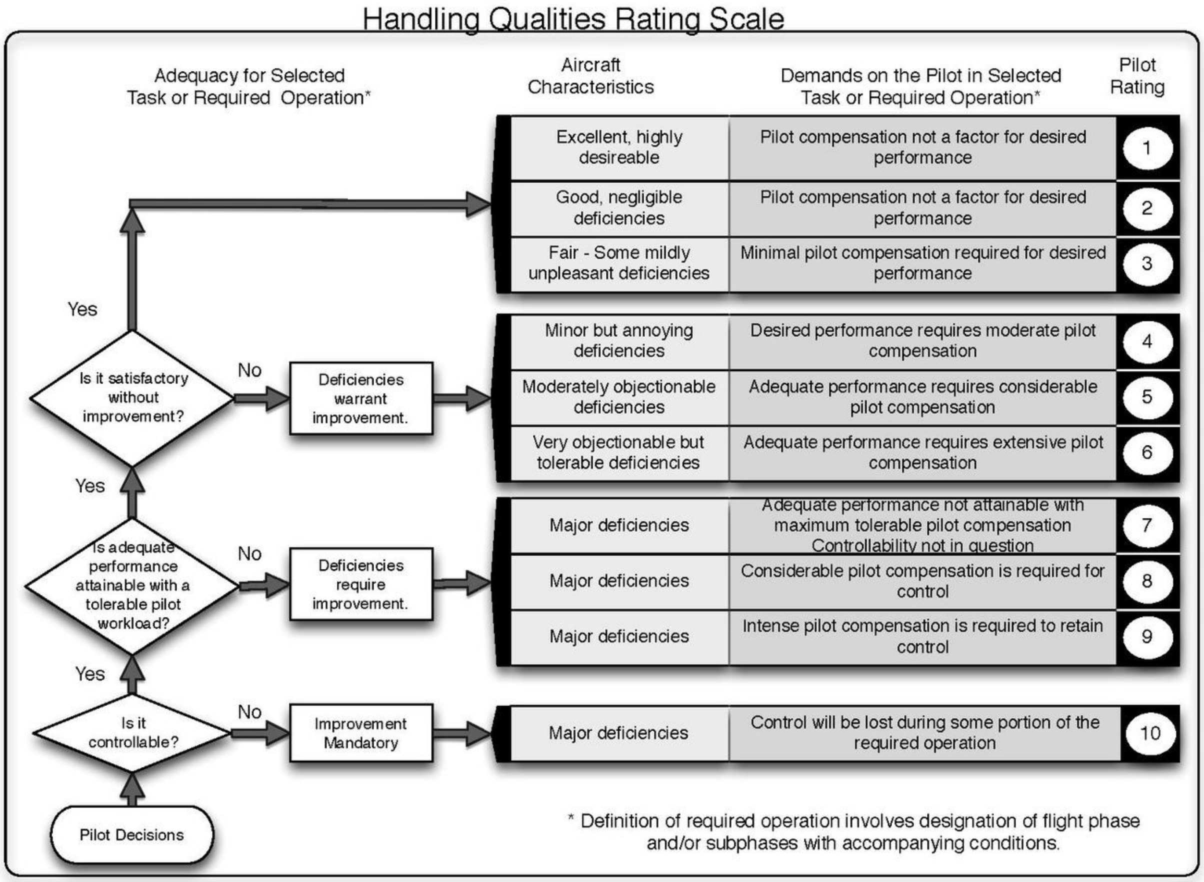


Figure 6: Go-around HUD.

5 Additional information

- For first-time pilots in the SIMONA Research Simulator, please watch the safety instruction video beforehand at https://www.youtube.com/watch?v=PXijsyJ3hro.
- The discussion of the Handling Qualities during the Pitch Tracking experiments will follow the Cooper-Harper approach to Handling Qualities Evaluation with piloted simulations. It is recommended to have some familiarity with the Cooper-Harper scale, shown in Figure 7.
- A side-stick shaker will be used as a stall warning device for angles of attack higher than 20 degrees. The pilot should try to not cross this limit. In any case, these simulations do not include stall dynamics.
- In some conditions, the difference between pitch angle and flight path is so large that the Flight Path marker (letter **F** in Figure 4) would disappear from the HUD. In order to avoid this, the HUD has been adapted to always keep the marker visible on the screen by re-scaling the pitch ladder when needed during a simulation.
- The pilots are invited to indicate whenever they need an additional break from the simulations.



Aircraft Characteristics	Demands on the Pilot in Selected Task or Required Operation*	Pilot Rating
Excellent, highly desireable	Pilot compensation not a factor for desired performance	1
Good, negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair - Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation Controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of the required operation	10

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 7: The Cooper-Harper rating scale.

E

Experiment Matrix

The following pages contain the experiment matrices for the three pilots, with some information regarding the experimental setup. In these tables the following indications are used:

- # - number of the run;
- FCS - Flight Control System, either ”bare” (Direct Law) or ”P/C” (Pitch Rate Command);
- Speed - airspeed in Mach, either 0.225 or 0.3;
- CG - center of gravity position, either fwd (forward), nom (nominal), or aft;
- Defl - maximum allowed elevons deflection
- Ref - tracking reference signal number, from 1 to 5. The cell is green for the ”measurement” runs;
- FPA - Flight Path Angle, either 0 (level flight) or -3 (approach);
- A/T - auto-throttle, wither on or off;
- S/W - stall-warning on the side-stick, either on or off;
- Task - either P/T (Pitch Tracking), G/A (Go-Around), or P/C (Pitch Capture);
- Disp - either on or off, indicates whether the pilots can see their scores during the run;
- sec - approximate duration of the run, in seconds;
- Adequate - adequate performance score, in percentage;
- Desired - desired performance score, in percentage;
- CH Rating - rating in the Cooper Harper scale according to the pilot;
- Altitude - altitude loss after the ”go-around” call, in meters;
- Time - time between the ”go-around” call at 190 ft and the moment a 3.2% rate of climb is reached, in seconds.

The tables are given in the following order:

1. Pilot A - Pitch Tracking - Direct Law
2. Pilot A - Pitch Tracking - Pitch Rate Command
3. Pilot A - Go-Around and Pitch Capture
4. Pilot B - Pitch Tracking - Direct Law
5. Pilot B - Pitch Tracking - Pitch Rate Command
6. Pilot B - Go-Around and Pitch Capture
7. Pilot C - Pitch Tracking - Direct Law
8. Pilot C - Pitch Tracking - Pitch Rate Command
9. Pilot C - Go-Around and Pitch Capture

Pilot A - Pitch Tracking - Bare Airframe

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec	Adequate	Desired	CH Rating
1	bare	0.225	fwd	20	1	0	on	on	P/T	on	90	75	62	
2	bare	0.225	fwd	20	2	0	on	on	P/T	on	90	skip		
3	bare	0.225	fwd	20	5	0	on	on	P/T	off	90	80	69	4
4	bare	0.225	fwd	30	3	0	on	on	P/T	on	90	87	76	
5	bare	0.225	fwd	30	4	0	on	on	P/T	on	90	skip		
6	bare	0.225	fwd	30	5	0	on	on	P/T	off	90	87	76	4
7	bare	0.225	nom	20	2	0	on	on	P/T	on	90	81	71	
8	bare	0.225	nom	20	1	0	on	on	P/T	on	90	skip		
9	bare	0.225	nom	20	5	0	on	on	P/T	off	90	86	75	4
10	bare	0.225	nom	30	4	0	on	on	P/T	on	90	85	69	
11	bare	0.225	nom	30	3	0	on	on	P/T	on	90	skip		
12	bare	0.225	nom	30	5	0	on	on	P/T	off	90	87	79	4
13	bare	0.225	aft	20	1	0	on	on	P/T	on	90	85	74	
14	bare	0.225	aft	20	3	0	on	on	P/T	on	90	skip		
15	bare	0.225	aft	20	5	0	on	on	P/T	off	90	86	75	3
16	bare	0.225	aft	30	2	0	on	on	P/T	on	90	84	75	
17	bare	0.225	aft	30	4	0	on	on	P/T	on	90	skip		
18	bare	0.225	aft	30	5	0	on	on	P/T	off	90	87	76	4
19	bare	0.3	fwd	20	3	0	on	on	P/T	on	90	85	70	
20	bare	0.3	fwd	20	4	0	on	on	P/T	on	90	85	74	
21	bare	0.3	fwd	20	5	0	on	on	P/T	off	90	88	77	4
22	bare	0.3	fwd	30	2	0	on	on	P/T	on	90	85	74	
23	bare	0.3	fwd	30	1	0	on	on	P/T	on	90	skip		
24	bare	0.3	fwd	30	5	0	on	on	P/T	off	90	89	80	3
25	bare	0.3	nom	20	4	0	on	on	P/T	on	90	88	79	
26	bare	0.3	nom	20	1	0	on	on	P/T	on	90	skip		
27	bare	0.3	nom	20	5	0	on	on	P/T	off	90	89	80	3
28	bare	0.3	nom	30	2	0	on	on	P/T	on	90	85	77	
29	bare	0.3	nom	30	3	0	on	on	P/T	on	90	skip		
30	bare	0.3	nom	30	5	0	on	on	P/T	off	90	89	78	3
31	bare	0.3	aft	20	2	0	on	on	P/T	on	90	82	70	
32	bare	0.3	aft	20	4	0	on	on	P/T	on	90	skip		
33	bare	0.3	aft	20	5	0	on	on	P/T	off	90	88	74	2
34	bare	0.3	aft	30	1	0	on	on	P/T	on	90	89	80	
35	bare	0.3	aft	30	3	0	on	on	P/T	on	90	skip		
36	bare	0.3	aft	30	5	0	on	on	P/T	off	90	88	79	2

Pilot A - Pitch Tracking - Pitch Rate Command

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec	Adequate	Desired	CH Rating
37	P/C	0.225	fwd	20	1	0	on	on	P/T	on	90	75	61	
38	P/C	0.225	fwd	20	2	0	on	on	P/T	on	90	skip		
39	P/C	0.225	fwd	20	5	0	on	on	P/T	off	90	78	69	5
40	P/C	0.225	fwd	30	3	0	on	on	P/T	on	90	84	74	
41	P/C	0.225	fwd	30	4	0	on	on	P/T	on	90	skip		
42	P/C	0.225	fwd	30	5	0	on	on	P/T	off	90	87	78	2
43	P/C	0.225	nom	20	2	0	on	on	P/T	on	90	skip		
44	P/C	0.225	nom	20	1	0	on	on	P/T	on	90	skip		
45	P/C	0.225	nom	20	5	0	on	on	P/T	off	90	88	75	2
46	P/C	0.225	nom	30	4	0	on	on	P/T	on	90	skip		
47	P/C	0.225	nom	30	3	0	on	on	P/T	on	90	skip		
48	P/C	0.225	nom	30	5	0	on	on	P/T	off	90	88	77	2
49	P/C	0.225	aft	20	1	0	on	on	P/T	on	90	skip		
50	P/C	0.225	aft	20	3	0	on	on	P/T	on	90	skip		
51	P/C	0.225	aft	20	5	0	on	on	P/T	off	90	88	76	2
52	P/C	0.225	aft	30	2	0	on	on	P/T	on	90	skip		
53	P/C	0.225	aft	30	4	0	on	on	P/T	on	90	skip		
54	P/C	0.225	aft	30	5	0	on	on	P/T	off	90	88	77	2
55	P/C	0.3	fwd	20	3	0	on	on	P/T	on	90	skip		
56	P/C	0.3	fwd	20	4	0	on	on	P/T	on	90	skip		
57	P/C	0.3	fwd	20	5	0	on	on	P/T	off	90	88	78	2
58	P/C	0.3	fwd	30	2	0	on	on	P/T	on	90	skip		
59	P/C	0.3	fwd	30	1	0	on	on	P/T	on	90	skip		
60	P/C	0.3	fwd	30	5	0	on	on	P/T	off	90	87	78	2
61	P/C	0.3	nom	20	4	0	on	on	P/T	on	90	skip		
62	P/C	0.3	nom	20	1	0	on	on	P/T	on	90	skip		
63	P/C	0.3	nom	20	5	0	on	on	P/T	off	90	88	77	2
64	P/C	0.3	nom	30	2	0	on	on	P/T	on	90	skip		
65	P/C	0.3	nom	30	3	0	on	on	P/T	on	90	skip		
66	P/C	0.3	nom	30	5	0	on	on	P/T	off	90	87	78	2
67	P/C	0.3	aft	20	2	0	on	on	P/T	on	90	skip		
68	P/C	0.3	aft	20	4	0	on	on	P/T	on	90	skip		
69	P/C	0.3	aft	20	5	0	on	on	P/T	off	90	88	80	2
70	P/C	0.3	aft	30	1	0	on	on	P/T	on	90	skip		
71	P/C	0.3	aft	30	3	0	on	on	P/T	on	90	skip		
72	P/C	0.3	aft	30	5	0	on	on	P/T	off	90	87	80	2

Pilot A - Go-Around and Pitch Capture

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec	Altitude	Time
101	bare	0.225	fwd	20	-	-3	off	on	G/A	on	60		
102	bare	0.225	fwd	20	-	-3	off	on	G/A	on	60	10.0	6.5
103	bare	0.225	nom	20	-	-3	off	on	G/A	on	60		
104	bare	0.225	nom	20	-	-3	off	on	G/A	on	60	10.8	6.4
105	bare	0.225	aft	20	-	-3	off	on	G/A	on	60		
106	bare	0.225	aft	20	-	-3	off	on	G/A	on	60	9.2	4.5
107	bare	0.3	fwd	20	-	-3	off	on	G/A	on	60		
108	bare	0.3	fwd	20	-	-3	off	on	G/A	on	60	8.9	3.2
109	bare	0.3	nom	20	-	-3	off	on	G/A	on	60		
110	bare	0.3	nom	20	-	-3	off	on	G/A	on	60	8.1	4.2
111	bare	0.3	aft	20	-	-3	off	on	G/A	on	60		
112	bare	0.3	aft	20	-	-3	off	on	G/A	on	60	9.7	3.2

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec
73	bare	0.3	fwd	20	-	0	on	on	P/C	on	30
74	bare	0.225	fwd	20	-	0	on	on	P/C	on	30
75	bare	0.225	nom	20	-	0	on	on	P/C	on	30
76	bare	0.225	aft	20	-	0	on	on	P/C	on	30
77	bare	0.225	fwd	30	-	0	on	on	P/C	on	30
78	bare	0.225	nom	30	-	0	on	on	P/C	on	30
79	bare	0.225	aft	30	-	0	on	on	P/C	on	30
80	bare	0.3	aft	30	-	0	on	on	P/C	on	30
81	bare	0.3	fwd	30	-	0	on	on	P/C	on	30
82	bare	0.3	nom	30	-	0	on	on	P/C	on	30
83	bare	0.3	aft	20	-	0	on	on	P/C	on	30
84	bare	0.3	fwd	20	-	0	on	on	P/C	on	30
85	bare	0.3	nom	20	-	0	on	on	P/C	on	30
86	bare	0.225	nom	20		0	on	on	P/C	on	30
87	P/C	0.3	fwd	20	-	0	on	on	P/C	on	30
88	P/C	0.225	fwd	20	-	0	on	on	P/C	on	30
89	P/C	0.225	nom	20	-	0	on	on	P/C	on	30
90	P/C	0.225	aft	20	-	0	on	on	P/C	on	30
91	P/C	0.225	fwd	30	-	0	on	on	P/C	on	30
92	P/C	0.225	nom	30	-	0	on	on	P/C	on	30
93	P/C	0.225	aft	30	-	0	on	on	P/C	on	30
94	P/C	0.3	aft	30	-	0	on	on	P/C	on	30
95	P/C	0.3	fwd	30	-	0	on	on	P/C	on	30
96	P/C	0.3	nom	30	-	0	on	on	P/C	on	30
97	P/C	0.3	aft	20	-	0	on	on	P/C	on	30
98	P/C	0.3	fwd	20	-	0	on	on	P/C	on	30
99	P/C	0.3	nom	20	-	0	on	on	P/C	on	30
100	P/C	0.225	nom	20		0	on	on	P/C	on	30

Pilot B - Pitch Tracking - Bare Airframe

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Score	sec	Adequate	Desired	CH Rating
1	bare	0.3	fwd	20	3	0	on	on	P/T	on	90	77	61	
2	bare	0.3	fwd	20	4	0	on	on	P/T	on	90	75	61	
3	bare	0.3	fwd	20	5	0	on	on	P/T	off	90	87	71	2
4	bare	0.3	fwd	30	2	0	on	on	P/T	on	90	81	67	
5	bare	0.3	fwd	30	1	0	on	on	P/T	on	90	skip		
6	bare	0.3	fwd	30	5	0	on	on	P/T	off	90	88	76	3
7	bare	0.3	nom	20	4	0	on	on	P/T	on	90	84	70	
8	bare	0.3	nom	20	1	0	on	on	P/T	on	90	skip		
9	bare	0.3	nom	20	5	0	on	on	P/T	off	90	86	76	1
10	bare	0.3	nom	30	2	0	on	on	P/T	on	90	84	74	
11	bare	0.3	nom	30	3	0	on	on	P/T	on	90	skip		
12	bare	0.3	nom	30	5	0	on	on	P/T	off	90	89	76	2
13	bare	0.3	aft	20	2	0	on	on	P/T	on	90	83	72	
14	bare	0.3	aft	20	4	0	on	on	P/T	on	90	skip		
15	bare	0.3	aft	20	5	0	on	on	P/T	off	90	86	72	3
16	bare	0.3	aft	30	1	0	on	on	P/T	on	90	84	73	
17	bare	0.3	aft	30	3	0	on	on	P/T	on	90	skip		
18	bare	0.3	aft	30	5	0	on	on	P/T	off	90	87	73	2
19	bare	0.225	fwd	20	1	0	on	on	P/T	on	90	72	52	
20	bare	0.225	fwd	20	2	0	on	on	P/T	on	90	skip		
21	bare	0.225	fwd	20	5	0	on	on	P/T	off	90	81	66	7
22	bare	0.225	fwd	30	3	0	on	on	P/T	on	90	82	69	
23	bare	0.225	fwd	30	4	0	on	on	P/T	on	90	skip		
24	bare	0.225	fwd	30	5	0	on	on	P/T	off	90	87	74	4
25	bare	0.225	nom	20	2	0	on	on	P/T	on	90	85	77	
26	bare	0.225	nom	20	1	0	on	on	P/T	on	90	skip		
27	bare	0.225	nom	20	5	0	on	on	P/T	off	90	88	76	3
28	bare	0.225	nom	30	4	0	on	on	P/T	on	90	78	68	
29	bare	0.225	nom	30	3	0	on	on	P/T	on	90	skip		
30	bare	0.225	nom	30	5	0	on	on	P/T	off	90	87	78	2
31	bare	0.225	aft	20	1	0	on	on	P/T	on	90	83	69	
32	bare	0.225	aft	20	3	0	on	on	P/T	on	90	skip		
33	bare	0.225	aft	20	5	0	on	on	P/T	off	90	86	70	3
34	bare	0.225	aft	30	2	0	on	on	P/T	on	90	77	67	
35	bare	0.225	aft	30	4	0	on	on	P/T	on	90	skip		
36	bare	0.225	aft	30	5	0	on	on	P/T	off	90	86	68	4

Pilot B - Pitch Tracking - Pitch Rate Command

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Score	sec	Adequate	Desired	CH Rating
37	P/C	0.3	fwd	20	3	0	on	on	P/T	on	90	84	67	
38	P/C	0.3	fwd	20	4	0	on	on	P/T	on	90	skip		
39	P/C	0.3	fwd	20	5	0	on	on	P/T	off	90	87	75	2
40	P/C	0.3	fwd	30	2	0	on	on	P/T	on	90	87	77	
41	P/C	0.3	fwd	30	1	0	on	on	P/T	on	90	skip		
42	P/C	0.3	fwd	30	5	0	on	on	P/T	off	90	88	79	2
43	P/C	0.3	nom	20	4	0	on	on	P/T	on	90	85	77	
44	P/C	0.3	nom	20	1	0	on	on	P/T	on	90	skip		
45	P/C	0.3	nom	20	5	0	on	on	P/T	off	90	88	78	2
46	P/C	0.3	nom	30	2	0	on	on	P/T	on	90	skip		
47	P/C	0.3	nom	30	3	0	on	on	P/T	on	90	skip		
48	P/C	0.3	nom	30	5	0	on	on	P/T	off	90	88	80	2
49	P/C	0.3	aft	20	2	0	on	on	P/T	on	90	skip		
50	P/C	0.3	aft	20	4	0	on	on	P/T	on	90	skip		
51	P/C	0.3	aft	20	5	0	on	on	P/T	off	90	88	80	2
52	P/C	0.3	aft	30	1	0	on	on	P/T	on	90	skip		
53	P/C	0.3	aft	30	3	0	on	on	P/T	on	90	skip		
54	P/C	0.3	aft	30	5	0	on	on	P/T	off	90	88	80	2
55	P/C	0.225	fwd	20	1	0	on	on	P/T	on	90	77	65	
56	P/C	0.225	fwd	20	2	0	on	on	P/T	on	90	skip		
57	P/C	0.225	fwd	20	5	0	on	on	P/T	off	90	78	64	7
58	P/C	0.225	fwd	30	3	0	on	on	P/T	on	90	skip		
59	P/C	0.225	fwd	30	4	0	on	on	P/T	on	90	skip		
60	P/C	0.225	fwd	30	5	0	on	on	P/T	off	90	88	79	3
61	P/C	0.225	nom	20	2	0	on	on	P/T	on	90	skip		
62	P/C	0.225	nom	20	1	0	on	on	P/T	on	90	skip		
63	P/C	0.225	nom	20	5	0	on	on	P/T	off	90	87	74	3
64	P/C	0.225	nom	30	4	0	on	on	P/T	on	90	skip		
65	P/C	0.225	nom	30	3	0	on	on	P/T	on	90	skip		
66	P/C	0.225	nom	30	5	0	on	on	P/T	off	90	88	77	2
67	P/C	0.225	aft	20	1	0	on	on	P/T	on	90	skip		
68	P/C	0.225	aft	20	3	0	on	on	P/T	on	90	skip		
69	P/C	0.225	aft	20	5	0	on	on	P/T	off	90	86	75	2
70	P/C	0.225	aft	30	2	0	on	on	P/T	on	90	skip		
71	P/C	0.225	aft	30	4	0	on	on	P/T	on	90	skip		
72	P/C	0.225	aft	30	5	0	on	on	P/T	off	90	88	74	2

Pilot B - Go-Around and Pitch Capture

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Score	sec	Altitude	Time
101	bare	0.3	fwd	20	-	-3	off	on	G/A	on	60		
102	bare	0.3	fwd	20	-	-3	off	on	G/A	on	60	5.5	3.6
103	bare	0.3	nom	20	-	-3	off	on	G/A	on	60		
104	bare	0.3	nom	20	-	-3	off	on	G/A	on	60	3.6	5.9
105	bare	0.3	aft	20	-	-3	off	on	G/A	on	60		
106	bare	0.3	aft	20	-	-3	off	on	G/A	on	60	8.5	3.4
107	bare	0.225	fwd	20	-	-3	off	on	G/A	on	60		
108	bare	0.225	fwd	20	-	-3	off	on	G/A	on	60	8.6	3.4
109	bare	0.225	nom	20	-	-3	off	on	G/A	on	60		
110	bare	0.225	nom	20	-	-3	off	on	G/A	on	60	4.6	3.3
111	bare	0.225	aft	20	-	-3	off	on	G/A	on	60		
112	bare	0.225	aft	20	-	-3	off	on	G/A	on	60	8.7	2.9

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Score	sec
73	bare	0.225	fwd	20	-	0	on	on	P/C	on	30
74	bare	0.3	fwd	20	-	0	on	on	P/C	on	30
75	bare	0.3	nom	20	-	0	on	on	P/C	on	30
76	bare	0.3	aft	20	-	0	on	on	P/C	on	30
77	bare	0.3	fwd	30	-	0	on	on	P/C	on	30
78	bare	0.3	nom	30	-	0	on	on	P/C	on	30
79	bare	0.3	aft	30	-	0	on	on	P/C	on	30
80	bare	0.225	aft	30	-	0	on	on	P/C	on	30
81	bare	0.225	fwd	30	-	0	on	on	P/C	on	30
82	bare	0.225	nom	30	-	0	on	on	P/C	on	30
83	bare	0.225	aft	20	-	0	on	on	P/C	on	30
84	bare	0.225	fwd	20	-	0	on	on	P/C	on	30
85	bare	0.225	nom	20	-	0	on	on	P/C	on	30
86	bare	0.3	nom	20		0	on	on	P/C	on	30
87	P/C	0.225	fwd	20	-	0	on	on	P/C	on	30
88	P/C	0.3	fwd	20	-	0	on	on	P/C	on	30
89	P/C	0.3	nom	20	-	0	on	on	P/C	on	30
90	P/C	0.3	aft	20	-	0	on	on	P/C	on	30
91	P/C	0.3	fwd	30	-	0	on	on	P/C	on	30
92	P/C	0.3	nom	30	-	0	on	on	P/C	on	30
93	P/C	0.3	aft	30	-	0	on	on	P/C	on	30
94	P/C	0.225	aft	30	-	0	on	on	P/C	on	30
95	P/C	0.225	fwd	30	-	0	on	on	P/C	on	30
96	P/C	0.225	nom	30	-	0	on	on	P/C	on	30
97	P/C	0.225	aft	20	-	0	on	on	P/C	on	30
98	P/C	0.225	fwd	20	-	0	on	on	P/C	on	30
99	P/C	0.225	nom	20	-	0	on	on	P/C	on	30
100	P/C	0.3	nom	20		0	on	on	P/C	on	30

Pilot C - Pitch Tracking - Bare Airframe

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec	Adequate	Desired	CH Rating
1	bare	0.225	fwd	20	1	0	on	on	P/T	on	90	75	50	
2	bare	0.225	fwd	20	2	0	on	on	P/T	on	90	skip		
3	bare	0.225	fwd	20	5	0	on	on	P/T	off	90	73	56	7
4	bare	0.225	nom	20	3	0	on	on	P/T	on	90	73	52	
5	bare	0.225	nom	20	4	0	on	on	P/T	on	90	80	59	
6	bare	0.225	nom	20	5	0	on	on	P/T	off	90	83	59	8
7	bare	0.225	aft	20	2	0	on	on	P/T	on	90	85	65	
8	bare	0.225	aft	20	1	0	on	on	P/T	on	90	skip		
9	bare	0.225	aft	20	5	0	on	on	P/T	off	90	79	61	8
10	bare	0.225	fwd	30	4	0	on	on	P/T	on	90	79	63	
11	bare	0.225	fwd	30	3	0	on	on	P/T	on	90	skip		
12	bare	0.225	fwd	30	5	0	on	on	P/T	off	90	79	57	5
13	bare	0.225	nom	30	1	0	on	on	P/T	on	90	73	47	
14	bare	0.225	nom	30	3	0	on	on	P/T	on	90	skip		
15	bare	0.225	nom	30	5	0	on	on	P/T	off	90	75	54	8
16	bare	0.225	aft	30	2	0	on	on	P/T	on	90	79	63	
17	bare	0.225	aft	30	4	0	on	on	P/T	on	90	skip		
18	bare	0.225	aft	30	5	0	on	on	P/T	off	90	82	57	8
19	bare	0.3	fwd	20	3	0	on	on	P/T	on	90	79	58	
20	bare	0.3	fwd	20	4	0	on	on	P/T	on	90	skip		
21	bare	0.3	fwd	20	5	0	on	on	P/T	off	90	84	64	5
22	bare	0.3	nom	20	2	0	on	on	P/T	on	90	85	68	
23	bare	0.3	nom	20	1	0	on	on	P/T	on	90	skip		
24	bare	0.3	nom	20	5	0	on	on	P/T	off	90	85	74	5
25	bare	0.3	aft	20	4	0	on	on	P/T	on	90	83	71	
26	bare	0.3	aft	20	1	0	on	on	P/T	on	90	skip		
27	bare	0.3	aft	20	5	0	on	on	P/T	off	90	83	76	5
28	bare	0.3	fwd	30	2	0	on	on	P/T	on	90	80	66	
29	bare	0.3	fwd	30	3	0	on	on	P/T	on	90	skip		
30	bare	0.3	fwd	30	5	0	on	on	P/T	off	90	84	70	4
31	bare	0.3	nom	30	2	0	on	on	P/T	on	90	79	68	
32	bare	0.3	nom	30	4	0	on	on	P/T	on	90	skip		
33	bare	0.3	nom	30	5	0	on	on	P/T	off	90	84	69	5
34	bare	0.3	aft	30	1	0	on	on	P/T	on	90	81	56	
35	bare	0.3	aft	30	3	0	on	on	P/T	on	90	skip		
36	bare	0.3	aft	30	5	0	on	on	P/T	off	90	86	70	5

Pilot C - Pitch Tracking - Pitch Rate Command

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec	Adequate	Desired	CH Rating
37	P/C	0.225	fwd	20	1	0	on	on	P/T	on	90	75	50	
38	P/C	0.225	fwd	20	2	0	on	on	P/T	on	90	skip		
39	P/C	0.225	fwd	20	5	0	on	on	P/T	off	90	73	62	4
40	P/C	0.225	nom	20	3	0	on	on	P/T	on	90	78	65	
41	P/C	0.225	nom	20	4	0	on	on	P/T	on	90	skip		
42	P/C	0.225	nom	20	5	0	on	on	P/T	off	90	81	69	4
43	P/C	0.225	aft	20	2	0	on	on	P/T	on	90	75	68	
44	P/C	0.225	aft	20	1	0	on	on	P/T	on	90	skip		
45	P/C	0.225	aft	20	5	0	on	on	P/T	off	90	81	64	4
46	P/C	0.225	fwd	30	4	0	on	on	P/T	on	90	skip		
47	P/C	0.225	fwd	30	3	0	on	on	P/T	on	90	skip		
48	P/C	0.225	fwd	30	5	0	on	on	P/T	off	90	83	68	2
49	P/C	0.225	nom	30	1	0	on	on	P/T	on	90	skip		
50	P/C	0.225	nom	30	3	0	on	on	P/T	on	90	skip		
51	P/C	0.225	nom	30	5	0	on	on	P/T	off	90	83	68	3
52	P/C	0.225	aft	30	2	0	on	on	P/T	on	90	skip		
53	P/C	0.225	aft	30	4	0	on	on	P/T	on	90	skip		
54	P/C	0.225	aft	30	5	0	on	on	P/T	off	90	82	68	3
55	P/C	0.3	fwd	20	3	0	on	on	P/T	on	90	skip		
56	P/C	0.3	fwd	20	4	0	on	on	P/T	on	90	skip		
57	P/C	0.3	fwd	20	5	0	on	on	P/T	off	90	85	70	2
58	P/C	0.3	nom	20	2	0	on	on	P/T	on	90	skip		
59	P/C	0.3	nom	20	1	0	on	on	P/T	on	90	skip		
60	P/C	0.3	nom	20	5	0	on	on	P/T	off	90	85	71	2
61	P/C	0.3	aft	20	4	0	on	on	P/T	on	90	skip		
62	P/C	0.3	aft	20	1	0	on	on	P/T	on	90	skip		
63	P/C	0.3	aft	20	5	0	on	on	P/T	off	90	85	72	2
64	P/C	0.3	fwd	30	2	0	on	on	P/T	on	90	skip		
65	P/C	0.3	fwd	30	3	0	on	on	P/T	on	90	skip		
66	P/C	0.3	fwd	30	5	0	on	on	P/T	off	90	86	74	2
67	P/C	0.3	nom	30	2	0	on	on	P/T	on	90	skip		
68	P/C	0.3	nom	30	4	0	on	on	P/T	on	90	skip		
69	P/C	0.3	nom	30	5	0	on	on	P/T	off	90	84	72	2
70	P/C	0.3	aft	30	1	0	on	on	P/T	on	90	skip		
71	P/C	0.3	aft	30	3	0	on	on	P/T	on	90	skip		
72	P/C	0.3	aft	30	5	0	on	on	P/T	off	90	85	72	2

Pilot C - Go-Around and Pitch Capture

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec	Altitude	Time
101	bare	0.225	fwd	20	-	-3	off	on	G/A	on	60		
102	bare	0.225	fwd	20	-	-3	off	on	G/A	on	60	9.2	6.8
103	bare	0.225	nom	20	-	-3	off	on	G/A	on	60		
104	bare	0.225	nom	20	-	-3	off	on	G/A	on	60	15.4	7.2
105	bare	0.225	aft	20	-	-3	off	on	G/A	on	60		
106	bare	0.225	aft	20	-	-3	off	on	G/A	on	60	12.1	6.8
107	bare	0.3	fwd	20	-	-3	off	on	G/A	on	60		
108	bare	0.3	fwd	20	-	-3	off	on	G/A	on	60	6.8	6.9
109	bare	0.3	nom	20	-	-3	off	on	G/A	on	60		
110	bare	0.3	nom	20	-	-3	off	on	G/A	on	60	5.2	8.1
111	bare	0.3	aft	20	-	-3	off	on	G/A	on	60		
112	bare	0.3	aft	20	-	-3	off	on	G/A	on	60	9.5	5.7

#	FCS	Speed	CG	Defl	Ref	FPA	A/T	S/W	Task	Disp	sec
73	bare	0.3	fwd	20	-	0	on	on	P/C	on	30
74	bare	0.225	fwd	20	-	0	on	on	P/C	on	30
75	bare	0.225	nom	20	-	0	on	on	P/C	on	30
76	bare	0.225	aft	20	-	0	on	on	P/C	on	30
77	bare	0.225	fwd	30	-	0	on	on	P/C	on	30
78	bare	0.225	nom	30	-	0	on	on	P/C	on	30
79	bare	0.225	aft	30	-	0	on	on	P/C	on	30
80	bare	0.3	aft	30	-	0	on	on	P/C	on	30
81	bare	0.3	fwd	30	-	0	on	on	P/C	on	30
82	bare	0.3	nom	30	-	0	on	on	P/C	on	30
83	bare	0.3	aft	20	-	0	on	on	P/C	on	30
84	bare	0.3	fwd	20	-	0	on	on	P/C	on	30
85	bare	0.3	nom	20	-	0	on	on	P/C	on	30
86	bare	0.225	nom	20		0	on	on	P/C	on	30
87	P/C	0.3	fwd	20	-	0	on	on	P/C	on	30
88	P/C	0.225	fwd	20	-	0	on	on	P/C	on	30
89	P/C	0.225	nom	20	-	0	on	on	P/C	on	30
90	P/C	0.225	aft	20	-	0	on	on	P/C	on	30
91	P/C	0.225	fwd	30	-	0	on	on	P/C	on	30
92	P/C	0.225	nom	30	-	0	on	on	P/C	on	30
93	P/C	0.225	aft	30	-	0	on	on	P/C	on	30
94	P/C	0.3	aft	30	-	0	on	on	P/C	on	30
95	P/C	0.3	fwd	30	-	0	on	on	P/C	on	30
96	P/C	0.3	nom	30	-	0	on	on	P/C	on	30
97	P/C	0.3	aft	20	-	0	on	on	P/C	on	30
98	P/C	0.3	fwd	20	-	0	on	on	P/C	on	30
99	P/C	0.3	nom	20	-	0	on	on	P/C	on	30
100	P/C	0.225	nom	20		0	on	on	P/C	on	30

F

Pilot Comments Log

This appendix contains the logs of the comments of the pilots as noted during the experiments. The following tables of log are presented:

- Pitch Tracking - Direct Law
- Pitch Tracking - Pitch Rate Command
- Go-around
- Pitch Capturing

For the Pitch Capturing Likert scale, the A,B and C letters represent the opinion of Pilot A, Pilot B, and Pilot C respectively. The sentences that were proposed to the pilots are indicated by a letter as in the following list:

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

Pilot A - Pitch Tracking - Bare Airframe

#	FCS	Speed	CG	Defl	Pilot	Pilot comments (in third person)
1	bare	0.225	fwd	20	A	Not too stressed, saturation and overshoot present and concerning operationally, happy with the pitch rate that he can get, scome PIO are going on but not too concerning. Laughs at side-stick stops. Fine for small captures, but sluggish overall.
2	bare	0.225	fwd	20	B	Stick position is scary. The strategy is: use all the available control authority as soon as you understand you have to pitch up, otherwise you will miss the ramp. Controllable, but the control authority is very limited and unaccceptable. Other than this, capturing does not feel difficult.
3	bare	0.225	fwd	20	C	Response is to slow, damping feels inadequate. Both undershot and overshoot. Tracking "Desired" performance gives some PIO tendency. Cannot pitch-up fast enough.
4	bare	0.225	fwd	30	A	Minor deficiencies, not too stressed, can talk during the experiments. Bothered by the short period, cannot give a higher rating than 4 without improvements. Feels poorely damped. Short period needs compensation. Some overshoot.
5	bare	0.225	fwd	30	B	Easier to track, much more control authority, basically never hit the limits. Some PIO. Tends too drop a little. Damping is fine, feels nice. Need more compensation due to more commanded input. Still sluggish.
6	bare	0.225	fwd	30	C	Likes it better because of improved control authority. Very "second order" response. Short period still bad. Have to be particularly careful not to overshoot. Even more tendency to PIO.
7	bare	0.225	nom	20	A	Getting less pitch rate than before, would like more. Less oscillations, probably learning to fly it. Feels that he can improve the scores easily. Hates the limited control capability.
8	bare	0.225	nom	20	B	Capturing easier, holding requires less corrections, overall very happy. Sluggish but acceptable. A little bit of dropback. His control strategy is to apply one or two corrections after reaching the target. Works well with this CG.
9	bare	0.225	nom	20	C	Bad and inadequate short period oscillations. Quite sluggish. Some (little) tendency to PIO, particularly for Desired performance. Tries to raise the gain to suppress PIO, but does not manage. Did not notice dropback. Performance will improve greatly with training.
10	bare	0.225	nom	30	A	Much better. Also starts to understand how this aircraft works. Easier to follow target, but more PIO. Pitch rate is fine, but capturing is a bit difficult. It is easier to capture from above. Requires compensation, but not bad overall, cannot go higher than 4.
11	bare	0.225	nom	30	B	Response is more direct, easier to stop. Just have to be careful not to overcompensate. This is his favourite configuraiton. PIO only if you are not careful. No escessive dropback or overshoot.
12	bare	0.225	nom	30	C	Feels badly damped, bad overshoot. Clear tendency to PIO. Very sluggish.
13	bare	0.225	aft	20	A	Easiest so far. Sees less PIO. Still feels sluggish, but now it's fine (compared to before?). Easy to see the difference from 20 to 30 deg max defl. Operationally this seems fine. Wants more control, but this CG is perfectly fine, better than before. Can use a different, easier control technique: after the input, comes back to neutral very smoothly and it works very well, much easier. Very happy with the overshoot-dropback balance, using the A/C dynamicsat his advantage.
14	bare	0.225	aft	20	B	Less responsive to steering input than other configurations, needs a faster reactions. A bit sluggish on capturing (after releasing the stick / reversing the input).
15	bare	0.225	aft	20	C	A lot of workload due to the very bad short period, a lot of overshoot (too much). Requires a lot of training. The response is sluggish so you are always too late. Workload is too high.
16	bare	0.225	aft	30	A	Definitely excessive maneuvering, 30 degrees feel excessive, gets very high rates. More overshoot, but it's easy to adapt to it. Had a lot of time to look around. Overshoots a lot. Should improve a lot with training. Not good enough for a 3.
17	bare	0.225	aft	30	B	More sluggish, you need to anticipate the overshoot more than before. The inertia of the pitch moment encourages overcompensation. Requires a bit more training.
18	bare	0.225	aft	30	C	Very bad, can casue PIO easily, not very differnt from nominal CG. Preferred forward CG since it felt more responsive.

19	bare	0.3	fwd	20	A	20 degrees now feels fine. Very happy to see the ground (better sight angle), feels a a lot more comfortable. Everything "speeds up nicely". Needs some more training to adapt to the new speed. Much less sluggish, but still needs some anticipation. Undershoots a bit. Has to remember not to release too soon. The "easier" control strategy does not work anymore, the difficult strategy is needed again. Compensating quite a bit, has to work for a high score, cannot give more than 4.
20	bare	0.3	fwd	20	B	When you leave the stick it damps down nicely. Easy to track. Easy to fly. Stays where you leave it. More agile than other aircrafts. Initially difficult to adjust and understand the type of response. Quite happy overall, no specific complains. You have to compensate a bit due to a bit of dropback.
21	bare	0.3	fwd	20	C	Better than 0.2 Mach. Response less sluggish. Damping feels better. Still not fast enough and still a bit sluggish, and damping not enough. Have to be careful not to overcompensate.
22	bare	0.3	fwd	30	A	Hates the dropback. When he lets go, the nose drops a lot. It is prone to PIO. Really responsive though, Feels really nice to have so much control authority. Maybe even too much, feels like a fighter. High pitch rate causes PIO. Dropback very annoying, cant give a higher rating. Learning how to deal with the dropback helps a lot. Pretty easy in the end.
23	bare	0.3	fwd	30	B	More sensitive than before. There is a tendency to PIO if you are too active on the stick. Touchy, also on small inputs. Not tendency to overshoot, quite a tendency to dropback, but if you know it and train for it it's fine.
24	bare	0.3	fwd	30	C	Not bad after all. Might be his favourite CG. Likes that it's more immediate and faster. The short period still needs improvements. Still have to be careful for the tendency to PIO. Still sluggish. Still has to work hard for good scores. Less overshoot than before, he thinks because of the new "pulses-like" control strategy.
25	bare	0.3	nom	20	A	Definitely less dropback, he prefers. Flies nice, better than with 30 degrees. More of what you would expect. Actually, the differneces due to CG position are small, and it does not take much to learn to adapt to the small dropback/overshoot difference.
26	bare	0.3	nom	20	B	On-going learning. Feels more friendly but lees direct. Flies good and predictable. More gently and predictable than the other configurations. Less corrections needed.
27	bare	0.3	nom	20	C	Have to work too hard to get desired performance. Still sluggish, still easy to get into PIO.
28	bare	0.3	nom	30	A	30 degrees is a bit too much. More PIO. Very easy one with a little bit of training, very easy to fly. So relaxed flying this.
29	bare	0.3	nom	30	B	Good response to initial and also to final inputs. Nice overall, but it's more sensitive and might tend to more overcompensation.
30	bare	0.3	nom	30	C	More tendency to overshoot (than forward CG). Not much more to say.
31	bare	0.3	aft	20	A	No unpleasant deficiencies. Needs to adapt to the new CG, but the difference is small. Needs a different type of anticipation, now he is overshooting a bit. So relaxing.
32	bare	0.3	aft	20	B	Need to be aware of the larger steering input. Feels like a slow, heavy aircraft, but it is nice to control. When you neautralize the deflection you can see more tendency to overshoot. A bit more sluggish.
33	bare	0.3	aft	20	C	Realizes he is flying a bit more "pulse-like", more 1st order dynamics. (after some extra runs with forward CG he says this strategy works better with forward CG). Still same issues as before, sluggish, tendency to PIO, he is surre tha training will help a lot. He is starting to like it better. There is more overshoot than before.
34	bare	0.3	aft	30	A	A lot of fun, feels like he is not even compensating, the pitch rate is really good. Would not call it sluggish, actually quite fast, but not abrupt. Very easy to control. Easy to get high scores.
35	bare	0.3	aft	30	B	Nothing to say. Really difficult to say which CG he prefers, probably the nominal one.
36	bare	0.3	aft	30	C	More overshoot, does not like it. Prefers the more responsive forward CG. If you fly it with impulses you reduce the overshoot. Training will be really beneficial.

