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Simulator Assessment of the Lateral-Directional Handling Qualities of the Flying-V

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Flying wings are known for their limited lateral-directional stability and handling qualities. This study aims at assessing the lateral-directional handling qualities of a conceptual flying wing aircraft currently in development at TU Delft, the Flying-V, in a moving-base flight simulator. It focuses on two aspects: First assess the lateral-directional handling qualities of the bare-airframe Flying-V, and the compliance to quantitative requirements. Second, improve these handling qualities through a prototype flight control system, and assess its effect on the handling qualities and the requirement compliance. These assessments were performed both analytically and with a pilot-in-the-loop simulator experiment, in order to experimentally validate analytical findings and obtain new pilot-subjective insights. The analytical and experimental assessment for low-speed flight conditions both show the lateral-directional handling qualities of the Flying-V to be insufficient for requirement compliance, due to a lack of pitch, roll and yaw control authority and an insufficiently stable Dutch roll eigenmode. The prototype flight control system, consisting of an adapted control allocation and a stability augmentation system, showed both analytically and experimentally to improve the control authority, stability, and handling qualities of the Flying-V. While the effect on the lateral-directional stability was sufficient for stability requirement compliance, the control authority was not sufficiently increased for maneuverability requirement compliance at low speed. Thus, if the landing speed is not increased from the current baseline, a challenge remains to improve the handling qualities of the Flying-V. An approximation of the control authority required for full requirement compliance in the low-speed flight conditions tested showed a control authority increase of over a factor four to be required in that case.

I. Introduction

The conventional wing-body-tail aircraft layout has been dominant in commercial aviation for over 50 years. It seems, however, that this configuration is converging to an asymptote of maximum performance and efficiency [1]. Therefore, new interest arises in unconventional aircraft layouts, such as the flying wing. This tail-less configuration was and is investigated by numerous companies and institutes, which led amongst others to designs of a blended-wing-body aircraft [2, 3]. Recently, TU Delft has researched the opportunities regarding a different flying wing design called the Flying-V, following a design by Benad [4]. A next design iteration was made at TU Delft by Faggiano [5]. Both show a promising performance, with a drag reduction of 10% compared to conventional aircraft with comparable performance requirements.

From a control perspective, flying wings are known for their limited lateral-directional stability [6] and their limited handling qualities [7], caused by the absence of a vertical tail surface, and a smaller moment arm from the control surfaces to the center of gravity than conventional aircraft. From this perspective followed a first handling quality assessment of the Flying-V by Cappuyns [8]. The study focused on developing the required aerodynamic model and simulation tools, with a brief analytical assessment of the handling quality performance of this model. It was found that, similar to earlier research, the lateral-directional stability and handling qualities were limited. It was recommended to further study this stability and these handling qualities.

Handling qualities can be assessed analytically and experimentally. The analytical assessment can be performed by simulating the aircraft and using this simulation to check against regulatory qualitative and quantitative requirements [9].

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These analytical results, however, can differ from (experimental) pilot-perceived handling qualities, since these are a subjective measure [10]. Hence, to perform a complete handling quality assessment, both the analytical and experimental handling qualities have to be assessed. Obtaining the pilot perceived handling qualities requires a pilot-in-the-loop experiment, and although previous research exists on the lateral-directional handling qualities of the Flying-V, no pilot-in-the-loop experiment has been performed yet.

This study aims at bringing the insights in the lateral-directional handling qualities of the Flying-V a step further, by not only performing further analytical assessment, but by also performing the first piloted assessment in a moving-base flight simulator. It focuses on two aspects: First, assess the handling qualities of the bare-airframe Flying-V, and the compliance to quantitative requirements selected from EASA CS-25 [11] and US Department of Defence military handbook MIL-HDBK-1797 [12]. Second, improve the handling qualities through designing a prototype flight control system, and assess its effect on the handling qualities and requirement compliance.

II. Background

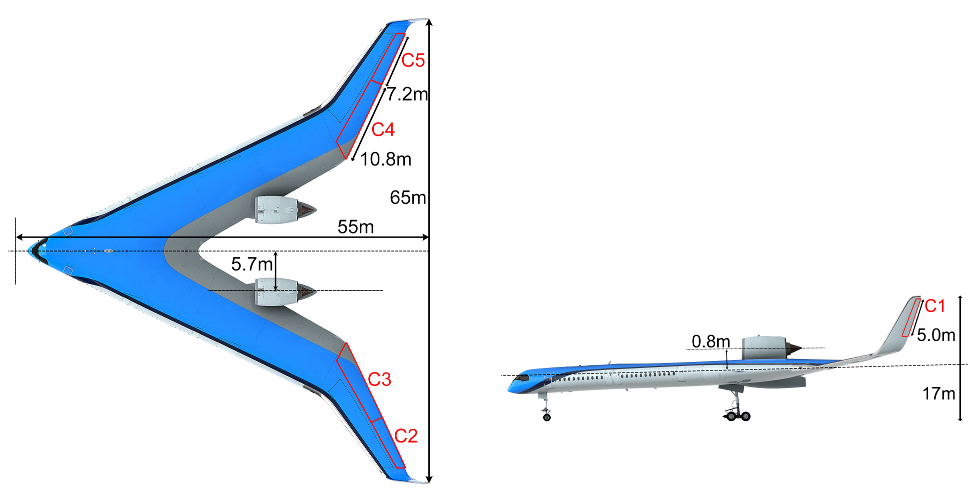
A. The Flying-V

1. Flying-V development

The Flying-V initial design was performed by Benad, who predicted a performance increase with a drag reduction of 10% compared to conventional aircraft with comparable performance requirements [4]. A further design iteration was performed at TU Delft by Faggiano, who performed an aerodynamic design optimization for the Flying-V [5]. The design iteration consisted of designing the wing planform and airfoil based on aerodynamic optimization, and sizing the winglet fins with integrated rudders based on static stability requirements. This new design was used for further analyses in several TU Delft theses [13–16]. Following this research, Cappuyns performed a preliminary handling quality analysis by developing a full-scale aerodynamic simulation of the Flying-V, based on the Vortex Lattice Method[8], including the control surfaces as designed by Faggiano and Palermo [5, 16]. The Flying-V geometry and properties used for this study were obtained from Cappuyns [8], with the engine location obtained from Pascual [17].

2. Flying-V properties

The geometry, mass, and mass moments of inertia properties of the Flying-V used in this study are based on the work by Cappuyns [8]. The Maximum Take-Off Weight (MTOW) and Maximum Landing Weight (MLW) of the Flying-V were directly available from Cappuyns [8], as well as the moments of inertia for the MTOW. The moments of inertia for the MLW, however, were not directly available, thus were determined [18] based on the weight difference between the MTOW and MLW and the weight distribution as used by Cappuyns [8]. Figures 1(a) and 1(b) give an impression of, respectively, the top- and side-view of the Flying-V with associated dimensions and control surfaces indicated.



(a) Top view of the Flying-V

(b) Side view of the Flying-V

Fig. 1 Flying-V impressions and dimensions*.

The control surfaces of the Flying-V are located at the outboard trailing edges. In the studied configuration, both aircraft sides possess 2 elevons (i.e., elevator-aileron combinations) and a rudder embedded in the winglet. The control surface dimensions were obtained from the aerodynamic model of the Flying-V, as initially developed by Cappuyns [8]. It should be noted that Cappuyns developed the control surfaces based on simplicity and recommended further research to optimize them. The dimensions of the right elevons are indicated in Figure 1(a), the dimension of the left winglet rudder is indicated in Figure 1(b). The control surfaces are indicated by C1, C2, C3, C4, C5 and C6. These, respectively, indicate the left winglet rudder, left outboard elevon, left inboard elevon, right inboard elevon, right outboard elevon, and right winglet rudder, as seen when standing behind the aircraft.

3. Aerodynamic model implementation and simulation

Cappuyns developed a full-scale aerodynamic simulation-model of the Flying-V in collaboration with Airbus, based on the Vortex Lattice Method (VLM) [8]. This VLM model was provided by Airbus, and one iteration was collaboratively made to expand the VLM model to contain multiple center of gravity locations, more flight conditions and separately controllable control surfaces. This yielded a model with the following variables as inputs: Center of gravity in %MAC (CG), aircraft velocity in Mach (M), angle of attack in degrees (α), sideslip angle in degrees (β), normalized roll rate in radians (p^*), normalized pitch rate in radians (q^*), normalized yaw rate in radians (r^*), and the deflection of all six control surfaces in degrees (δ_{c1} to δ_{c6}). The range of input variables available for inter- and extrapolation is shown in Table 18 in the appendix of this paper.

The output of the VLM model is given in terms of contributions of the input variables to (non-dimensional) force and moment coefficients. The force coefficients are, in the aerodynamic reference frame, the backward force coefficient C_X, the side (right) force coefficient C_Y, and the upward force coefficient C_Z. The moment coefficients are, in the body reference frame, the roll moment coefficient C_L, the pitch moment coefficient C_M, and the yaw moment coefficient C_N. The force and moment coefficients are obtained by inter- or extrapolating the contribution of all input states to the corresponding coefficients and summing those. Illustrating the determination of a force or moment coefficient for a given Center of Gravity and velocity in Mach, the following equation shows the determination of force coefficient C_X, based on the VLM model output coefficients:

$$\begin{aligned} C_X = C_{X_0}(\alpha) + C_{X_\beta}(\alpha, \beta) + .. \\ C_{X_{p^*}}(\alpha, p^*) + C_{X_{q^*}}(\alpha, q^*) + C_{X_{r^*}}(\alpha, r^*) + .. \\ C_{X_{\delta_{c1}}}(\alpha, \delta_{c1}) + C_{X_{\delta_{c2}}}(\alpha, \delta_{c2}) + C_{X_{\delta_{c3}}}(\alpha, \delta_{c3}) + .. \\ C_{X_{\delta_{c4}}}(\alpha, \delta_{c4}) + C_{X_{\delta_{c5}}}(\alpha, \delta_{c5}) + C_{X_{\delta_{c6}}}(\alpha, \delta_{c6}) \end{aligned} \tag{1}$$

The force and moment coefficients are dimensionalized using the air density, velocity, and for the moment coefficients also the mean aerodynamic chord. Using the mean aerodynamic chord for (non-)dimensionalizing the moment coefficients regardless of the axis of the coefficient is an Airbus convention. Next to these aerodynamic forces, two thrust vectors were added to the model: $T1$ for the left engine and $T2$ for the right engine, when seen from behind the aircraft. For each engine, a thrust vector was modeled as being aligned with the aircraft body-frame X-axis (nose forward direction). Thus, the additional force was added to the existing X-axis body-frame force component, and the additional body-frame moments around the Y and Z body-axes were calculated based on each engine's location with respect to these axes.

The aircraft state vector used consists of 12 states: the earth-fixed positions X_e, Y_e and Z_e, the velocities along the body frame U_b, V_b and W_b, the angular velocities p, q and r and the attitude angles φ, θ and ψ. With the aerodynamic forces X, Y, Z and the moments M_x, M_y, M_z obtained as previously discussed, equations of motion were used to simulate the aircraft response to inputs [19]. For the analytical assessment, Euler integration was used to simulate the aircraft over time. For the experimental assessment, this was adapted to Runge-Kutta integration at 100 Hz, to allow higher integration accuracy.

A linearized model of the aircraft was obtained by trimming the aircraft numerically at a set flight condition, following the same procedure of determining state derivatives as the non-linear simulation discussed above, and linearizing the aircraft around the trimmed state. The linear state-space model provided an uncomplicated way of assessing the eigenmode damping and frequency responses of the aircraft by assessing the eigenvalues of the state matrix (A), rapidly showing the aircraft eigenmode stability and damping [18, 20].

*Flying-V impressions obtained from `https://www.tudelft.nl/lr/flying-v`, combined with geometry properties obtained from Cappuyns [8] and Pascual [17].

4. Flying-V handling qualities

Flying wings are known for their limited lateral-directional stability [6] and limited handling qualities [7], due to the absence of a vertical tail surface. The preliminary winglet and rudder designs by Faggiano [5] and Palermo [16] took this stability into account, but were primarily based on the static stability of the Flying-V. Further analysis by Cappuyns [8] showed the dynamic lateral-directional stability of the Flying-V to be insufficient. Amongst others because of this, the lateral-directional handling qualities were found limited on two aspects. First on the lateral-directional eigenmodes, which showed an unstable Dutch roll. Second, on the lateral-directional maneuverability, for which the control authority was shown to be insufficient for multiple handling quality requirements. Cappuyns recommended further research to focus on a more elaborate investigation into the handling qualities of the Flying-V. Recommended solutions for the limited lateral-directional handling qualities were, amongst others, a redesign of the control surfaces, the use of unconventional control surfaces, optimizing the control allocation and imposing a stability augmentation system. Of these, the control allocation and stability augmentation system are assessed further in this study.

It should be noted that the analysis by Cappuyns [8] was performed analytically, and no piloted experiment was performed. Hence, the obtained results were not validated as pilot-perceived, yielding a research-opportunity for the current study.

B. Lateral-Directional Handling Qualities and Requirements

Both Cooper and Harper [21] as well as Roskam [22] describe handling qualities in a qualitative sense. Although they provide general requirements on aircraft performance, no quantitative requirements are set on aircraft attitudes or maneuvers. Hence, in order to objectively assess whether the handling quality requirements were met, quantitative handling quality requirements were used. In line with Cappuyns [8], the US Department of Defence military handbook MIL-HDBK-1797 [12] and the EASA aircraft regulations of CS-25 [11] were used as this quantitative benchmark. The military handbook specifies quantitative stability requirements on frequency and damping parameters of aircraft eigenmodes, and associated handling quality classification. The EASA regulations specify airworthiness (maneuverability) requirements, with quantitative constraints on amongst others the control deflections used and time to perform a set maneuver. Since this study focuses on the lateral-directional handling qualities, only the requirements set on these were taken into account.

To further limit the scope of the handling quality assessment, literature was used to select the requirements and regulations to be tested. Research by Perez and Wahler [23, 24] discussed the design-constraining conditions selected from EASA CS-25 and the MIL-HDBK-1797 of the US Department of Defence for, respectively, conventional and unconventional aircraft configurations. In being the design-constraining conditions, these were chosen as the most relevant conditions to test the Flying-V design on. Finally, requirements were selected which allow for both an analytical and an experimental analysis. Table 1 shows an overview of the requirements and regulations tested.