Pilot A - Pitch Tracking - Pitch Rate Command

#	FCS	Speed	CG	Defl	Pilot	Pilot comments (in third person)
37	P/C	0.225	fwd	20	A	So easy to track and capture. Full stick back is not enough and there is nothing he can do about it. The control saturation is a big deal, scary. No overshoot or dropback, but he would be concerned flying with this little control authority.
38	P/C	0.225	fwd	20	B	Lack of control authority is very concerning for emergency scenarios. If you miss a target it's difficult to go back. In real wheather this would be insufficient and dangerous. Pitch-up very slow, pitch-down acceptable.
39	P/C	0.225	fwd	20	C	Pitch Rate Command makes your life so much easier. Control authority however was poor. Still would like a faster response. No dropback or overshoot, zero tendency to PIO. Still a little bit sluggish, can be improved.
40	P/C	0.225	fwd	30	A	Still a bit sluggish, compensating but not much. Minor annoying compensation needed. Very very annoyed by the reduced sight angle. Since controlling requires less attention now, he can focus on outside view, and hates the sight angle. A bit sluggish, but very nice and predictable overall.
41	P/C	0.225	fwd	30	B	Fixed all the 20 degrees issues. Adequate pitch rate, easy to keep up with the target.
42	P/C	0.225	fwd	30	C	Easier to fly, follows your commands better, good damping of the response. No tendency too PIO. Not much to complain about. Not a 1: some very minor improvements can be made for a faster and less overshooting response. Not a 3: the workload is really really low. Clearly better than 20 deg: more control authority and less sluggish.
43	P/C	0.225	nom	20	A	Scared by how "nose-high" this is. Cannot feel a lot of difference compared to before. Aircraft a bit sluggish but very ok, almost perfect for the rest.
44	P/C	0.225	nom	20	B	A bit less direct than before, more friendly, likes more. Needs large inputs to control. A little bit of overshoot. Very concerned for the sigh angle: visibility is not sufficient and does not see air traffic. Might feel very weird for the passengers.
45	P/C	0.225	nom	20	C	Would like to be able to command higher pitch rates. Would like a faster response. There is a little bit more overshoot than forward CG. Still requires quite some effort to get desired performance.
46	P/C	0.225	nom	30	A	More pleasant than the previous one. Really easy. Not compensating at all. Totally eliminated the oscillations. Feels very nice and predictable.
47	P/C	0.225	nom	30	B	Feels a bit more damped (confused). The rest is same as before.
48	P/C	0.225	nom	30	C	Little difference compared to the other configurations. Just a tiny bit more overshoot, maybe. No PIO.
49	P/C	0.225	aft	20	A	Feels very similar. Probably would not be able to tell them apart. All good, just minor corrections for compensation.
50	P/C	0.225	aft	20	B	More tendency to overshoot. Less abrupt stops compared to before. Hard to say which one he prefers. No PIO or excessive sluggishness. Should be improved for on-set and stop-off response.
51	P/C	0.225	aft	20	C	Response is still a little bit too slow, would like higher rates. Overshoot again a little bit more. Preferred forward CG.
52	P/C	0.225	aft	30	A	Same as before.
53	P/C	0.225	aft	30	B	Follow nicely, very good control system. Would like higher pitch rate. More relaxing than Direct Law. More precise, less PIO tendency.
54	P/C	0.225	aft	30	C	Would like to command higher pitch rates. Maybe the damping was a little bit worse.
55	P/C	0.3	fwd	20	A	Operationally it feels perfectly fine. Some overshoot, probably because no training. The attitude and reduced sight angle is still annoying, but definitely acceptable. Training would help.

56	P/C	0.3	fwd	20	B	A bit too conservative on commandable pitch rate. Have to get a feeling for the onset. Immediately holds the target, should be a bit more damped. Hardly any dropback or overshoot. Very nice overall.
57	P/C	0.3	fwd	20	C	I don't see so much difference. Nothing really to complain about.
58	P/C	0.3	fwd	30	A	Differences are really minimal, cannot tell the configuraitons apart anymore. Just some very minor issues prevent him from giving a 1 rating.
59	P/C	0.3	fwd	30	B	It's good, a bit binary. Onset is a bit easier, more pronounced.
60	P/C	0.3	fwd	30	C	Can't see much difference. Same rating, same reasons.
61	P/C	0.3	nom	20	A	Same as before.
62	P/C	0.3	nom	20	B	Easy to fly, all goes really well, just at the very beginning it's a bit difficult to understand the motion cues. Likes how it responds. Comes back a bit fast when you release the stick, but not too much. Responsive, maybe more than civilian A/C. Some minor doubts on initial and final response, can do a bit better, but almost perfect overall.
63	P/C	0.3	nom	20	C	Can't see much difference. Same rating, same reasons.
64	P/C	0.3	nom	30	A	Same as before.
65	P/C	0.3	nom	30	B	Not a 3 because there is nothing unpleasant, not a 1 because on-set and final reponse can be slightly improved. Basically no overshoot, dropback or PIO.
66	P/C	0.3	nom	30	C	Can't see much difference. Same rating, same reasons.
67	P/C	0.3	aft	20	A	Basically the same again. Operationally just perfect. Attitude is not annoying now.
68	P/C	0.3	aft	20	B	Very similar to before. Sees a little tendency to overshoot. The previous one (nominal CG) feels just a little bit more predictable.
69	P/C	0.3	aft	20	C	Can't see much difference. Same rating, same reasons. Really like the Pitch Rate Command, hides all the deficiencies.
70	P/C	0.3	aft	30	A	Same as before.
71	P/C	0.3	aft	30	B	Same as before. Would expect more difference, but does not see much.
72	P/C	0.3	aft	30	C	Same as before.

Pilot A - Go-Around and Pitch Capture						
#	FCS	Speed	CG	Defl	Pilot	Comments (in third person)
73	bare	0.225	fwd	20	A	Don't see a lot, have to really lean forward to see. Has to adjust the seat to be positioned higher and more comfortably. Immediately felt the stops of control authority, which is very uncomfortable. The reaction of the aircraft, however, was quite ok. Did not feel too sluggish. During pull-up did not see any unexpected loss of altitude. The sight angle did have a negative impact on the task, but the pitch angle did not. The aircraft was not abrupt at all. Climbing was "super easy", but the flight path angle can shoot up a bit more than what you would expect. Levelling-off at 500ft was also very easy. Very bad sight angle - cannot see runway properly. But maneuvering was easy and compensation was very low.
74	bare	0.225	fwd	20	B	The high pitch attitude is very annoying. The view is scary: see basically nothing, just a little bit of horizon. Not enough control authority, very dangerous in real situations and emergencies. It is controllable, flyable, but in case of contigencies it feels dangerous. Certainly not an abrupt response, actually a quite sluggish.
75	bare	0.225	fwd	20	C	You need to know the aircraft, since the response is different from what you would expect. A flight path angle controller would be beneficial. Control authority is very limited. Pulling-up requires knowledge. Climb is very easy. Levelling-off is particularly difficult because the angle of attack is very high and you would not expect it. Training is mandatory, because it is difficult to predict the attitude of the aircraft and the distance from the runway just based on the visuals. A FPA indicator is mandatory, and possibly also a vertical speed indicator, that would help a lot. Pilots will have a hard time landing this aircraft.
76	bare	0.225	nom	20	A	This is way better than forward CG. The reaction of the aircraft is really ok. Sight angle has a very negative impact on the task. Natural tendency to push the nose down to see more. The rest is as before - no unusual loss of altitude, sluggish response but not too bad, actually close to ideal. Having enough control authority feels so much better than with forward CG.
77	bare	0.225	nom	20	B	Much more authority and comfort than with forward CG. It flies gently. There remain issues related to sight angle and sluggish response, but this feels more acceptable than the other configuration (forward CG).
78	bare	0.225	nom	20	C	Now can see the runway a bit better, sight angle is better but it is still difficult to see well. Tries to fly controlling directly the FPA, but this makes the aircraft unstable due to lag.
79	bare	0.225	aft	20	A	Same as for nominal CG.
80	bare	0.225	aft	20	B	Can feel the better sight angle and pitch attitude compared to forward CG, and it feels mucch better. Would still like a couple of degrees more nose-down. Sight angle is still bad, but much better than before. Gives more time to see the runway and perform a proper go-around. Hard to tell if the pull-up response is better with this CG. The angle of attack is very high at level-off, which makes it difficult to understand how to level-off. Needs practice/specific knowledge, since with normal aircraft you would level-off with much a smaller angle of attack. Climb is very easy.
81	bare	0.225	aft	20	C	Likes to control both FPA and pitch angle at the same time. It seems to work best for him. When doing so, the response of the aircraft seems quite good. Instrumental approach and landing seem ok, and approach based on visuals seems ok as well. However he is very concerned for visual landing.
82	bare	0.3	fwd	20	A	Sight angle is much better than at low speed. Now "I see everything that I want to see." Feels comfortable. Thinks that training will be beneficial to perform the task more confidently, but it is not essential.

83	bare	0.3	fwd	20	B	Altitude loss was acceptable. Easy, very light to fly. Stable, good visibility, pitch rate is good, can be gentle on the controls. Overall very happy.
84	bare	0.3	fwd	20	C	This feels more normal, more like what he is used to. Still a bit high pith attitude, would prefer less. Everything goes faster and you have to be more focused. Still requires quite some anticipation for levelling-off. Visual landing seems still scary, a lot of training is mandatory.
85	bare	0.3	nom	20	A	Same as for forward CG - sight angle is better, A/C response is overall better at this speed, and all the three phases of the go-around can be performed comfortably (pull-up, climb, level-off).
86	bare	0.3	nom	20	B	A little bit easier to pull-up. Confirms his mildd preference for this CG position. Visuals and pitch angle are ok.
87	bare	0.3	nom	20	C	Feasible, but same as before, requires quite some training. FPA is a bit unpredictable and one must know the target pitch attitude.
88	bare	0.3	aft	20	A	Very good to have all this control authority. Coming from the more sluggish configurations makes him fly more aggresively. Sees a big difference between fast and slow configurations, but not too much between different CG positions. Comfort wise, in the end he thinks he sees enough but only if he sits a little differently compared to usual aircraft.
89	bare	0.3	aft	20	B	Easy to pull-up too much, there is more control authority than before. Maybe even a bit too responsive.
90	bare	0.3	aft	20	C	You really have to get used to this different sight angle. He is sure it will be a real challenge for pilots. Very difficult to guess the distance from main gears to ground. The response is pretty much the same as before, a little bit worse short period and a bit more difficult to level-off, but only minor differences.

#	FCS	Speed	CG	Defl							
91	bare	0.225	fwd	20	a	b	c	d	e	f	g
		Strongly disagree					A		A		
		Disagree				BC	C			A	B
		Neutral			ABC			C	BC	C	A
		Agree				A	B	B		B	C
		Strongly agree						A			
92	bare	0.225	nom	20	a	b	c	d	e	f	g
		Strongly disagree			AB		A		A		
		Disagree				B	B		BC	AB	
		Neutral				C	C	AB		C	
		Agree			C	A		C			C
		Strongly agree									AB
93	bare	0.225	aft	20	a	b	c	d	e	f	g
		Strongly disagree			AB					A	
		Disagree				AB	ABC		ABC	B	
		Neutral						A			
		Agree			C	C		C		C	C
		Strongly agree						B			AB
94	bare	0.3	fwd	20	a	b	c	d	e	f	g
		Strongly disagree			AB		A		B	B	
		Disagree			C	C		AB	A	AC	
		Neutral				B	BC	C	C		
		Agree				A					B
		Strongly agree									AC
95	bare	0.3	nom	20	a	b	c	d	e	f	g
		Strongly disagree			AB		A	B		B	
		Disagree			C	BC	BC	A	AB	AC	
		Neutral				A		C	C		
		Agree									
		Strongly agree									ABC
96	bare	0.3	aft	20	a	b	c	d	e	f	g
		Strongly disagree			AB				A	AB	
		Disagree				AB		AB	BC	C	
		Neutral			C		ABC				
		Agree				C		C			
		Strongly agree									ABC
97	bare	0.225	fwd	30	a	b	c	d	e	f	g
		Strongly disagree			A						
		Disagree			BC	BC	AC			A	
		Neutral						AC	AB		
		Agree				A	B	B	C	BC	
		Strongly agree									ABC
98	bare	0.225	nom	30	a	b	c	d	e	f	g

		Strongly disagree			AB						
		Disagree			C	B	AB	A	AB	AB	
		Neutral				C	C	B			
		Agree				A		C	C	C	
		Strongly agree									ABC
99	bare	0.225	aft	30	a	b	c	d	e	f	g
		Strongly disagree			AB					A	
		Disagree				AB	ABC	A	AB	B	
		Neutral			C						
		Agree				C		C	C	C	
		Strongly agree						B			ABC
100	bare	0.3	fwd	30	a	b	c	d	e	f	g
		Strongly disagree			B			A	B		
		Disagree			C	C		B		B	
		Neutral				B	ABC	C	AC	A	
		Agree				A					
		Strongly agree								C	ABC
101	bare	0.3	nom	30	a	b	c	d	e	f	g
		Strongly disagree			AB			AB		B	
		Disagree			C	BC	ABC		B	A	
		Neutral						C	AC		
		Agree				A					
		Strongly agree								C	ABC
102	bare	0.3	aft	30	a	b	c	d	e	f	g
		Strongly disagree			AB	A		A			
		Disagree				B	A	B	B	AB	
		Neutral			C		BC		AC		
		Agree				C		C			
		Strongly agree								C	ABC
103	P/C	0.225	fwd	20	a	b	c	d	e	f	g
		Strongly disagree				ABC	BC	B	ABC	AB	
		Disagree			AC					C	
		Neutral			B		A	AC			C
		Agree									AB
		Strongly agree									
104	P/C	All the other configs.			a	b	c	d	e	f	g
		Strongly disagree			ABC	AB	BC	AB	ABC	ABC	
		Disagree				C	A				
		Neutral						C			
		Agree									
		Strongly agree									ABC

G

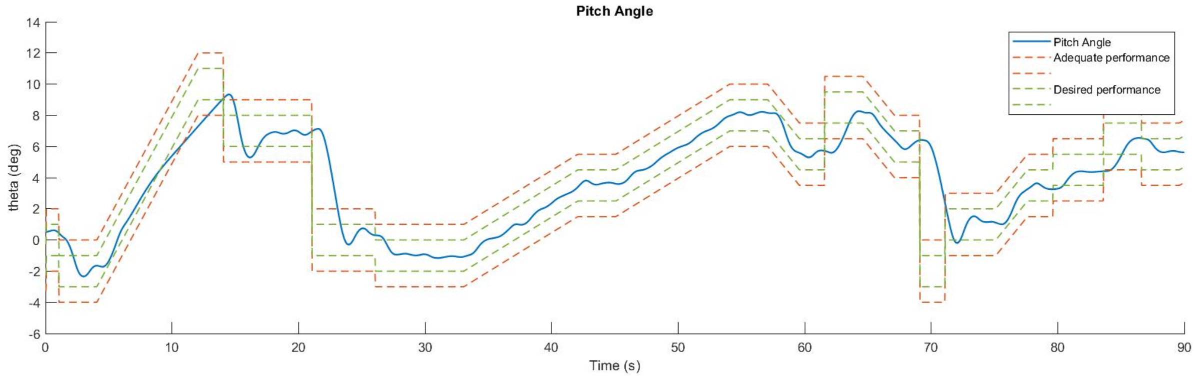
Pitch Tracking time logs

A selection of representative time logs from the Pitch Tracking experiments is collected in this appendix. The figures presented are:

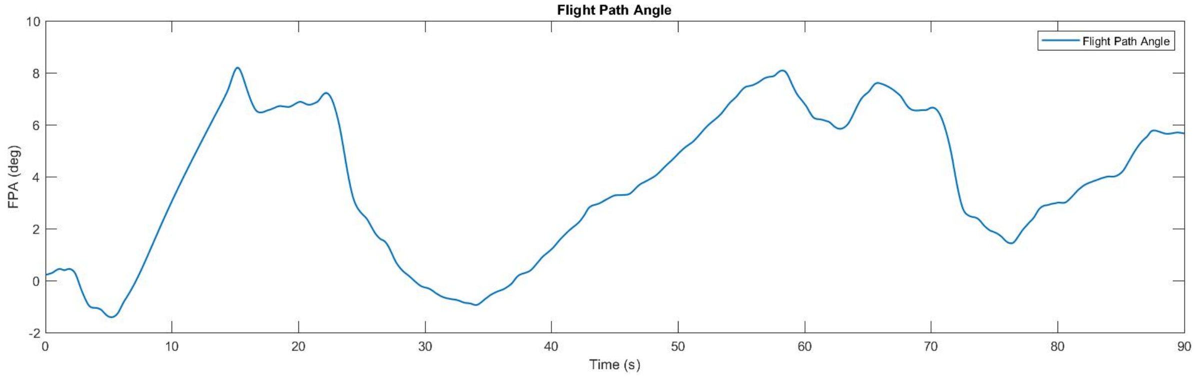
- Pitch Angle vs Target,
- Flight Path Angle,
- Pitch Rate,
- Side-stick input.

The four figures are presented for the following seven scenarios, which include the control saturation problem as dealt with by the three pilots, two runs at 0.3 Mach, and two runs with Pitch Rate Command:

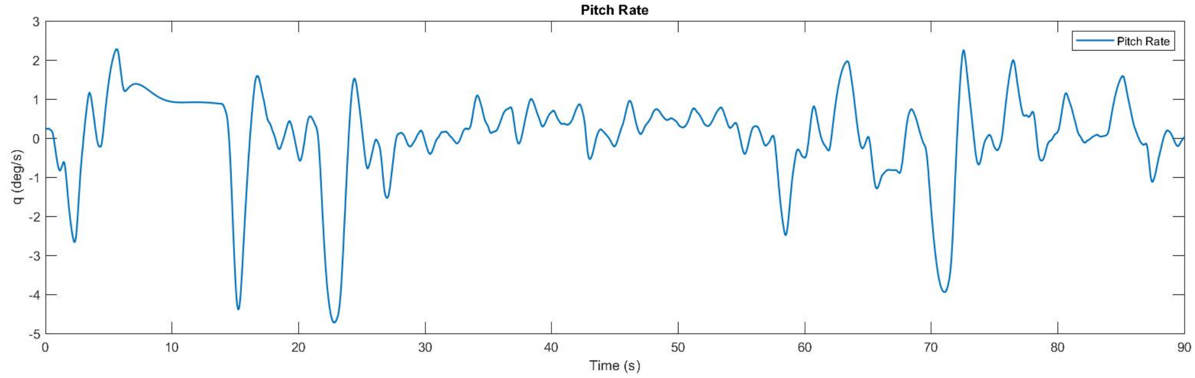
- Figure G.1: fwd CG, 0.225 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot A;
- Figure G.2: fwd CG, 0.225 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot B;
- Figure G.3: fwd CG, 0.225 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot C;
- Figure G.4: fwd CG, 0.300 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot A;
- Figure G.5: aft CG, 0.300 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot A;
- Figure G.6: fwd CG, 0.225 Mach, 20 deg max elevons deflection, Pitch Rate Command - Pilot A;
- Figure G.7: aft CG, 0.225 Mach, 20 deg max elevons deflection, Pitch Rate Command - Pilot A;



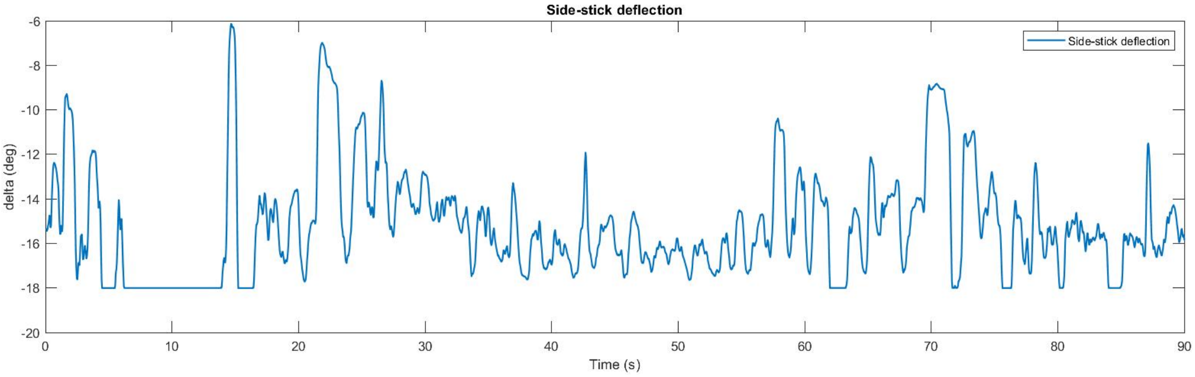
(a) Pitch Angle



(b) Flight Path Angle

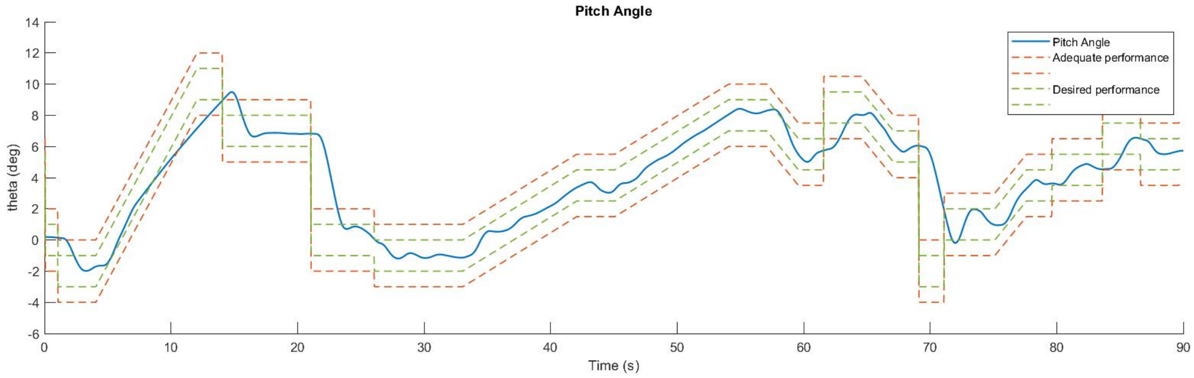


(c) Pitch Rate

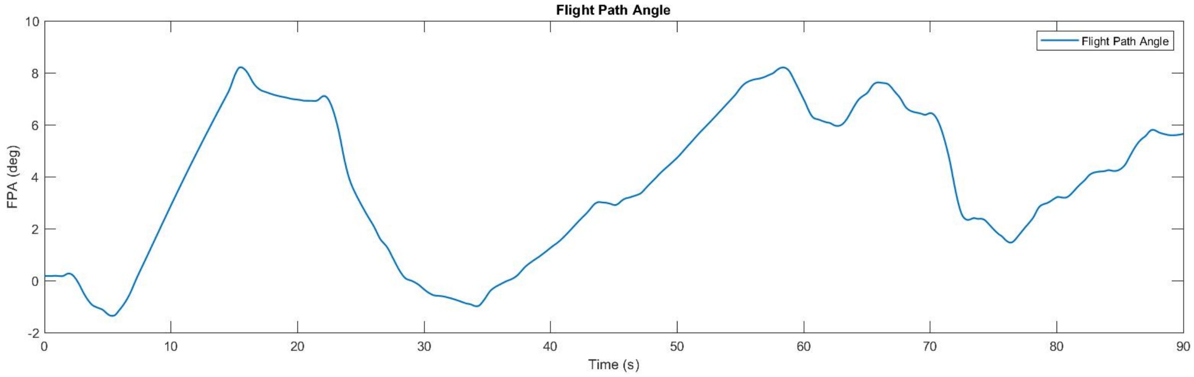


(d) Side-stick deflection

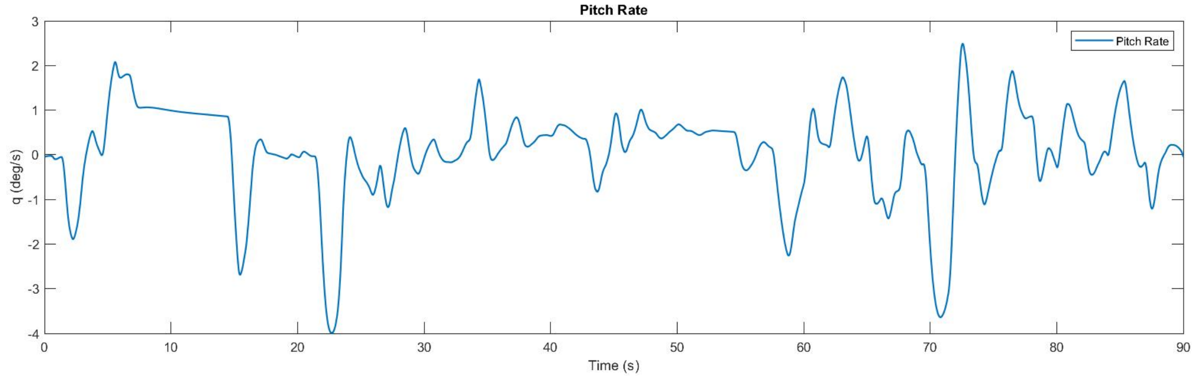
Figure G.1: Forward CG, 0.225 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot A.



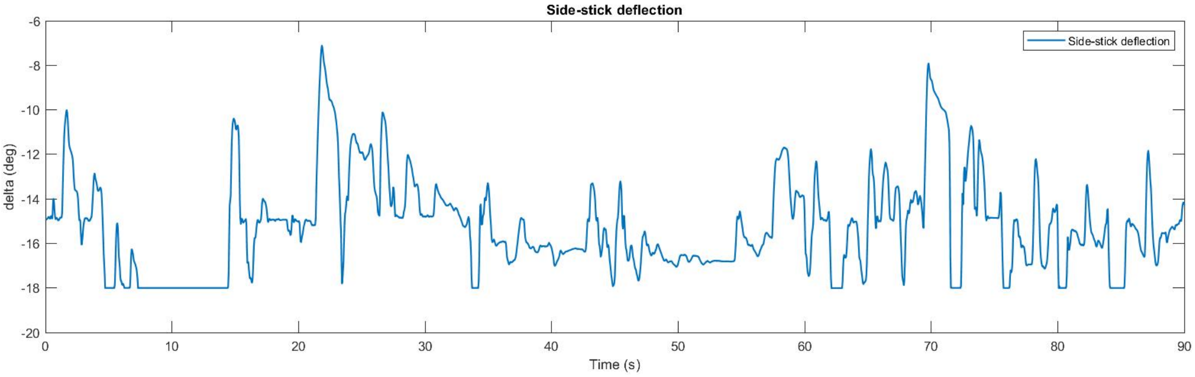
(a) Pitch Angle



(b) Flight Path Angle

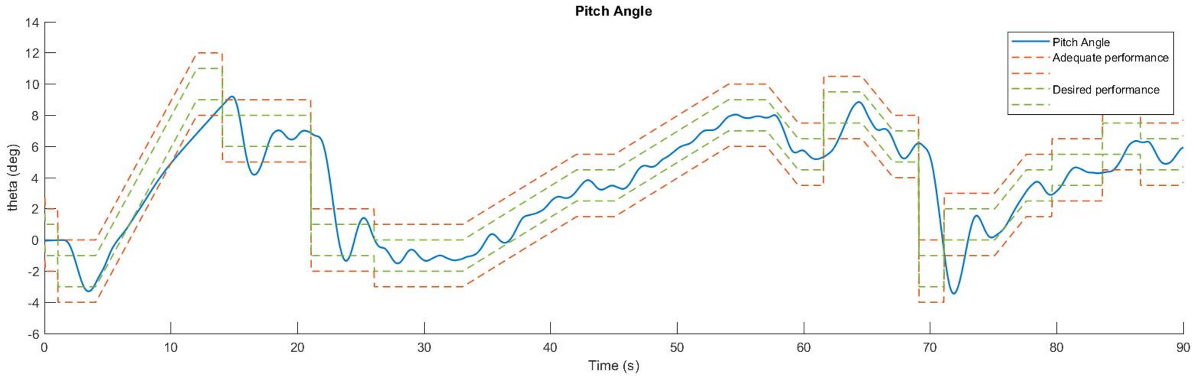


(c) Pitch Rate

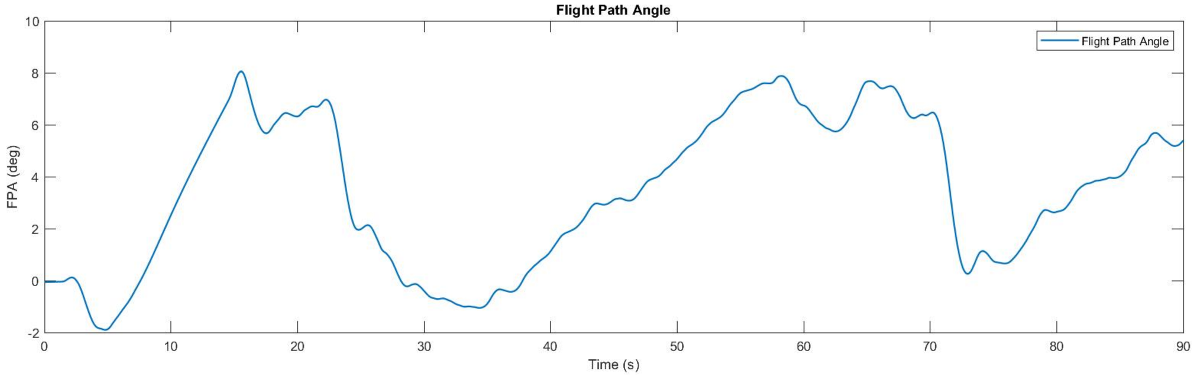


(d) Side-stick deflection

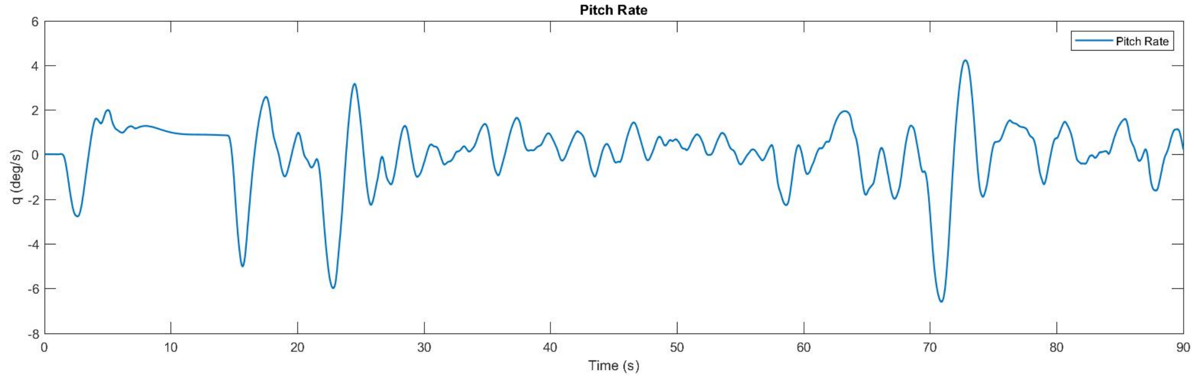
Figure G.2: Forward CG, 0.225 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot B.



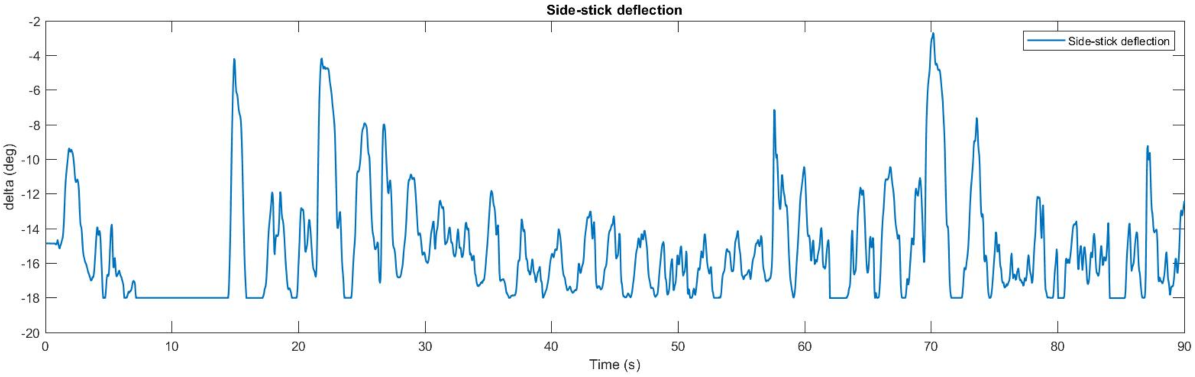
(a) Pitch Angle



(b) Flight Path Angle

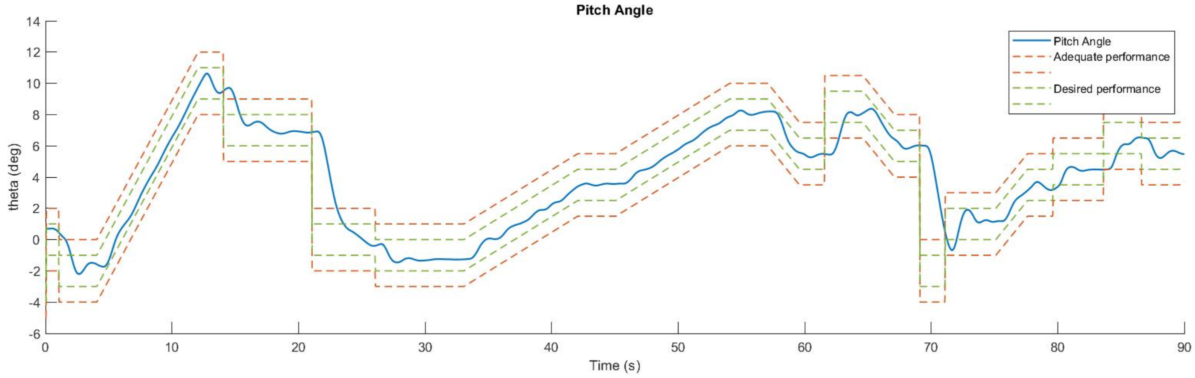


(c) Pitch Rate

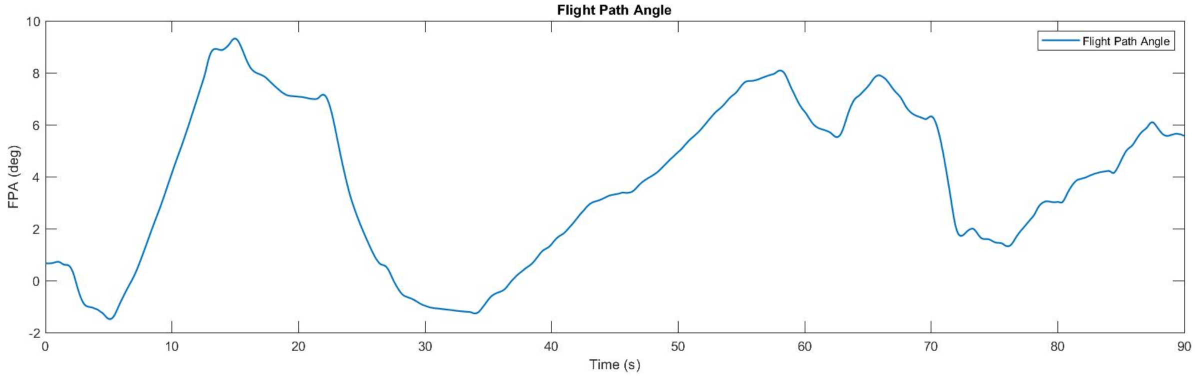


(d) Side-stick deflection

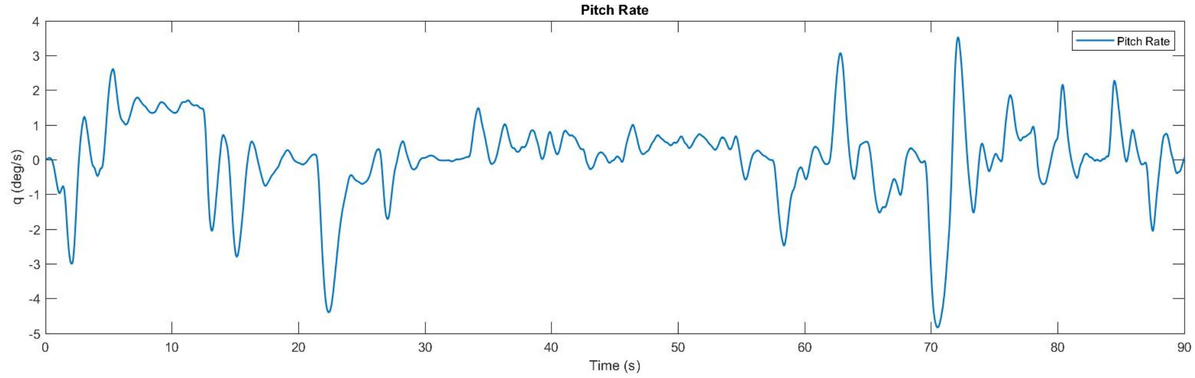
Figure G.3: Forward CG, 0.225 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot C.



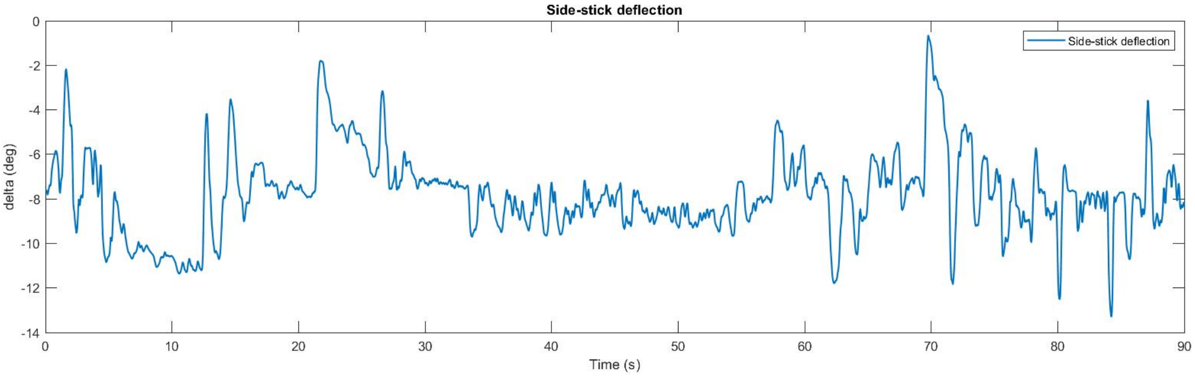
(a) Pitch Angle



(b) Flight Path Angle

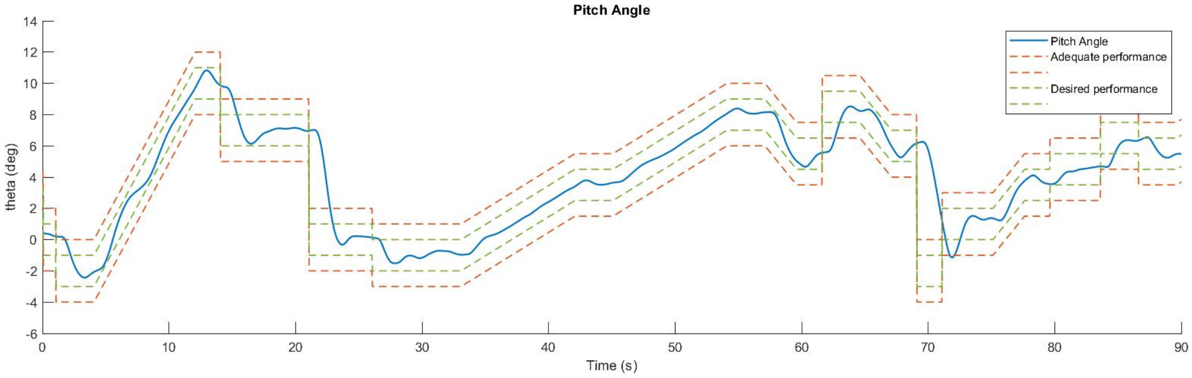


(c) Pitch Rate

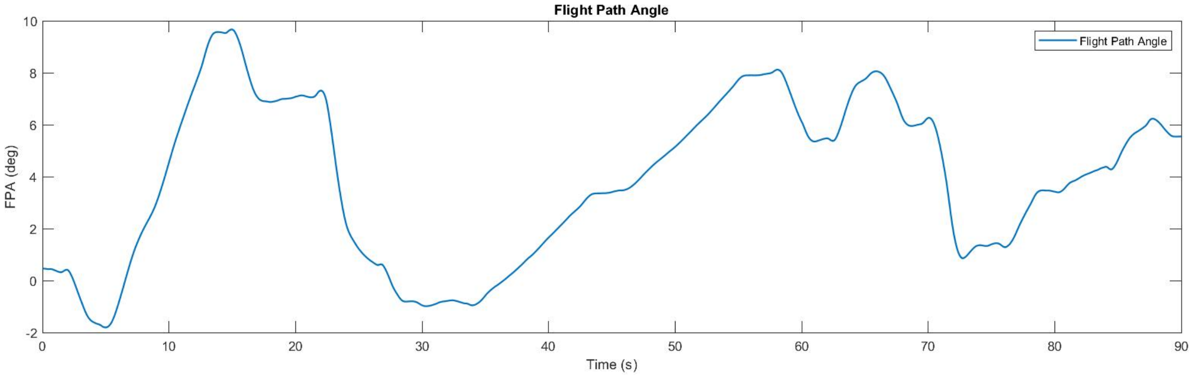


(d) Side-stick deflection

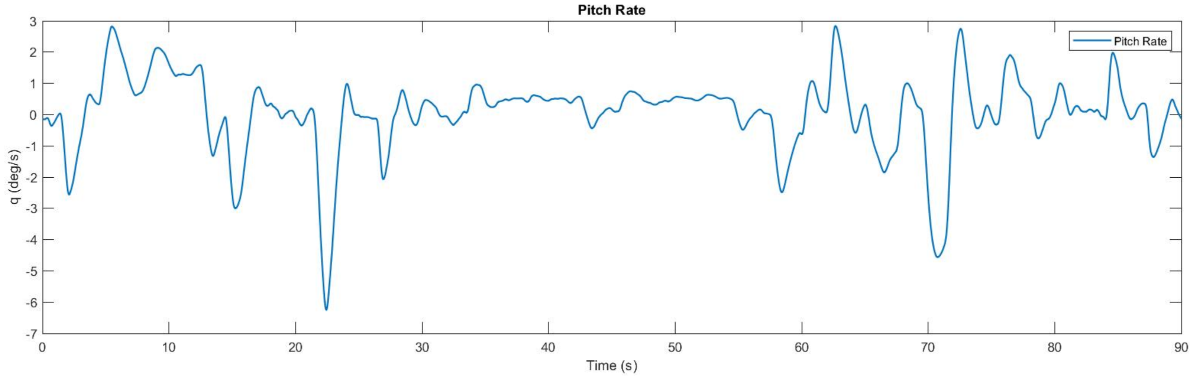
Figure G.4: Forward CG, 0.3 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot A.