Table 1 Selection of handling quality requirements for evaluation.

Requirement	Book	Article
Dutch roll Stability (DR)	MIL-HDBK-1797	4.6.1.1
Coordinated Turn Capability (CTC)	CS-25	143(h)
Time to Bank, Roll Capability (TTB)	CS-25	147(f)
One Engine Inoperative Trim (OEI-T)	CS-25	161(d)
Steady Heading Sideslip (SHS)	CS-25	177(c)

C. Flight Control Systems and Handling Qualities

In order to take a first step in improving the lateral-directional handling qualities of the Flying-V, a prototype flight control system was designed. A flight control system can improve the handling qualities of the aircraft without the need to re-design the aircraft's planform or control surfaces. In a fly-by-wire controlled aircraft, the flight control system converts the pilot inputs to control surface actuation. Due to the flight control system being in between the pilot and the control surfaces, indirect control surface control is possible. This yields opportunities for unconventional (i.e., not direct, mechanically linked) control. In this study, two of those opportunities are focused on: an adapted (unconventional) control allocation and stability augmentation.

1. Control allocation and handling qualities

The control allocation determines which control surface contributes to the generation of which angular moments and by how much. Due to the lack of a conventional tail, the Flying-V control surfaces have a less clear predetermined allocation than those of a conventional wing-body-tail aircraft. Thus, a study into this control allocation can contribute to increasing the overall control-effectiveness and controllability of the Flying-V. Previous research on the control allocation of other flying wings, such as a blended-wing-body, showed the control allocation to have a large impact on the aircraft's command responses [25] and trim-drag [26].

When the handling qualities prove to be limiting in the control surface sizing and design, control allocation can increase the control-effectiveness such that smaller control surfaces are required [27]. Alternatively, for a given control surface design the increase of control-effectiveness due to adapting the control allocation can improve the handling qualities at (previously) limiting aircraft maneuvers during the handling quality assessment. Only a limited increase in control authority is available with this method, however. The control allocation can be optimized to increase control effectiveness, but the overall control authority will still be limited by the maximum deflections available of the control surfaces.

2. Stability augmentation and handling qualities

Stability augmentation uses the aircraft state to change the commanded deflection of control surfaces. In this way, an aircraft can respond to state or condition changes without the pilot intervening. Stability augmentation is commonly used when the bare-airframe stability is found insufficient. Research has shown stability augmentation to be suitable to improve this lateral-directional stability of flying wings by the use of roll damping, yaw damping and sideslip angle feedback [7, 9, 28].

When increasing the lateral-directional stability with the use of stability augmentation, the handling qualities of an aircraft can inherently be improved. Specifically the eigenmodes of an aircraft can be heavily influenced by stability augmentation, by either altering an eigenmode's damping, frequency or both [9, 29]. Since the damping and frequency parameters of eigenmodes are part of the Dutch roll Stability handling quality requirement, implementing a stability augmentation system can improve compliance with this requirement.

III. Method

A. Flight Control System Design

1. Control allocation design

The aerodynamic model of the Flying-V contains six control surfaces, while three pilot inputs are assumed: two of the sidestick and one of the rudder pedals. A control allocation between these pilot inputs and the six control surfaces is required. The bare-airframe Flying-V uses a conventional elevator-aileron-rudder control allocation, analogous to previous research [8]. The control allocation method is called explicit ganging in literature [30], which assigns each control surface to a specific moment direction based on the designer's choice. The inboard elevons were allocated to respond to a longitudinal stick input, providing a pitch moment by symmetric deflection. The outboard elevons were allocated to respond to a lateral stick input, providing a roll moment by asymmetric deflection. The rudders were allocated to respond to the rudder pedal input, providing a yaw moment by asymmetric (but in the same body Y-direction) deflection. Equation 2 represents this control allocation by K_{alloc}, and shows how the pilot inputs (pitch input δ_e, roll input δ_a and yaw input δ_r) were allocated to the control surface deflections (δ_{C1}, δ_{C2}, δ_{C3}, δ_{C4}, δ_{C5}, δ_{C6}) with the bare-airframe Flying-V.

$$\begin{bmatrix} \delta_{C1} \\ \delta_{C2} \\ \delta_{C3} \\ \delta_{C4} \\ \delta_{C5} \\ \delta_{C6} \end{bmatrix} = K_{alloc} \cdot \begin{bmatrix} \delta_e \\ \delta_a \\ \delta_r \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} \delta_e \\ \delta_a \\ \delta_r \end{bmatrix} \tag{2}$$

Due to the unconventional control surfaces of the tailless Flying-V, an opportunity exists to improve the control effectiveness with an unconventional control allocation. Numerous control allocation methods can be found in literature [25, 31], from which the generalized inverse was chosen. Amongst others Denieul [27] used the generalized inverse to design the control allocation of a blended-wing-body and Oppenheimer [32] used the generalized inverse for the control allocation of over-actuated systems.

The generalized inverse method uses the control effectiveness of each control surface around each moment axis to distribute the roles of controlling these moments between the control surfaces. The control effectiveness matrix, as shown in Equation 3, is a 3 by 6 matrix holding the derivatives of the moments around the Y, X and Z body axes, respectively, m, l and n, with respect to deflection of each of the six control surfaces. This matrix can be obtained by linearizing the aircraft including the control surfaces around a trimmed state. Next, the coefficients of Equation 3 are obtained from the B matrix of the state-space system. Second, the control effectiveness matrix is used to determine the adapted control allocation matrix $K_{alloc_{new}}$ using the unweighted pseudo-inverse of the control allocation as shown in Equation 4.

$$B = \begin{bmatrix} \frac{dm}{d\delta_{c1}} & \frac{dm}{d\delta_{c2}} & \frac{dm}{d\delta_{c3}} & \frac{dm}{d\delta_{c4}} & \frac{dm}{d\delta_{c5}} & \frac{dm}{d\delta_{c6}} \\ \frac{dl}{d\delta_{c1}} & \frac{dl}{d\delta_{c2}} & \frac{dl}{d\delta_{c3}} & \frac{dl}{d\delta_{c4}} & \frac{dl}{d\delta_{c5}} & \frac{dl}{d\delta_{c6}} \\ \frac{dn}{d\delta_{c1}} & \frac{dn}{d\delta_{c2}} & \frac{dn}{d\delta_{c3}} & \frac{dn}{d\delta_{c4}} & \frac{dn}{d\delta_{c5}} & \frac{dn}{d\delta_{c6}} \end{bmatrix} \tag{3}$$

$$K_{alloc_{new}} = B^T (BB^T)^{-1} \tag{4}$$

To obtain the control effectiveness matrix, the aircraft was linearized in cruise flight conditions with the aft CG position. This condition is expected to be occurring most during the aircraft mission, thus optimizing for this condition is expected to yield the least overall drag. Moreover, linearizing the aircraft in this condition yielded the most intuitive control allocation. To limit the complexity of the adapted control allocation, it was decided not to alter the control allocation for each flight condition. Equation 5 shows the obtained control allocation matrix $K_{alloc_{new}}$. Using the equivalent moments $\delta_{m_{equi}}, \delta_{l_{equi}}$ and $\delta_{n_{equi}}$, each column of the control allocation matrix was scaled such that the largest magnitude equals 1, to make the relative control allocation more apparent. This does not limit the use of the controls, since the scaling and limiting of the pilot inputs was performed separately in the piloted experiment preparation.