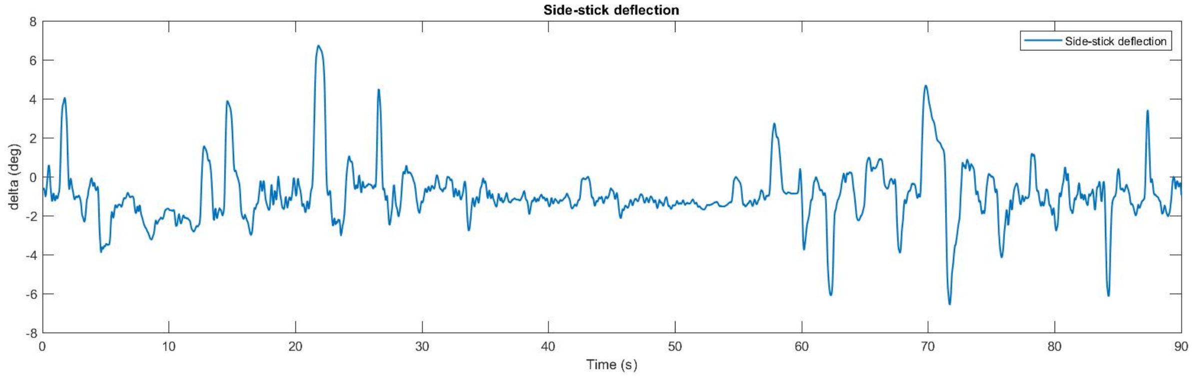
(a) Pitch Angle



(b) Flight Path Angle

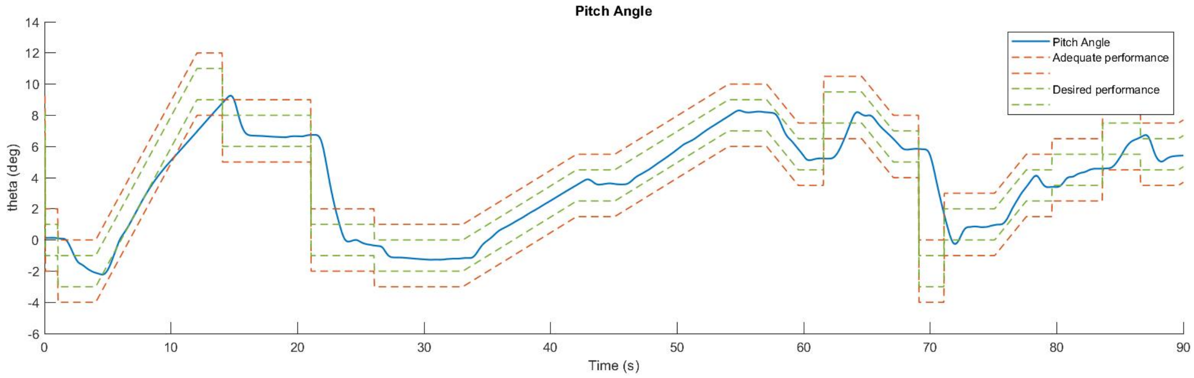


(c) Pitch Rate

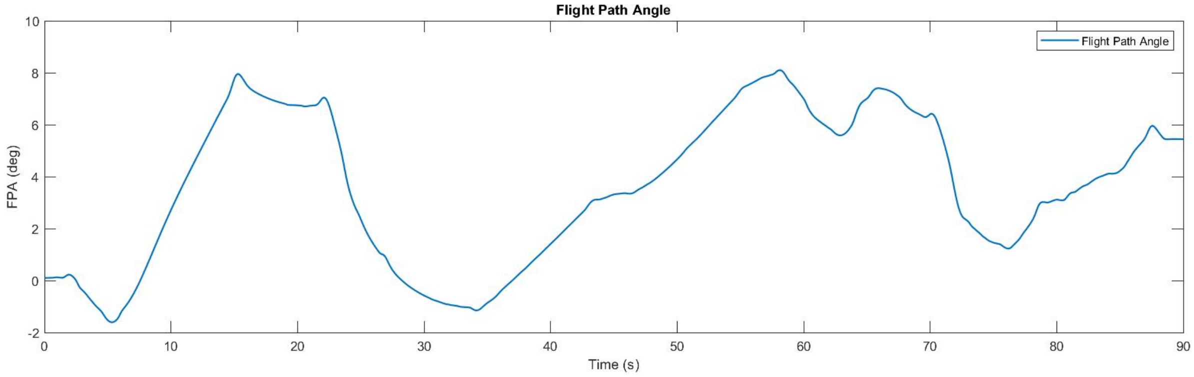


(d) Side-stick deflection

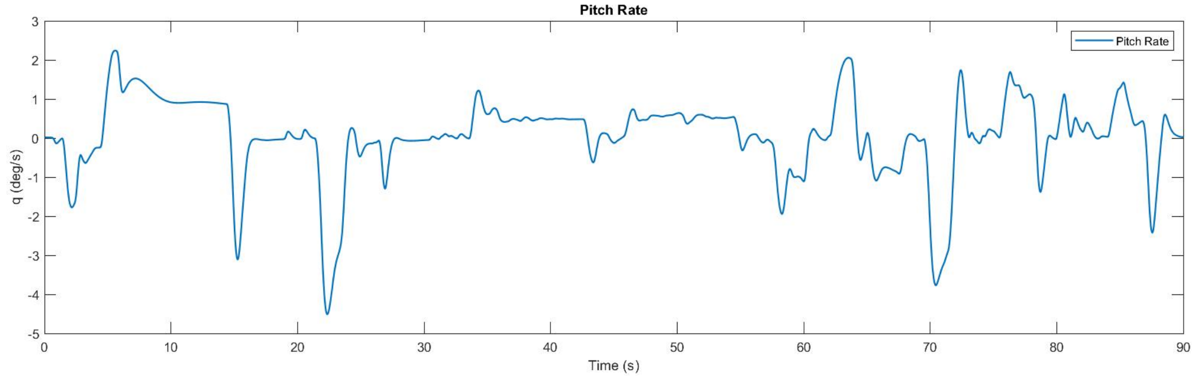
Figure G.5: Aft CG, 0.3 Mach, 20 deg maximum elevons deflection, Direct Law - Pilot A.



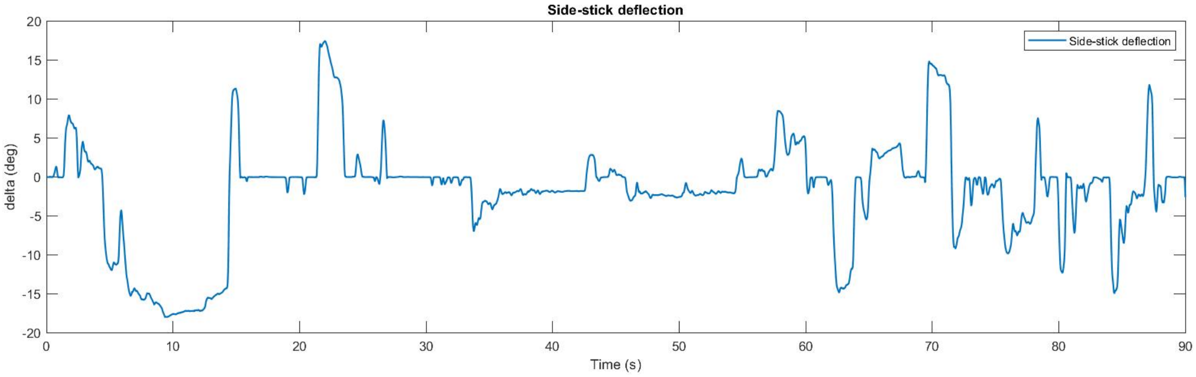
(a) Pitch Angle



(b) Flight Path Angle

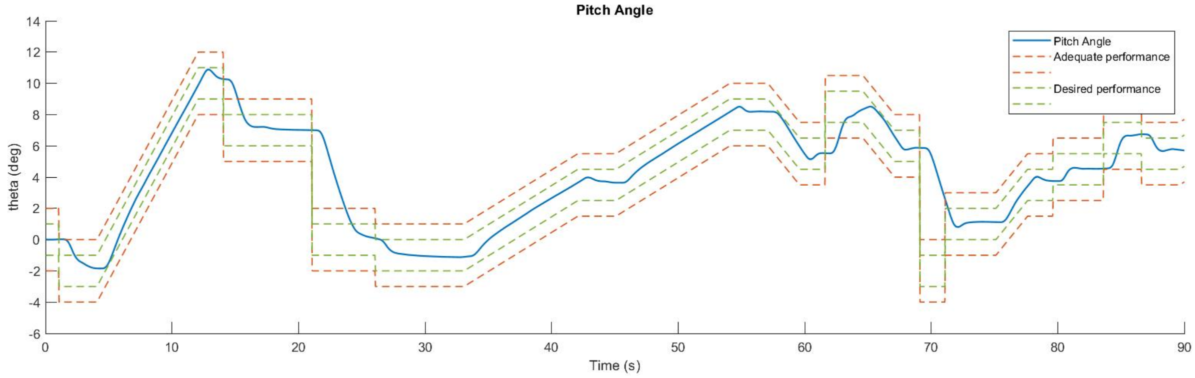


(c) Pitch Rate

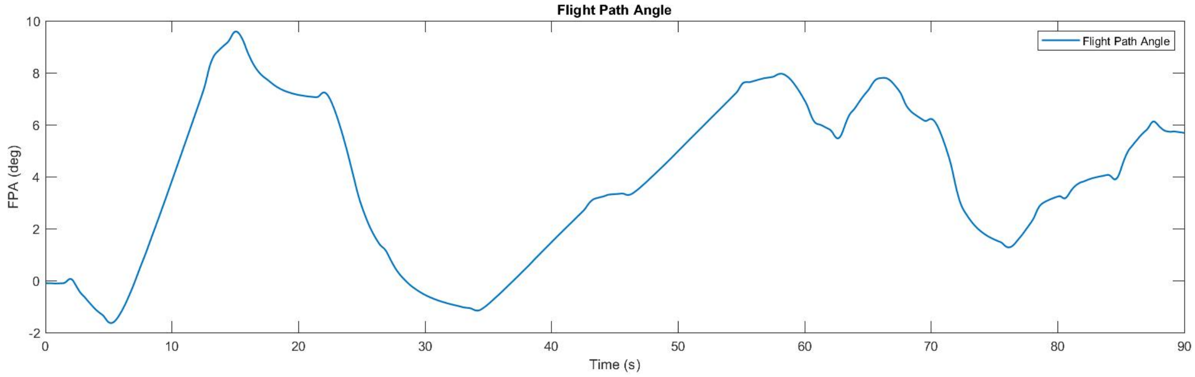


(d) Side-stick deflection

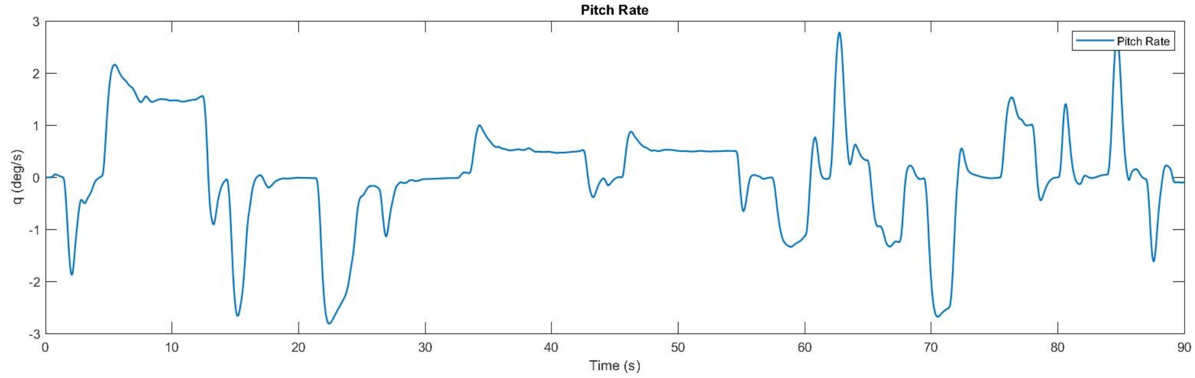
Figure G.6: Forward CG, 0.225 Mach, 20 deg maximum elevons deflection, Pitch Rate Command - Pilot A.



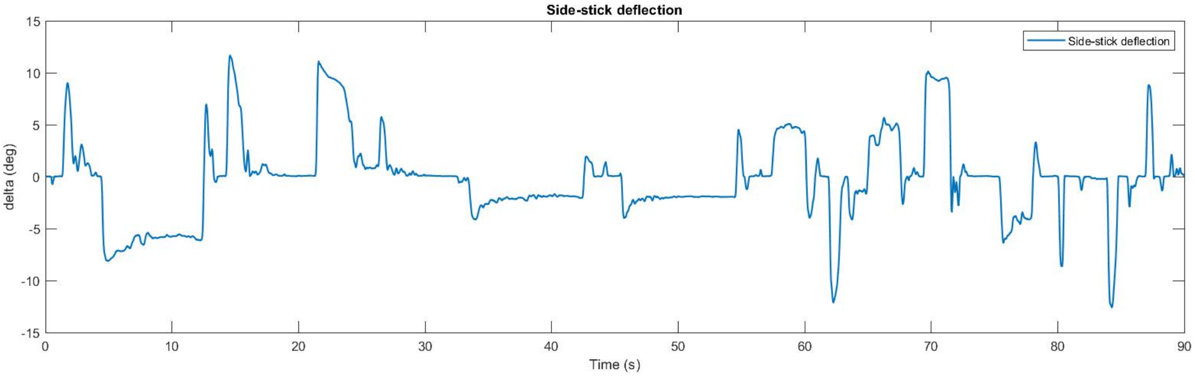
(a) Pitch Angle



(b) Flight Path Angle



(c) Pitch Rate



(d) Side-stick deflection

Figure G.7: Aft CG, 0.225 Mach, 20 deg maximum elevons deflection, Pitch Rate Command - Pilot A.

H

Preliminary Analysis Supplement

This appendix contains a supplement to the preliminary analysis presented in the paper. In particular, the following plots are presented:

- Figure H.2 - Time domain response of the short-period only approximation; forward CG, 0.3 Mach, -0.1 deg step input on all elevons.
- Figure H.3 - Time domain response of the short-period only approximation; nominal CG, 0.25 Mach, -0.1 deg step input on all elevons.
- Figure H.4 - Time domain response of the short-period only approximation; aft CG, 0.2 Mach, -0.1 deg step input on all elevons.
- Figure H.5 - Short period pole-zero map, all configurations.
- Figure H.6 - Phugoid pole-zero map, all configurations.
- Figure H.7 - Comparison of original equations of motion with Auto-throttle mode engaged vs short period only approximation; pitch angle.
- Figure H.8 - CAP computation with pitch rate derivative and normal acceleration; forward CG, 0.3 Mach, -0.1 deg step input on all elevons.
- Figure H.9 - CAP computation with pitch rate derivative and normal acceleration; nominal CG, 0.25 Mach, -0.1 deg step
- Figure H.10 - CAP computation with pitch rate derivative and normal acceleration; aft CG, 0.2 Mach, -0.1 deg step
- Figure H.11 - Bandwidth criterion evaluation; forward CG, 0.3 Mach.
- Figure H.12 - Bandwidth criterion evaluation; nominal CG, 0.25 Mach.
- Figure H.13 - Bandwidth criterion evaluation; aft CG, 0.2 Mach.
- Figure H.14 - Flight Path Gibson criterion evaluation; full picture; all configurations.
- Figure H.15 - Flight Path Gibson criterion evaluation; medium zoom; all configurations.
- Figure H.16 - Flight Path Gibson criterion evaluation; close zoom; all configurations.
- Figure H.17 - Dropback Gibson criterion evaluation; dropback analysis; all configurations.
- Figure H.18 - Dropback Gibson criterion evaluation; pitch rate analysis computation; all configurations.
- Figure H.1 - Separated eigenmodes comparison; short period vs phugoid; complete dynamics; example for aft CG, 0.2 Mach.

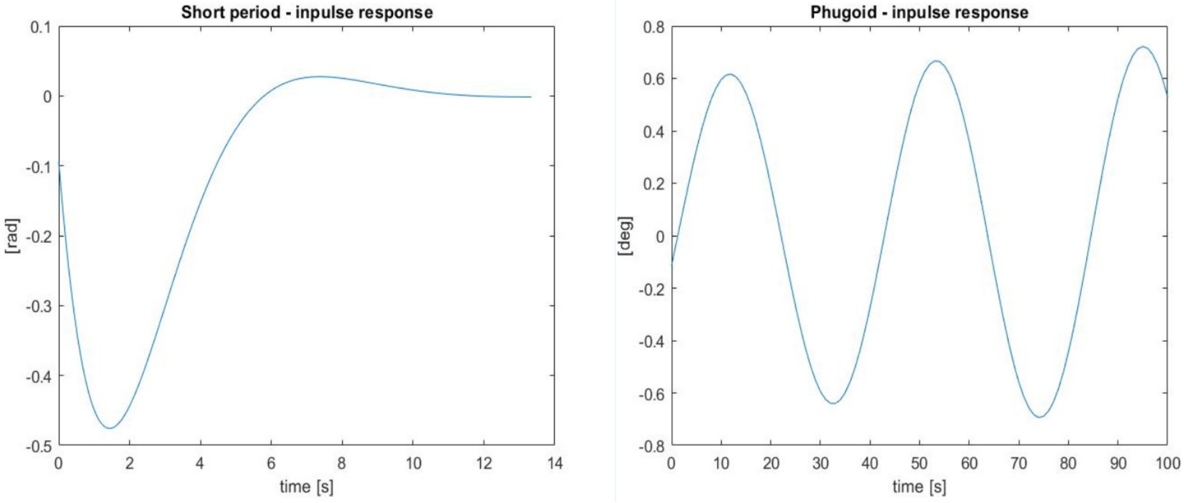


Figure H.1: Separated eigenmodes comparison; short period vs phugoid; complete dynamics; example for aft CG, 0.2 Mach.

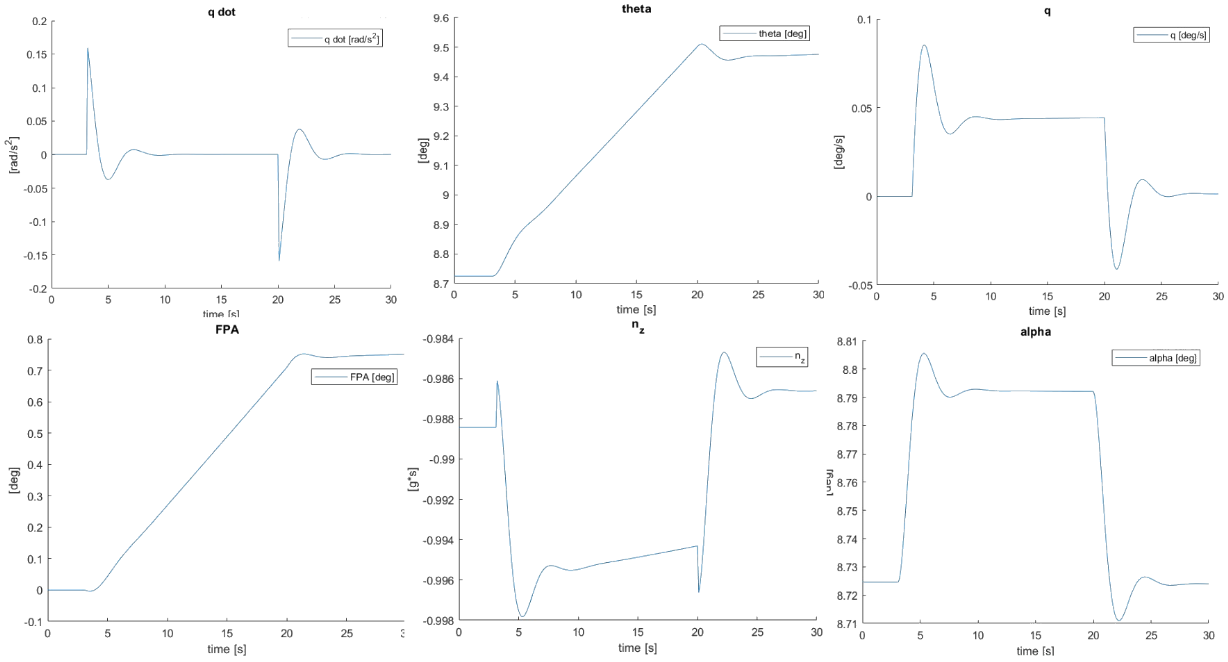


Figure H.2: Time domain response of the short-period only approximation; forward CG, 0.3 Mach, -0.1 deg step input on all elevons.

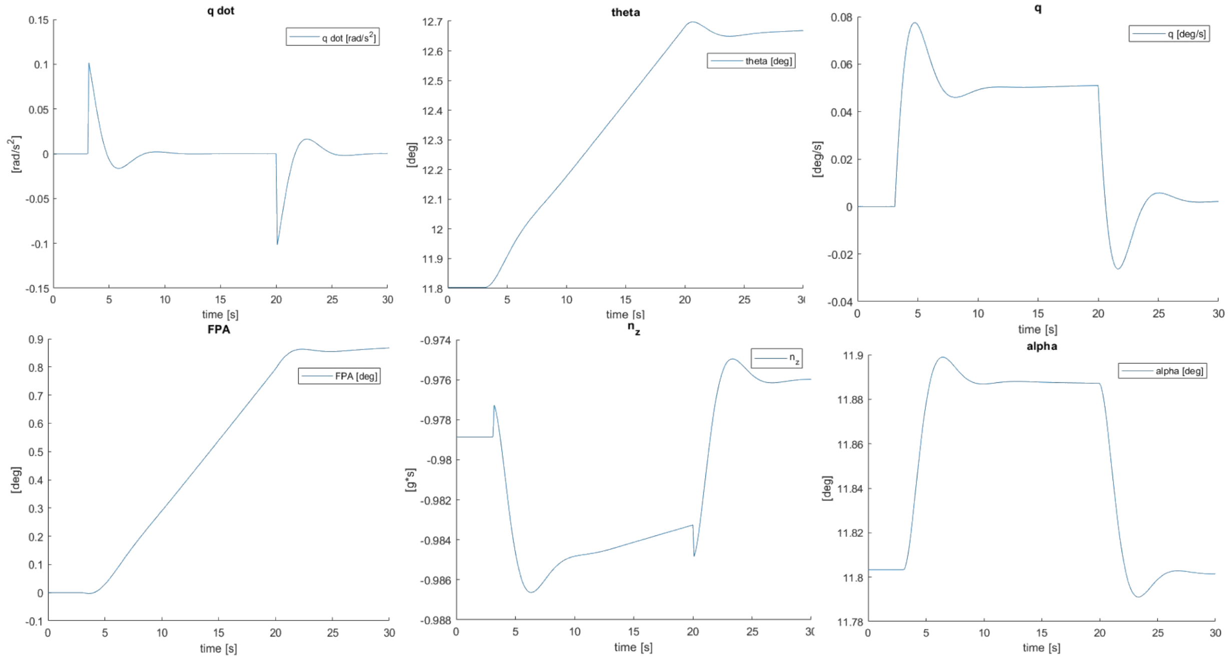


Figure H.3: Time domain response of the short-period only approximation; nominal CG, 0.25 Mach, -0.1 deg step input on all elevons.

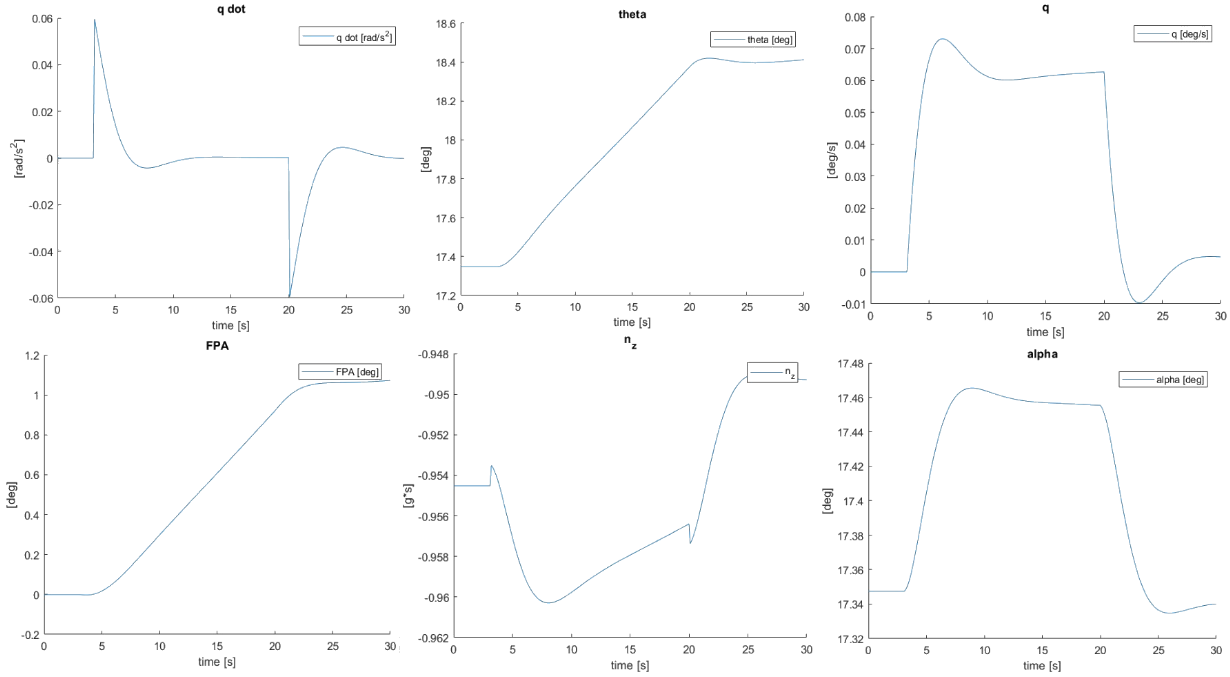


Figure H.4: Time domain response of the short-period only approximation; aft CG, 0.2 Mach, -0.1 deg step input on all elevons.

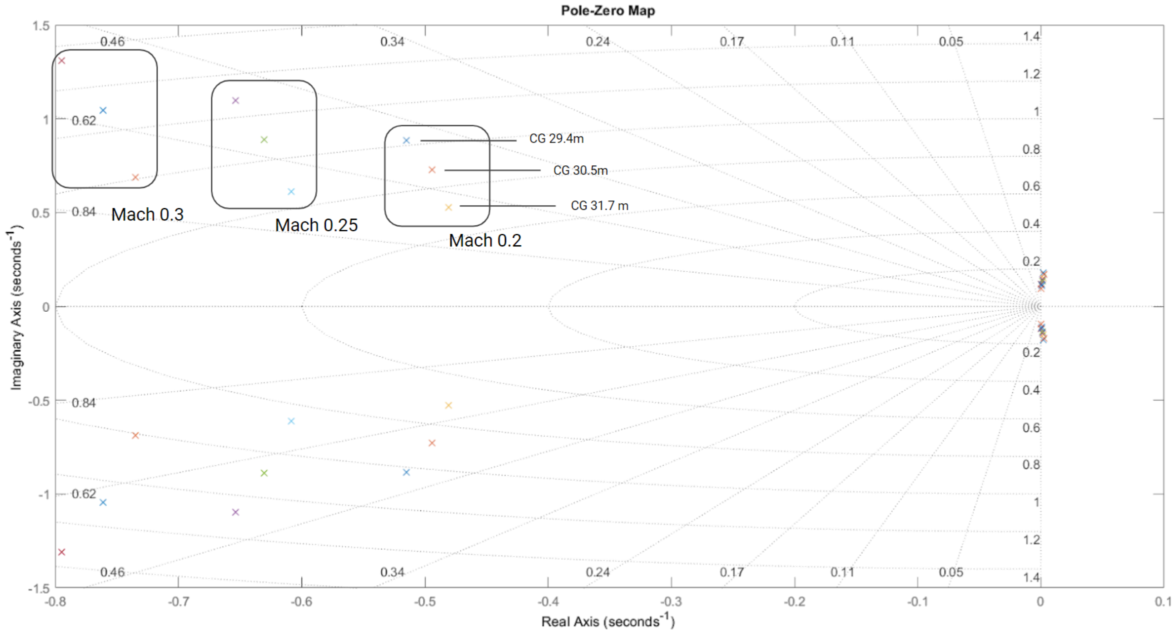


Figure H.5: Short period pole-zero map, all configurations.

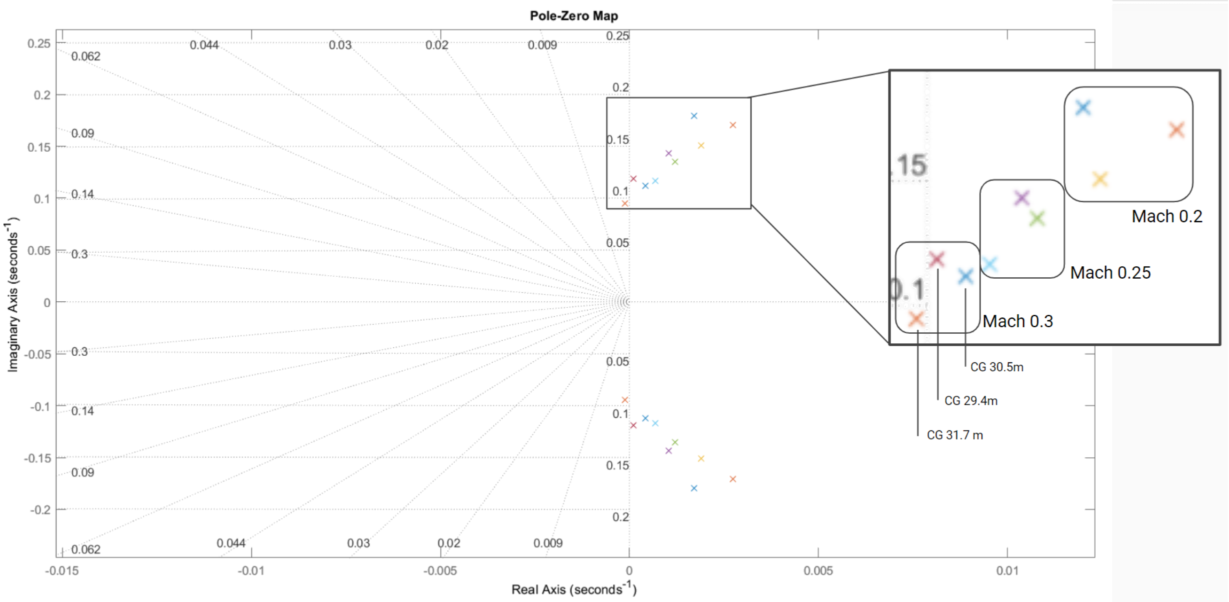


Figure H.6: Phugoid pole-zero map, all configurations.

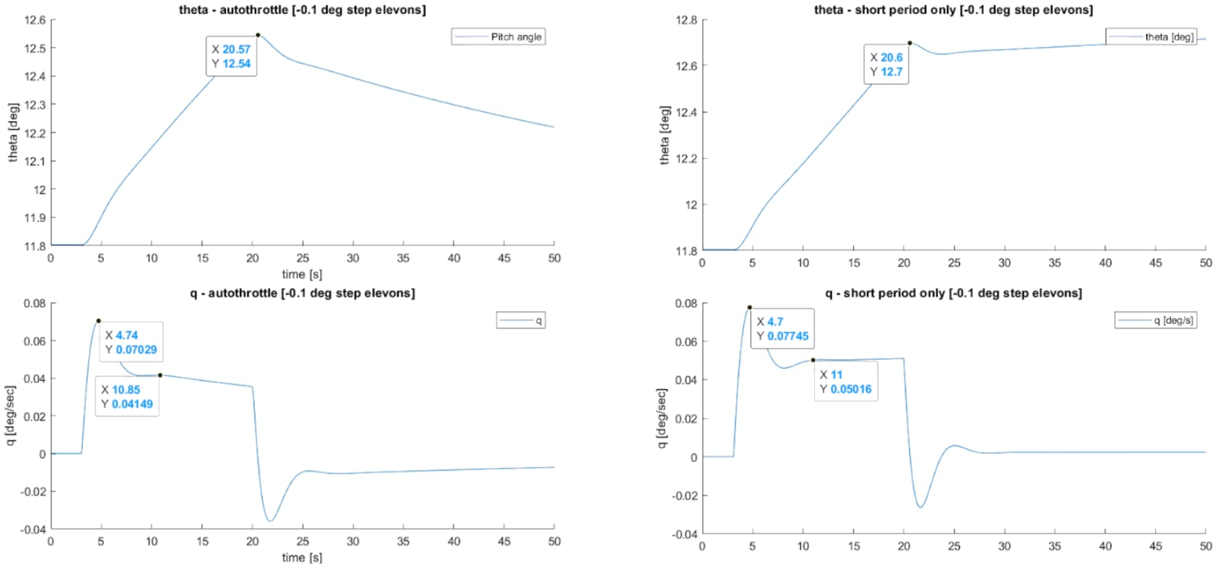


Figure H.7: Comparison of original equations of motion with Auto-throttle mode engaged vs short period only approximation; pitch angle.

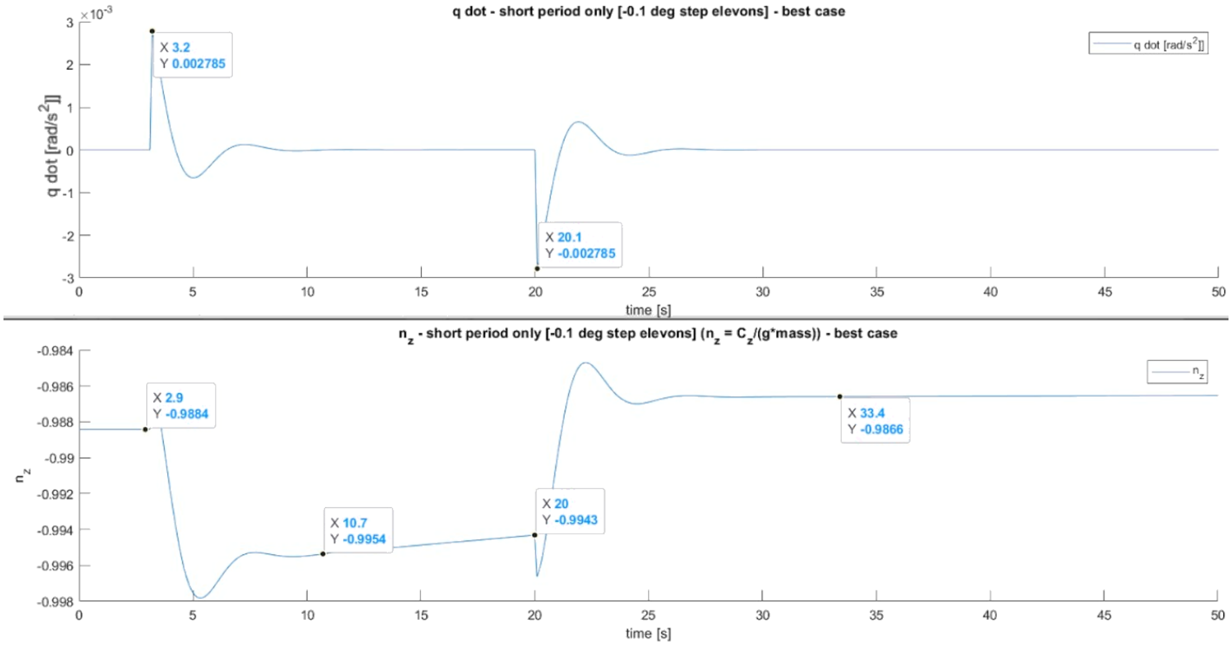


Figure H.8: CAP computation with pitch rate derivative and normal acceleration; forward CG, 0.3 Mach, -0.1 deg step input on all elevons.

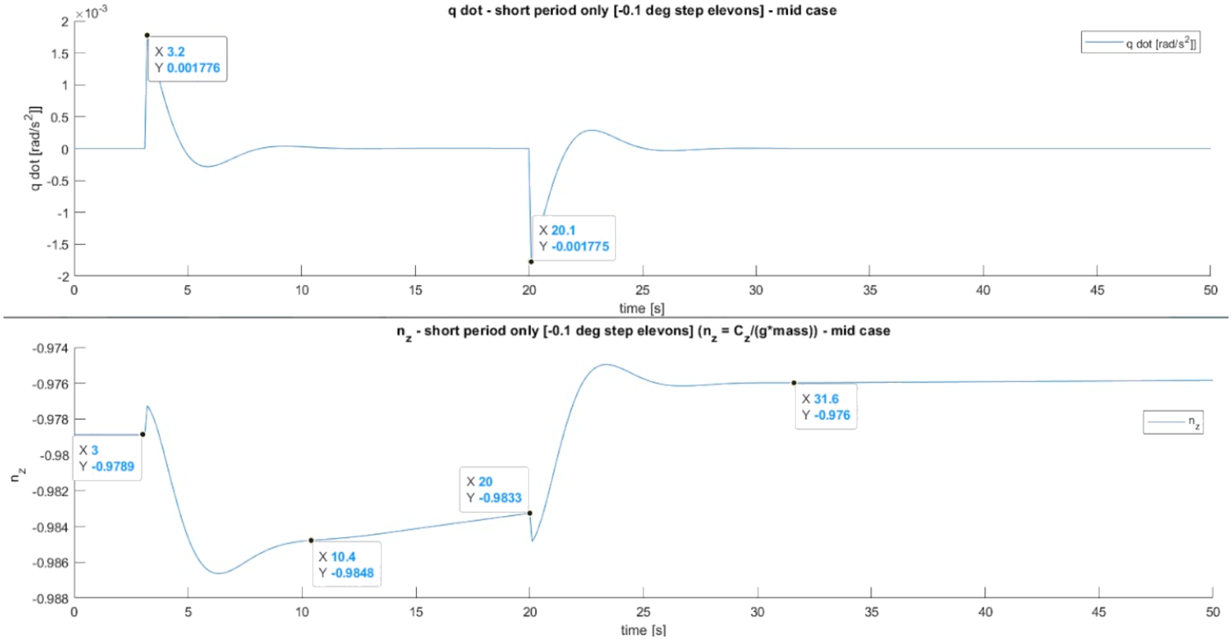


Figure H.9: CAP computation with pitch rate derivative and normal acceleration; nominal CG, 0.25 Mach, -0.1 deg step

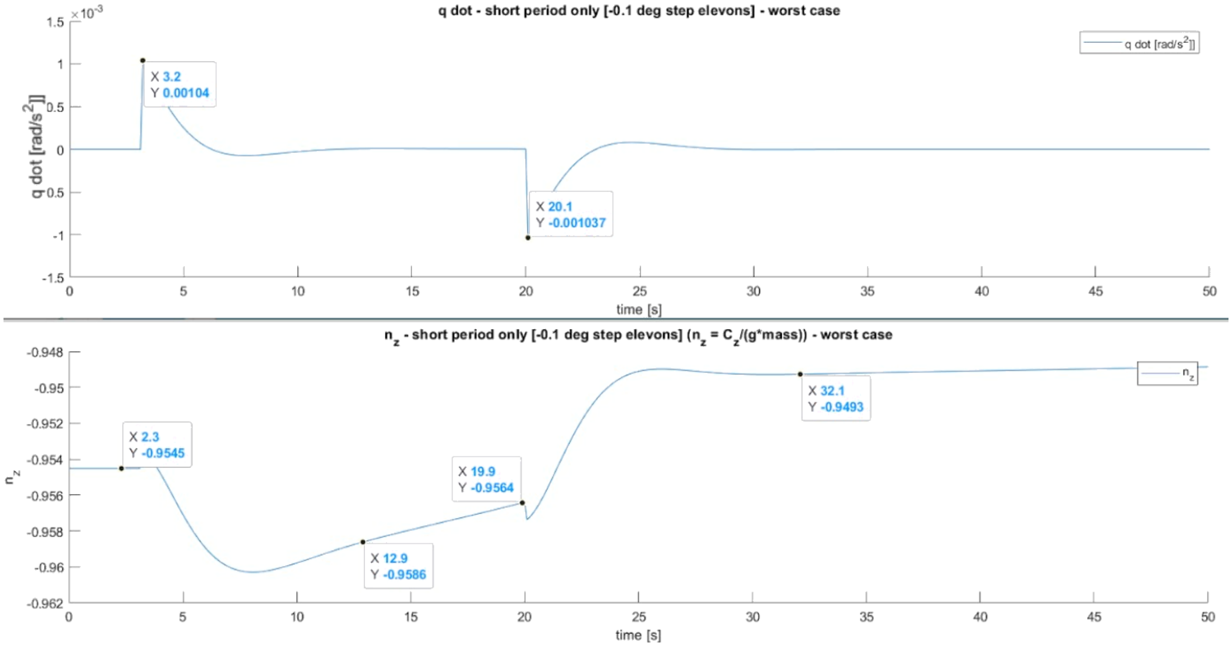


Figure H.10: CAP computation with pitch rate derivative and normal acceleration; aft CG, 0.2 Mach, -0.1 deg step

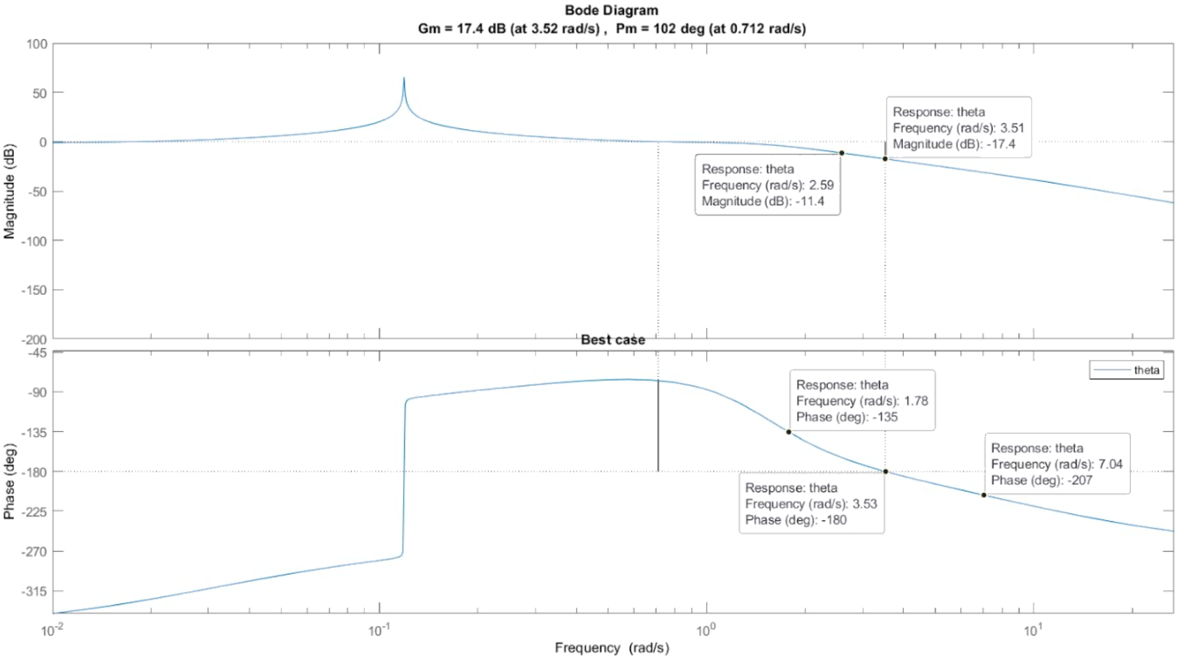


Figure H.11: Bandwidth criterion evaluation with frequency domain response; forward CG, 0.3 Mach.

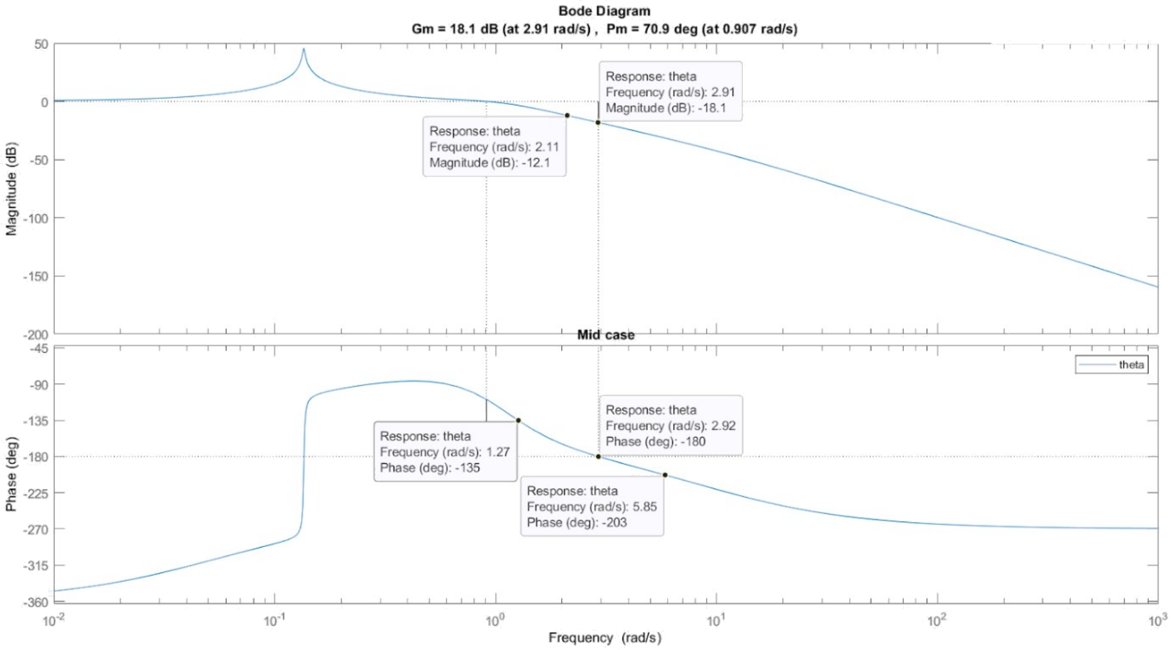


Figure H.12: Bandwidth criterion evaluation with frequency domain response; nominal CG, 0.25 Mach.

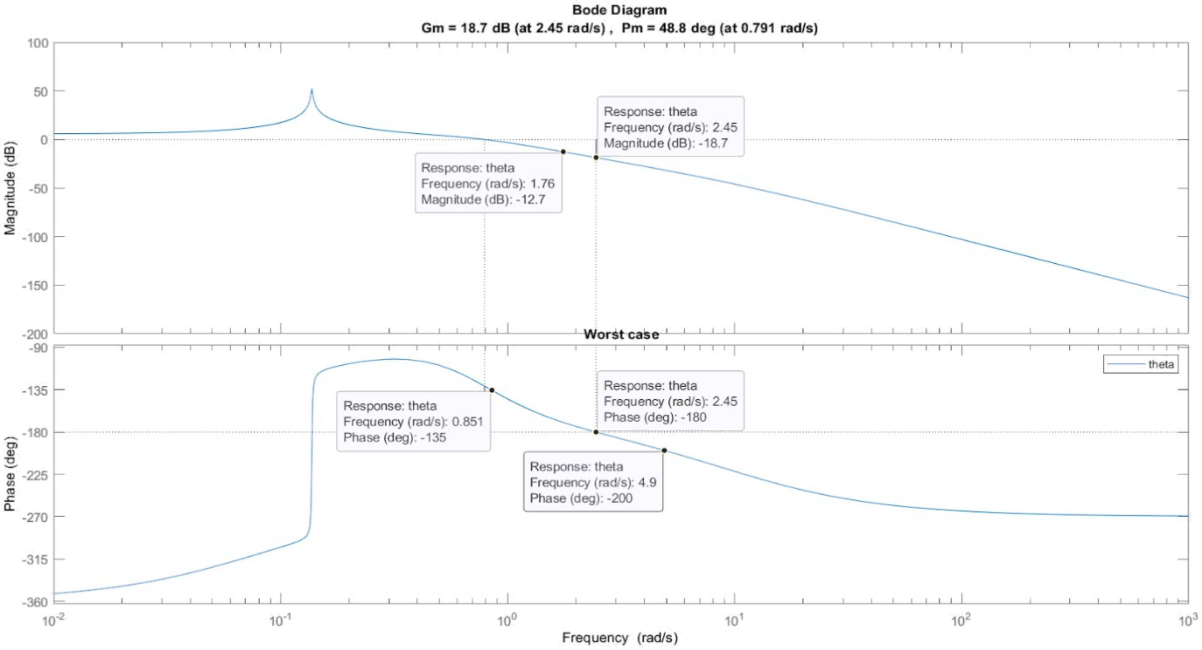


Figure H.13: Bandwidth criterion evaluation with frequency domain response; aft CG, 0.2 Mach.

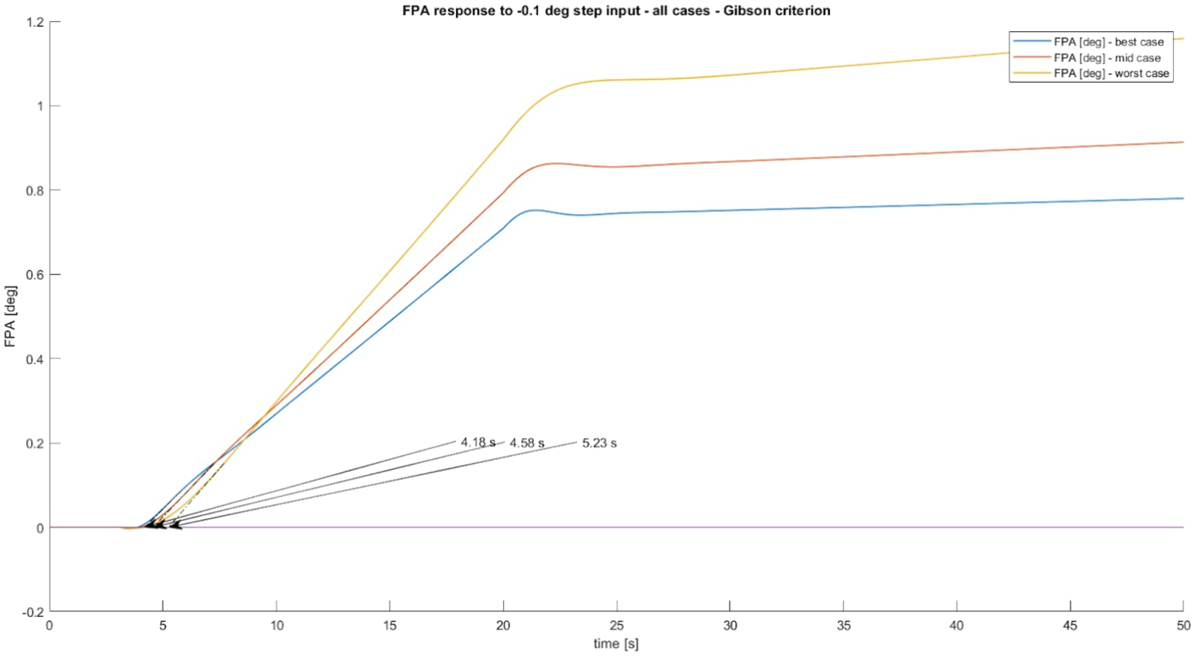


Figure H.14: Flight Path Gibson criterion evaluation with short period approximation; full picture; all configurations.

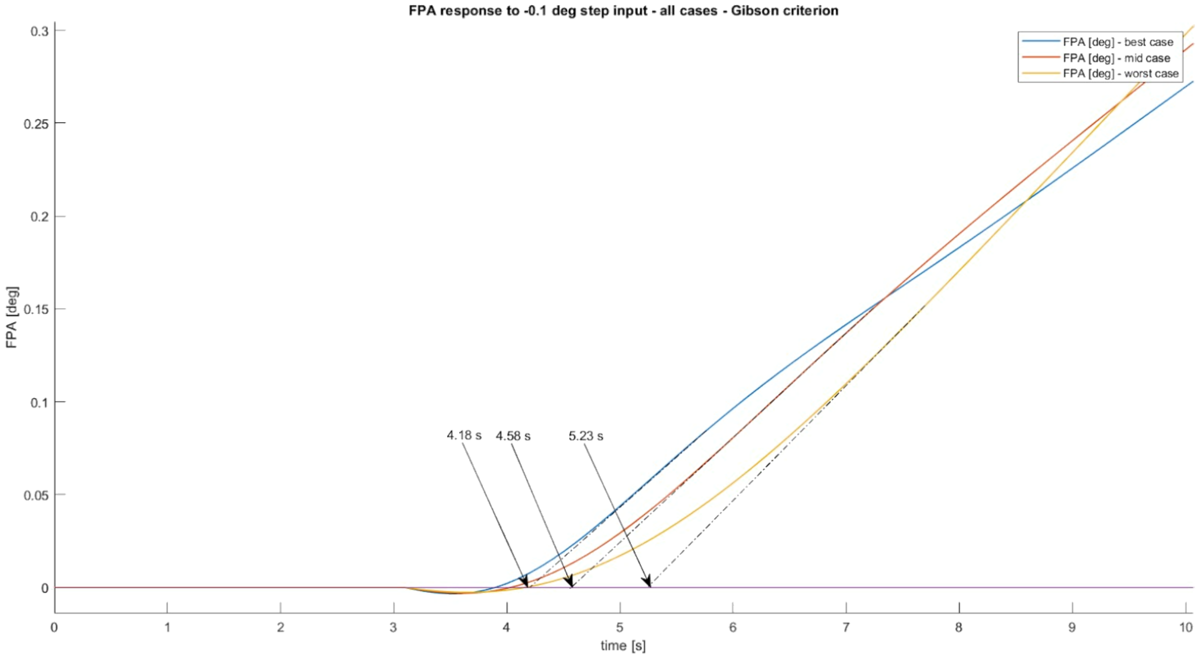


Figure H.15: Flight Path Gibson criterion evaluation with short period approximation; medium zoom; all configurations.

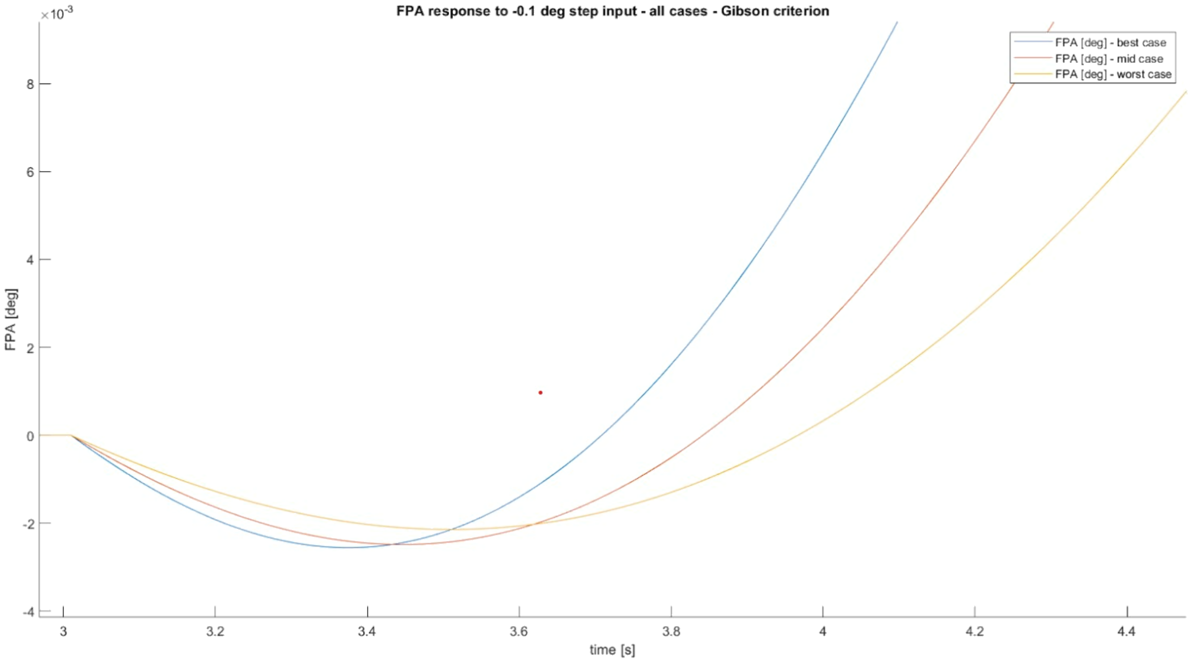


Figure H.16: Flight Path Gibson criterion evaluation with short period approximation; close zoom; all configurations.

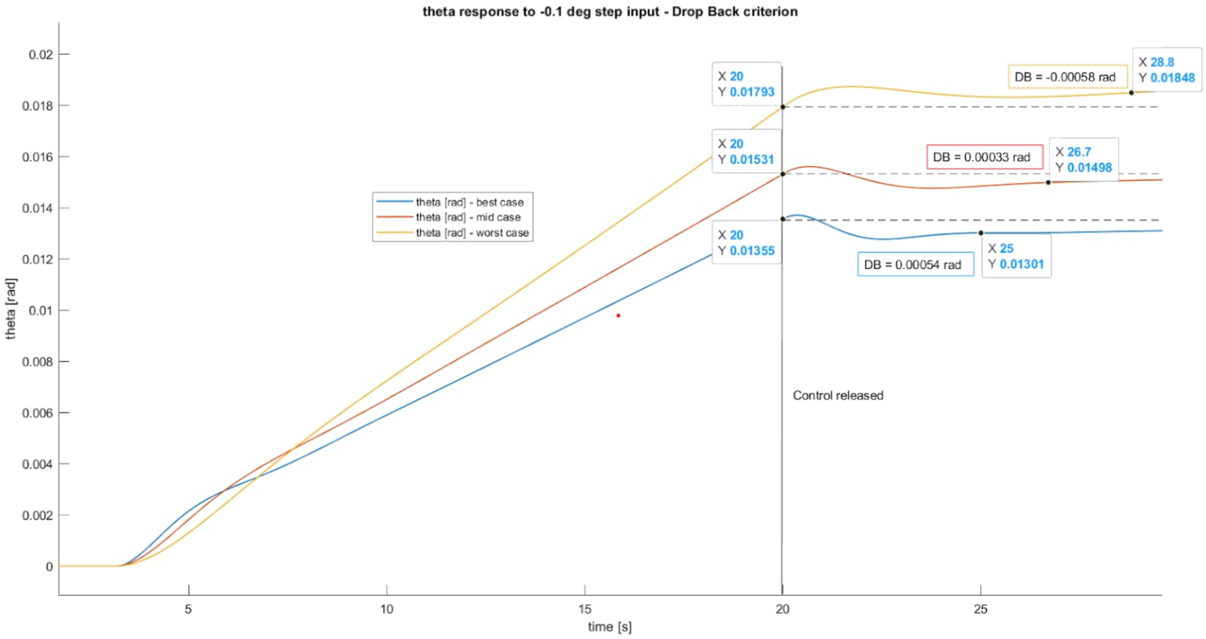


Figure H.17: Dropback Gibson criterion evaluation with short period approximation; dropback analysis; all configurations.

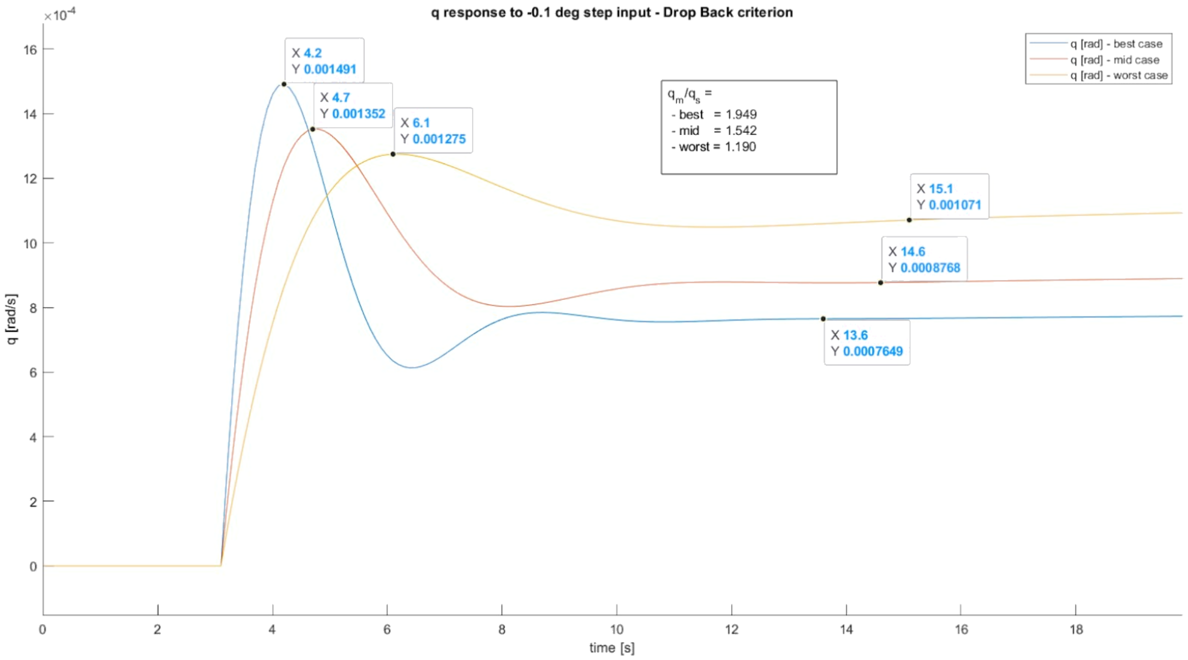


Figure H.18: Dropback Gibson criterion evaluation with short period approximation; pitch rate analysis computation; all configurations.

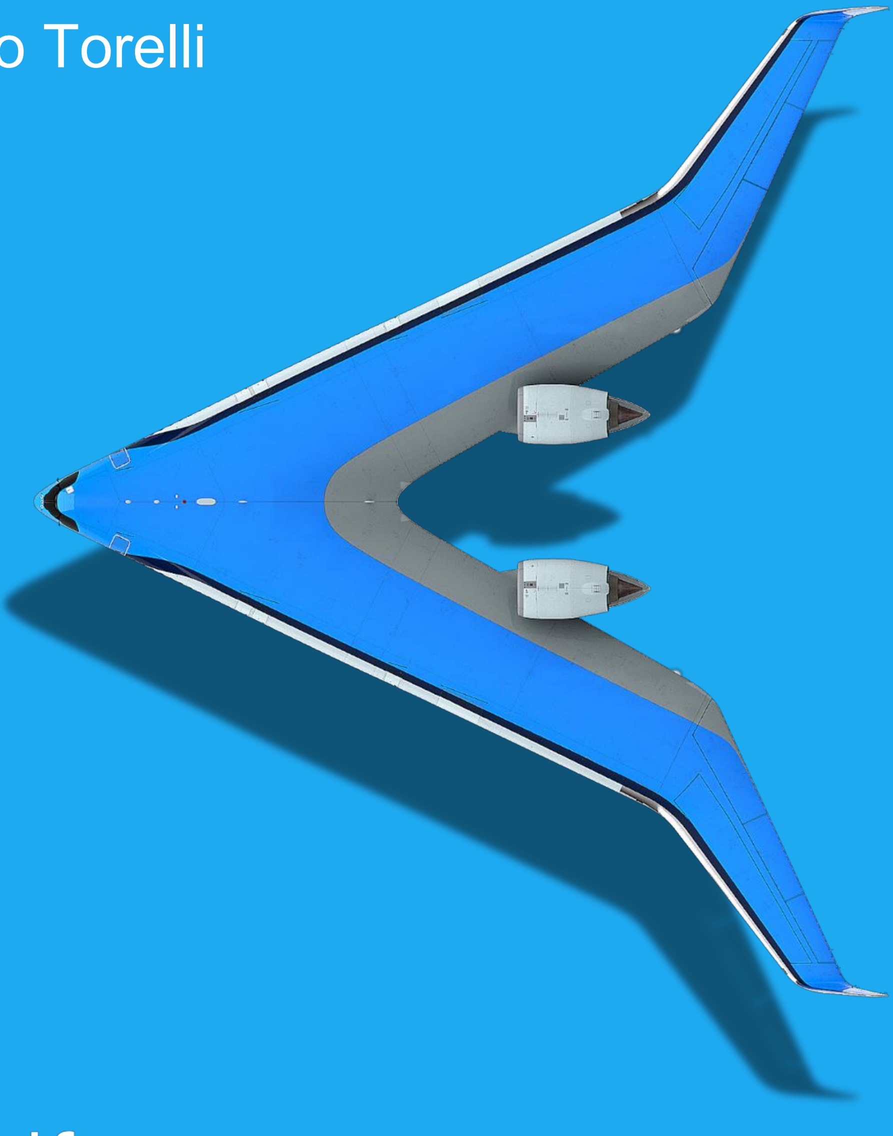
Part III - Preliminary Thesis Report

Previously graded for course AE4020

Preliminary Thesis Report

Piloted simulator evaluation of low speed handling qualities of the Flying-V

Riccardo Torelli



TU Delft

Piloted simulator evaluation of low speed handling qualities of the Flying-V

Preliminary thesis report

by

Riccardo Torelli

to obtain the degree of Master of Science
at the Delft University of Technology,

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Abstract

The Flying-V novel aircraft design aims at reducing fuel consumption by an innovative low-drag, fuselage-free geometry. Some possible issues with the certification requirements have been highlighted related to the handling qualities for pull-up manoeuver and flight path angle response at low speed.

In this research, the most critical EASA certification requirements have been selected for the Flying-V, together with their acceptable means of compliance. In particular, specific performance and handling qualities levels are requested for the pull-up maneuver and for the go-around task.

With a mathematical model of the Flying-V based on the vortex lattice method, a preliminary off-line analysis is conducted on the handling qualities of the Flying-V. Three center of gravity positions - forward, nominal, and aft - are taken into consideration based on the safe stability limits suggested by previous research. The airspeed range considered is between 0.3 and 0.2 Mach.

The results of the analysis show that the bare-airframe Flying-V has good expected handling qualities for forward center of gravity position and higher airspeed. However, when the center of gravity is shifted aft and the aircraft slows down, the handling qualities decline into Level 2 or 3 (according to the levels convention of MIL-STD-1797B). In particular, at these configurations the Flying-V might exhibit a rather sluggish response. A possible source of handling qualities issues is identified in the small separation between the natural frequencies of the short period and phugoid modes.

Piloted simulations will be carried out to extend this analysis. To test the performance of the Flying-V against the critical certification requirements and to further understand the handling qualities, three tasks will be simulated: go-around, pitch control, and flight path angle control.

The aircraft will be first simulated with no control augmentation, since it might be required to obtain certification. Then, pitch rate control will be tested for its potential to solve the slow short period frequency issues, and auto-throttle will control the phugoid. Based on the preliminary analysis of this control system, possible handling quality improvements are expected if compared to the bare airframe. Fine tuning and optimization of the control system will be addressed in the upcoming part of this research (after this report).

The experiments will be performed in the SIMONA simulator of TU Delft, with the participation of KLM pilots. After the experiments, it should be clear to which extent the current model of the Flying-V is comfortable and safe to fly according to pilots and to the regulation requirements.

1

Introduction

1.1. Context

In the past, constant improvements have been achieved in the context of aircraft fuel efficiency by means of new engines, aerodynamics and economics technologies [43]. Lately, this constant trend has been slowing down, and an 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 [37], but the most recent projections show that these goals are not expected to be met at the current pace of improvement [38].

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%[5]. 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 [5]. Its geometry comes with the advantage of an improved lift-to-drag ratio compared to conventional aircraft [42], at the expense of a potentially unconventional maneuverability. In this regard, in June 2020 a scaled model flight test was conducted in which some poor handling qualities were noted during the landing phase. In particular, Dutch-roll was found to be unstable, and the longitudinal controllability at high angles of attack was unsatisfactory [4]. This research focuses on the full-scale model, for which the scaled model analysis only provides approximate qualitative results.

1.2. Purpose of this research

The non conventional geometry of the Flying-V is still under development. The design used in this study should be defined according to the research that has been done in the past to optimize the lift-to-drag ratio and the handling qualities. The design of the control surfaces needs a special note, since it is relevant for the analysis of the handling qualities but it has not been optimized yet. The results of this research should contribute to current and future design iterations.

More in particular, this research aims at three main contributions to the body of knowledge: to understand how the Flying-V compares to the certification requirements on the handling qualities; to explore the potential of a flight control system to improve the handling qualities; and to confirm and extend the handling qualities analysis by means of piloted simulations.

Regarding airworthiness certification, the regulatory authorities demand compliance to a set of requirements that should be taken into consideration during the design iterations. As a consequence, understanding the relevant and critical requirements is key for planning useful experiments and to contribute to the next steps of the design of the Flying-V. Due to its non conventional characteristics, the regulations and the accepted means of compliance should be selected carefully.

A preliminary analysis should be done to prepare meaningful experiments and to understand what to expect from them. Since this preliminary analysis is done off-line, with no pilot in the loop, it is necessary to select a series of criteria and procedures to analyse the handling qualities and identify critical aspects of the Flying-V before the piloted simulations will take place. Normally, this is done by means of common handling qualities analysis criteria. However, the Flying-V is a new model and its response can be atypical. As a consequence, selecting the appropriate criteria for its analysis is not a straight-forward process, and theory and relevance of the criteria should be considered critically on the base of previous work done on the Flying-V. To conduct this preliminary analysis, a mathematical model of the Flying-V is necessary and the implications of its baseline assumptions should be clear.

By means of the off-line analysis, it should be possible to determine how the aircraft is expected to respond to the critical manoeuver of longitudinal 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 should provide a picture of the predicted handling qualities of the full pilot-aircraft system.

A flight control system can have an impact on the handling qualities of an aircraft. To complete the analysis of the handling qualities of the Flying-V, the possibility to improve them by means of augmentation should be considered. In this respect, the flight control system should be designed to deal with the issues that emerge from the off-line analysis above mentioned, and different tuning and approaches should be examined in order to understand their general potential.

Finally, piloted simulations will complement and finalize this research. A test plan is needed to account for all the research questions just presented, so that the human-in-the-loop experiments can confirm all the work done in the preliminary analysis. The piloted simulations are here intended to research 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.

1.3. Organization of the report

Following this introduction, in Chapter 2 a summary of the current state of the art of the Flying-V is presented, together with an explanation of the geometrical design used in this research.

A review of the certification requirements of an aircraft is given in Chapter 3, where the Military Standard handbook, the EASA CS-25 and the EASA AMC-CS-25 are considered together.

In Chapter 4, the most common methods used to predict the handling qualities of an aircraft are reviewed in their theoretical background. The validity and significance of each method is also examined.

Chapter 5 introduces the mathematical model, its computation and its implementation in the form of integrable equations of motion, and the main assumptions behind the aerodynamic modelling software (ODILILA) are discussed.

The main results of the preliminary analysis are shown in Chapter 6, where an overall interpretation of the response of the Flying-V is given and the main consequences for the remainder of this research are considered.

A preliminary design of a flight control system is proposed based on the results of the preliminary analysis and on a review of the literature of flight control system for flying wings and wing bodies. The potential HQ improvement of this design is presented in Chapter 7, while fine tuning and optimization will be addressed only in the upcoming part of the research.

Chapter 8 takes into account the conclusions of all the previous chapter to outline the plan for a test simulation campaign. In this Chapter the Cooper-Harper approach is reviewed, an initial plan for the piloted simulations is shown, and the SIMONA simulator environment is introduced.

Finally, in Chapter 9 the conclusions of this preliminary research are summarized, with a focus on the next steps to be taken for the preparation and the execution of the piloted simulations.

For the remainder of this document, unless otherwise stated, the term ”handling qualities” and its acronym ”HQ” is used to refer to the handling qualities during longitudinal flight at low speed configurations.

2

Flying-V design

2.1. Concept

The Flying-V concept is a design of a long-distance travelling aircraft that incorporates all the parts of an aircraft in a V-shaped body. Not only is this aircraft prototype lighter than other reference aircraft (such as the A350, ideally the most similar aircraft in terms of intended operations), but Computational Fluid Dynamics (CFD) studies on the aerodynamics of the V-shaped body predict a reduction in fuel consumption up to 20% ([50], [41]).

It shares some similarities with the Blended Wing Body and Delta Wing aircraft (for instance the one developed in Airbus [51]), namely that they both aim at reducing fuel consumption by means of reducing aerodynamic resistance by a smaller ratio of inflow surface area over available volume.

For these innovative types of aircrafts, the handling qualities present essentially two unique challenges. First, the approach to handling qualities evaluation for standard aircraft follows the extensive literature and experience that comes from decades of specialization in this field on the same type of vehicle, response and characteristics. This is not the case for the Flying-V, since no attempts at evaluating its handling qualities have been made yet. Second, when the response of an aircraft is not known with precision, as for the Flying-V, few assumptions can be made on the way it flies. As a consequence, it might be that fewer common practices can be applied to the analysis of this aircraft, since they might be based on assumptions that cannot be taken in this case.

2.2. Current state of research

Since the first idea came to the mind of Justus Benad in 2015 [16], many researchers of TU Delft, KLM and Airbus have been focusing on the realization of the Flying-V ([46], [50], [17], [41], [42], [52], [25]).

First of all, the problem of computing an aerodynamic model for the aircraft has been studied. In his work, Garzia [46] was the first to describe the behaviour of the Flying-V in its tentative initial geometry, working on a spline-interpolated model and a polynomial-interpolated model. Faggiano [25] computes the expected lift-to-drag ratio of this geometry, finding that the Flying V Aircraft can have a 25% higher lift-to-drag ratio than the reference aircraft. In his work, a study on all the drag forces of the Flying-V is given for this geometry, which proves useful in Chapter 5 to correct for the inaccuracies of the aerodynamic model.

With this geometry, later improved in collaboration with Airbus, Cappuyns [50] noticed that the longitudinal response of the aircraft imposes a limited range of locations for its center of gravity [redacted] which is narrower compared to a conventional aircraft, since stability is otherwise lost and the handling qualities are reduced.

The dihedral angle between the two wings is a key parameter in the design of the Flying-V. For the geometry used in this research, the dihedral angle has been suggested by Bourget [17]. He investigated the influence of landing gears on the Flying-V aerodynamics, stability and controllability. His findings highlighted a correlation between the airplane dihedral and the required mass of the landing gear. By means of the analysis of two different dihedral configurations, it was determined that the original geometry of the Flying-V requires relatively high landing gears (landing gear mass 20% bigger than reference aircraft), whereas with an increased dihedral it would require a landing gear with 4% less mass than reference aircraft. Bourget's work is also helpful for the integration of the landing gears into the simulation model.

Palermo [41] and Pascual [42] worked on a 4.6% scaled model of the Flying-V, with 3.06m wing span, 2.76m length and 22.5kg weight. The outcome of Palermo's analysis is particularly relevant for this research, since it consists in the 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). Among the other findings, it is worth mentioning that with the center of gravity at 1.33 meters from the nose (45.63%MAC, proposed most forward location) and at 1.39 meters (52.586 %MAC), the model can produce a maximum lift coefficient of about 0.7 and 0.6 respectively in a statically stable configuration, which gives as a first validation of the full aircraft model used here (see Chapter 5).

Rob Viet [52] also worked on the 4.6% scaled model. He identified the optimal position of the center of gravity at 1.365 meters behind the nose, stall speed of 14.8 m/s (again, for the 4.6& scale model) at an angle of attack of 28.5 degrees and safe stall (aircraft still in its stable range of angle of attack) of 19.2 m/s at 15.9 degrees angle of attack. The research on the scaled model does not directly translate into the full model, for which a scalability analysis is needed; however, it is useful to use these numbers as an approximate reference for the validation of the full model. In this sense, stall angle of attack is assumed to be higher than 20 degrees, but future stall analysis on the full model is recommended (as explained in Chapter 5).

Pascual [42], on the other hand, highlighted the importance of the location of the engines, since misplaced engines can reduce the lift coefficient up to 55% of the ideal configuration. The optimal location of the engine was found to reduce the lift-to-drag ratio of 10%. Such location is the product of a compromise of controllability, structure and probability of impact. The position of the engines in the model used for this research comes from Pascual's work.

At the time of writing of this report, there are four ongoing studies related to controls, identification and simulation of the Flying-V [7]. Van Overeem is designing a stability and control augmentation system for the scaled model based on windtunnel and flight test data; Vugts is investigating the general longitudinal handling qualities with a basic control system and a pilot-in-the-loop configuration; Joosten is focusing on the evaluation of lateral-directional handling qualities; Siemonsma is working on system identification for the full model of the Flying-V. The outcomes of these studies are expected to be available in the first half of 2022.

2.3. Flying-V design for this research

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' [50] research. It is justified by the findings summarized in the previous section, with the addition of the engines in the position found by Rubio [42]. Engines and landing gear do not influence the aerodynamics computation of Chapter 5.

The configuration chosen for this research is shown in Figure 2.1; the control surfaces configuration is displayed in Figure 2.2; and the design parameters are given in Table 2.1. Notice the three control surfaces on each wing: one is a vertical rudder-like surface which serves as a rudder (see Figure 2.1), while two surfaces serve both as elevators and ailerons (see Figure 2.2), and are consequently called ”elevons”. In an attempt to increase the accuracy of this analysis, actuators and engines are modelled too, in the form of first order lag transfer functions with time constants equal to $\tau_{act} = 0.1s$ and $\tau_{eng} = 10s$ respectively. The limit for the deflection of the actuator is assumed to be standard, hence it is here set as $\delta_{lim} = 25\,\mathrm{deg}$. However, this will only be relevant for the piloted simulations, since the deflection limits are disregarded during this preliminary analysis for simplicity. It should be noted that in other works on blended wing bodies [11], it was highlighted that flying wings require a particularly complex control system that takes into account the issues related to limited control authority, allocation, and control surface sizing.

The twofold action of the four elevons as both elevators and ailerons raises a control allocation question on how to optimize their use. In principle, the idea is to regulate each actuator based on their efficiency either as a elevators or as ailerons. However, this would involve the analysis of lateral-directional response of the aircraft, which is not in the scope of this research; and accurate control surface models, which is not the case 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, it is assumed that control is equally allocated among the four surfaces. As a consequence, the four deflections can all be described with a single actuation angle, and pilot's longitudinal control can be mapped equally on all the four elevons. This control is always symmetrical, which means that the four elevons are essentially used together as one elevator.

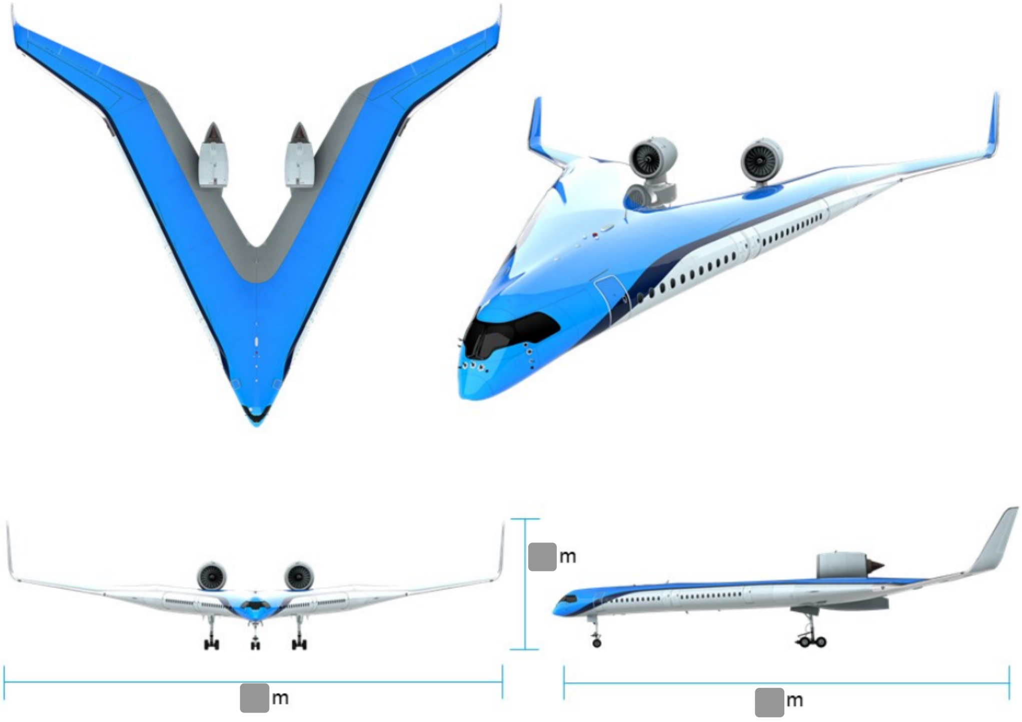


Figure 2.1: Flying-V, three view renders adopted from TU Delft; "Flying-V, flying long distances energy-efficiently", 3 June 2019, https://www.tudelft.nl/en/ae/flying-v/

Table 2.1: Design Parameters for Flying-V conceptual design. From Cappuyns, (2019) [50]

Parameter	**Value**	**Unit**
Length	[redacted]	m
Wingspan	[redacted]	m
Height	[redacted]	m
Pax	[redacted]	-
Fuel Capacity	[redacted]	l
Cargo Capacity	[redacted]	m^3
Design Mach number	[redacted]	-
Cruise altitude	[redacted]	ft

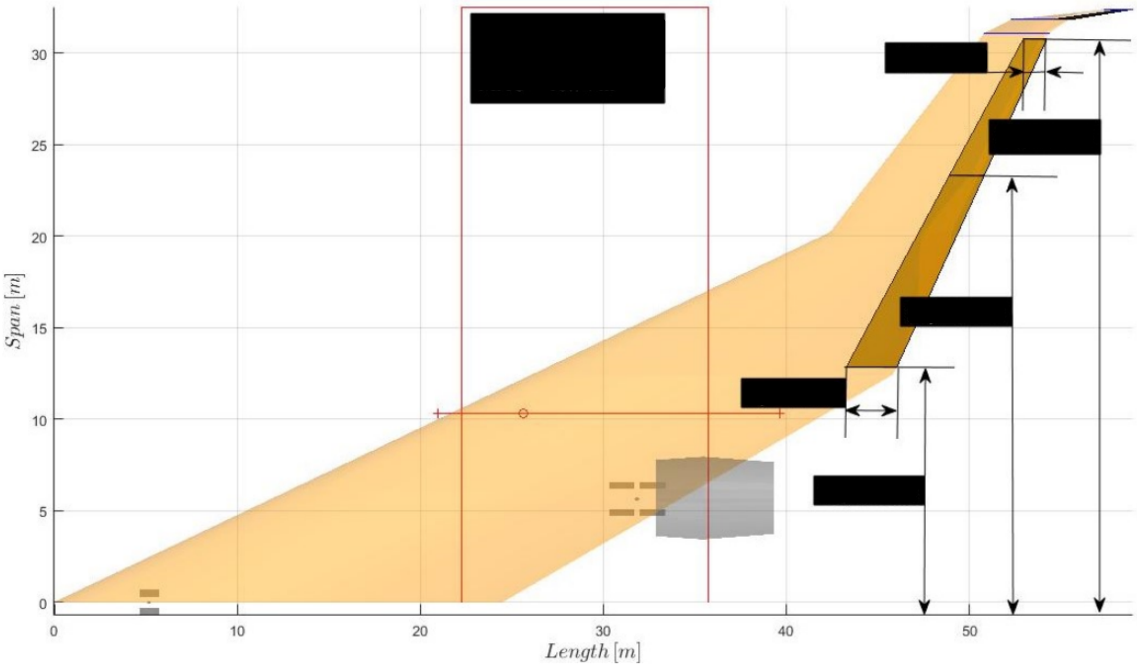


Figure 2.2: Flying-V elevon dimenions. From Cappuyns, (2019) [50]

Advantages and limits of this geometry have been explained in the previous section, where it was shown that previous research focused on optimizing the lift-to-drag ratio and on limiting possible control related issues. Additionally, Cappuyns' research identifies some critical disadvantages of this geometry as compared to some analysis criteria and to EASA Certification Requirements (CS-25, [3]). According to his work, the pull-up manoeuver (CS-25.143) is critical for the Flying-V, since *"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."*. The requirements on the pull-up manoeuver will be presented, together with the other relevant requirements, in chapter 3. [redacted]. Due to its significance, the analysis by means of the CAP will be repeated in Chapters 4 and 6 and expanded with additional parameters.