$$\begin{aligned} \begin{bmatrix} \delta_{C1} \\ \delta_{C2} \\ \delta_{C3} \\ \delta_{C4} \\ \delta_{C5} \\ \delta_{C6} \end{bmatrix} &= K_{alloc_{new}} \cdot \begin{bmatrix} \delta_e \cdot \delta_{m_{equi}} \\ \delta_a \cdot \delta_{l_{equi}} \\ \delta_r \cdot \delta_{n_{equi}} \end{bmatrix} \\ &= \begin{bmatrix} -0.046 & -0.439 & 1.000 \\ -0.601 & 0.496 & 0.150 \\ -1.000 & 1.000 & -0.179 \\ -1.000 & -1.000 & 0.179 \\ -0.601 & -0.496 & -0.150 \\ -0.046 & 0.439 & -1.000 \end{bmatrix} \cdot \begin{bmatrix} \delta_e \\ \delta_a \\ \delta_r \end{bmatrix} \end{aligned} \tag{5}$$

2. Stability augmentation system design

The stability augmentation system design was based on the research of Castro [9], who designed a stability augmentation system for a blended-wing-body aircraft. For lateral-directional stability augmentation, a combination of sideslip feedback with a reference command, a yaw damper with washout filter, and roll rate feedback with reference command was used. For longitudinal control, pitch rate feedback with a reference command was used. Since the sideslip angle β was not directly available as aircraft state, the body-frame side velocity V_b is used, since β converges to zero when V_b converges to zero.

Earlier research into the design and assessment of a flight control system for an unconventional (blended-wing-body) aircraft showed the effect of including or excluding roll damping in the stability augmentation system to be pilot-subjective

[9]. Hence, the stability augmentation system will be tested both with, and without roll rate feedback. Without roll rate feedback, direct roll control was available, where full lateral stick deflection yields maximum roll input to the lateral control allocation input channel δ_a. The stability augmentation system (SAS) without roll rate feedback is labeled SAS-1, the stability augmentation system with roll rate feedback is labeled SAS-2. Figure 2 shows an overview of the stability augmentation system by means of a system diagram, with the lateral control of both SAS-1 and SAS-2 shown. Gain tuning was performed per SAS and flight condition based on the Dutch roll Stability requirement, time-responses to inputs, and preliminary piloted simulation. An overview of the gain tuning is shown in Table 19 in the appendix of this paper.

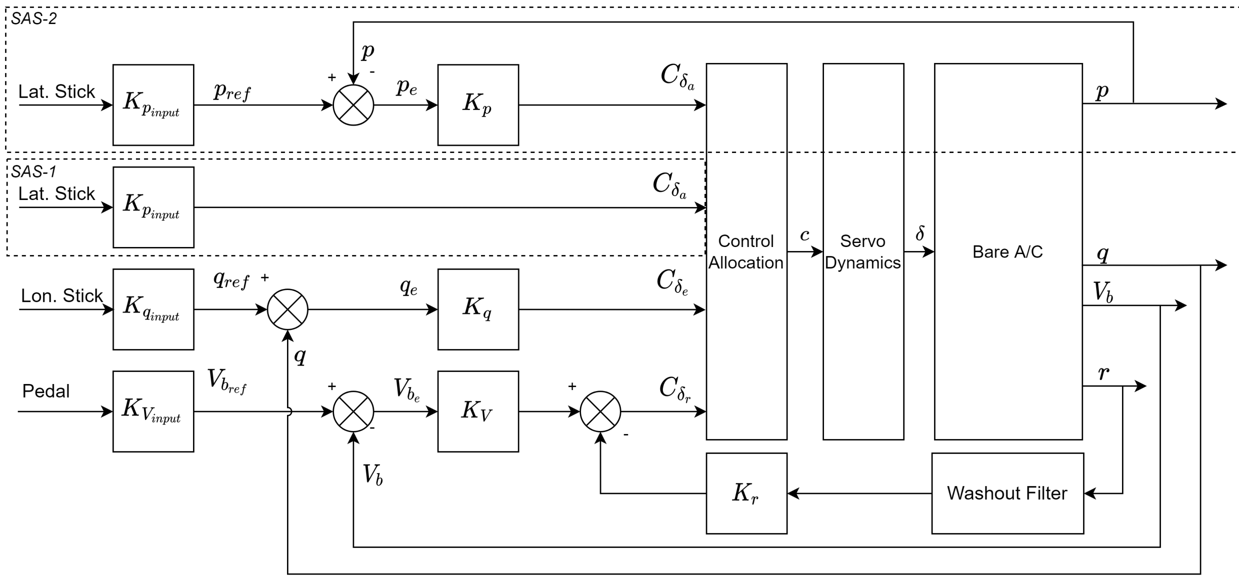


Fig. 2 Stability augmentation system design, with SAS-1 and SAS-2 lateral input indicated.

B. Analytical Handling Quality Assessment

1. Flight condition and aircraft configuration selection

The flight conditions tested were chosen to be in line with earlier research, and were based on the flight conditions available in the aerodynamic aircraft model. Three different air speeds in Mach were used: Mach 0.2, 0.3 and 0.85, which were assumed to be applicable for, respectively, Approach, Take-Off and Cruise flight conditions. Table 2 shows an overview of these flight conditions, with their corresponding True Air Speed (TAS), altitude, air density, assumed aircraft weight (Maximum Take-Off or Maximum Landing Weight) and aircraft mass.

Table 2 Flight condition assumptions.

Condition	Mach	TAS	Altitude	Air Density	A/C Weight
	–	$knots$	m	kg/m^3	–
Approach (APP)	0.2	133	0	1.225	MLW
Take-Off (TO)	0.3	200	0	1.225	MTOW
Cruise (CR)	0.85	488	13000	0.2655	MTOW

Next to these flight conditions, two Center of Gravity (CG) locations and two engine settings were tested. The CG locations tested were the forward and aft limit, as determined in earlier research [8]. The engine settings tested were an All Engines Operative (AEO) condition with both engines providing equal thrust, and an One Engine Inoperative (OEI) condition, in which the right engine was providing no thrust. The engine settings assessed differed per maneuver, as specified in the requirements tested.

2. Analytical simulation of requirements

Analytical simulation of the bare-airframe Flying-V dynamics and trim states was used to assess the CS-25 [11] requirements specified in Table 1. The Coordinated Turn Capability, One Engine Inoperative Trim Condition, and Steady Heading Sideslip requirements specify trim states the aircraft should be able to attain and maintain. For the assessment of these requirements the aircraft was numerically trimmed. The requirements set on the aircraft states as stated in CS-25 were used as constraints, while the aircraft states without constraints and the control surface deflections were numerically optimized to trim the aircraft. The constraints used for the different maneuvers are shown in Table 3. For the Time to Bank maneuver, the initial trim state is shown, from which the rolling maneuver started.

Table 3 State constraints for analytical assessment of handling quality requirements.