3

Certification Requirements

3.1. Purpose of certification requirements

Assessing the safety of an airplane is not a straightforward process. Regarding flight dynamics, the concept of ”safety” varies depending on the intended purpose of the airplane. Overall, it always comes down to a complex trade-off between maneuverability, stability and performance that, in one term, is called Handling Qualities.

The regulatory authorities (EASA, FAA) publish requirements on Handling Qualities that are thought for standard aircraft (i.e. with fuselage and usual flight dynamics), and their application is not always straight-forward for new prototypes such as the Flying-V. For instance, the concept of ”elevons” is never mentioned in the EASA requirements. However, it is recommended for the acceptance of the Flying-V as a commercial means of transportation that it does not deviate from the standard requirements, so that airworthiness will be easier to achieve.

3.2. EASA CS-25

Federal Aviation Administration (FAA) in the USA and European Union Aviation Safety Agency (EASA) in Europe each have their own set of requirements. In this study the only requirements of interest are those related to flight.

Since the Flying-V is comparable in size, use and performance to the Airbus A350, the requirements against which this airplane was certified can be considered relevant for the Flying-V as well. In particular, the reference regulation for the A350 is the CS-25 published by EASA [3]. The corresponding regulation by FAA is the PART-25. Between the two, CS-25 and FAR-25, only some minor differences are present (see [10]), and in general EASA seems slightly stricter on some requirements. Hence it makes sense to try to abide by the European standards.

CS-25 requirements are fairly generic on controllability and maneuverability. For instance:

- EASA CS 25.143: “Controllability and Manoeuvrability”:

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

To complement these requirements, however, the EASA “Acceptable Mean of Compliance AMC-20” [8](or the corresponding FAA “Flight Test Guide for Certification of FAR-25 Airplanes” [24]) provide operational procedures to demonstrate compliance with CS-25.

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

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)

From this list, (1) and (2) (climb and pull-up performance) have been previously observed as critical by Cappuyns [50]. From his preliminary calculations, the position of the CG is limited by this requirements, since the Flying-V cannot easily attain a fast pull-up acceleration and several tens of meters are lost from the pull-up input of the pilot to the actual climb.

Focusing on maneuver (3) is encouraged by the outcome of the 2020 scaled model flight, where direct-lift control was observed and the landing failed. Moreover, it is representative of the low-speed flight envelope studied in this research.

The failed landing of the 2020 scaled model flight test hints at some criticalities in maneuver (3), which also represents the main rationale of this research.

Tasks (4) and (5) are relevant for piloted simulations. In fact, it is difficult to evaluate the quality of the transition between different trim conditions without pilot rating, and piloted simulations are particularly useful for the analysis of this kind of tasks.

For all these tasks, the requirement essentially states that the handling qualities must be optimal during all the maneuvers and the airplane must be ”safely controllable and maneuverable”.

This list of requirement will be determinant for the definition of the simulation tasks (see Chapter 8). The experiments will be designed in order to include the execution of maneuvers which aim at investigating the performance of the Flying-V as compared to these requirements.

While EASA suggests the means of compliance to meet the requirements, the vast majority of these regulations do not provide direct and measurable methods to predict the compliance of an aircraft. However, before pilot's assessments of handling qualities, a so called “off-line” evaluation can be performed by means of some criteria for the response of the aircraft, normally with no need of human inputs to the system. In general, since no specific preliminary analysis of this sort are required by EASA or FAA, these ”off-line evaluation” criteria can be selected from different sources, the most common being military publications such as the ”Flying Qualities of Piloted Aircraft” by the American Department of Defense [40], introduced in the next section.

For reference, a similar approach to design by handling qualities certification for non conventional aircraft has been adopted by researchers such as Saucez [47] (Airbus BWB handling qualities analysis) and Schmollgruber [48] (aircraft design process optimization with certification constraints). In his work on blended wing bodies, Chen [11] points out that, often, these aircraft models cannot provide high enough maximum lift coefficient as required by the regulations on landing performance.

3.3. MIL-STD

This publication, commonly referred to as ”Military Standard 1797B”, ”MIL-STD 1797B” or simply ”MIL-STD”, contains an extensive collection of mathematical criteria that have been empirically associated with certain levels of handling qualities. These criteria, which will be further explained and used in Chapters 4 and 6, provide the tools to map certain aircraft response characteristics into one out of three handling qualities levels. Where used in the reminder of this report, the convention for these levels is as follows (based on the MIL-STD):

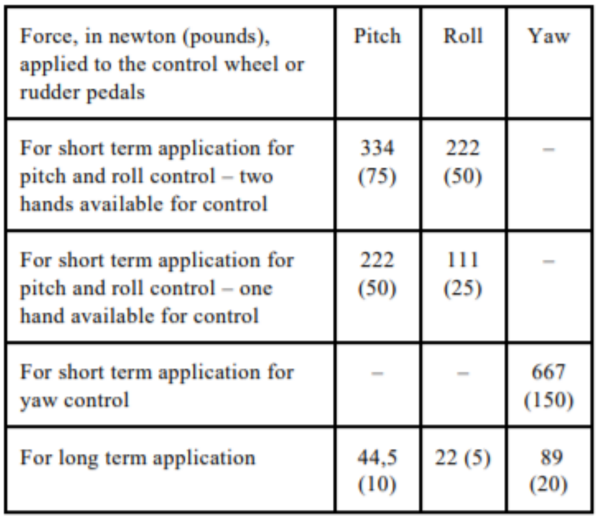
- Level 1: handling qualities clearly adequate for the mission flight phase;
- Level 2: handling qualities adequate to accomplish the mission flight phase, but with an increase in pilot workload and/or degradation in mission effectiveness;

- Level 3: Degraded handling qualities, but such that the airplane can be controlled, inadequate mission effectiveness and high, or limiting, pilot workload.

3.4. Fly-by-Wire

Part of the requirements of CS-25 are related to control forces. As an example of this, the requirements of EASA CS 25.143(d) are shown in the following table:

- EASA CS 25.143(d): *"The following table prescribes, for conventional wheel type controls, the maximum control forces permitted during the testing required by sub-paragraphs (a) through (c) of this paragraph. (See AMC 25.143(d))"*:



Force, in newton (pounds), applied to the control wheel or rudder pedals	Pitch	Roll	Yaw
For short term application for pitch and roll control – two hands available for control	334 (75)	222 (50)	–
For short term application for pitch and roll control – one hand available for control	222 (50)	111 (25)	–
For short term application for yaw control	–	–	667 (150)
For long term application	44,5 (10)	22 (5)	89 (20)

Anyway, it is expected that the Flying-V will be controlled with a Fly-by-Wire system, in which the concept of limiting the control forces is less defined since the control system can be tuned to alter the input requirement. For this reason, it is decided for this research not to focus on parts of the CS-25 which regulate control forces. However, these limits prove useful as handling qualities criteria to tune the feel system. In fact, feel system for the simulations presented in Section 8.4.1 will be tuned according to these criteria.

To guarantee the safety of the Fly-by-Wire system hereby assumed, it is common practice (see for example Airbus A310 and Boeing B777) to design a redundant Flight Control System, for instance by means of a duplex FBW system (FCC, sensors, ...) *with* a mechanical backup mode, or a triplex or quadruplex FBW system *without* a mechanical backup mode. The Flight Augmentation System is designed for redundancy so that different control laws are actuated for different failure conditions. For example (A310), two Alternate Law, a Direct Law and a Mechanical Back-Up Law exist in the case that a failure happens in one actuator (Alt. Law 1), both engines or two sensors (Alt. Law 2), two actuators or all sensors (Direct Law), or there is a temporary loss of power that forces the FCC to reset (Mechanical Back-up Law).

In conclusion, the main consequence of adopting a Fly-by-Wire system is that the regulatory authority might demand some handling qualities requirements for the most degraded control law, such as the Mechanical Back-up. As will be described Chapter 6, the bare airframe response of the aircraft shows some possible control issues. Hence, it is clear that piloted evaluations of the non-augmented Flying-V are necessary to get the full picture of its airworthiness potential. In this research, the Mechanical Back-up mode will be tested during the simulation campaign, granted that the Flying-V is actually flyable with no augmentation. In case it is not, which will be clear during the first piloted simulations, future studies will be needed in order to make sure that the Flying-V complies with the non-augmented flight certification requirements.

4

Theory and relevance of selected HQ criteria

The topic of handling qualities has been central in aircraft engineering since the Wright brothers realized the challenge of balancing an airplane [29]. With the advent of fly-by-wire flight control systems, then, the evaluation of handling qualities became a compulsory step already during the design phase of an aircraft. 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 [18], then revised in 1986 [29]. 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, [18], 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, [29], p. 1). Today, their work is still commonly considered the state-of-the-art for the evaluation of handling qualities with test pilots based on the concept of pilot workload.

In the complex field of HQ assessment, 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.

This Chapter serves as a theoretical background to Chapter 6, in which the criteria explained here will be applied to the model introduced in Chapter 5. The logic for the selection of useful criteria has been shown in section 4.1. For most of these criteria, the reference text is the MIL-STD 1797B [40] already mentioned, but other sources complete the literature background.

In terms of the MIL-STD convention, the criteria considered here 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 goal is to address the HQ problem in the most critical way, 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. As a consequence, the criteria that involve fewer assumptions were preferred.

4.1. Common practices for Handling Qualities certifications

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 [23], or Humphreys-Jennings, Lappas and Mihai Sovar [34]), 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 [28], Stoliker [49], Field and Rossitto [26]).

To select a number of meaningful criteria for the preliminary study of the HQ of the Flying-V, a survey has been made on the publications related to HQ in landing phase and for new prototypes and flying wings. The main outcome was that, in general, researchers prefer the criteria commonly used for standard aircraft rather than new criteria.

Ordered by the rate of occurrence, the most used criteria appeared to be:

- Control Anticipation Parameter (CAP) ([26], [15], [34], [39], [1])
- Short period damping ratio ([15], [6], [34], [39], [33])
- Phugoid damping ratio and time to double ([6], [34], [39], [33])
- Bandwidth criteria ([26], [15], [39])
- Gibson dropback and flight path angle criteria ([26], [15], [39])
- C* criterion ([6], [33])
- Neal-Smith criterion ([6], [39])
- Smith-Geddes criterion ([6]).

The most common criteria of this list are discussed in the following sections.

4.2. Modes frequency and damping ratio

To begin with, some criteria exist to study the response of a system by means of its poles in the s-plane. One way to do so is to write the response of the system in form of a transfer function from any control input to any the state variable of the aircraft in the Laplace domain, which for longitudinal flight normally are (or can be approximated as) products of two second-order polynomials in the s variable. These two polynomials represent the two natural modes of the response of an airplane, namely Phugoid and Short Period, whose combined response is in general different for different aircraft.

When the two second-order polynomials are isolated, the transfer functions for i inputs and j outputs looks like in the following:

$$tf_{i,j}(s) = \frac{p_{i,j}(s)}{[s^2 + 2\zeta_p\omega_p s + \omega_p^2][s^2 + 2\zeta_{sp}\omega_{sp} s + \omega_{sp}^2]} \tag{4.1}$$

where $p_{i,j}(s)$ is a polynomial in the s variable of lower order than the denominator, determined by each combination of inputs and outputs.

In this form, ζ_p and ω_p are, respectively, damping ratio and natural frequency of the phugoid mode, whereas ζ_{sp} and ω_{sp} are damping ratio and natural frequency of the short period. In the following subsections the main related criteria are explained: phugoid damping ratio, short period damping ratio and natural frequency, and the so called ”short period thumbprint”. These are all based on the assumption that the system response for longitudinal flight has the typical form of an aircraft response (combination of two second order, normally oscillatory modes), which is the case for the Flying-V. For this research the transfer functions are easily obtained from the model introduced in Chapter 5. When the data is in the form of flight data, the theory of Equivalent Systems (e.g. see [32]) provides a methodology to write the system response in an equivalent form that matches the available data.

4.2.1. Phugoid damping ratio

While EASA and FAA have no specific requirements for phugoid damping ratio, MIL-STD suggests the following HQ levels:

	Phugoid damping ratio
Level 1	$\zeta_{ph} \geq 0.04$
Level 2	$\zeta_{ph} \geq 0$
Level 3	$T_{2_{ph}} \geq 55s$

Table 4.1: MIL-F-8785C: Phugoid damping ratio levels, Class III, CAT C

where ζph is the damping ratio as explained before, and $T_{2_{ph}}$ is the ”time to double amplitude” which can be shown to be equal to

$$T_{2_{ph}} = -\frac{\ln 2}{\zeta_{ph}\omega_{ph}}. \tag{4.2}$$

In this case, level three refers to aircraft in which the phugoid is unstable, but so slow that the pilot can easily suppress it with no major degradation in task effectiveness.

4.2.2. Short Period damping ratio

Short period response is used for numerous criteria and, in general, it is more important than phugoid damping ratio for HQ purposes. In fact, from a piloting point of view the short term response of an aircraft is more decisive and the slow phugoid mode does not influence it in a significant way.

The first criterion, based on the same few assumptions as for the phugoid damping ratio, is for the short period damping ratio. The MIL-STD proposes the following levels:

	Short period damping ratio
Level 1	$0.35 \leq \zeta_{ph} \leq 1.30$
Level 2	$0.25 \leq \zeta_{ph} \leq 2.00$
Level 3	$0.15 \leq \zeta_{ph}$

Table 4.2: MIL-F-8785C: Short period damping ratio levels, Class III, CAT C

4.2.3. Thumbprint

The first criteria adopted for HQ analysis focused mainly on short period frequency and damping ratio [26]. In a so called ”short period thumbprint” (Figure 4.1), the two criteria (damping ratio and frequency) were combined to assess the HQ of an aircraft. With the advancement in the field of HQ analysis, it soon became apparent that the thumbprint does not address the full HQ problem for pitch attitude response, since pilot rating did not always relate to the thumbprint criterion. However, it can still be used to get some initial insights on the kind of response of a prototype, which is particularly valuable in the context of this research. In fact, each area of the thumbprint is labelled according to the expected response of the system.

The use of the thumbprint in Chapter 6 must be interpreted in light of this premise.

4.3. Frequency analysis

The frequency response of the system can be studied by means of Bode plots. This part of the analysis will play a central role in Chapter 6, since many insightful observations can be made from it.

The main idea behind frequency domain analysis is that it can show how the system is expected to respond to closed loop control. MIL-STD formalizes this concept by means of the so called ”Bandwidth” criterion. According to this, ”*the bandwidth of the open-loop pitch attitude response to pilot control force [...] shall be within the bounds shown on figure* 4.2*, where ω_{BW} is the highest frequency at which the responses of aircraft pitch attitude to pilot control-force and control-deflection inputs have both 45 degrees or more of phase margin and 6 dB or more of gain margin and*

$$\tau_p = -(\phi_{2_{\omega_{180}}} + 180°)/(57.3x2\omega_{180}) \tag{4.3}$$

where ω_{180} is the frequency corresponding to -180 deg phase and $\phi_{2_{\omega_{180}}}$ is the phase angle at twice that frequency.” (MIL-STD,[40], Appendix A, p.235).

To compute the quantities used for this criterion, the procedure is shown in Figure 4.3. The two bandwidth frequencies ω_{BW} should be obtained according to the figure, and the lowest one should be selected, since that is the one limiting the handling qualities.

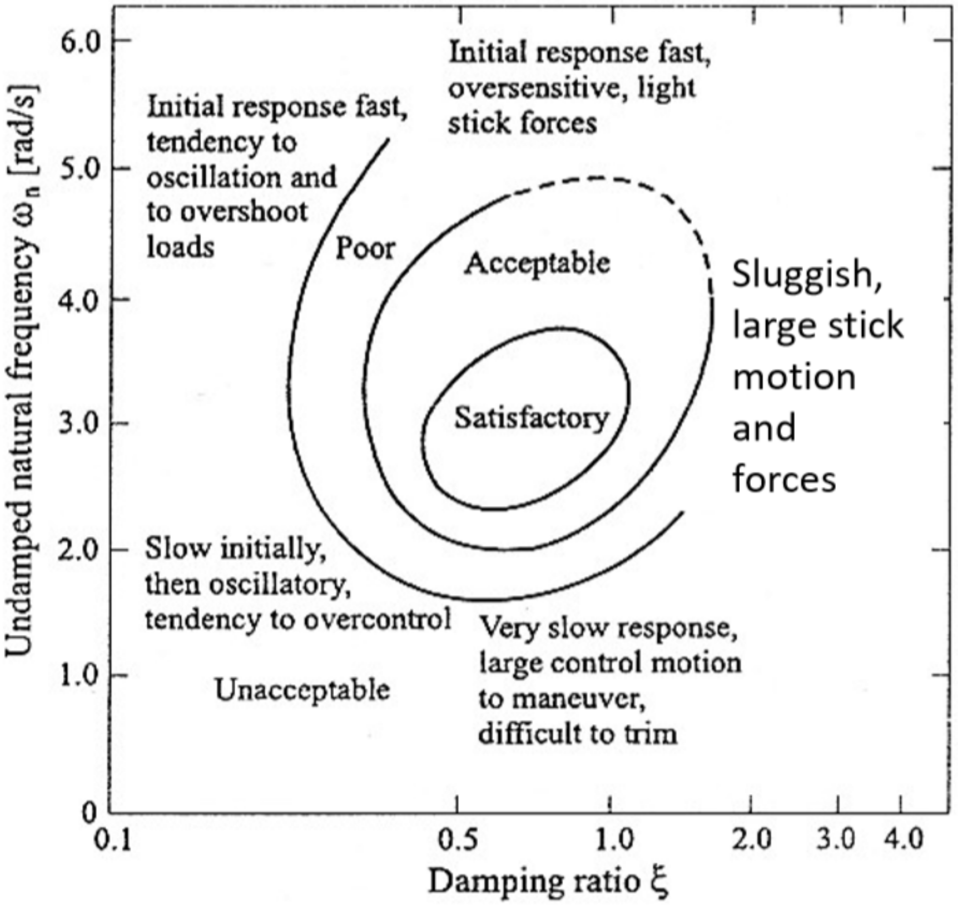


Figure 4.1: Short period Thumbprint. From [26]

Note also that the τ_p parameter is an indicator of the delay caused by feel system, the actuator dynamics and other delays sources. For the case of the Flying-V, the elevator dynamics are modeled as a simple first order lag, as explained in Chapter 2. Due to this, and to the fact that the feel system is not included, the relevance of τ_p here is limited and should be further investigated in the future with different models for feel and actuator systems.

This criterion is also sensitive to the shape of the frequency phase plot after ω_{BW}. Steep roll-offs have been associated with poor pilot rating, whereas more gradual phase plots after ω_{BW} normally receive higher ratings. The source of these possible poor handling qualities is to be found in the sudden change of the frequency plots after the ω_{BW} limit, due to which small changes in the operational frequency might fall immediately outside of the good frequency bandwidth.

In general the following observations can be made that turn useful for the analysis of Chapter 6:

- Pilots' control is mainly active for frequencies between 0.1 and $10 rad/s$ [26]
- Handling Qualities may show some degradation when the frequency ratio of phugoid and short period is $\omega_{ph}/\omega sp \leq 0.1 rad/s$ ([12],[27]).
- In transport aircraft, phugoid frequency is often above $0.1 rad/s$ [26]

4.4. Gibson time response criteria

Time response histories provide additional tools for the understanding of HQ. The two most commonly used criteria based on time response are the Gibson Dropback Criterion and the Gibson Flight Path Time Delay Criterion.

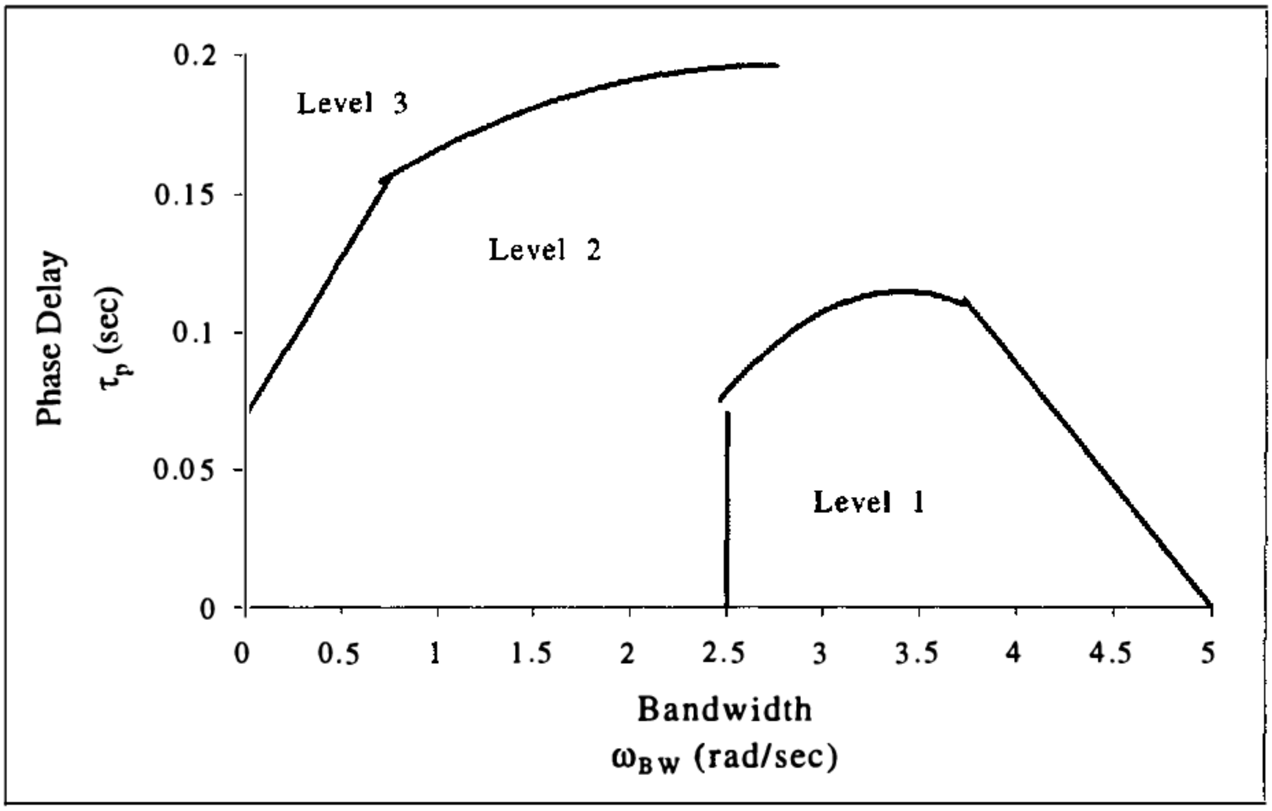


Figure 4.2: Bandwidth requirement, Category C flight phases. From [40], Appendix A, p.235

The purpose of these criteria is, in principle, similar to that of the previous ones - not necessarily to determine the HQ of the Flying-V, but to analyze the system in order to find possible hints of critical aspects of its response.

4.4.1. Dropback Criterion

The Dropback Criterion determines the HQ of an aircraft by computing two parameters [31]:

- q_{max}/q_{ss}, the ratio of pitch rate overshoot to steady state pitch rate; and
- DB/q_{ss}, the ratio of attitude dropback to steady state pitch rate,

both from the elevator step response. The graphic definition of these parameters is displayed in Figure 4.5, where the typical time response is shown for which this criterion is valid. The predicted HQ are then obtained from these two parameters by reading the plot of Figure 4.4. In Chapters 6 and 7 the response of the Flying-V will be compared to the typical response expected based on Gibson's analysis. It will be apparent that the bare airframe response of the Flying-V is too different from the typical one of Figure 4.5, and that a certain level of augmentation is required in order to apply the two Gibson criteria.

4.4.2. Flight Path Time Delay Criterion

In figure 4.6 the quantity t_γ is derived from flight path angle time history for a step input in longitudinal control surfaces.

The requirement proposed by Gibson is that $t_\gamma \leq 1.5s$ for landing and approach tasks. Essentially, t_γ should be seen as a measure of the observed delay between stick input and FPA response.

4.5. Control Anticipation Parameter

Finally, Control Anticipation Parameter (CAP) is one of the most commonly used criteria in the field of HQ. It is based on the concept that pilots look for indications of the steady state normal acceleration response by observing the initial pitch acceleration response. Hence, it consists in the ratio of initial

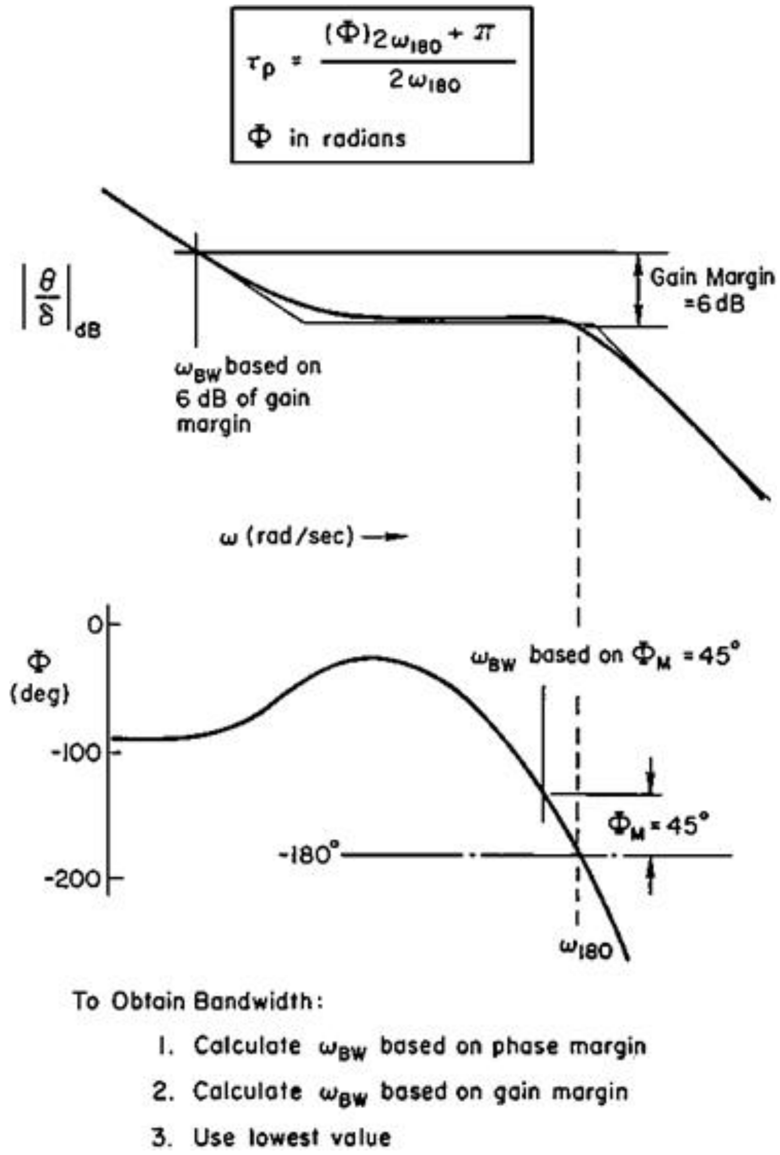


Figure 4.3: Bandwidth criterion quantities computation - model example. From [9].

pitch acceleration response to an elevator input over the steady state response of normal acceleration to the same input:

$$\frac{\dot{q}(0)}{n_z(\infty)} = \frac{\lim\limits_{s\to\infty} s\frac{1}{s}\dot{q}(s)}{\lim\limits_{s\to 0} s\frac{1}{s}n_z(s)} \tag{4.4}$$

where the equivalence of Eq. 4.5 is proven by the initial and final value theorems in the Laplace domain. According to the initial value theorem, in the Laplace domain the initial response (at time $t = 0+$) of a system is given by the limit for $s \to \infty$ of s multiplied by the Laplace transform of the input signal and by the Laplace transform of the transfer function of the system. Similarly, according to the final value theorem, in the Laplace domain the final response (at time $t = \infty$) of a system is given by the limit for $s \to 0$ of s multiplied by the Laplace transform of the input signal and by the Laplace transform of the transfer function of the system. In this case, the input signal is the step function ($\frac{1}{s}$ in the Laplace domain) for both the initial and the final values, whereas the transfer functions used here are the pitch angle acceleration ($\dot{q}(s)$) for the initial value theorem and the normal acceleration ($n_z(s)$) for the final

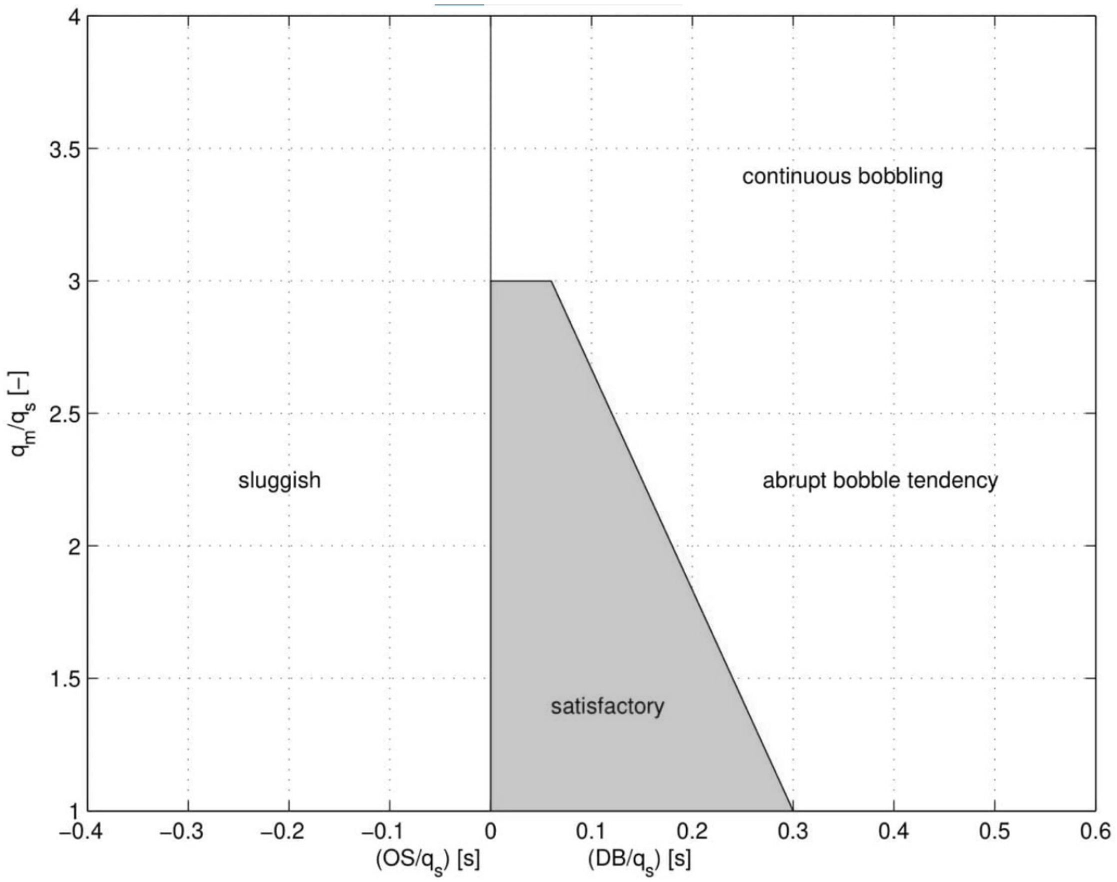


Figure 4.4: Boundaries of Gibson Dropback Criterion. From [31].

value theorem. Effectively, $s\frac{1}{s} = 1$, so that the CAP formula is reduced to

$$\frac{\dot{q}(0)}{n_z(\infty)} = \frac{\lim_{s\to\infty} \dot{q}(s)}{\lim_{s\to 0} n_z(s)} \tag{4.5}$$

if it is assumed that the control input is a step function.

The historical success of this criterion, still vastly used today, is that it addresses better than other criteria the actual way a pilot controls an aircraft (MIL-STD [40], p188). In fact, pilots try to interpret the relation between initial pitch response and flight path angle, which they ultimately try to control. Moreover, in order to regulate the control action they need to understand this relation before reaching the steady state. For this reason, a pilot tends to associate better HQ to aircraft in which pitch acceleration is neither too slow or too fast compared to flight path angle response.

Also, it is advised in the MIL-STD that the CAP is only applied to aircraft in which direct lift control is not significant. In fact, the HQ deriving from direct control on normal acceleration are not accurately represented by the CAP concept. Since it has been noted [50] that the Flying-V has an inclination for direct lift control, the CAP criterion should be used with special care.

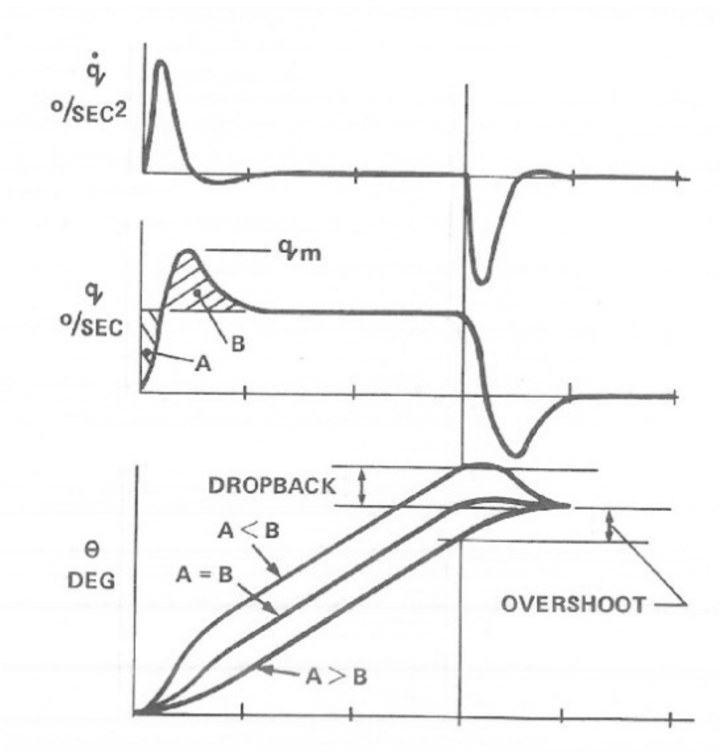


Figure 4.5: Typical pitch step response, analysed with the Gibson Dropback Criterion. From [19].

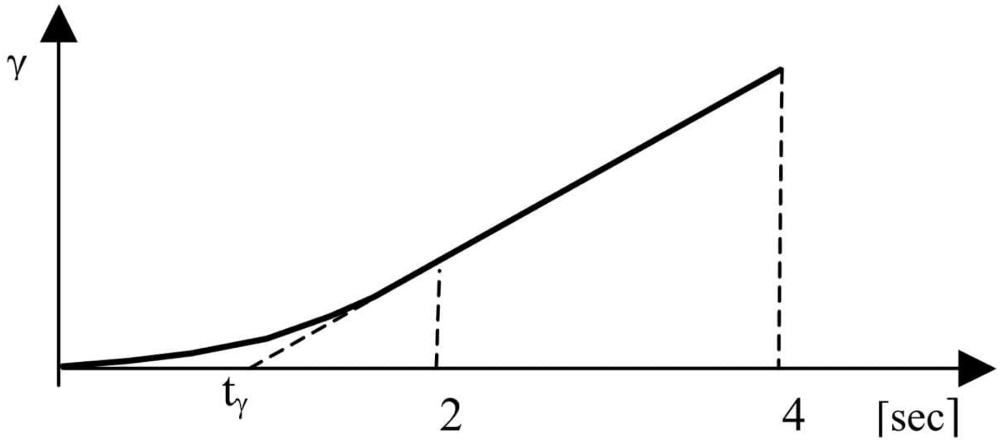


Figure 4.6: Flight Path Time Delay Criterion definition. The time interval (in this case 2 to 4 seconds) should be selected according to the shape of the response. From [31].

5

Flying-V model

5.1. The Aerodynamic model

The model used for this research plays a central role in both the preliminary analysis and the piloted simulations. In this chapter the generation and the validity of the used model are discussed, and the linearization procedure is introduced to allow for classic control theory analysis.

5.1.1. Airbus ODILILA

Airbus collaborates on the Flying-V project by providing essential tools, such as the model data for this research. This aerodynamic model is generated through the ODILILA software (see, for example, the first paper by J. Benad [16], an Airbus proprietary tool for Computational Fluid Dynamics).

The software is based on the Vortex Lattice Method [35] hereby summed up:

1. The fluid is assumed to be incompressible, inviscid, and irrotational; the lifting surfaces are thin; angle of attack and sideslip are small. The consequences of these assumptions will be assessed in Section 5.1.2. The flow field is hence a conservative vector field (constant total velocity vector V), for which is possible to write
$$\mathrm{V} = \mathrm{V}_\infty + \nabla\phi$$
where ϕ is the perturbation velocity potential;
2. the aircraft body, assumed to be thin, is divided into a Lattex of N panels over which the perturbation velocity is computed by means of Aerodynamic Influence Coefficients w_{ij}
$$\nabla\phi_i = \sum_{j=1}^{N} \mathrm{w}_{ij}\Gamma_j;$$
3. a Boundary Neumann condition is applied on each panel to impose zero normal velocity:
$$\mathrm{v}_i \cdot \mathrm{n}_i = \left(\mathrm{V}_\infty + \sum_{j=1}^{N} \mathrm{w}_{ij}\Gamma_j\right) \cdot \mathrm{n}_i = 0;$$
4. by solving the previous equation for each panel, the total force vector is computed as
$$\mathrm{F} = \sum_{i=1}^{N} \rho\Gamma_i \left(\mathrm{V}_\infty + \mathrm{v}_i\right) \times \mathrm{l}_i,$$
where ρ is the fluid density, l_i is the vortex's transverse segment vector, and v_i is the perturbation velocity at this segment's center location r_i.

5. Similarly, the momentum vector M is computed about the origin reference point, which is the center of gravity, as

$$\mathrm{M} = \sum_{i=1}^{N} \mathrm{F}_i \times \mathrm{r}_i,$$

where r_i is the distance from the origin to the center of the i panel.

6. Finally, Lift and Drag are computed by projection of the total force vector F along the aerodynamic frame (origin at center of gravity, x-axis along the relative wind vector projected onto the aircraft plane of symmetry, y-axis along the right wing, z-axis completes the right-hand axes system).

The complete implementation of the Vortex Lattice Method requires a careful description of the lattice geometry. For this, refer to the book of Katz and Plotkin already mentioned [35]. Furthermore, ODILILA implements an advanced Vortex Lattice Method that takes into account taper, twist, camber, control surfaces, high lift devices and nacelles (Cappuyns [50]).

The final model was computed in ODILILA about the following break points:

State/Input	Lower pnt.				Middle pnt.				Upper pnt.
Alpha [deg]	-5	0	5	10	12.5	15	16.5	18	20
Beta [deg]	-15	10	5	2	0	2	5	10	15
pstar [rad]	-0.1	-0.05	-0.02	-0.005	0	0.005	0.02	0.05	0.1
qstar [rad]	-0.1	-0.05	-0.02	-0.005	0	0.005	0.02	0.05	0.1
rstar [rad]	-0.1	-0.05	-0.02	-0.005	0	0.005	0.02	0.05	0.1
c1 [deg]	-1				0				1
c2 [deg]	-1				0				1
c3 [deg]	-1				0				1

Mach numbers	0.2	0.225	0.25	0.275	0.3	0.8

The rationale of this set of breakpoints is to focus on low velocities (Mach number dense between 0.2 and 0.3), high angle of attack (Alpha dense around 16 deg) and a wide range of side slip (Beta) and rotations. Due to the way ODILILA is implemented, c1, c2 and c3 (representing one half of the control surfaces) can only be set to 0 and ± 1 deg, whereas larger deflections will be extrapolated linearly. The Center of Gravity is given in three positions: the two stable limits determined by Cappuyns [50], and a point in the middle of this range.