Requirement	Condition	β *deg*	ϕ *deg*	γ *deg*
CTC	ALL	0	40	0
TTB (init.)	ALL	0	30	0
OEI-T	ALL	n/a	< 5	0
	APP	13.1	n/a	0
SHS	TO	8.69	n/a	0
	CR	3.56	n/a	0

A requirement was complied with if the required control surface deflections for the trim state were within set control surface deflection limits: *37 degrees* for rudder deflection and *30 degrees* for elevon deflection, based on Cappuyns [8] and Castro [9]. For the Time to Bank requirement, assessing the roll capability of the aircraft, a non-linear simulation of the Flying-V dynamics was used. By iteratively simulating the roll maneuver as specified in CS-25, the minimum (constant) lateral control surface deflections were found to perform the maneuver within the required time. Here, the lateral input δ_a was iterated to perform the roll maneuver. For the bare-airframe assessment the rudder input δ_r was also used, in order to reduce sideslip during this maneuver. For the assessment with stability augmentation system zero pedal input was assumed, since no pilot input should be required to reduce sideslip. Again, a requirement was complied with if the required control surface deflections for the maneuver were within the set control surface deflection limits.

The Dutch roll Stability requirement, as stated in MIL-HDBK-1797 [12], requires the eigenvalues of the aircraft to obtain the Dutch roll damping and frequency parameter. To determine these eigenvalues, the linearization procedure as discussed in Section II.A.3 was used. The eigenvalues were attributed to each eigenmode based on their eigenvectors [20]. Each eigenvalue then yielded the damping and frequency parameter of an eigenmode, amongst which the Dutch roll. The Dutch roll was assessed in trimmed, straight, horizontal flight, for each flight condition tested.

3. Flight control system influence on analytical assessment

The flight control system influence on the analytical handling quality assessment differed for the two flight control system elements, the adapted control allocation and the stability augmentation system. The increase in control effectiveness by adapting the control allocation can improve the requirement compliance for edge-of-the-envelope trim states and maneuvers, by increasing the overall control effectiveness. Adapting the control allocation however does not influence the stability of the eigenmodes of the aircraft. Control allocation only takes effect in translating desired angular control inputs to control surface deflections, while the eigenmode stability is determined without pilot input. Thus, only the CS-25 requirements had to be reassessed when implementing the adapted control allocation, since the MIL-HDBK-1797 Dutch roll Stability was not influenced.

Stability augmentation can positively influence the eigenmodes of an aircraft, by either improving an eigenmode its damping, frequency or both [9, 29]. Hence, of the handling quality requirements listed in Table 1, primarily the Dutch roll Stability requirement is influenced. The stability augmentation system was developed such that most EASA CS-25 requirements do not require re-assessment: the same trim control deflections as without the stability augmentation system are still attainable. However, the stability augmentation system does influence the aircraft's response on pilot inputs. Thus of the EASA CS-25 requirements, only the Time to Bank requirement is influenced, since this requirement does not only involve a trim condition but also performing a maneuver within a set time.

C. Experimental Handling Quality Assessment

1. Piloted simulation of the Flying-V

Real-time piloted simulation of the Flying-V was set-up using the *Delft University Environment for Communication and Activation* (DUECA) middleware. DUECA simplifies the composition of a simulation or experiment using new or existing models and facilitates data access and timing of activation [33]. The aerodynamic model, as discussed in Section II.A.3, was used as the basis to develop a non-linear simulation. The aircraft dynamics were implemented in a real-time simulation to respond to pilot inputs on stick, pedal, and thrust. Control surface and engine dynamics were modeled using a first-order lag approximation, with a time constant of 0.05 seconds for control surface dynamics [18] and a time constant of 1.0 seconds for engine dynamics [34]. Moreover, based on discussion with the representative from Airbus providing the aerodynamic model for this study, a control surface deflection rate-limit was set on 40 degrees per second. Finally, the different control allocations, stability augmentation systems, flight conditions, aircraft properties and experiment maneuvers were made available to be selected externally by the researchers.

2. Piloted simulation of handling quality requirements

To simulate the different stability and maneuverability requirements, the maneuver to be performed in the simulator was determined for each. For this, a US Federal Aviation Administration flight test guide for certification of transport category airplanes, Advisory Circular (AC) 25-7D [35], was used. It includes flight test methods and procedures to show compliance with regulations as presented in EASA CS-25. For each of the CS-25 requirements tested, AC 25-7D discusses a maneuver which can be performed in flight (or flight simulation) and the allowed state limits to prove requirement compliance.

Since the Dutch roll Stability requirement is set on a damping and frequency parameter, no corresponding flight maneuver with target state is present. To still obtain pilot feedback on the Dutch roll stability of the aircraft, the pilot was asked to excite the Dutch roll by means of a rudder doublet input, and when the eigenmode was in a sustained oscillation to counteract it by either lateral stick or pedal inputs. This yielded pilot-subjective feedback on the severity of the Dutch roll eigenmode compared to conventional aircraft, and on the ease of counteracting it.

The Dutch roll was expected to not only act when actively excited, but to also have an influence on other maneuvers. Specifically maneuvers where a roll angle, roll rate or sideslip angle is demanded were expected to be influenced by the Dutch roll eigenmode. To assess whether and by how much the Dutch roll eigenmode was excited or suppressed throughout an experiment maneuver, the Mode Participation Factor of the Dutch roll throughout each experiment maneuver was determined. The state-vector of the logged experiment data was transformed to modal coordinates. First, the trim state was subtracted from the state vector in the original coordinates $x(t)$. Second, the eigenvector-matrix V was used to transform the state vector to a vector in modal coordinates, $r(t)$, as shown in Equation 6 [36]. Next, the columns representing the Dutch roll eigenmode in the eigenvector-matrix were determined, and used to obtain the corresponding rows in the state vector in modal coordinates $r(t)$. By taking the absolute value of one of the two rows representing the Dutch roll at every time-step, the Mode Participation Factor was obtained throughout each maneuver. An increasing Dutch roll Mode Participation Factor represents an increase in the presence of this eigenmode in the aircraft response. The Dutch roll Mode Participation Factor next was used to validate pilot comments on both the difficulty of counteracting the Dutch roll eigenmode, as well as the Dutch roll eigenmode interfering with other maneuvers.

$$r(t) = V^{-1}x(t) \tag{6}$$

For the CS-25 requirements, state targets with associated limits for each maneuver were set. All attitude (lower) margins were based on those in the analytical assessment, such that requirement compliance was met when the piloted maneuver was performed within margins from the target state. To set adequate outer margins from the target state, preliminary piloted simulation was used. Next to the analytically prescribed constraints, a maximum speed deviation from the target speed of 5% was set, and the target state had to be kept for 10 seconds to assure the maintainability of the state. For the Time to Bank maneuver, a time limit of 7 seconds to complete the maneuver was set, analogous to the analytical assessment of this CS-25 requirement. Besides, the positive Flight Path Angle was only required while starting the roll maneuver. An overview of the resulting limits as used in the experimental assessment is given in Table 4.

In order to assess the boundary of the flight envelope with acceptable handling qualities, many of the maneuvers selected for the experiment were by analytical assessment hypothesized impossible to be performed successfully in a piloted simulation. To limit the time spent per test maneuver, a procedure was developed to determine when a test was passed or failed. A test was passed when the aircraft was kept within the target state for 10 seconds or when, in case of

Table 4 State targets and adequate- and desired-margins for experimental requirement assessment.

Req.	Cond.	β			ϕ			γ			ψ		
		Targ. *deg*	$\Delta_{Ade.}$ *deg*	$\Delta_{Des.}$ *deg*	Targ. *deg*	$\Delta_{Ade.}$ *deg*	$\Delta_{Des.}$ *deg*	Targ. *deg*	$\Delta_{Ade.}$ *deg*	$\Delta_{Des.}$ *deg*	Targ. *deg*	$\Delta_{Ade.}$ *deg*	$\Delta_{Des.}$ *deg*
CTC	ALL	0	±2	±1	42.5	±2.5	±1.5	2.5	±2.5	±1.5	n/a	n/a	n/a
TTB	ALL	n/a	n/a	n/a	33.5	±3.5	±2.5	2.5	±2.5	±1.5	n/a	n/a	n/a
OEI-T	ALL	n/a	n/a	n/a	0	±5	±4	2.5	±2.5	±1.5	0	±5	±10
	APP	15.1	±2	±1	n/a	n/a	n/a	2.5	±2.5	±1.5	-15.1	±7.5	±5
SHS	TO	10.7	±2	±1	n/a	n/a	n/a	2.5	±2.5	±1.5	-10.7	±7.5	±5
	CR	5.56	±2	±1	n/a	n/a	n/a	2.5	±2.5	±1.5	-5.56	±7.5	±5

the Time to Bank test, the roll maneuver was performed within 7 seconds or less. When a pilot was not able to attain, or sufficiently maintain, the target state for longer than several minutes, the simulation was paused. Next, in consultation with the pilot, it was determined whether a further, in due time, try had a chance of success. If not, the test was assessed to be failed, else the simulation was reset and another try was performed. The maximum tries allowed per maneuver was set to five, the maximum total time spent per test to 7 minutes, both based on preliminary piloted simulations.

3. Experiment design

Use of flight control systems

The main goal of the experiment is assessing the bare-airframe handling qualities, and the influence of a prototype flight control system on these handling qualities. The flight control system design yielded SAS-1 without, and SAS-2 with roll damping. Based on analytical assessment of these, insufficient control authority was expected to be available in the low-speed approach and take-off flight conditions. In order to assess whether increasing the control authority would yield sufficient handling qualities for experimental requirement compliance in these flight conditions, a flight control system with increased control authority was set up. The maximum allowed control surface deflections were increased with a factor 5, allowing the deflections analytically predicted to be required while also providing excess deflection for attaining the target states. This configuration is labeled SAS-2 extended, or *SAS-2 ext.*. The *SAS-1* variant without roll damping was evaluated in a side experiment, as described in the next section.

Adding the flight control system with augmented extra control authority, *SAS-2 ext.*, to the main focus of the study, yielded three aircraft flight control system configurations to be tested in the main experiment: the bare-airframe, *SAS-2*, and *SAS-2 ext.*.

Selection of maneuvers

Due to limited pilot availability, not all combinations of flight conditions, aircraft center of gravity locations, flight control system implementations, engine settings and requirements tested in the analytical assessment were feasible to test in a pilot-in-the-loop experiment. Hence, a selection of test conditions and requirements was made, focusing on assessing the worst and best cases from the analytical assessment. These were, respectively, the approach condition with forward limit center of gravity and cruise condition with aft limit center of gravity. Moreover, it was decided that a thorough validation of the flight control system implementation required the conditions on which the flight control system effect was found largest in preliminary simulation to also be tested: the forward center of gravity conditions of the Dutch roll Stability and Steady Heading Sideslip requirement. This yielded 14 selected combinations of requirement, flight condition, engine setting and center of gravity, as shown in Table 5. Since these 14 maneuvers needed to be flown with the bare-airframe, with *SAS-2,* and with *SAS-2 ext.*, a total of 42 maneuvers were selected to be tested in the main experiment.

Next to the selected combinations of conditions and requirements for the main experiment, extra tests were included to assess the pilot-subjective difference between a stability augmentation system with and without roll damping. For this, the Dutch roll Stability, Steady Heading Sideslip and Time to Bank requirement for the forward center of gravity and all three flight conditions are selected, as preliminary simulations showed these to require the largest lateral inputs, thus are expected to be influenced most by the roll damper. This yielded 9 maneuvers, as shown in Table 6, to be tested with both *SAS-1* and *SAS-2*. Of these 18 tests, 7 were already present in the selection of the main experiment. Hence, when including 9 extra experiment runs, a total of 53 maneuvers had to be tested.

Table 5 Selected test conditions for experimental assessment of different maneuvers.

	CG Forward	CG Aft
DR	APP, TO, CR (AEO)	CR (AEO)
CTC	APP (AEO)	CR (OEI)
TTB	APP (AEO)	CR (AEO)
OEI-T	APP (OEI)	CR (OEI)
SHS	APP, TO, CR (OEI)	CR (AEO)

Table 6 Selected test conditions for experimental assessment of the roll damper effect.

	CG Forward
DR	APP, TO, CR (AEO)
TTB	APP, CR (AEO), TO (OEI)
SHS	APP, TO, CR (OEI)

Test pilots and experiment matrices

The pilot-in-the-loop experiment was performed by four pilots, denominated as Pilot 1 to 4. Table 7 shows an overview of the credentials of these pilots. Due to limited availability, Pilots 3 and 4 only performed the main experiment of 42 maneuvers. Pilots 1 and 2 also performed the extra experiment runs to assess the roll damper, thus 53 maneuvers. In order to eliminate bias from the results, for the experiment design matrix initially a Latin-square distribution was used. Unfortunately, pilot availability limitations led to a less structured experiment design matrix. Table 8(a) shows the initial experiment design, Table 8(b) shows the final experiment design, altered due to pilot availability. It can be noted that the experiment runs of *SAS-2 ext.* were split in two parts, p1 and p2. This was done to at least allow the maneuvers in approach and take-off flight conditions to be tested with *SAS-2 ext.*, since *SAS-2 ext.* was expected to yield the largest differences in requirement compliance with *SAS-2* in those conditions. The maneuvers in cruise flight conditions were only tested with *SAS-2 ext.* when sufficient time was available.

Table 7 Test pilot credentials.

Pilot	Credentials
P1	Technical pilot (airliner)
P2	Flight Test Engineer, National Test Pilot School US
P3	Research pilot (airliner/business jet)
P4	Technical pilot (airliner)

Simulator

The pilot-in-the-loop experiment was performed in the SIMONA Research Simulator (SRS) of the TU Delft Aerospace Engineering faculty, shown in Figure 3. The SRS is a high fidelity, six-degree of freedom ground-based research simulator, initially developed for advanced research into simulation techniques, motion system control and navigation systems technologies [37]. Ever since, it has been used for a broad range of research such as piloted handling quality assessments [38] and pilot control behavior research [39]. The SRS was shown to have correlated results to simulators leading in fidelity such as the Calspan Total In-Flight Simulator (TIFS) and the NASA Ames Vertical Motion Simulator (VMS) [40]. The SRS thus was assumed to be of sufficiently high fidelity for the current development phase of the Flying-V to perform pilot-in-the-loop handling quality experiments.