(See Appendix A for the structure of the model and its implementation into MATLAB and DUECA.)

5.1.2. Model Validity

Vortex Lattice CFD is particularly attractive for the first design iteration of an aircraft since it is light on a computational point of view, relatively easy to implement, and provides the right insight on the dynamics of a body. However, it comes with limited validity due to the baseline assumptions that have been mentioned above and that will be discussed in this section.

- The flow is assumed to be **incompressible**.

  In an incompressible flow the divergence of the velocity is zero, which is acceptably accurate only up to Mach numbers between 0 and 0.3. In fact, compressible phenomena are evident for flows with a velocity higher than Mach 0.3 and they cannot be ignored. However, since in this research the speed range of interest is that between 0 and 0.3 Mach (landing speed is expected to be around 0.22 Mach), this assumption is not critical.

  Even so, it must be mentioned that in this case, 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, more significant for higher Mach numbers.

- The flow is also assumed to be **inviscid**.

  As a consequence, the fluid is modelled with zero viscosity, and all the boundary layer phenomena are ignored. This has two main effects on the validity of the model, both critical.

  The first is that no flow separation can be model in a zero viscosity fluid, hence no stall behaviour is apparent from the Vortex Lattice Method. This is relevant for this research since the angle of attack of the Flying-V can be close to the critical angle during landing and approach. In fact, a typical lift curve represented in a lift-over-angle of attack plot shows a linear trend up until a stall point at which the lift coefficient is maxed and after which the curve goes down. However, in the model computed in ODILILA the curve is only linear and no stall point is present. For the simulations and the analysis which are carried out on this model, it is expected that the aircraft will fly up to 20 degrees of angle of attack. All considered, this means that future research on stall angle of attack will be needed to locate the critical angle, and the outcomes of this research are to be deemed accurate only up until the stall point.

  Secondly, 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 computed by Faggiano [25], $C_{d_0} = 0.00572$. However, its validity for the Flying-V is uncertain, since it was computed based on empirical equations valid for conventional aircraft. In this research, it is hence preferred to work with the original ODILILA model and not to add this zero-lift contribution, which is left for future research.

- Another assumption is that of **irrotational** fluid.

  It implies that no vorticity is present in the fluid, and this is unacceptable for regions where vorticity is known to be high, such as at wakes and boundary layers. However, these regions are not in the scope of this research, hence this assumption is valid. It is sufficient that one is aware that the model might be slightly optimistic, since the flow is ideal and unspoiled by vortices.

- 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 further influence on the drag, however, is not expected to alter the outcome of this research in a major way. Nonetheless, future studies should address these inaccuracies to confirm this research.

- Finally, the Vortex Lattice Method is based on the assumption of **small angles**.

  This assumption is only valid if the actual angles are small. In this research, side slip is set to zero and thus it can be safely considered always 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 [redacted]. 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.

5.2. Equations of Motion

The coefficients provided by the ODILILA software are used to compute the forces and moments on the aircraft by means of aerodynamics formulas (e.g. $L = \frac{1}{2}\rho v^2 S C_L$). These are then inputted in the equation of motions of a 6-DoF flying body, accordingly to the following formulas:

$$\begin{bmatrix} \dot{\mathrm{P}}_e \\ \dot{\mathrm{v}}_b \\ \dot{\omega}_b \end{bmatrix} = \begin{bmatrix} 0 & {\Gamma_{be}}^{-1} & 0 \\ 0 & -\omega_b & 0 \\ 0 & 0 & \mathrm{I}^{-1}\omega_b \mathrm{I} \end{bmatrix} \cdot \begin{bmatrix} \mathrm{P} \\ \mathrm{v}_b \\ \omega_b \end{bmatrix} + \begin{bmatrix} 0 \\ -g_b + \frac{F_b}{m} \\ \mathrm{I}^{-1}\mathrm{T} \end{bmatrix}, \tag{5.1}$$

where P is the position vector, v is the velocity vector, ω is the rotation velocity vector, b stands for body frame, e stands for earth frame, F and T are the total force torque computed from the aerodynamic data of ODILILA, and

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi/\cos\theta & \cos\phi/\cos\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}_b \tag{5.2}$$

$$\mathrm{g}_b = \Gamma_{be} \begin{bmatrix} 0 \\ 0 \\ g_0 \end{bmatrix} \tag{5.3}$$

$$\Omega_b = \begin{bmatrix} 0 & -R & Q \\ R & 0 & -P \\ -Q & P & 0 \end{bmatrix} \tag{5.4}$$

$$\mathrm{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \tag{5.5}$$

$$\Gamma_{ba} = \begin{bmatrix} \cos\alpha\cos\beta & -\cos\alpha\sin\beta & -\sin\alpha \\ \sin\beta & \cos\beta & 0 \\ \sin\alpha\cos\beta & -\sin\alpha\sin\beta & \cos\alpha \end{bmatrix} \tag{5.6}$$

$$\Gamma_{be} = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \cos\theta\sin\phi \\ \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi & \sin\psi\sin\theta\sin\theta\cos\phi - \cos\psi\sin\phi & \cos\theta\cos\phi \end{bmatrix}, \tag{5.7}$$

where g_b is the gravity vector in body reference frame, P,Q,R are the rotation rates, I is the inertia matrix, Γ_{ba} is the rotation matrix from body to aerodynamic reference frames, and Γ_{be} is the rotation matrix from body to earth reference systems.

5.3. Trim and Linearization

Many of the criteria used for the off-line assessment of the HQ of an aircraft, together with most of the tools of classical control theory, require that the aerodynamic model be trimmed and then linearized around the trim point. The trimming process is the same as in De Marco's work [21], while linearization is shown in Appendix B.

The linear model is examined in detail in Chapter 6. To obtain it, the following steps are repeated for each different configuration:

- the desired flight condition is chosen, and the resulting implications are written as constraints for the trimming algorithm. In the case of this research, the flight condition is always that of symmetrical, level flight; hence horizontal acceleration, vertical acceleration, and pitch acceleration are all required to be zero by means of trimming constraints. All the asymmetrical equations of motion can be neglected.
- The configuration parameters are chosen - in this case CG position and airspeed. CG position determines the aerodynamic model; airspeed is obtained by requiring the difference between aircraft speed and desired speed to zero, which provides the fourth constraint.
- With four constraints, the equations of motion can be trimmed around the desired point by tuning the four variables: horizontal velocity, pitch angle, elevons deflection (one equal deflection for all the four elevons) and engine power.

- The success of the trimming process is checked by means of a cost function of the four constraints. It was observed that, in order to trim correctly and more consistently for different configurations, the constraints on pitch acceleration and airspeed should be given a weight of 100 compared to those on horizontal and vertical velocity. The trimming process is considered successful if the cost function gives a small number ($< 10^{-10}$).
- If the equations are successfully trimmed, linearization is possible around this point. It was observed that the application of the numerical linearization method of Appendix B requires no particular weight tuning, and it proved to be effective for all the configurations when verified against analytical linearization of the same equations.

6

HQ preliminary analysis

The theory explained in Chapter 4 is applied to the data model of Chapter 5 to predict the HQ of the Flying-V. In this Chapter, the most relevant results of this analysis will be presented, with the purpose of determining useful experiments for the piloted simulations that will be presented in Chapter 8.

The structure of this chapter follows the same order of Chapter 4: each section of Chapter 6 is the application of the theory of the same section in Chapter 4.

6.1. Modes frequency and damping ratio

When the model is linearized around a trimmed point it is possible to write the system in form of a transfer function and observe the poles in the s plane of the Laplace Domain. This is shown in Figure 6.1, while in Figure 6.2 the same plot is zoomed-in on the phugoid poles.

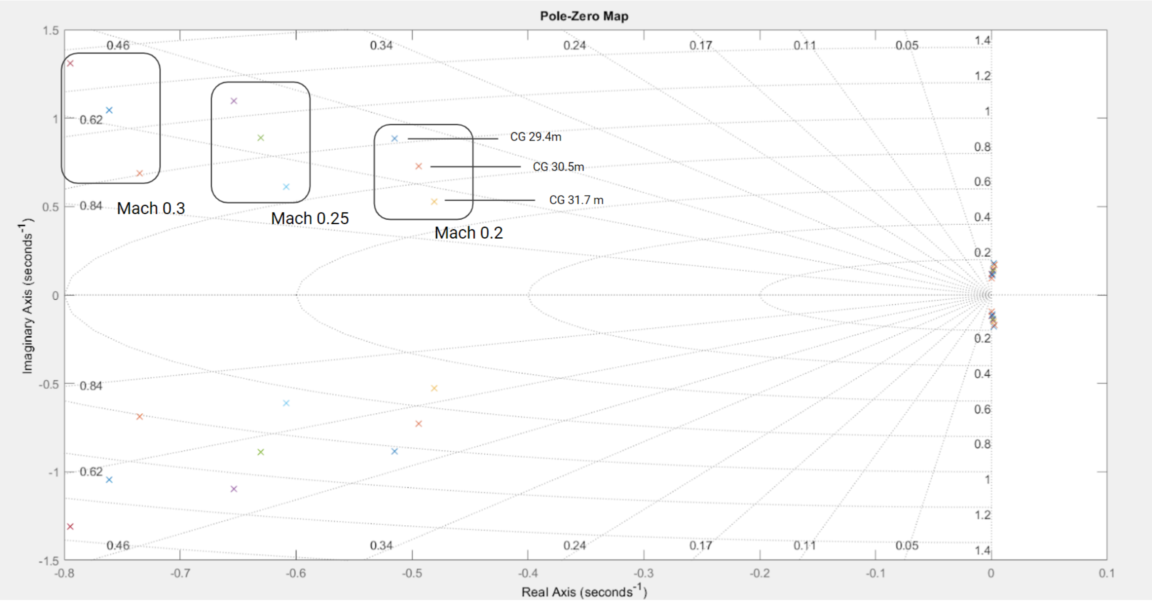


Figure 6.1: Longitudinal poles of the Flying-V for different CGs and Mach numbers.

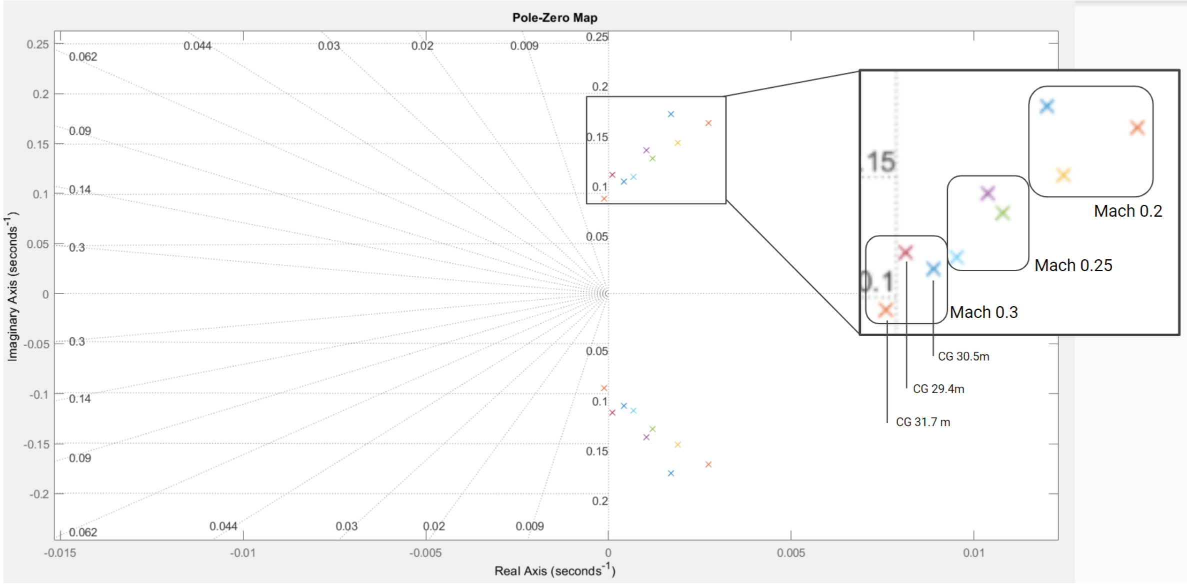


Figure 6.2: Longitudinal poles of the Flying-V for different CGs and Mach numbers. Detail on phugoid poles.

From this plot, damping ratio and natural frequency of phugoid and short period are obtained. For the phugoid, both damping ratio and frequency are in the limits of acceptable handling qualities for standard airplanes (see Sections 4.2.1 and 4.2.2). For example, at nominal CG and $Mach = 0.25$ (middle case), the phugoid poles are at $1.21e-03 \pm 1.35e-01i$, with frequency

$$\omega_{ph} = 0.135 rad/s,$$

damping ratio

$$\zeta_{ph} = -8.92e-03$$

and time to double

$$-\frac{\ln 2}{\zeta_{ph}\omega_{ph}} = 575,6s,$$

which is Level 3 according to MIL-F-8785C (see Section 4.2.1), the ”time to double” being positive yet very large.

While the phugoid is in the recommended limits, the short period shows unsatisfactory qualities. The damping ratio is always good, with the average between CGs and Mach numbers being

$$\zeta_{sp} = 0.579,$$

which is Level 1 according to MIL-F-8785C; but the frequency of the short period is slow in all the cases. The short period frequencies for the nine configurations (3 CGs, 3 Mach numbers) are reported in Figure 6.3, where all the frequencies appear relatively close to each other. This figure is used to select three flight conditions that are most representative of this short period frequency issue for the analysis and for the piloted simulations experiments, see Section 6.6: a ”fast” short period configuration (forward CG and high velocity at 0.3 Mach), an ”average” short period configuration (nominal CG and average velocity at 0.25 Mach), and a ”slow” short period configuration (aft CG and ”low” velocity at 0.2 Mach).

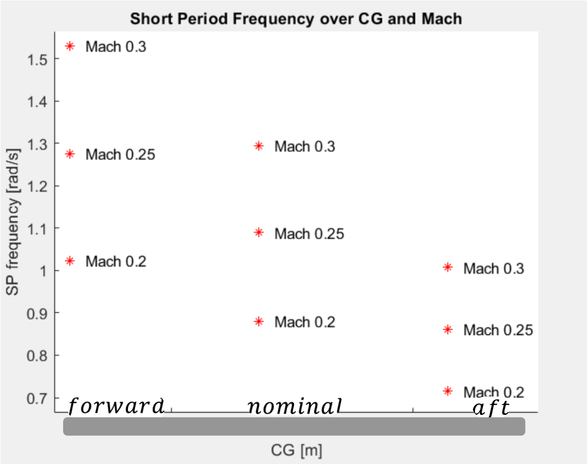


Figure 6.3: Natural frequency of the short period of the Flying-V for $CG = forward, nominal, aft$; and $Mach = 0.2,\ 0.25,\ 0.3$.

To understand the relevance of this aspect, it is insightful to plot short period damping and frequency in the *short period thumbprint* of figure 6.4, introduced in Section 4.2.3.

All the combinations of frequency and damping ratio fall in the same area, which reads *"Very slow response, large control motion to maneuver, difficult to trim"*. In this zone of the thumbprint, the damping ratio is acceptable but the frequency is too slow to reach the satisfactory zone.

The slow short period is expected to have a major impact on the handling qualities, and a flight control system seems necessary to correct for this slow response. For the piloted simulations, pitch tracking at different control frequencies should prove insightful in this sense.

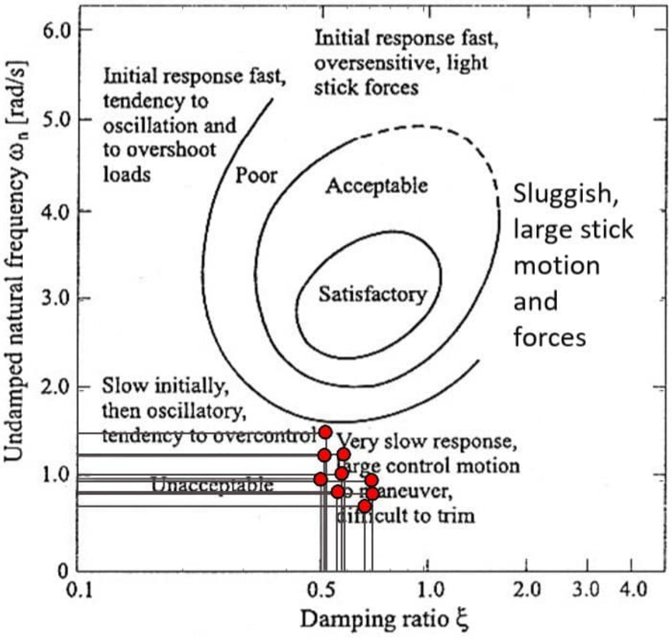


Figure 6.4: Short period *thumbprint* of the Flying-V for $CG = forward, nominal, aft$; and $Mach = 0.2,\ 0.25,\ 0.3$. For more information about the short period thumbprint plot, see Roskam [45].

6.2. Frequency analysis

6.2.1. Bode plot and frequency separation

In the frequency domain, the Bode plots are the tools of election for analyzing the response of a system. The input to the system is modelled as a single control for all the four elevons, as explained in Section

2.3. With this control input, the frequency response of pitch angle and pitch rate are shown in figures 6.5 and 6.6 for the average configuration.

In these, the gain peak corresponds to the phugoid frequency, which is related to a pole in the right half plane and is negatively damped. The dip in the phase response is also originated by the unstable phugoid. After the phugoid frequency, a $-20db$ per decade slope is expected in the pitch bode plot and a $0db$ slope in the rate bode plot, since an airplane typically shows an integrator-like behaviour between the phugoid and the short period frequency [40]. This is the case in these plots.

However, differently from standard aircraft, the frequency range of this part of the bode plot between the frequency of the two modes is very narrow, due to the slow frequency of the short period (which is approximately where the slope gets an additional $-20db$ per decade). As a consequence, the shape of the bode plot is partially different from the usual bode plot of an aircraft, indicating some potential control issues of the airplane with closed loop control.

In fact, pilot control activity lies usually within the frequency range of 0.1 to 10 rad/s, and it is desirable that in this frequency range the aircraft pitch responds integrator-like ($-20db$ per decade slope) so that tracking tasks are not hindered.

One problem that arises from this type of response is that many of the commonly used criteria (that is, most of the criteria suggested in the MIL-STD) are based on the assumption that short period and phugoid frequencies are well separated. With this assumption not being respected, all the criteria must be used with special care and some might not even be directly applicable. In any case, the piloted simulation experiments will have to carefully investigate the vicinity of the two modes to understand the impact of the small modes separation on the HQ. For this reason, a flight control system will be designed in Chapter 7 to regulate phugoid and short period frequency and test how their separation influences the response of the aircraft.

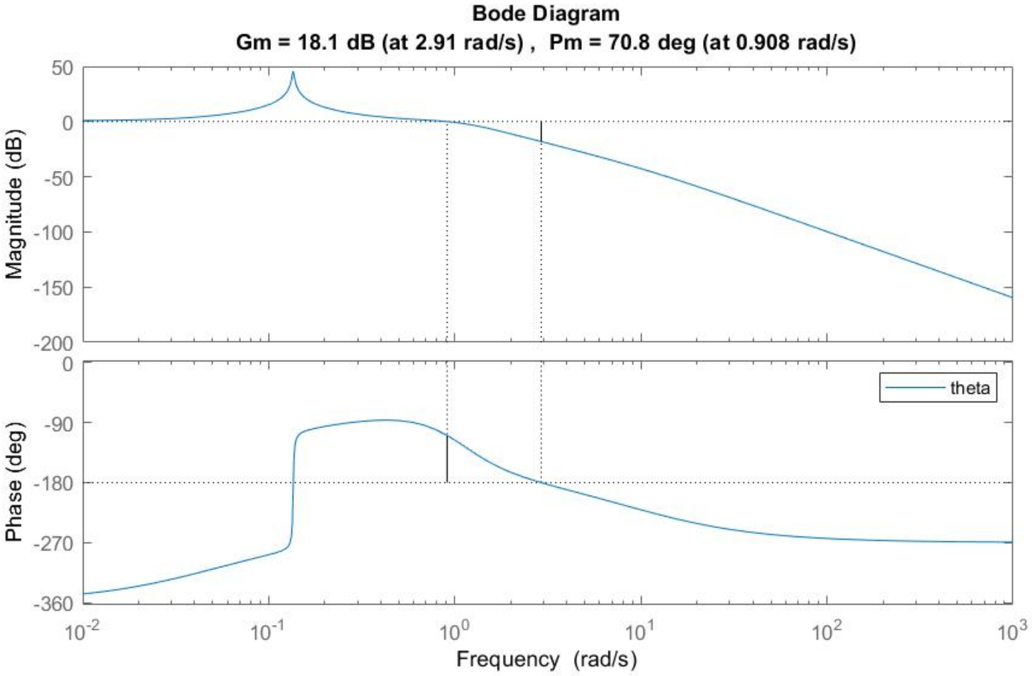


Figure 6.5: Bode plot of pitch angle response to longitudinal symmetrical control of the four elevons.

Here it is nominal CG and V = 0.25 Mach.

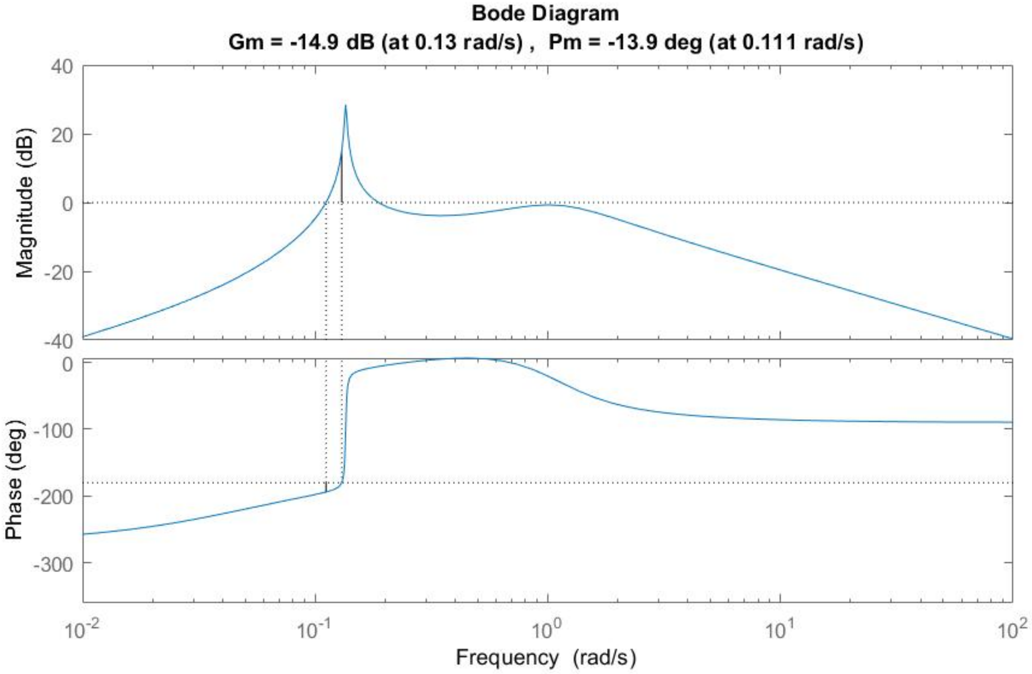


Figure 6.6: Bode plot of pitch rate response to longitudinal symmetrical control of the four elevons.

Here it is nominal CG and V = 0.25 Mach.

6.2.2. Bandwidth

The chosen criterion for the frequency domain is the MIL-STD Bandwidth criterion, as explained in Section 4.3.

For nominal CG, V = 0.25 Mach and first order lag actuators introduced before, the Bandwidth criterion is applied to the frequency response of Figure 6.7. From this plot, it is possible to compute all the quantities used for this criterion as shown in Figure 4.3, Section 4.3: ω_{BW} here is $\omega_{135} = 1.27 rad/s$, since it is the lowest frequency between ω_{135} and ω_{6db}; τ_p here is

$$\tau_p = -(\phi_{2_{\omega_{180}}} + 180°)/(57.3x2\omega_{180}) = 0.07s,$$

where $\phi_{2_{\omega_{180}}} = -203deg$ is also from 6.7.

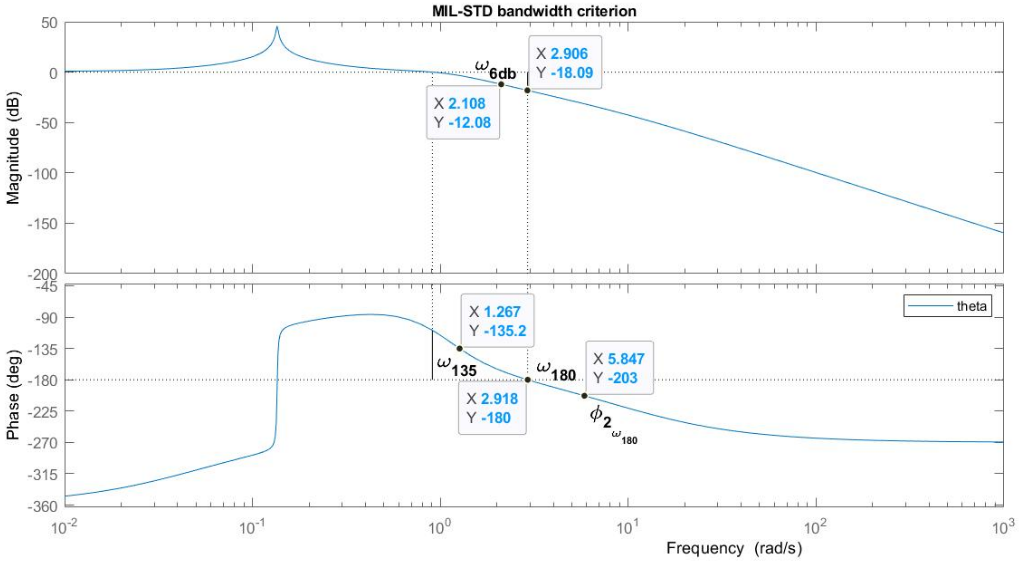


Figure 6.7: Bode plot for MIL-STD Bandwidth criterion, nominal CG and V = 0.25 Mach, elevons actuator dynamics included.

Based on these quantities, the criterion for the Flying-V is shown in Figure 6.8. As mentioned before, the τ_p quantity is correlated (not equivalent) to the delay caused by the feel system and the actuator dynamics, but here the actuators are modelled as a basic first order lag and the feel system is excluded from the analysis. As a reference, the test-vehicle used in MIL-STD (USAF/CALSPAN T-33) and the Boeing 367-80 have $\tau_p = 0.07$ due to actuation and feel systems. As a consequence, the relevance of τ_p here is limited. This being said, the Flying-V in this configuration shows Level 2 HQ according to this criterion, with the Bandwidth frequency ω_{BW} being determined in this case by the -45 phase margin and not by the gain margin.

The phase plot after ω_{BW} does not look particularly steep, hence no concerning degradation of the HQ is expected to be caused by a sudden change in the frequency response as explained in Section 4.3. However, feel system and more realistic actuator dynamics might have an impact on its shape.

As a consequence, it would be insightful to make use of piloted simulations to

- test how system delays (feel system, actuators, ...) might change the shape of the frequency response and reduce the HQ predicted with the Bandwidth criterion; the feel system will be included in the simulator for the human-in-the-loop experiments and it will be tuned as in Section 8.4.1.
- try to increase the ω_{BW} of the system and push it into Level1 by means of control augmentation, see Chapter 7.

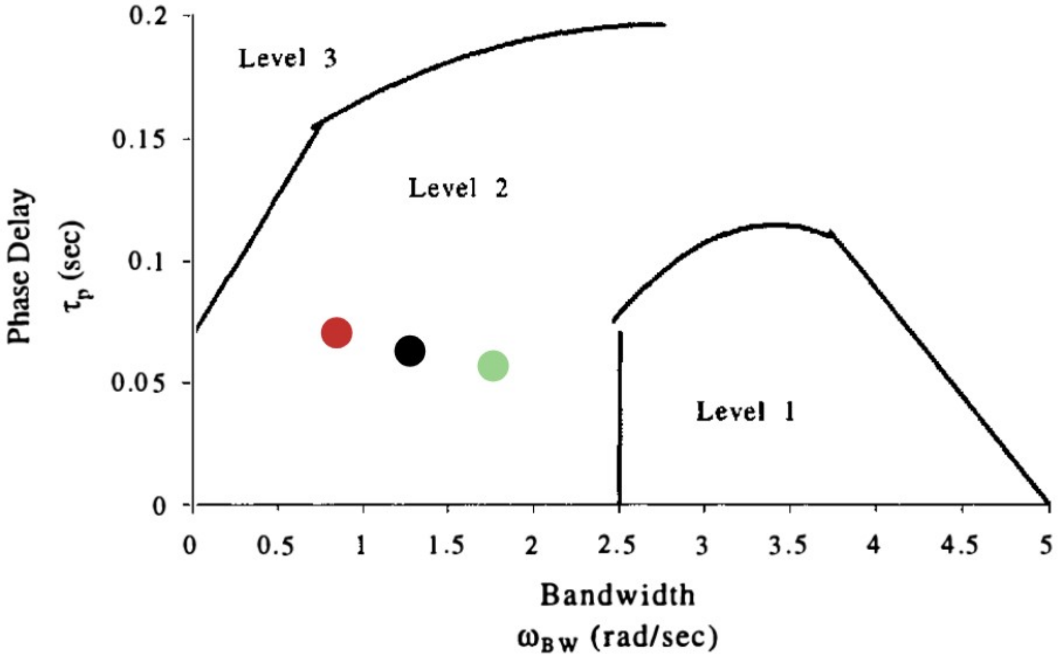


Figure 6.8: MIL-STD Bandwidth criterion, forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

6.3. Gibson time response criteria

The two Gibson criteria, Flight Path Angle and Dropback, aim at predicting the HQ of an aircraft based on the pull-up time response, see Section 4.4.

6.3.1. Dropback

To measure dropback and the pitch rate information needed for this criteria, the full non-linear Flying-V response is tested with a -0.1 deg input on all the elevons at second 3, then released at second 25. The response is shown in Figure 6.9 (dropback and overshoot) and Figure 6.10 (pitch rate) for the three different configurations obtained in Section 6.1 (forward, nominal, and aft CG; Mach = 0.2, 0.25, 0.3).

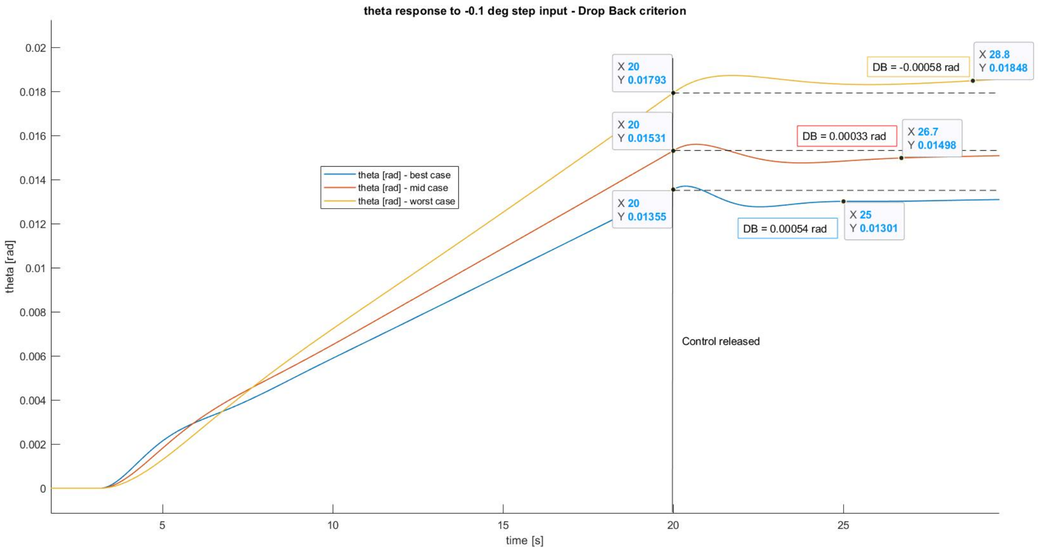


Figure 6.9: Dropback criterion - dropback and overshoot. Forward, nominal, and aft CG; Mach = 0.2, 0.25, 0.3. Elevons actuator dynamics included.

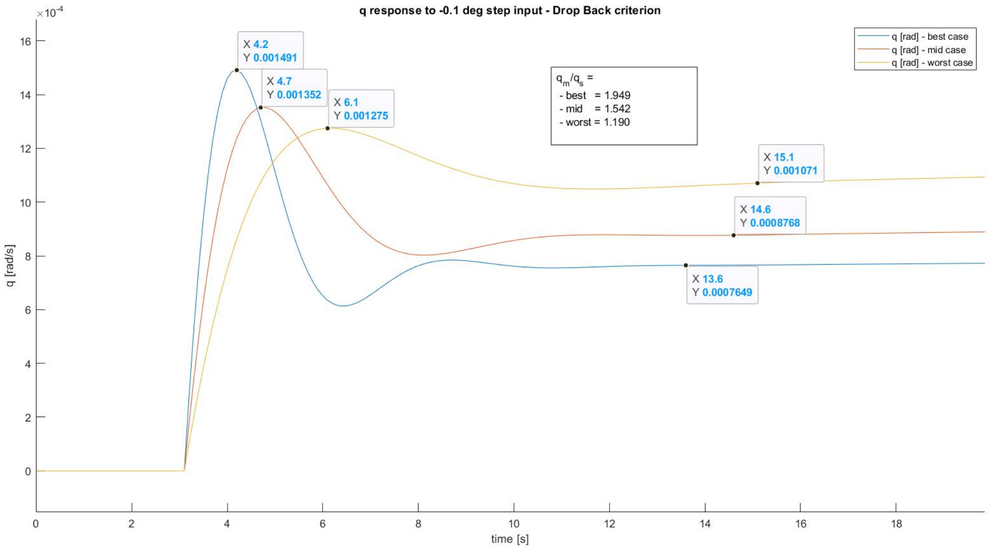


Figure 6.10: Dropback criterion - pitch rate. Forward, nominal, and aft CG; Mach = 0.2, 0.25, 0.3. Elevons actuator dynamics included.

By combining the analysis of these two figures one can locate each configuration in the Gibson Dropback boundaries plot, Figure 6.11. From the analysis of these three figures (dropback/overshoot, pitch rate max and steady state, boundaries), it appears that the fast short-period configurations (green and black) are associated with a bad proportion between dropback and q_m/q_ss. This locates these faster configurations in an area of the boundary plot that the MIL-STD book describes with the following observation: *”Increasing attitude drop back led to abrupt response and bobbling, from ”slight tendency” to ”continuous oscillations”, in tracking tasks. Sometimes this was called PIO but it did not cause concern for safety.”* [40].

On the other hand, for the slower short period configurations (red in Figure 6.9), the overshoot hints at a possible sluggish response of the Flying-V.

All the configurations fall in the satisfactory area as far as the q_m/q_{ss} ratio is concerned, but a low

q_{ss} might be the reason behind wide spread of the configurations in the boundaries plot of Figure 6.11.

A further detailed sensitivity analysis on 9 configurations (all the combination of 3 center of gravity positions, forward, nominal, and aft, and 3 speeds Mach = 0.2, 0.25, 0.3) confirms the analysis just presented, with the additional information that it is the CG position to determine the nature of the response (whether overshoot or dropback is present) and that for slower velocities the overshoot is more distinct, while for higher velocities the dropback is more significant.

With the piloted simulations, the pull-up maneuver should be tested at different configurations and with different control augmentations. The goal should be to study the correlation between the aircraft configurations and the dropback/overshoot type of responses.

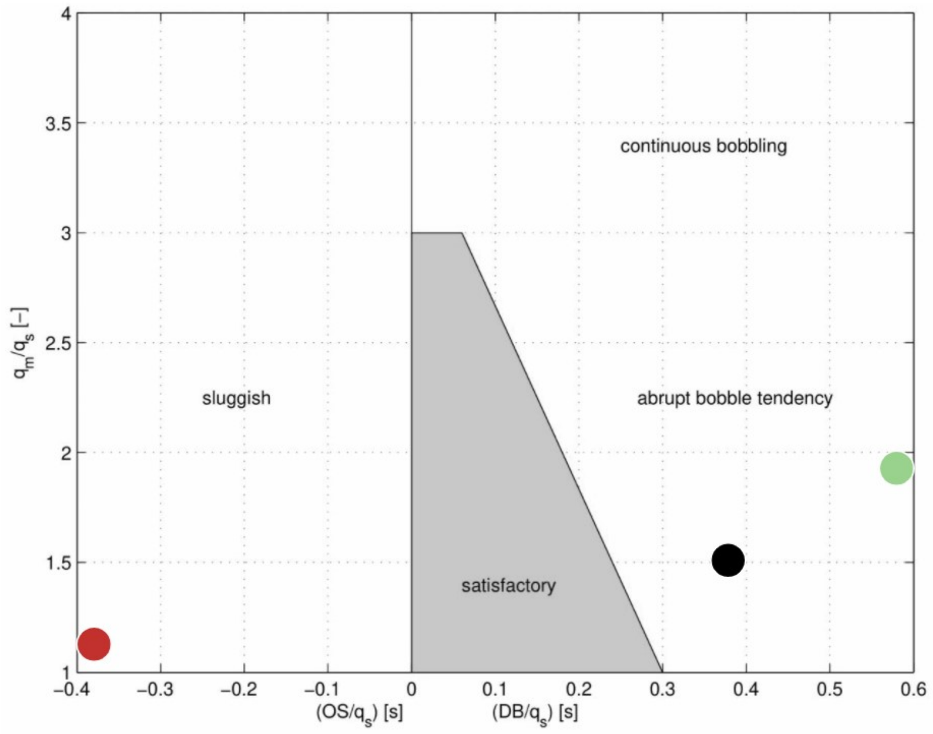


Figure 6.11: Dropback criterion - boundaries. Forward CG, Mach = 0.3 (green); nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

6.3.2. Flight Path Angle

The Flight Path Angle response can be analysed to integrate the Dropback criterion. Gibson analysis suggests to look at the time delay between the control input and the visible Flight Path Angle response. Figure 6.12 displays the response for the three representative cases of slow, average and fast short period responses.

The time delays for all the 9 configurations are shown in Figure 6.13.

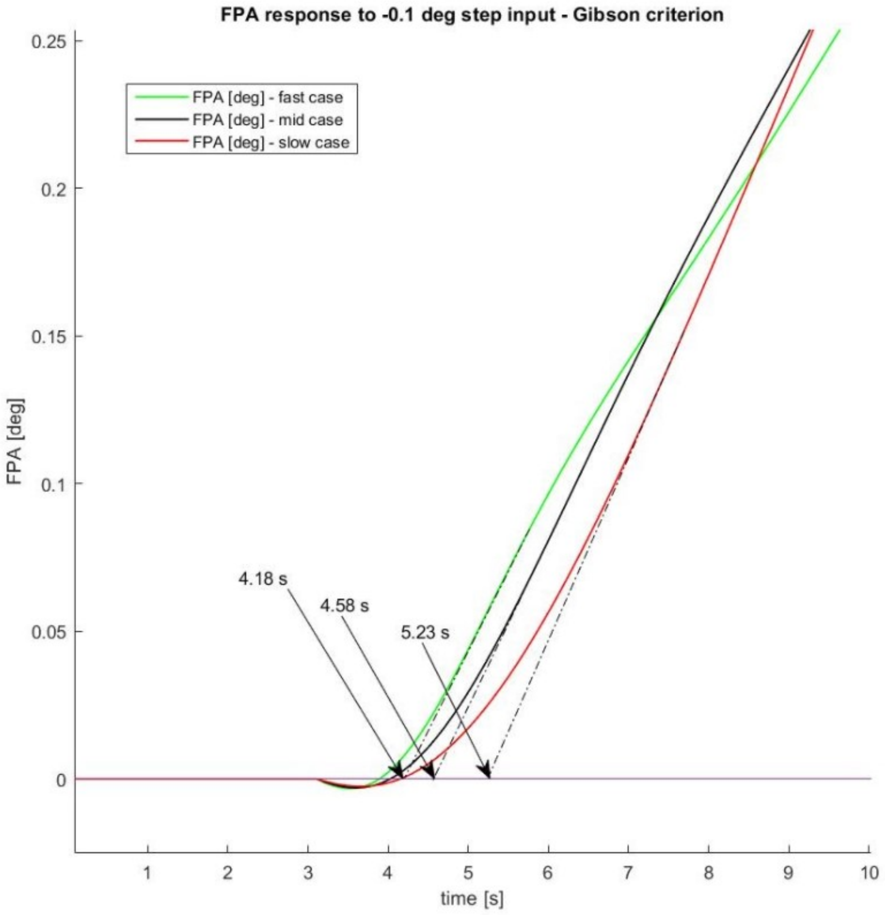


Figure 6.12: Gibson Flight Path Angle. Forward CG, Mach = 0.3 (green);

nominal CG, Mach = 0.25 (black); aft CG, Mach = 0.2 (red). Elevons actuator dynamics included.