In-flight display

The primary flight display of the simulator cockpit was used to present the pilot with available aircraft information in a head-up display (HUD) alike, green on black, layout. This included Indicated Air Speed, Mach number, thrust lever setting and output, roll angle, pitch angle, flight path angle, sideslip angle and altitude. For the different maneuvers, different indicators with targets and limits were used. To de-clutter the HUD, only relevant indicators were shown

Table 8 Experiment designs.

(a) Initial experiment design matrix.

P1	SAS 2 ext	Bare-AC	SAS 2	SAS 1
P2	Bare-AC	SAS 2 ext	SAS 1	SAS 2
P3	SAS 2	SAS 1	SAS 2 ext	Bare-AC
P4	SAS 1	SAS 2	Bare-AC	SAS 2 ext

(b) Final experiment design matrix.

SAS 2 ext	Bare-AC	SAS 2	SAS 1	
Bare-AC	SAS 2 ext p1	SAS 1	SAS 2	SAS 2 ext p2
SAS 2 ext p1	SAS 2	Bare-AC		
SAS 2	Bare-AC	SAS 2 ext p1		

(a) Experiment setup inside SIMONA Research Simulator.

(b) Outside impression of SIMONA.

Fig. 3 SIMONA Research Simulator, experiment setup.

when simulating a maneuver. Figure 4 shows a black and white example of the HUD with all indicators, with arbitrary targets and limits. Yellow inner margins were used as warning, while red outer margins were used to show the pilot the aircraft's state was out of the target bounds. Margins colored green when they were met.

Motion Cueing

The SRS allows for six-degree of freedom motion cueing to the pilot, using the hexapod hydraulic actuators. In order to allow for this motion cueing, filtering between the aircraft states and simulator motion was performed. For this, high pass filters were used to translate the aircraft model's specific forces in surge (x), sway (y) and heave (z) to analogous simulator motion, and to translate aircraft model roll (ϕ), pitch (θ) and yaw (ψ) to analogous simulator motion. Moreover, low pass filters were used to translate aircraft low frequency surge and sway to simulator rotations, using tilt coordination in pitch and roll to replace the low frequency surge and sway specific forces. Gain tuning was performed to allow for (desired) maximal cueing, while keeping the simulator within its motion space. For this, the Gouverneur Tuning Approach was adopted [41], by identifying where motion limits were breached for different tuning settings and expected aircraft simulation maneuvers. This yielded the gain tuning as shown in Table 9, showing an overview of the high- and low-pass filter parameters used for each aircraft degree of freedom.

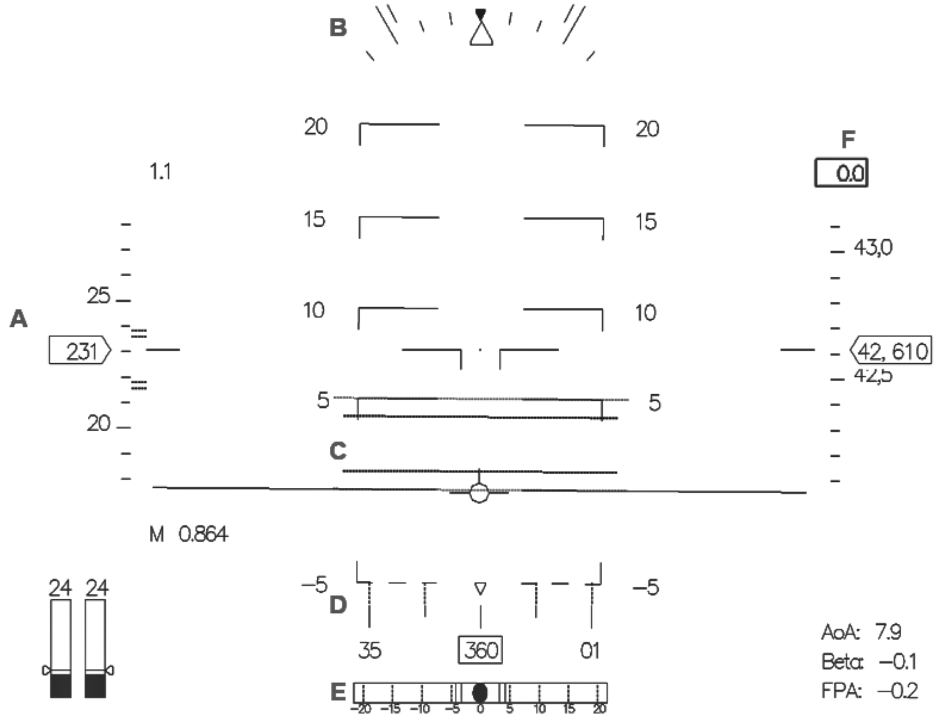


Fig. 4 Primary flight display HUD view, with at A: Velocity indicator with (stippled) target margins; B: Roll angle indicator with target margins; C: Flight Path Marker with (stippled) target margins; D: Sideslip angle indicator with target margins; E: Heading indicator with (stippled) target margins; F: maneuver timer.

Control Loading

The sidestick and pedal pilot controls in the SRS make use of a control loading mechanism to simulate sidestick spring stiffness and pedal force feel, which had to be set for the experiment. First, an estimation of conventional aircraft sidestick spring stiffness and pedal forces was made based on CS-25 regulations. Second, preliminary piloted simulation was used to further increase the fidelity compared to conventional aircraft. This yielded the sidestick spring stiffness and pedal force as shown in Table 10.

Dependent measures

From the pilot-in-the-loop experiment runs, different types of output were obtained. Each experiment run yielded a pass or fail on whether the requirements of the maneuver were met. These were used to validate the analytical research, from which hypotheses on the success of each maneuver were set. For the maneuvers used to compare the flight control system with and without roll damping, the pilots were asked to assign a Cooper-Harper rating to the maneuver [21, page 12]. These were used next to assess whether a significant difference in (subjective) handling qualities was present

Table 9 SRS motion tuning settings used in experiment, filter settings for aircraft degrees of freedom (DOF); *indicating filter order, gain K, 2^{nd} order natural frequency ω_n, damping ζ, 1^{st} order break frequency ω_b.*

	High-pass filter					Low-pass filter		
DOF	Order	K	ω_n	ζ	ω_b	Order	ω_n	ζ
x	2^{nd}	0.4	1.0	0.7	-	2^{nd}	2.0	0.7
y	2^{nd}	0.4	1.0	0.7	-	2^{nd}	2.0	0.7
z	3^{rd}	0.4	2.0	0.7	1.5			
ϕ	1^{st}	0.4	1.0	0.7	-			
θ	1^{st}	0.4	1.0	0.7	-			
ψ	1^{st}	0.4	1.0	0.7	-			

Table 10 Experiment control loading settings.

Pilot input	Stiffness		Motion space	
Longitudinal stick	5	N/deg	±18	deg
Lateral stick	2	N/deg	±18	deg
Pedal deflection	2100	N/m	± 8	cm

between the systems. The pilot was asked for their opinion on the handling qualities and controllability of the aircraft after every maneuver, yielding (subjective) feedback. Finally, the simulation variables such as the aircraft state vector, control surface deflections and pilot control inputs were logged throughout the entire experiment. These data were later used to assess mismatches between analytical and experimental findings and to validate pilot comments on the aircraft dynamics.