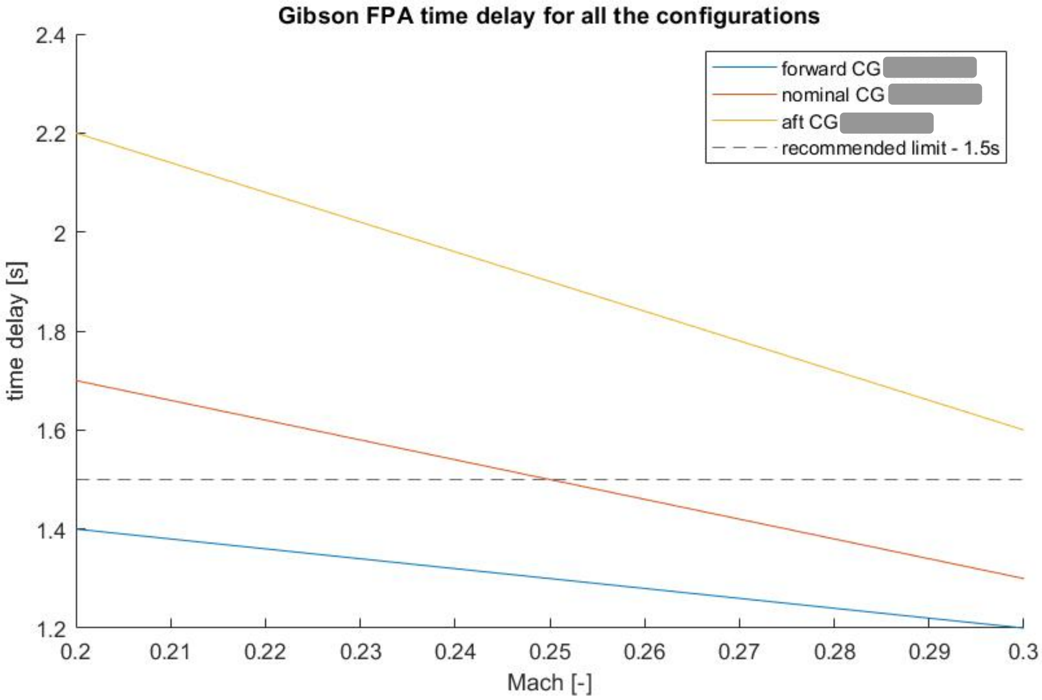


Figure 6.13: Gibson Flight Path Angle time delays for all the configurations considered in this research. The dashed line is the limit suggested by Gibson for good handling qualities. Elevons actuator dynamics included.

From a combined analysis of these results, it is clear that there is a correlation between the FPA delay and both the CG and the velocity of the aircraft. The more forward the CG and faster the aircraft, the smaller the delay. If one considers the recommended limit for this delay to be 1.5 seconds as a result of Gibson's research, then all the configurations with the aft CG fall out of this limit, those with the nominal CG are just borderline, and those with the forward CG are always satisfactory. In other words, the configurations associated with slow short-period frequency are also predicted to be hard to manoeuver because of a delay in the response of the FPA to the control input. Remind from Section 5.1.1 that of these three locations, two are the stable limits determined by Cappuyns [50] and one is the point in the middle of this range.

Additionally, it emerges from this preliminary analysis that while the configuration with aft CG generally performs worse than the rest of the configurations, it achieves higher (hence generally better) steady state values of pitch rate during climb.

It is clear that the FPA response is critical for the handling qualities of the Flying-V. The CG seems to have an important influence that needs to be furthered understood, and the certification standards of Chapter 3 require precise FPA performance that resulted critical in previous research (see Cappuyns, [50]). As a consequence, a FPA tracking task will be carried out in the piloted-simulations and special attention will be given to the pull-up manoeuver. The Stability Augmentation system implemented in Chapter 7 should also be tuned taking into consideration the FPA quality as predicted by this criterion.

6.4. Control Anticipation Parameter

The three critical configurations obtained in Section 6.1 based on the short period frequency (forward CG and Mach = 0.3 (green); nominal CG and Mach = 0.25 (black); aft CG and Mach = 0.2 (red)) are representative of all the 9 configurations considered in this analysis, since the slower the short period frequency, the lower the HQ predicted with the CAP criterion. This is shown in Figure 6.14, where it is apparent that 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 the case of slower configurations. In particular, the focus will be 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.

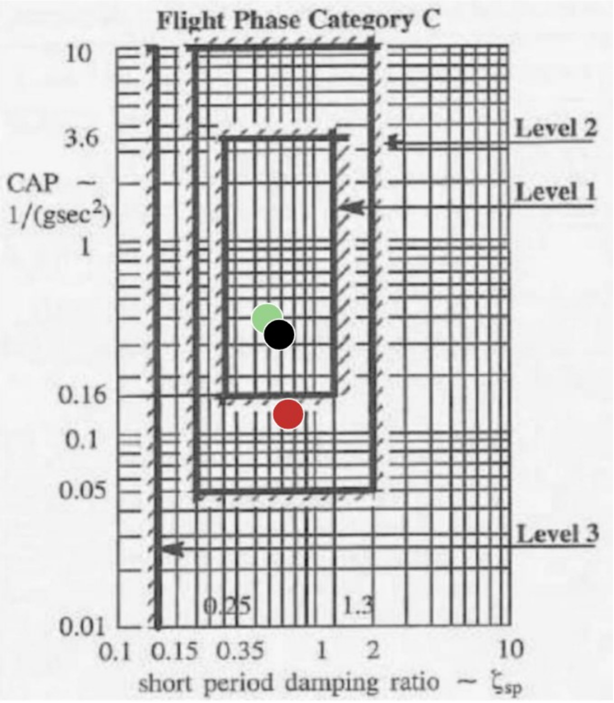


Figure 6.14: Control Anticipation Parameter. Forward CG, Mach = 0.3 (green); nominal CG Mach = 0.25 (black); aft CG Mach = 0.2 (red). Elevons actuator dynamics included.

6.5. Sensitivity analysis over rotational inertia and CG

For the exploratory nature of this research, it is useful to look into the effect of inertial characteristics on the HQ.

First of all, the CG position can be shifted. Again the three CG locations introduced in Section 5.1.1 are considered: forward CG, nominal CG, and aft CG from the nose. As far as stability is concerned, it is clear from the analysis of the root-locus map that the CG shows better phugoid characteristics for the aft CG, where the poles have negative real part for fast configurations and just mildly positive for slower configurations. On the other hand, the forward CG implies an unstable phugoid, again with decreasing performance for slower configurations.

When taking in consideration the frequency separation of phugoid and short period, however, the closer the CG to the nose, the larger the frequency separation. In other words, the configuration with forward CG has faster short period frequency and better phugoid-short period separation than the configuration with forward CG.

Due to the obvious relation of y-axis inertia I_{yy} with longitudinal HQ, it is interesting to study the sensitivity of the short period frequency on I_{yy}. To get an insightful picture of the sensitivity, three CG configurations are considered (forward, nominal, and aft, as usual), airspeed is set to Mach = 0.25 (average of the Mach numbers considered so far in this research), and the inertia I_{yy} is reduced progressively down to 70% of the initial design value ($2.7619e + 07[kgm^2]$). The resulting short period frequency plots are displayed in Figure 6.15.

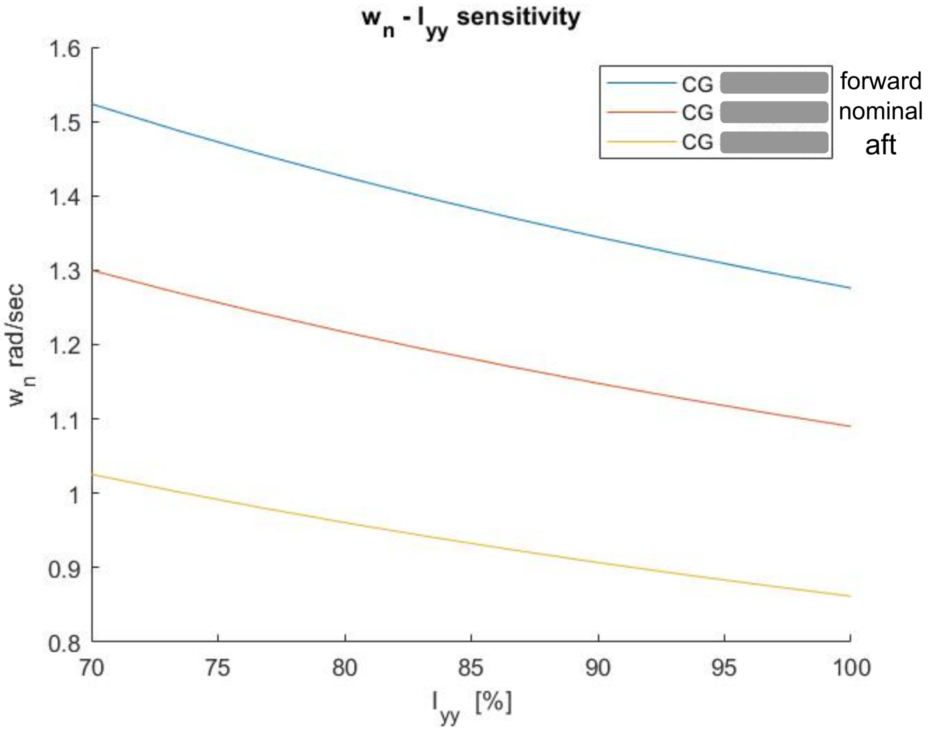


Figure 6.15: Sensitivity analysis of natural short period frequency w_n over y-axis inertia I_{yy} for the three CG (forward, nominal, aft). I_{yy} is designed to be $2.7619e + 07[kg * m^2]$ at 100%. All the plots are drawn for Mach 0.25.

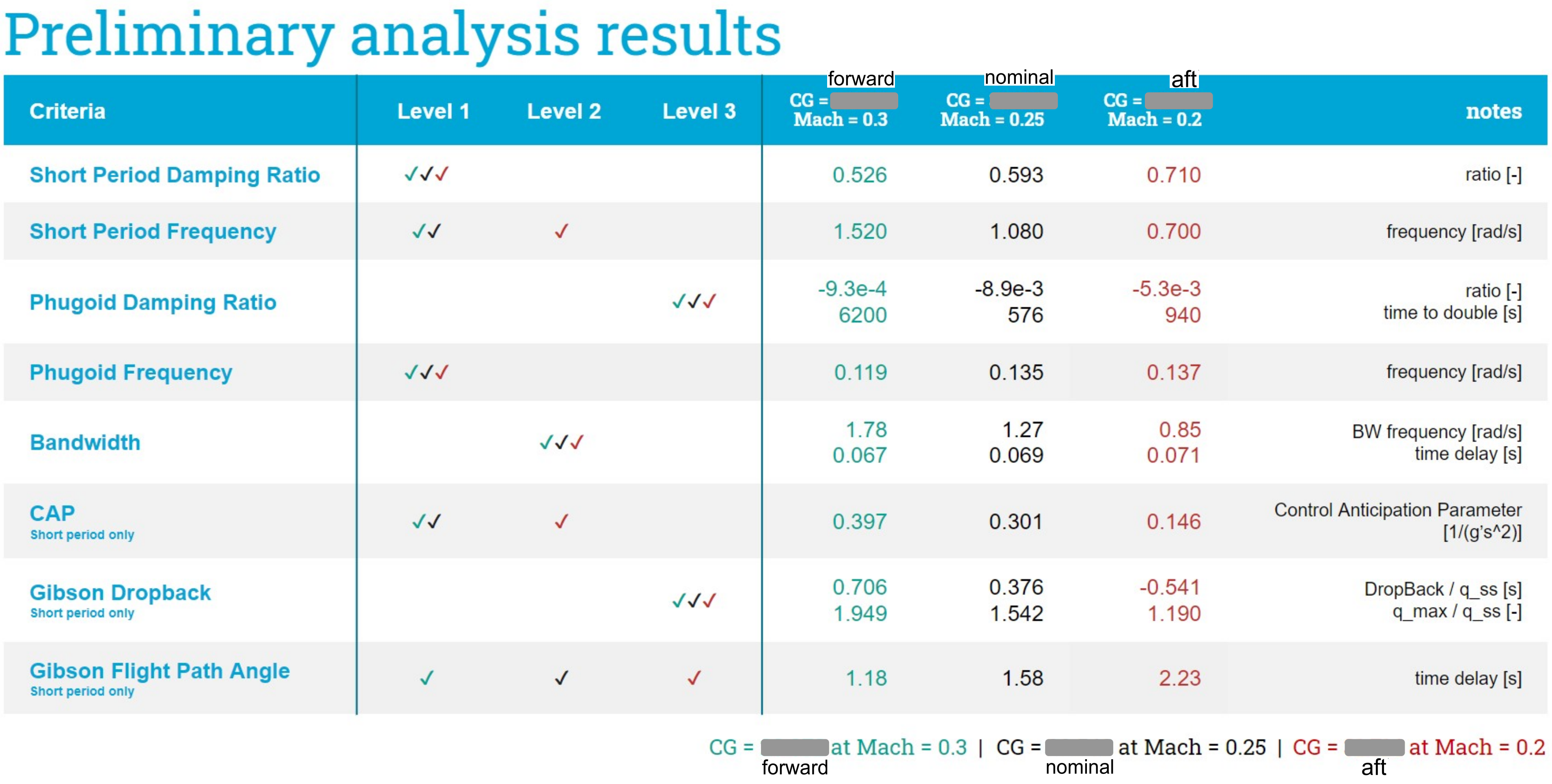
This suggests that by reducing I_{yy} better HQ are to be expected overall.

6.6. Summary of expected HQ

A useful overview of the HQ of the Flying-V can be obtained by considering the results of the preliminary analysis on a limited number of cases. Due to the significance of it for this research (see section 6.1), the short period frequency is a suitable driver for this overview. In Figure 6.16 the predicted levels of HQ according to each of the criteria used in this chapter are given for three different configurations: one is associated with the slowest short period frequency among all the configurations considered in this research (red case,aft CG, Mach = 0.2); one is associated to the fastest short period frequency (green case, forward CG, Mach = 0.3); and one is in the middle of these two (black case, nominal CG, Mach = 0.25). (This table should be seen as an overview summary of this Chapter. Its content has been discussed in the previous sections). For reference, Chan [11] highlights generally inferior handling qualities for blended wing bodies due to relaxed stability, insufficient FPA control, PIO tendencies in FPA tracking, higher angle of attack at landing and severe lift losses after elevons deflection.

Overall, it is clear that the Flying-V would benefit from the augmentation of its response with a Stability Augmentation System. In fact, based on some of the criteria shown in this Chapter, without a Control and Stability Augmentation System (CSAS) the Flying-V is expected to have poor handling qualities for its slower configurations. In particular, the short period frequency seems to play a significant role in the overall quality of the aircraft response, and the CSAS should be designed starting from the issues related to the close vicinity of short period and phugoid frequencies. The approach to CSAS implementation is treated in Chapter 7.

The results of this preliminary analysis also provide some flight tasks that should be performed in the piloted simulations. Pitch tracking will be useful to further analyse the effects of the slow short period frequency, to understand the issues that emerged with the Drop Back criterion, to confirm the HQ degradation predicted with the CAP, and to explore the control issues highlighted by the bandwidth criterion. All of this will be elaborated in Chapter 8.



Preliminary analysis results

Criteria	Level 1	Level 2	Level 3	CG = [redacted] forward Mach = 0.3	CG = [redacted] nominal Mach = 0.25	CG = [redacted] aft Mach = 0.2	notes
Short Period Damping Ratio	✓✓✓			0.526	0.593	0.710	ratio [-]
Short Period Frequency	✓✓	✓		1.520	1.080	0.700	frequency [rad/s]
Phugoid Damping Ratio			✓✓✓	-9.3e-4 6200	-8.9e-3 576	-5.3e-3 940	ratio [-] time to double [s]
Phugoid Frequency	✓✓✓			0.119	0.135	0.137	frequency [rad/s]
Bandwidth		✓✓✓		1.78 0.067	1.27 0.069	0.85 0.071	BW frequency [rad/s] time delay [s]
CAP Short period only	✓✓	✓		0.397	0.301	0.146	Control Anticipation Parameter [1/(g's^2)]
Gibson Dropback Short period only			✓✓✓	0.706 1.949	0.376 1.542	-0.541 1.190	DropBack / q_ss [s] q_max / q_ss [-]
Gibson Flight Path Angle Short period only	✓	✓	✓	1.18	1.58	2.23	time delay [s]

CG = [redacted] forward at Mach = 0.3 | CG = [redacted] nominal at Mach = 0.25 | CG = [redacted] aft at Mach = 0.2

Figure 6.16: Summary of the preliminary analysis results for the three critical cases explained in section 6.6.

7

Control and Stability Augmentation System

7.1. The need for control augmentation

The response of an aircraft to pilot inputs can be manipulated by means of a Stability Augmentation System (SAS) and of a Control Augmentation System (CAS). The SAS addresses the characteristics of the inner-loop response of the aircraft, taking care of dynamic stability and damping; while the CAS enhances and improves tracking and flying capabilities of the aircraft, addressing the outer-loop.

In this research, the piloted simulations will also serve to explore the potential of an augmentation system to improve the HQ of the Flying-V. Moreover, according to the results of the preliminary analysis of Chapter 6, a certain degree of augmentation seems necessary to improve the overall HQ into Level 1 and avoid control issues.

The augmentation system can be generally seen as made up of two parts - the inner-loop and the outer-loop, which will be here briefly introduced.

7.1.1. Inner-loop augmentation - Stability Augmentation System

The inner-loop of a control system aims at handling the basic characteristics of the response of the aircraft, such as stability and oscillations. It is implemented to make sure that the outer-loop can effectively operate to improve the HQ. If the inner-loop performs poorly, it might be difficult or impossible for the outer-loop to be implemented correctly.

Designing an optimal inner-loop is out of the scope of this research. A classical PID approach is used, where the PID gains are tuned to improve pole damping and support poles separation according to the results of Chapter 6, in particular of Section 6.2.1.

In the future, more complex stability augmentation systems should be considered. Many non-linear control augmentation systems rely mainly on a model of the controlled vehicle. This is undesirable for the current state of the Flying-V due to the uncertainties of the new model design. More sensor-based approaches should be preferred, such as Incremental Nonlinear Dynamic Inversion (INDI) Control. Its main advantages, according to recent research (see for instance [53] and [56]), reside in the robust performance against aerodynamic model uncertainties.

Some studies have been carried out on augmentation systems for other flying-wing prototypes which might share some HQ characteristics with the Flying-V. In particular, studies can be found on UAV flying-wings, such as [14] which focuses on a nonlinear methodology to decouple the lateral and longitudinal dynamics; and [54], in which the effectiveness of a control law that assures high landing precision under different wind conditions is assessed.

7.1.2. Outer-loop augmentation - Control Augmentation System

The outer-loop actually determines the HQ, the response type and its characteristics (granted that the inner-loop is properly designed and tuned). During the experiments of this research, an outer-loop augmentation system will be 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 optimize the outer-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.

The straight-forward approach to the design of the control system for this study is explained in the next section. In the future, however, more complex approaches might be taken in consideration. For instance, in [55], a distributed genetic algorithm is used to design a control system for flying wings based on evaluation functions of overshoot, steady time, steady error, and oscillation of the response of the model. This forms an automatic and efficient way to design a Flight Control System.

7.2. CSAS design for the Flying-V

Based on the analysis performed in Chapter 6, both a SAS and a CAS were designed to try to enhance the HQ of the Flying-V. According to the preliminary analysis presented in Chapter 6, pitch rate control emerged as a possible control approach, since it might increase the controllable bandwidth range hence improving the HQ. On top of this, pitch rate control is a rather standard control system and pilots are generally used to it.

If implemented in the form of a pitch controller, the idea is to

- smooth down the phugoid by feeding back forward velocity over throttle;
- regulate damping by feeding back pitch rate over the elevons;
- speed up the otherwise slow short period mode by fine-tuning the feedback loop of pitch angle over the elevons;

where the four elevons are deflected symmetrically by a single common controller, following the control allocation design choice presented in Section 2.3. In the case of pitch rate control, the same CSAS is implemented by opening the outer pitch angle loop. The CSAS for the pitch angle control case is shown in figure 7.1. To test the effectiveness of this CSAS design, the HQ analysis is repeated with the augmented system.

Based on the results of the first simulations, alternative control systems might be designed for pitch control, such as C*. In general, the focus will be more on exploring the HQ potential of outer-loop tuning rather than fine tuning the inner-loop.

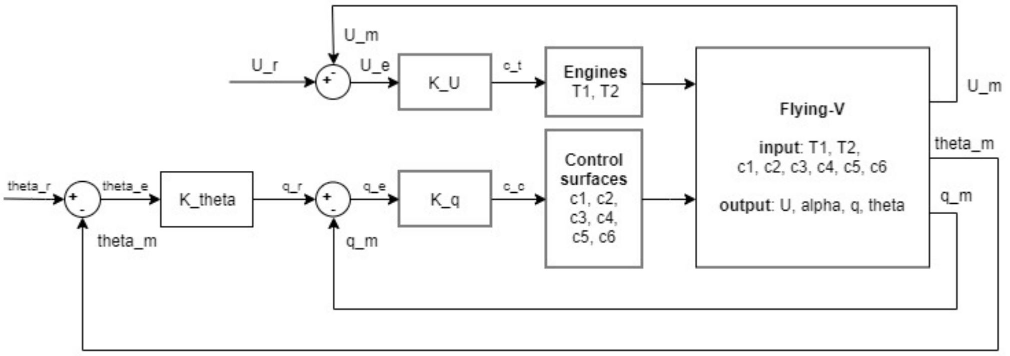


Figure 7.1: CSAS block diagram, pitch control case.

Some preliminary simulations were conducted to test the effectiveness of this type of augmentation system on the Flying-V. It is important to notice that in this phase of the research, the control system has not yet been tuned to obtain optimal handling qualities. On the contrary, only a simple and preliminary version of this control system was implemented. Its purpose is to verify the potential of augmentation for improving the HQ, while fine tuning and realistic design will be addressed later in this research.

As an example of the response of this system, the pitch rate response of the Flying-V to a commanded rate of -0.1 deg/s is shown in Figure 7.2. Here a pitch rate control system was tuned to increase the short period frequency. This response can be compared, in the same figure, with the bare airframe response to a 10 deg input on the elevons. The elevons deflection angle are displayed for the two configurations in Figure 7.3. In both cases, it is forward CG and Mach = 0.3. While the response of the system shows better handling qualities than the bare frame system, the control surface deflection needed for control with this kind of augmentation seems too large. As a consequence, further tuning will be needed to get a realistic and feasible system. The auto-throttle feedback loop effectively controls the phugoid, and it does increase the separation between short period and phugoid frequency. Overall, this control system approach seems applicable to the Flying-V to improve the HQ, and piloted evaluations will be used to confirm its potential. Based on the simulations of this preliminary control system, HQ improvements are expected if compared to the bare airframe.

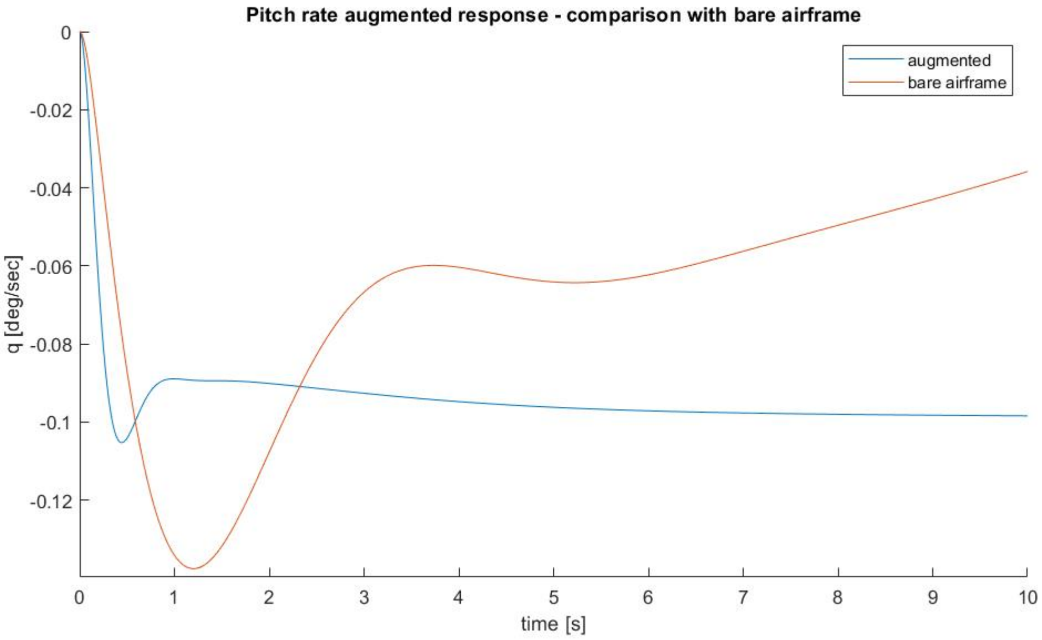


Figure 7.2: Pitch rate response of the Flying-V for two different control systems: pitch rate command augmented (-0.1deg/s pitch rate step input) and bare airframe (10 deg elevons deflection step input). The augmented case is tuned to increase short period frequency. Forward CG and Mach = 0.3.

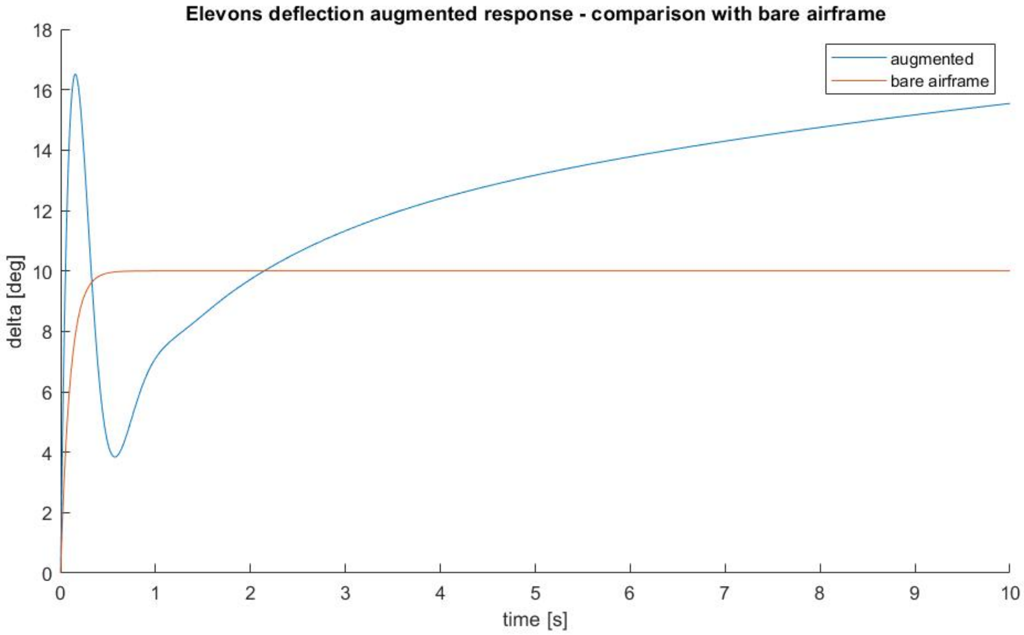


Figure 7.3: Elevons deflection response of the Flying-V for two different control systems: pitch rate command augmented (-0.1deg/s pitch rate step input) and bare airframe (10 deg elevons deflection step input). The augmented case is tuned to increase short period frequency. Forward CG and Mach = 0.3.

8

Piloted evaluation of Handling Qualities

8.1. The purpose of piloted evaluation

The mathematical criteria introduced in Chapter 4 and then applied in Chapter 6 on the aircraft model of Chapter 5 provided an overview of the expected handling qualities of the Flying-V in longitudinal, low speed flight. This preliminary analysis, however, needs to be confirmed and possibly expanded by human-in-the-loop simulations, in which pilots can give specific feedback on the handling qualities of the aircraft according to their opinion. This opinion, which will be collected in the form of a rating as explained in Section 8.2, is valuable to understand the quality of the response of the complex pilot-aircraft system, which the analytical criteria can only approximately describe.

The piloted experiments will consist in the execution of a number of flying tasks, treated in Section 8.3, which will all be carried out in the SIMONA simulator of TU Delft, presented in Section 8.4

8.2. Rating Scale

In the context of this evaluation effort, the first theory that must be mentioned is that of the Cooper-Harper rating scale. The scale is a useful framework used to give a quantitative form to the qualitative opinion of the pilots [18, 29]. It is based on a straightforward concept: the higher the HQ of an aircraft, the easier it is for the pilot to fly it and perform some tasks. Therefore, it is essential to plan carefully the set of tasks that the pilots will have to perform, and to determine what is the level of performance expected by the pilots during these activities. Based on these tasks, the Cooper-Harper rating scale can be filled in by combining the objective performance of the pilot and their subjective opinion on the HQ during the task.

The Cooper Harper scale is shown in Figure 8.1. Notice that the rating exists only as a specific evaluation of the HQ during a certain task, and not as an inherent characteristic of the sole aircraft. Also, if on one hand the rating allows for a quantitative expression of the HQ, on the other hand it is important to know that the ratings are not meant to be averaged among the several tests and pilots. On the contrary, they are supposed to be read as a whole, in order to get an overall picture of the evaluation. In general, the outcome of any experiment rated with the Cooper-Harper scale can be read in plots such as a bar chart.

It should be mentioned that alternative rating scales have been considered for this research as well. In particular, the ”Cranfield Aircraft Handling Qualities Rating Scale (CAHQRS)” [30], the ”Bedford Workload Scale” [44], the ”NASA Task Load Index” [13] and the ”Modified Cooper Harper for highly automated Human-Machine systems” [22] were considered, which are some of the most common rating scales together with the Cooper-Harper one. However, the CAHQRS is more suitable for advanced tests that combine longitudinal and lateral control; the Bedford scale requires the integration of the primary tasks with secondary tasks which would require a model with better accuracy than the one used in this research; the Modified Cooper Harper Scale for highly automated systems is not applicable to the Flying-V, since no high level display implementation has been studied yet; and the NASA task load index seems superfluous for the purpose of this research.

As a consequence, the original Cooper-Harper scale is chosen as the preferred rating scale for the experiments of this research.

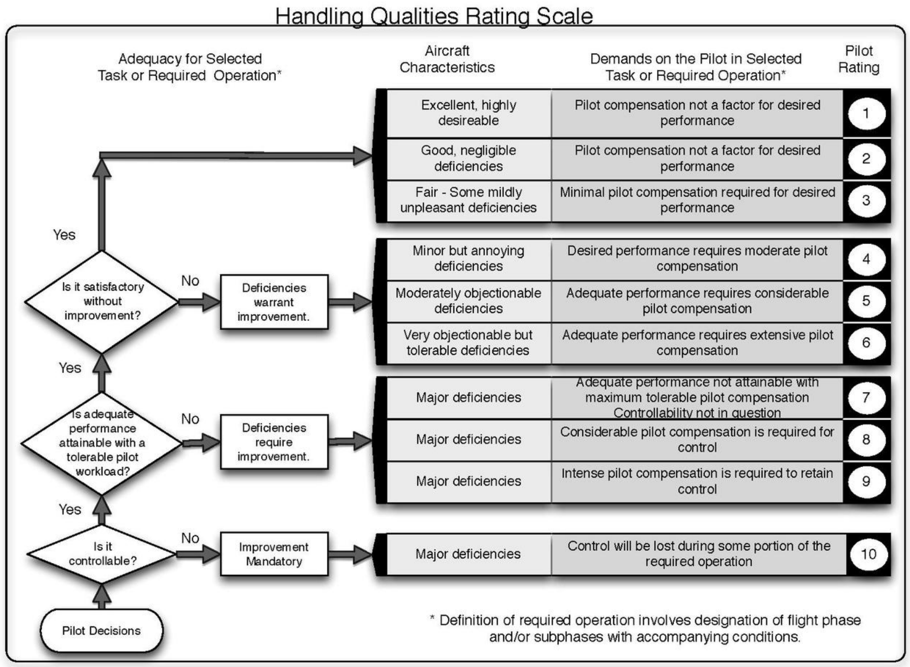


Figure 8.1: The Cooper-Harper rating scale, from [29].

8.3. Evaluation Tasks and Test Plan

As mentioned above, it is important for the correct use of the Cooper-Harper scale that the tasks for the piloted simulations are well defined and agreed with the pilots. A measurable quantity should be decided as a benchmark for the performance of the pilots during the simulations, and the Cooper-Harper pilot rating should be read in combination with this measured benchmark. In particular, adequate and desirable performance levels need to be defined for each task under evaluation. The goal of the pilot, then, is to achieve the desired level of performance.

The dependent variables for the experiments (see section 8.2) are:

- the (subjective) rating of the pilots on the HQ,
- the (objective) measurable performance of the pilots during each flight task as compared to the desired performance.

These variables will be used to determine the handling qualities of the Flying-V by manipulating the independent variables that come from the preliminary analysis presented so far:

- the location of the center of gravity, to study its influence on the longitudinal dynamics of the aircraft that was evident all throughout Chapter 6;
- the rotational inertia of the aircraft, to analyse its expected impact on the short period frequency as pointed out in Section 6.5;
- the Control and Stability Augmentation System (CSAS), to explore its potential to improve the handling qualities as discussed in Section 7.2);
- the Tasks to be performed during the simulation (discussed in this section).

The exhaustiveness and mutually exclusiveness of the rating is guaranteed by the Cooper-Harper scale [29], whereas the performance in the tasks is measured in a metric scale (e.g., the distance in meters between the target landing location and the pilot actual landing location). For each metric, adequate and desired performance levels are decided in order to give a precise goal to the pilot and to evaluate the performance on an objective scale.

Different combinations of the independent variables will yield a number of simulation activities that will be carried out in the SIMONA simulator of TU Delft. The goal is to perform two rounds of experiments, separated by a one-week gap to work on the intermediate results and possibly re-think the simulations accordingly.

The tasks that are going to be simulated are determined from a combination of conclusions of Chapter 6 (HQ off-line analysis) and of the certification requirements of Chapter 3:

- Transition from approach/landing into go-around: obtain desired climb in desired time.

  This is essentially an open loop task with no tracking, related to the requirements of EASA C25.119 already mentioned in Chapter 3. With this task, the pilot is expected to be able to comment on the performance of the Flying-V during go-around and pull-up maneuvers. Some potential issues were identified during the offline analysis (see section 6.3) related in particular to the sluggish FPA response.

  The objective performance metrics for this task are the obtained climb and the time to reach the desired climb. EASA C25.119 requirement will be used to set the adequate and desired levels for this task. See for reference [20] and [36].

- Pitch tracking

  This task investigates potential issues in closed loop control. When it comes down to tracking, the narrow bandwidth of stable control (see section 4.3) is expected to be a limiting factor. For the civil transportation purpose of the Flying-V, large amplitude maneuvers are the most relevant to focus on. However, testing the tracking capabilities of the aircraft also for faster tasks might give useful insights on the limitations caused by the slow short period frequency.

  The squared difference from the target pitch angle is the objective performance metric in this task. The adequate and desired level will be determined after the first preliminary simulations. See for reference [24] and [39].

- Flight path angle (FPA) tracking

  The tracking task will be repeated for FPA tracking. The experiments aim at exploring the FPA control potential of the Flying-V and possibly at identifying the slow FPA response that emerged in Section 6.3.2. As a closed loop control task, it should also help to further understand the performance limits of the Flying-V as highlighted by Cappuyns ([50]) and again by the certification requirements of Chapter 3.

  The squared difference from the target FPA is the objective performance metric in this task. The adequate and desired level will be determined after the first preliminary simulations. See for reference [24] and [39].

8.4. SIMONA Simulator

Similar to an EASA level-D simulator (but not qualified as such), the SIMONA simulator of TU Delft is the facility in which the experiments of this research will be conducted. Being an educational and research simulator, it is naturally suitable for studies of new aerospace concepts such as the Flying-V.

8.4.1. Implementation

Part of this research consists in the implementation of the software required to simulate the Flying-V in SIMONA. The simulator interface is based partly on C++ and partly on Python, in a simulation environment called DUECA. DUECA has its own functions and modules and requires specialized knowledge, for which its documentation [2] is exhaustive. A useful feature of DUECA is the possibility of easily copying the modules used in other simulations and integrate them in a new project.

For this study, the modules that will be taken and, if necessary, adapted are:

- Image generation (FlightGear)
- Sidestick interface
- Control Loading
- Cueing (Visual, Motion, Sound, Force feel)
- Instruments and Avionics display (EFIS)

whereas the research-specific modules that need to be implemented are:

- Equation of motion of the aircraft. This is a complex module that takes pilot's control as an input and yields the response of the aircraft. It comprehends:
  - JSON file reader (to read the ODILILA model file)
  - Extrapolation and interpolation (to extend the dataset starting from the ODILILA model breakpoints, as discusses in Chapter 5)
  - Flight Control System (see Chapter 7)
  - Actuators dynamics (see Chapter 2)
  - Engines model (to be integrated into EOM module, (see Chapter 2))
  - Trimming (following Airbus approach to trimming with automatic reset of sidestick center)
- Cockpit rotation (if needed to adjust pilot's view at high angle of attack during landing)
- Task manager
- Task-specific displays

The feel system will be tuned according to the maximum control forces requested by the EASA certification requirements presented in Section 3.4.

8.4.2. Validity of the simulation

Piloted simulations for HQ should aim at high levels of accuracy. When assessing the outcome of the experiments, it is important to keep in mind all the limitations of the model (see section 5.1.2), and those of the simulator. In figure 8.2 (from [29]), some of the elements that compose the pilot-vehicle in a simulation are displayed. Basically all the blocks in this figure have a certain degree of uncertainty and difference from a real flight. Just to mention some, the moving base of a simulator introduces artificial dynamics such as wash-out and limited motion feedback; the displays and the control paths might have altered delays compared to real aircraft; the pilots might have different training and experiences, or even different adaptation approaches; turbulence and crosswind are neglected in this research; and many more. Cooper and Harper argue that *”In some cases, a test pilot will recognize the disparity and provide guidance in interpretation of results, but the final answer in many cases will only be known when ground and flight evaluations are obtained for the same aircraft and task.”* ([29] 1986, p.5).

Furthermore, in the NATO technical report RTO-TR-029 some advice is given on the use of simulator flight for HQ verification. In particular, it is recommended that *”all dynamic models, like sensor noise and dynamics, anti-aliasing filters, stick dynamics and structural mode filters, sampling and computer delay effects, are incorporated as early as possible. If these models do not exist, approximations should be used.”* ([6], p. 164).

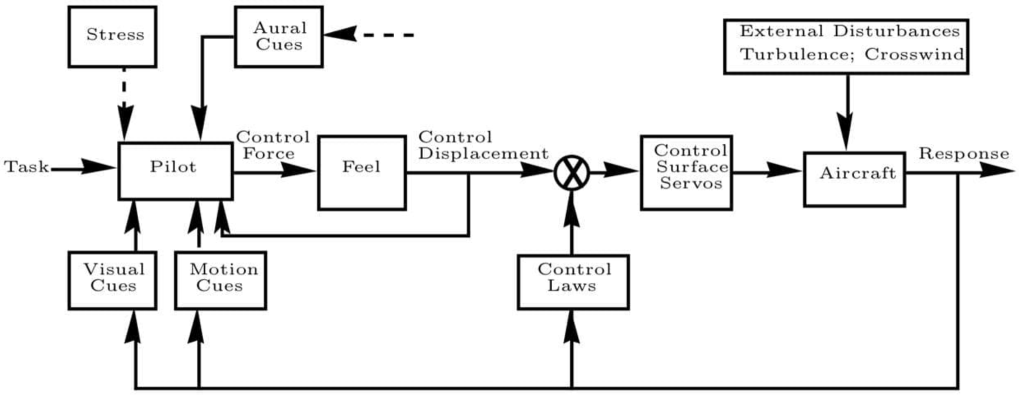


Figure 8.2: Pilot-vehicle dynamic system, from [29] p.3

In the same documents it is suggested that pilot control should be as much decoupled as possible, and that interaction between roll and pitch loops should be taken into consideration in the final evaluation of the results. ([6], BP4.5 and BP4.10).

Some of these aspects will not be fully addressed in this research. The dynamics, determined by the model presented in Chapter 5, are assumed to be completely de-coupled. Moreover, the aircraft sub-systems which have not been mentioned in this section will be copied from other projects and will not be specifically designed for the Flying-V. As a consequence, the results of these experiments need to be confirmed and integrated by future studies with more accurate and specific models.

9

Conclusions

Previous research on the Flying-V defined the geometry of the aircraft prototype for this research. The full model parameters were determined in previous research by optimizing a number of factors, in particular lift-to-drag ratio and stability. The control surfaces were tentatively designed as four elevons and two rudders.

A list of critical maneuvers has been selected out of the most relevant EASA requirements and the relative acceptable means of compliance. In particular, certain performance levels are requested for the pull-up maneuver and good handling qualities have to be proven during go-around tasks. According to previous work and to this research, these requirements are critical for the certification of the Flying-V since the aircraft might struggle to achieve the demanded performance levels in the slowest configurations.

As an approach to predicting the handling qualities of the Flying-V, a review of the most commonly used analysis criteria was conducted. The series of criteria that resulted from this review was inspected critically to assess their validity for the case of the Flying-V. Some of the assumptions that form the theoretical background of these criteria were in fact not applicable to this research. In particular, the small separation between the short period and the phugoid frequencies require special care. Overall, it was concluded that it makes sense to apply the criteria to acquire a preliminary understanding of the response of the Flying-V, since the baseline assumptions of the selected criteria are not expected to invalidate significantly the outcome of the analysis.

Based on the Flying-V design just defined, Airbus supplied the aerodynamics model by means of their house software, the ODILILA Vortex Lattice Method. Due to the assumptions behind this method, the model needs to be corrected with additional zero-lift drag, and in the future additional studies on flow separation around the Flying-V will be required for the definition of the validity of this research. The data from this model were then implemented into an EOM model to perform preliminary simulations.

This model was used to carry out a preliminary analysis with the selected evaluation criteria. The results point at an overall well-performing aircraft, with Level 1 handling qualities for many configurations of center of gravity location (forward and nominal CG) and airspeed (0.3 and 0.25 Mach). However, for the aftmost center of gravity location considered in this research and the slower configurations (0.2 Mach), the handling qualities degrade into Level 2 and Level 3 according to some criteria (short period frequency, phugoid damping ratio, bandwidth, CAP, Gibson Dropback, Gibson Flight Path Angle). The reason is that in this configurations the Flying-V responds in a sluggish way, with large maneuvering needed to achieve control. Additionally, it is apparent that the aircraft might tend towards pilot induced oscillations for these slower configurations. The short period frequency was found to be slow compared to the recommended standard, and the small separation between short period and phugoid frequencies hints at possible further handling qualities degradation for slower configurations.

The outcome of the preliminary analysis was used as a starting principle for the design of a flight control system. The idea is to implement a pitch-rate control system while an auto-throttle feedback loop improves the separation of phugoid and short period frequency. This control system was tuned to increase the short period frequency and some simulations were conducted to verify its feasibility. The interpretation of these simulations suggests that large control surface deflections are needed for effective control, but the architecture of the control system seems to be fit for the desired improvement of the handling qualities of the Flying-V.

Based on this preliminary study, a test plan was made. The pilot will perform a number of tasks (go-around, pitch tracking, flight path angle tracking) to investigate how the Flying-V compares with the certification requirements (pull-up and go-around maneuvers in particular), and to inspect the correlation between the handling qualities and the short period frequency. A number of independent variables will be manipulated during the simulations in order to map the correlation between inertial characteristics (center of gravity location, y-axis inertia), speed (0.2 to 0.3 Mach), and handling qualities. Finally, the flight control system will be tuned in at least two different ways, so as to explore the possibility of enhancing the handling qualities by means of augmentation.

The simulations will be executed with the participation of a limited number of KLM pilots (2-3) using the simulator facility of TU Delft, the SIMONA simulator. The outcome of the simulations will be twofold: on one hand, the opinion of the pilots on the performance of the Flying-V will be collected according to the Cooper-Harper approach to handling qualities piloted evaluations; on the other hand, the objective performance of the pilots for the specific task will be measured and used to complete the overall picture of the handling qualities.

A

Aerodynamics data

The aerodynamics model supplied by Airbus is computed by means of ODILILA, a Vortex Lattice Method CFD algorithm. The data is given in the form of a JSON file which was exported to MATLAB and read as a list.

Some inaccuracies have been noticed in the data, most likely due to approximation errors in ODILILA. Where the software had returned a clearly wrong value it was decided to manually correct for these errors.

In the following pages, four representative plots are shown for each CG position: lift coefficient over alpha, drag coefficient over alpha, M coefficient over alpha, and M derivative coefficient over alpha for c1 = ±1 deg (c1 = left rudder) for Forward CG.

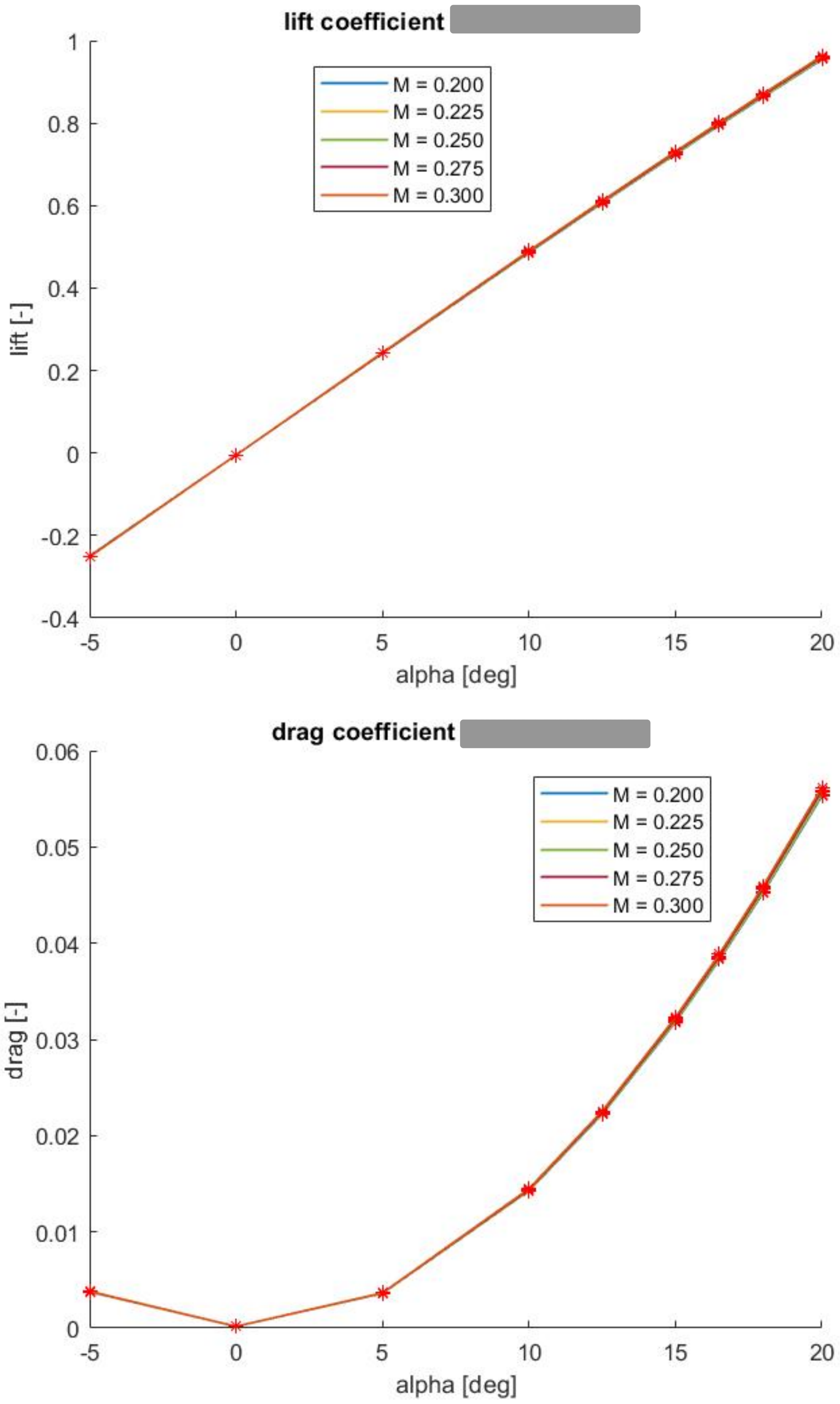


Figure A.1: Aerodynamic coefficients data over alpha: lift, drag. Forward CG.

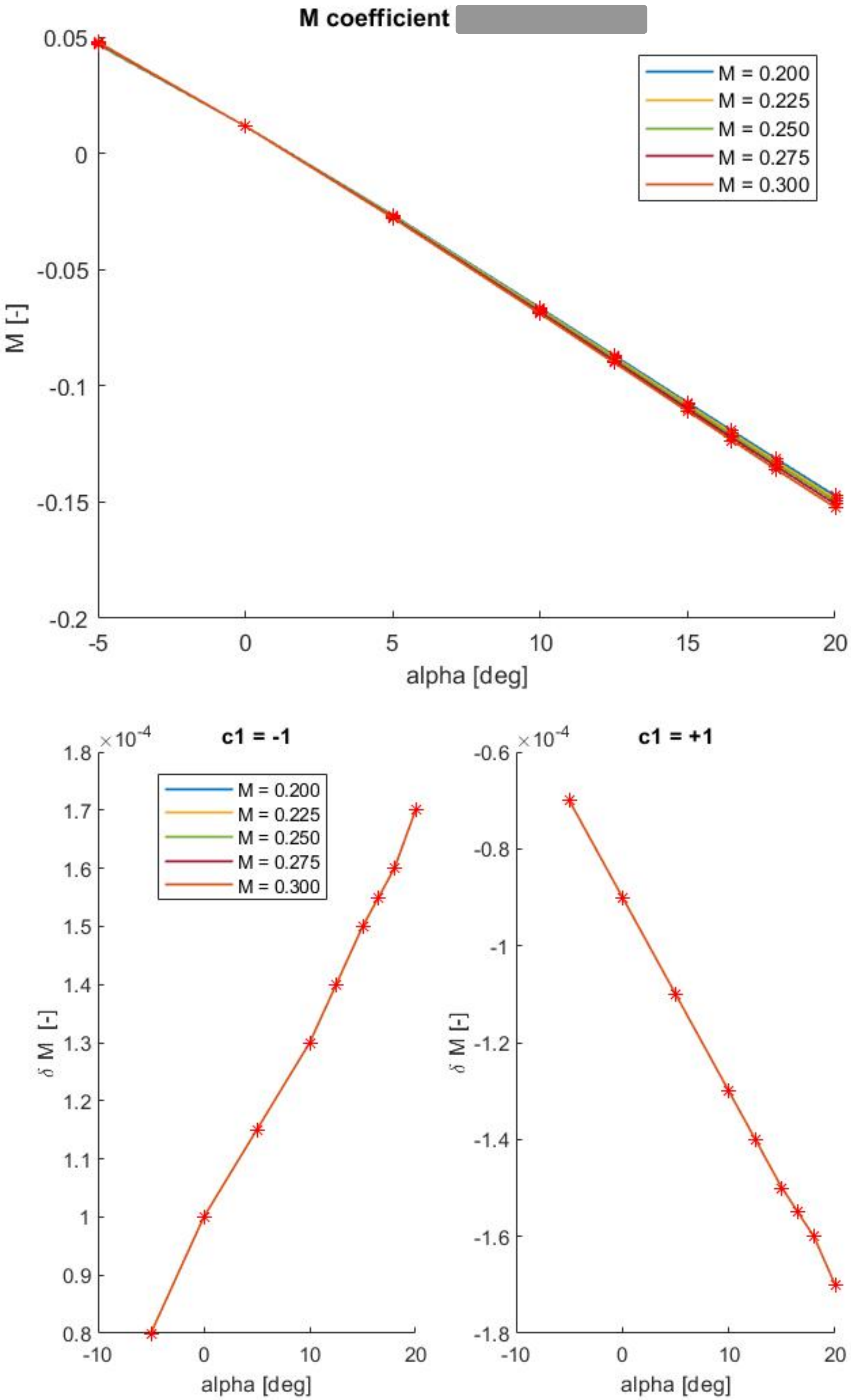


Figure A.2: Aerodynamic coefficients data over alpha: M, M derivative for c1=±1 deg. Forward CG.

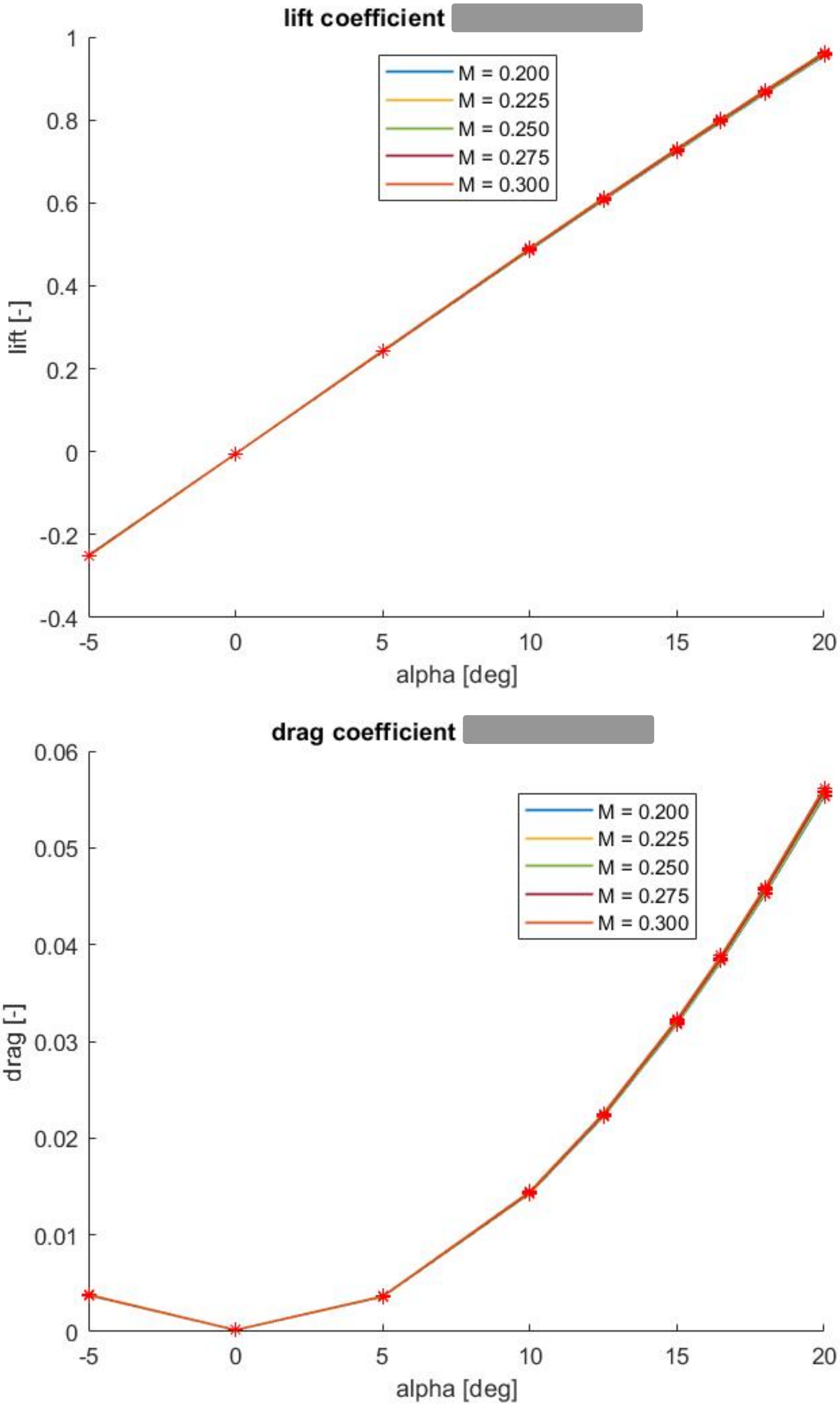


Figure A.3: Aerodynamic coefficients data over alpha: lift, drag. Nominal CG.

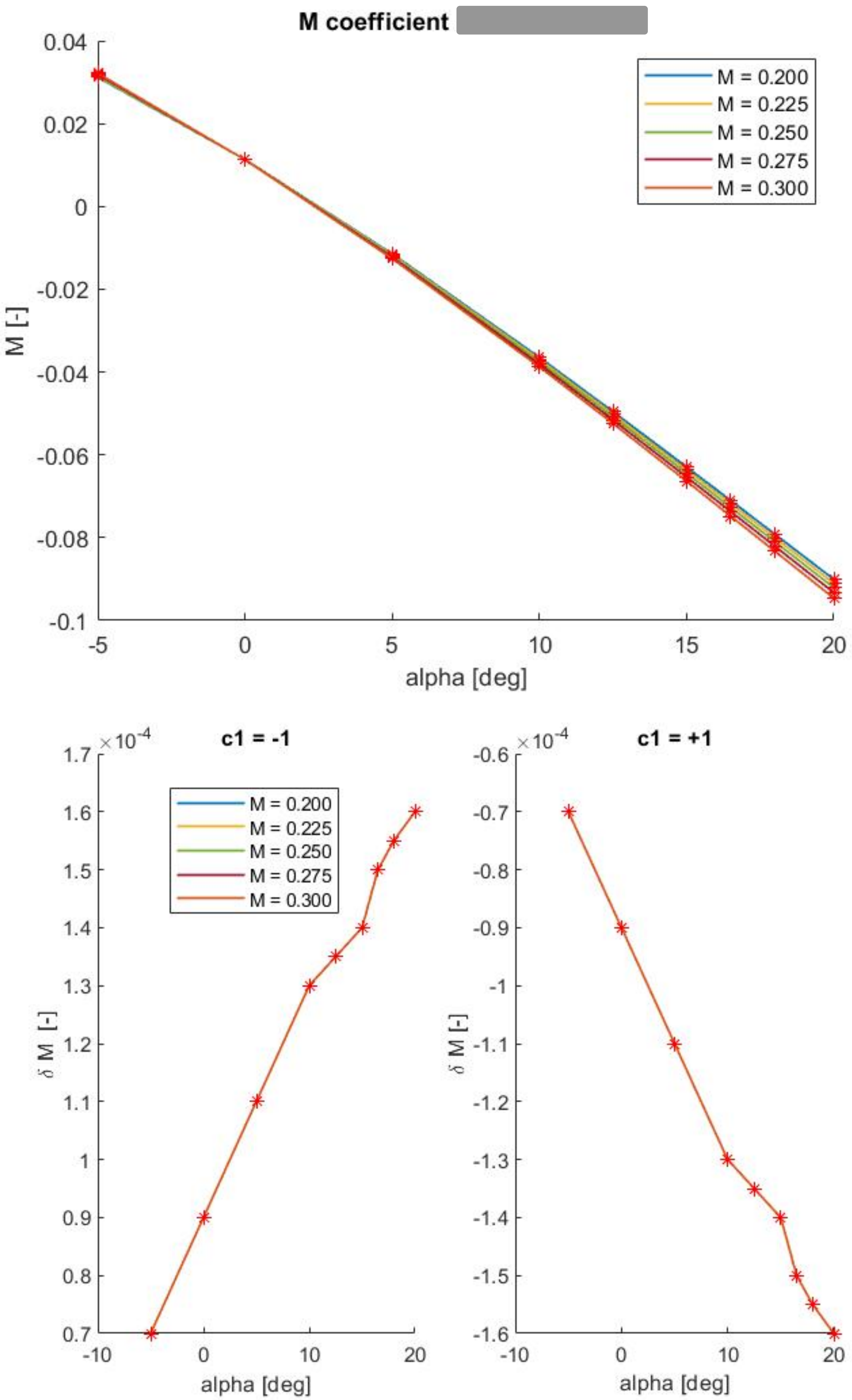


Figure A.4: Aerodynamic coefficients data over alpha: M, M derivative for c1=±1 deg. Nominal CG.

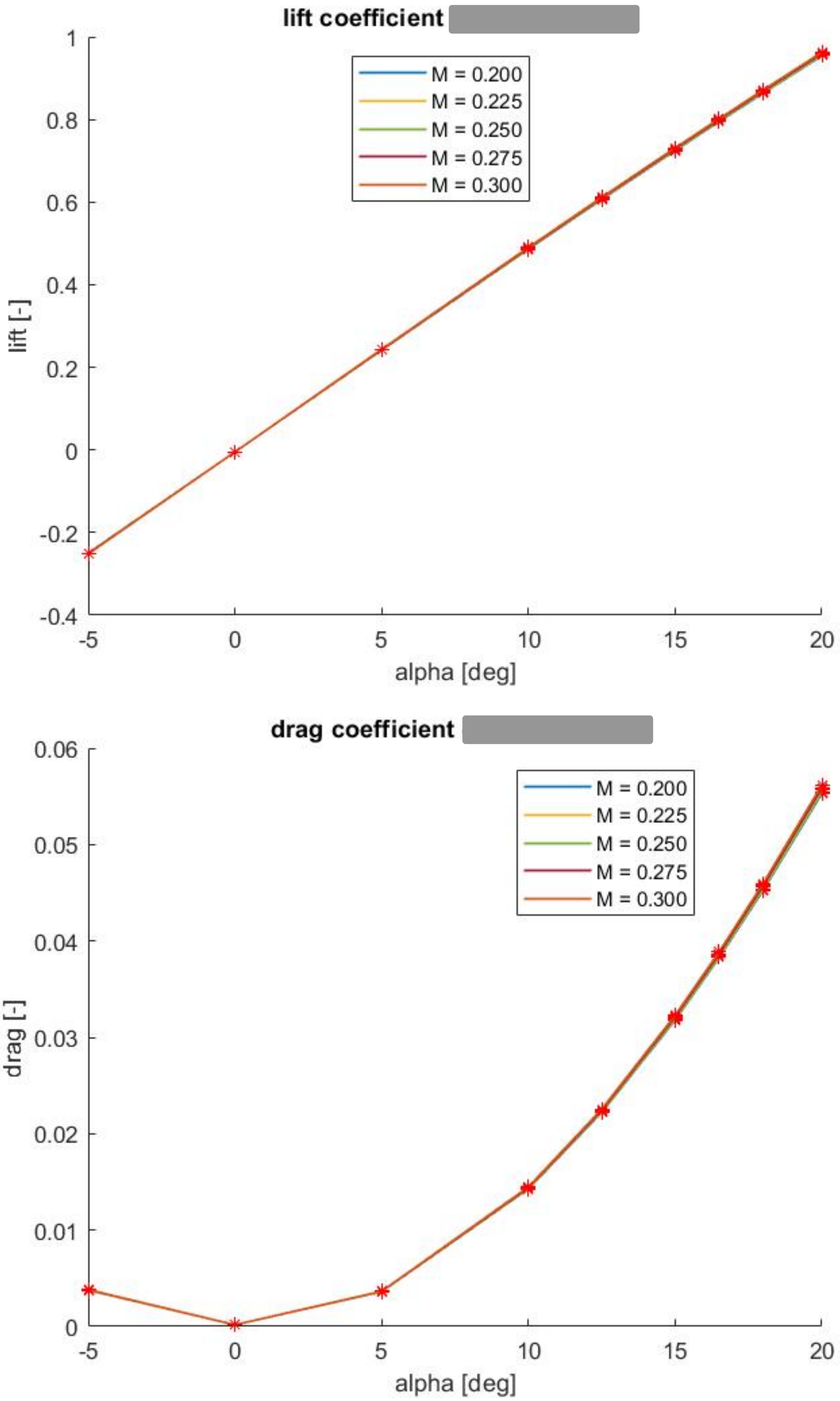


Figure A.5: Aerodynamic coefficients data over alpha: lift, drag. Aft CG.

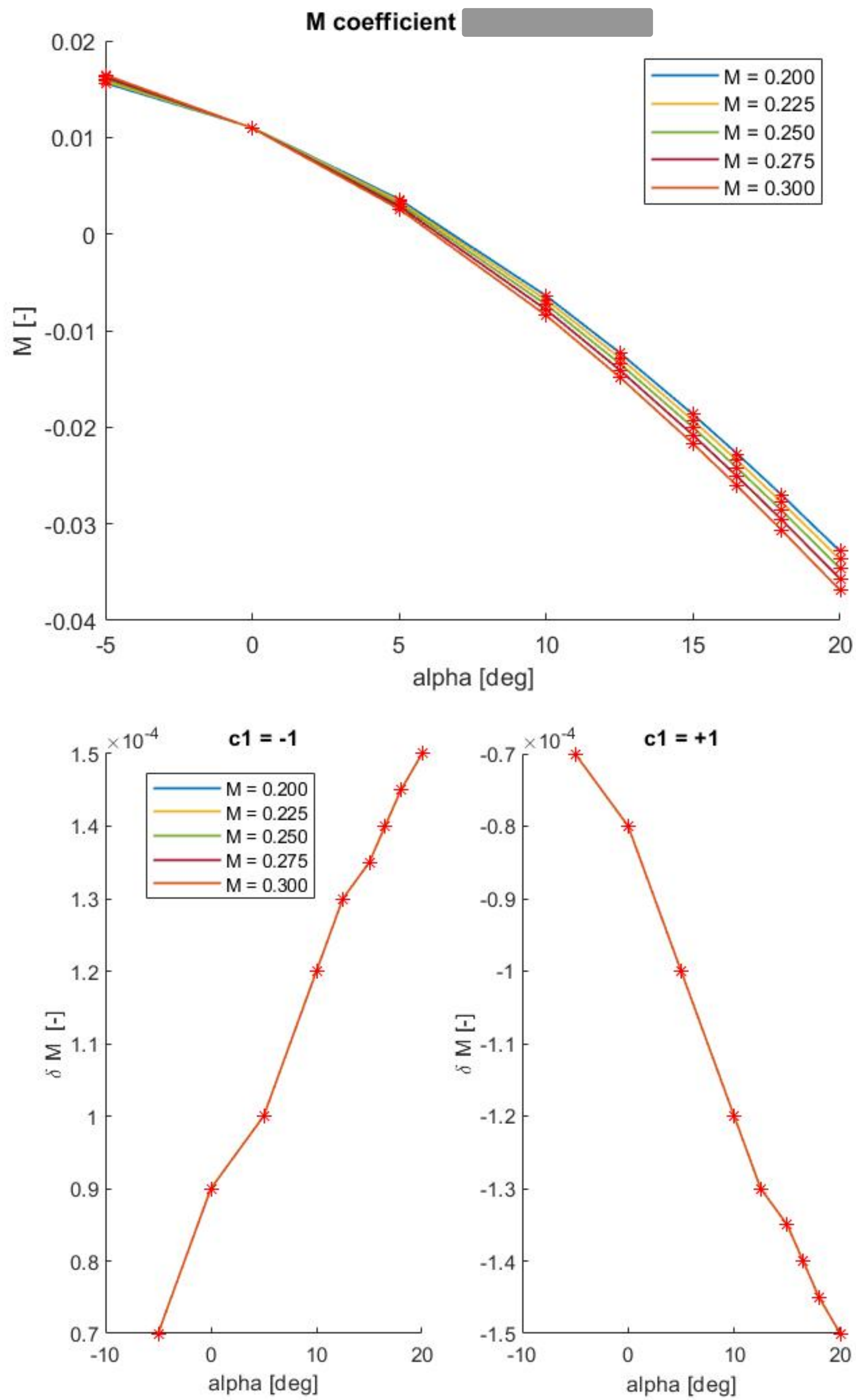


Figure A.6: Aerodynamic coefficients data over alpha: M, M derivative for c1=±1 deg. Aft CG.

B

Linearization

The linear model was obtained by linearizing the full model by means of numerical linearization, according to a finite difference method approach:

$$f'(x_0) \approx \frac{f(x_0+h)-f(x_0)}{h}.$$

where $f'(x)$ is the desired derivative of the function $f(x)$, x_0 is the point around which the derivative is computed, and h is a small number ($\approx 10^-5$). For this research, the functions $f(x)$ are given by the equations of motion of the Flying-V, which are based on the aerodynamic data explained in Chapter 5.

With this method, the state space representation of the Flying-V response can be written as

$$\dot{x} = Ax + Bu$$

A is the matrix of the derivatives of each state with respect to each state, B is the matrix of the derivatives of each state with respect to each control input, x and u are respectively the state vector

$$x = [X_e, Y_e, Z_e, U_b, V_b, W_b, p, q, r, \phi, \theta, \psi]$$

and the input vector

$$u = [c_1, c_2, c_3, c_4, c_5, c_6, T_1, T_2].$$

In these vectors, the variables are those discussed in Chapter 5:

- X_e, Y_e, Z_e are the x,y,z positions with reference to Earth,
- U_b, V_b, W_b are the x,y,z velocities with reference to the body frame of the Flying-V,
- p, q, r are the rotation rates,
- ϕ, θ, ψ are the euler angles with reference to Earth,
- c_1, c_6 are the rudder-like control surfaces,
- c_2, C_5 are the outer ailerons,
- c_3, c_4 are the inner ailerons,
- T_1, T_1 are the thrust for the left and right engines respectively.

Using these naming convention, the A and B matrices as introduced above are as follows:

$$A = \begin{bmatrix}
\frac{d\dot{X}_e}{dX_e} & \frac{d\dot{X}_e}{dY_e} & \frac{d\dot{X}_e}{dZ_e} & \frac{d\dot{X}_e}{dU_b} & \frac{d\dot{X}_e}{dV_b} & \frac{d\dot{X}_e}{dW_b} & \frac{d\dot{X}_e}{dp} & \frac{d\dot{X}_e}{dq} & \frac{d\dot{X}_e}{dr} & \frac{d\dot{X}_e}{d\varphi} & \frac{d\dot{X}_e}{d\theta} & \frac{d\dot{X}_e}{d\psi} \\
\frac{d\dot{Y}_e}{dX_e} & \frac{d\dot{Y}_e}{dY_e} & \frac{d\dot{Y}_e}{dZ_e} & \frac{d\dot{Y}_e}{dU_b} & \frac{dY_e}{dV_b} & \frac{d\dot{Y}_e}{dW_b} & \frac{d\dot{Y}_e}{dp} & \frac{dY_e}{dq} & \frac{d\dot{Y}_e}{dr} & \frac{d\dot{Y}_e}{d\varphi} & \frac{d\dot{Y}_e}{d\theta} & \frac{dY_e}{d\psi} \\
\frac{d\dot{Z}_e}{dX_e} & \frac{d\dot{Z}_e}{dY_e} & \frac{d\dot{Z}_e}{dZ_e} & \frac{d\dot{Z}_e}{dU_b} & \frac{dZ_e}{dV_b} & \frac{d\dot{Z}_e}{dW_b} & \frac{d\dot{Z}_e}{dp} & \frac{d\dot{Z}_e}{dq} & \frac{d\dot{Z}_e}{dr} & \frac{d\dot{Z}_e}{d\varphi} & \frac{d\dot{Z}_e}{d\theta} & \frac{d\dot{Z}_e}{d\psi} \\
\frac{d\dot{U}_b}{dX_e} & \frac{d\dot{U}_b}{dY_e} & \frac{d\dot{U}_b}{dZ_e} & \frac{d\dot{U}_b}{dU_b} & \frac{dU_b}{dV_b} & \frac{d\dot{U}_b}{dW_b} & \frac{d\dot{U}_b}{dp} & \frac{dU_b}{dq} & \frac{d\dot{U}_b}{dr} & \frac{d\dot{U}_b}{d\varphi} & \frac{d\dot{U}_b}{d\theta} & \frac{d\dot{U}_b}{d\psi} \\
\frac{d\dot{V}_b}{dX_e} & \frac{d\dot{V}_b}{dY_e} & \frac{d\dot{V}_b}{dZ_e} & \frac{d\dot{V}_b}{dU_b} & \frac{dV_b}{dV_b} & \frac{d\dot{V}_b}{dW_b} & \frac{d\dot{V}_b}{dp} & \frac{dV_b}{dq} & \frac{d\dot{V}_b}{dr} & \frac{d\dot{V}_b}{d\varphi} & \frac{d\dot{V}_b}{d\theta} & \frac{d\dot{V}_b}{d\psi} \\
\frac{d\dot{W}_b}{dX_e} & \frac{d\dot{W}_b}{dY_e} & \frac{d\dot{W}_b}{dZ_e} & \frac{d\dot{W}_b}{dU_b} & \frac{dW_b}{dV_b} & \frac{d\dot{W}_b}{dW_b} & \frac{d\dot{W}_b}{dp} & \frac{dW_b}{dq} & \frac{d\dot{W}_b}{dr} & \frac{d\dot{W}_b}{d\varphi} & \frac{d\dot{W}_b}{d\theta} & \frac{dW_b}{d\psi} \\
\frac{d\dot{p}}{dX_e} & \frac{d\dot{p}}{dY_e} & \frac{d\dot{p}}{dZ_e} & \frac{d\dot{p}}{dU_b} & \frac{d\dot{p}}{dV_b} & \frac{d\dot{p}}{dW_b} & \frac{d\dot{p}}{dp} & \frac{d\dot{p}}{dq} & \frac{d\dot{p}}{dr} & \frac{d\dot{p}}{d\varphi} & \frac{d\dot{p}}{d\theta} & \frac{d\dot{p}}{d\psi_b} \\
\frac{d\dot{q}}{dX_e} & \frac{d\dot{q}}{dY_e} & \frac{d\dot{q}}{dZ_e} & \frac{d\dot{q}}{dU_b} & \frac{dq}{dV_b} & \frac{d\dot{q}}{dW_b} & \frac{d\dot{q}}{dp} & \frac{d\dot{q}}{dq} & \frac{d\dot{q}}{dr} & \frac{d\dot{q}}{d\varphi} & \frac{d\dot{q}}{d\theta} & \frac{d\dot{q}}{d\psi_b} \\
\frac{d\dot{r}}{dX_e} & \frac{d\dot{r}}{dY_e} & \frac{d\dot{r}}{dZ_e} & \frac{d\dot{r}}{dU_b} & \frac{d\dot{r}}{dV_b} & \frac{d\dot{r}}{dW_b} & \frac{d\dot{r}}{dp} & \frac{d\dot{r}}{dq} & \frac{d\dot{r}}{dr} & \frac{d\dot{r}}{d\varphi} & \frac{d\dot{r}}{d\theta} & \frac{d\dot{r}}{d\psi} \\
\frac{d\dot{\phi}}{dX_e} & \frac{d\dot{\phi}}{dY_e} & \frac{d\dot{\phi}}{dZ_e} & \frac{d\dot{\phi}}{dU_b} & \frac{d\dot{\phi}}{dV_b} & \frac{d\dot{\phi}}{dW_b} & \frac{d\dot{\phi}}{dp} & \frac{d\dot{\phi}}{dq} & \frac{d\dot{\phi}}{dr} & \frac{d\dot{\phi}}{d\varphi} & \frac{d\dot{\phi}}{d\theta} & \frac{d\dot{\phi}}{d\psi} \\
\frac{d\dot{\theta}}{dX_e} & \frac{d\dot{\theta}}{dY_e} & \frac{d\dot{\theta}}{dZ_e} & \frac{d\dot{\theta}}{dU_b} & \frac{d\dot{\theta}}{dV_b} & \frac{d\dot{\theta}}{dW_b} & \frac{d\dot{\theta}}{dp} & \frac{d\dot{\theta}}{dq} & \frac{d\dot{\theta}}{dr} & \frac{d\dot{\theta}}{d\varphi} & \frac{d\dot{\theta}}{d\theta} & \frac{d\dot{\theta}}{d\psi} \\
\frac{d\dot{\psi}}{dX_e} & \frac{d\dot{\psi}}{dY_e} & \frac{d\dot{\psi}}{dZ_e} & \frac{d\dot{\psi}}{dU_b} & \frac{d\dot{\psi}}{dV_b} & \frac{d\dot{\psi}}{dW_b} & \frac{d\dot{\psi}}{dp} & \frac{d\dot{\psi}}{dq} & \frac{d\dot{\psi}}{dr} & \frac{d\dot{\psi}}{d\varphi} & \frac{d\dot{\psi}}{d\theta} & \frac{d\dot{\psi}}{d\psi}
\end{bmatrix}, \tag{B.1}$$

$$B = \begin{bmatrix}
\frac{d\dot{X}_e}{dc_1} & \frac{d\dot{X}_e}{dc_2} & \frac{d\dot{X}_e}{dc_3} & \frac{d\dot{X}_e}{dc_4} & \frac{d\dot{X}_e}{dc_5} & \frac{d\dot{X}_e}{dc_6} & \frac{d\dot{X}_e}{dT_1} & \frac{d\dot{X}_e}{dT_2} \\
\frac{d\dot{Y}_e}{dc_1} & \frac{d\dot{Y}_e}{dc_2} & \frac{d\dot{Y}_e}{dc_3} & \frac{d\dot{Y}_e}{dc_4} & \frac{d\dot{Y}_e}{dc_5} & \frac{d\dot{Y}_e}{dc_6} & \frac{d\dot{Y}_e}{dT_1} & \frac{d\dot{Y}_e}{dT_2} \\
\frac{d\dot{Z}_e}{dc_1} & \frac{d\dot{Z}_e}{dc_2} & \frac{d\dot{Z}_e}{dc_3} & \frac{d\dot{Z}_e}{dc_4} & \frac{d\dot{Z}_e}{dc_5} & \frac{d\dot{Z}_e}{dc_6} & \frac{d\dot{Z}_e}{dT_1} & \frac{d\dot{Z}_e}{dT_2} \\
\frac{d\dot{U}_b}{dc_1} & \frac{d\dot{U}_b}{dc_2} & \frac{d\dot{U}_b}{dc_3} & \frac{d\dot{U}_b}{dc_4} & \frac{d\dot{U}_b}{dc_5} & \frac{d\dot{U}_b}{dc_6} & \frac{d\dot{U}_b}{dT_1} & \frac{d\dot{U}_b}{dT_2} \\
\frac{d\dot{V}_b}{dc_1} & \frac{d\dot{V}_b}{dc_2} & \frac{d\dot{V}_b}{dc_3} & \frac{d\dot{V}_b}{dc_4} & \frac{d\dot{V}_b}{dc_5} & \frac{d\dot{V}_b}{dc_6} & \frac{d\dot{V}_b}{dT_1} & \frac{d\dot{V}_b}{dT_2} \\
\frac{d\dot{W}_b}{dc_1} & \frac{d\dot{W}_b}{dc_2} & \frac{d\dot{W}_b}{dc_3} & \frac{d\dot{W}_b}{dc_4} & \frac{d\dot{W}_b}{dc_5} & \frac{d\dot{W}_b}{dc_6} & \frac{d\dot{W}_b}{dT_1} & \frac{d\dot{W}_b}{dT_2} \\
\frac{d\dot{p}}{dc_1} & \frac{d\dot{p}}{dc_2} & \frac{d\dot{p}}{dc_3} & \frac{d\dot{p}}{dc_4} & \frac{d\dot{p}}{dc_5} & \frac{d\dot{p}}{dc_6} & \frac{d\dot{p}}{dT_1} & \frac{d\dot{p}}{dT_2} \\
\frac{d\dot{q}}{dc_1} & \frac{d\dot{q}}{dc_2} & \frac{d\dot{q}}{dc_3} & \frac{d\dot{q}}{dc_4} & \frac{d\dot{q}}{dc_5} & \frac{d\dot{q}}{dc_6} & \frac{d\dot{q}}{dT_1} & \frac{d\dot{q}}{dT_2} \\
\frac{d\dot{r}}{dc_1} & \frac{d\dot{r}}{dc_2} & \frac{d\dot{r}}{dc_3} & \frac{d\dot{r}}{dc_4} & \frac{d\dot{r}}{dc_5} & \frac{d\dot{r}}{dc_6} & \frac{d\dot{r}}{dT_1} & \frac{d\dot{r}}{dT_2} \\
\frac{d\dot{\phi}}{dc_1} & \frac{d\dot{\phi}}{dc_2} & \frac{d\dot{\phi}}{dc_3} & \frac{d\dot{\phi}}{dc_4} & \frac{d\dot{\phi}}{dc_5} & \frac{d\dot{\phi}}{dc_6} & \frac{d\dot{\phi}}{dT_1} & \frac{d\dot{\phi}}{dT_2} \\
\frac{d\dot{\theta}}{dc_1} & \frac{d\dot{\theta}}{dc_2} & \frac{d\dot{\theta}}{dc_3} & \frac{d\dot{\theta}}{dc_4} & \frac{d\dot{\theta}}{dc_5} & \frac{d\dot{\theta}}{dc_6} & \frac{d\dot{\theta}}{dT_1} & \frac{d\dot{\theta}}{dT_2} \\
\frac{d\dot{\psi}}{dc_1} & \frac{d\dot{\psi}}{dc_2} & \frac{d\dot{\psi}}{dc_3} & \frac{d\dot{\psi}}{dc_4} & \frac{d\dot{\psi}}{dc_5} & \frac{d\dot{\psi}}{dc_6} & \frac{d\dot{\psi}}{dT_1} & \frac{d\dot{\psi}}{dT_2}
\end{bmatrix}. \tag{B.2}$$

The numerical linearization method is applied to obtain all the elements of matrices A and B of the state-space representation of the response of the Flying-V. This way, the two matrices are written as follows:

$$A \approx \begin{bmatrix}
\frac{X_e(X_{e_0}+h)-X_e(X_{e-0})}{h} & \frac{X_e(Y_{e_0}+h)-X_e(Y_{e_0})}{h} & \cdots & \frac{X_e(\psi_0+h)-X_e(\psi_0)}{h} \\
\frac{Y_e(X_{e_0}+h)-Y_e(X_{e_0})}{h} & \ddots & & \\
\vdots & & \ddots & \\
\frac{\psi(X_{e_0}+h)-\psi(X_{e_0})}{h} & \cdots & & \frac{\psi(\psi_0+h)-\psi(\psi_0)}{h}
\end{bmatrix}, \tag{B.3}$$

$$B \approx \begin{bmatrix} \frac{X_e(c_{1_0}+h)-X_e(c_{1_0})}{h} & \frac{X_e(c_{2_0}+h)-X_e(c_{2_0})}{h} & \cdots & \frac{X_e(c_{1_0}+h)-X_e(T_{2_0})}{h} \\ \frac{Y_e(c_{1_0}+h)-Y_e(c_{1_0})}{h} & \ddots & & \\ \vdots & & \ddots & \\ \frac{\psi(c_{1_0}+h)-\psi(c_{1_0})}{h} & \cdots & & \frac{\psi(T_{2_0}+h)-\psi(T_{2_0})}{h} \end{bmatrix}. \tag{B.4}$$

The outcome of this linearization is accurate, and it has been validated against the analytical linearization of the same equations (computed by writing the analytical derivative of each state equation with respect to each state and input), and against the non-linear model around the linearization point. In the following figure, a comparison between linearized and non-linear models is shown for the pitch angle response to a symmetric 1-degree step input on the four ailerons. As can be seen, the two responses are essentially equivalent.

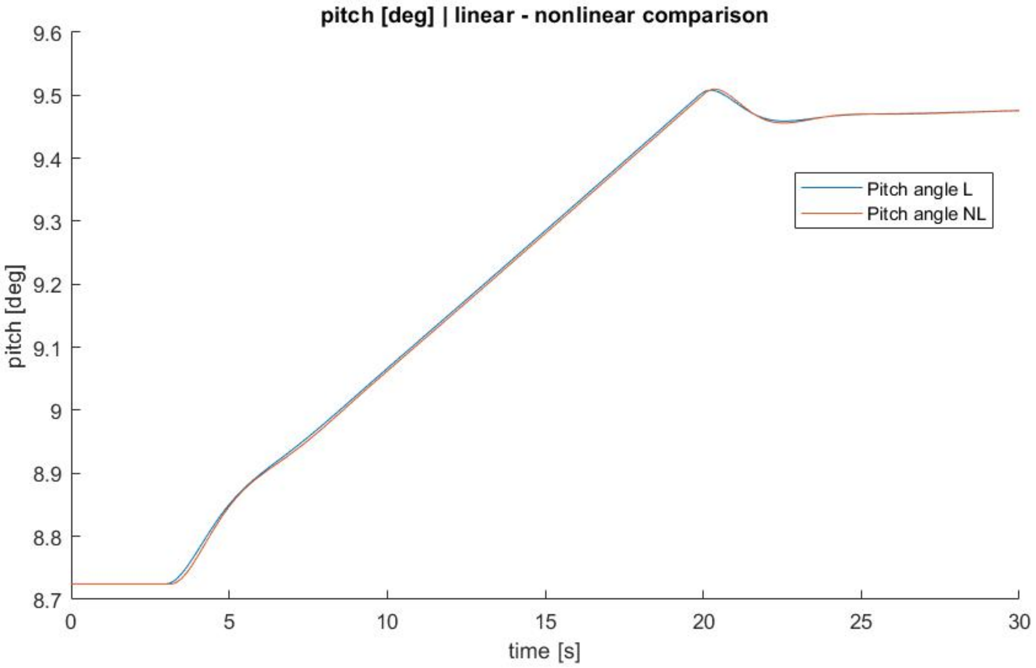


Figure B.1: Comparison between linearized and non-linear models. Short period only, forward CG, Mach = 0.3.

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