Processing pilot feedback
The pilot feedback after every tested maneuver provided a large set of comments. To aggregate the comments of over 200 maneuvers, a set of defined keywords was used to comprise each comment into one or multiple keywords. By reducing the amount of describing keywords to eventually 26, a trend analysis could be performed. The keyword occurrence was set out against the different independent variables of the simulations. This yielded the opportunity to obtain between-pilot trends for distinct flight conditions, flight control systems, maneuvers or combinations of these.

IV. Results

A. Bare-Airframe Handling Quality Analysis Results

1. Analytical assessment results
The analytical assessment of the handling qualities of the bare-airframe Flying-V yielded requirement compliance for tested combinations of flight conditions, aircraft center of gravity locations, flight control system implementations and engine settings with the five different handling quality requirements. Table 11 shows an overview of this requirement compliance, with the maneuvers which failed to comply with the requirements shown as critical conditions with critical center of gravity locations. For the Dutch Roll Stability requirement, Figure 5 shows the obtained Dutch Roll damping and frequency parameters plotted against the MIL-HDBK-1797 handling quality requirement levels. Level III is required for compliance, Level I is desired. It should be noted that all tested conditions failed requirement compliance, except the cruise flight condition with aft center of gravity. Furthermore, Table 20 in the appendix of this paper shows the required control surface deflections for the critical requirement conditions. The control surface deflections larger than the set limits are indicated in red.

Table 11 Overview of the analytically assessed requirement compliance of the bare-airframe Flying-V.

Requirement	Compliance	Critical Condition(s)	Critical CG
DR	Failed	APP, TO, CR	Forward, Aft
CTC	Failed	APP AEO	Forward
TTB	Failed	APP AEO	Forward, Aft
OEI-T	Failed	APP	Forward
SHS	Failed	APP AEO & OEI	Forward, Aft
		TO AEO & OEI	Forward, Aft

2. Piloted assessment results
From the piloted assessment, the requirement compliance with each tested maneuver was obtained. As a validation of the analytical assessment, the experimental requirement compliance was compared to the analytically hypothesized requirement compliance. 52 out of the 56 maneuvers were validated positively, which can be stated the vast majority. The maneuvers with a mismatch to the hypothesized outcome are shown in Table 12.

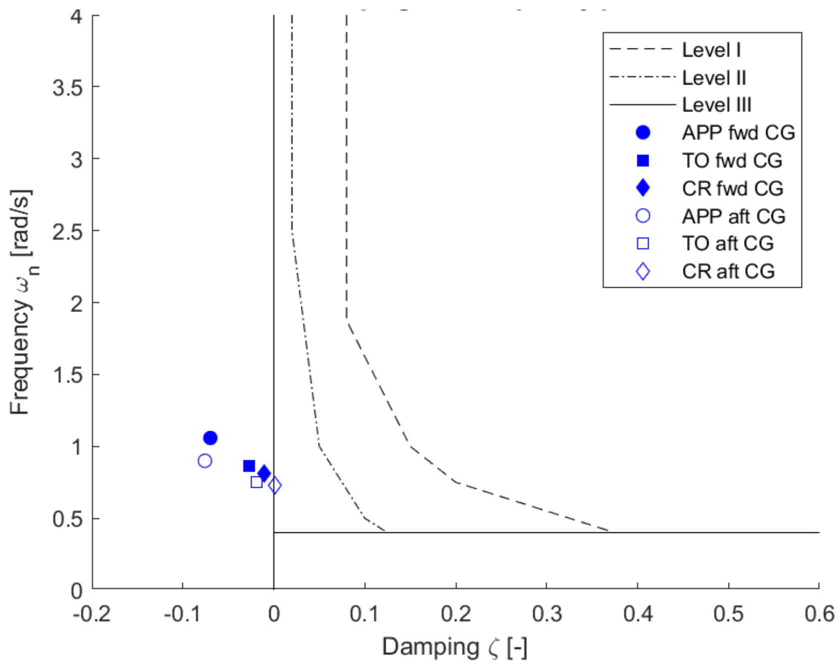


Fig. 5 Dutch Roll parameters of bare-airframe analytical handling quality analysis.

Table 12 Bare-airframe experimental analysis, mismatches with analytical assessment.

Requirement	Predicted Compliance	Experimental Compliance	Condition	CG	Pilot(s)
CTC	Passed	Failed	CR	aft	P3, P4
TTB	Passed	Failed	CR	aft	P3
SHS	Passed	Failed	CR	aft	P3

From the feedback retrieved from the pilots after each experiment run, several trends were obtained regarding the bare-airframe aircraft:

1) Control of the bare-airframe Flying-V was found difficult and inadequate when using conventional control allocation.
2) Insufficient pitch control authority was found available in approach conditions.
3) The Dutch Roll Stability was found unstable in approach flight conditions, but controllable in take-off and cruise flight conditions.
4) Using the rudder pedals to counteract the Dutch Roll eigenmode was found difficult and counter-intuitive.
5) Inadvertent excitation of the Dutch Roll eigenmode interfered with performing other maneuvers.
6) The roll control authority was at times found insufficient, mainly during the Time to Bank and Steady Heading Sideslip maneuvers.
7) With the Steady Heading Sideslip maneuver, the roll control authority was found insufficient to keep the aircraft wings level.
8) The thrust effect was found unconventional, specifically the low thrust value required in trim and high value required for acceleration of the aircraft.

The maneuvers with a mismatch between the analytically hypothesized result and experimental result, shown in Table 12, were further assessed. Whereas requirement compliance was expected, all failed to comply. The logged simulation data of each of these runs were assessed: comparing (between-pilots) passed versus failed experiment runs showed the failed runs to have larger oscillations in aircraft attitude, preventing target-state margin maintainability. Next, due to the pilot comments on the Dutch Roll eigenmode interference with other maneuvers, the Dutch Roll Mode Participation Factor was assessed and compared between the passed and (unexpectedly) failed runs. For the failed runs, the Dutch Roll showed to build up (more) throughout the run, which is expected to cause the increase in attitude oscillation and to prevent target state maintainability.

B. Prototype Flight Control System *SAS-2* Implementation Results

1. Analytical assessment results

The analytical assessment of the handling quality requirements was repeated with the prototype flight control system *SAS-2* implemented. This yielded the requirement compliance as shown in Table 13. Figure 6 shows the Dutch Roll damping and frequency parameters with the flight control system implemented. Table 21 in the appendix of this paper shows the new required control surface deflections and thrust values to complete the maneuvers, for the same conditions as (previously) critical in the bare-airframe analysis, as were shown in Table 20. Additionally, a new critical condition is present in the Time to Bank (TTB) maneuver in take-off flight conditions. Again, the control surface deflections larger than the set limits are indicated in red.

Table 13 Overview of the analytically assessed requirement compliance with SAS-2 implemented.

Requirement	Predicted Compliance	Critical Condition(s)	Critical CG
DR	Failed	-	-
CTC	Passed	APP AEO	Forward
TTB	Passed	APP, TO	Forward, Aft
OEI-T	Passed	APP AEO	Forward
SHS	Passed	APP AEO, APP OEI	Forward, Aft

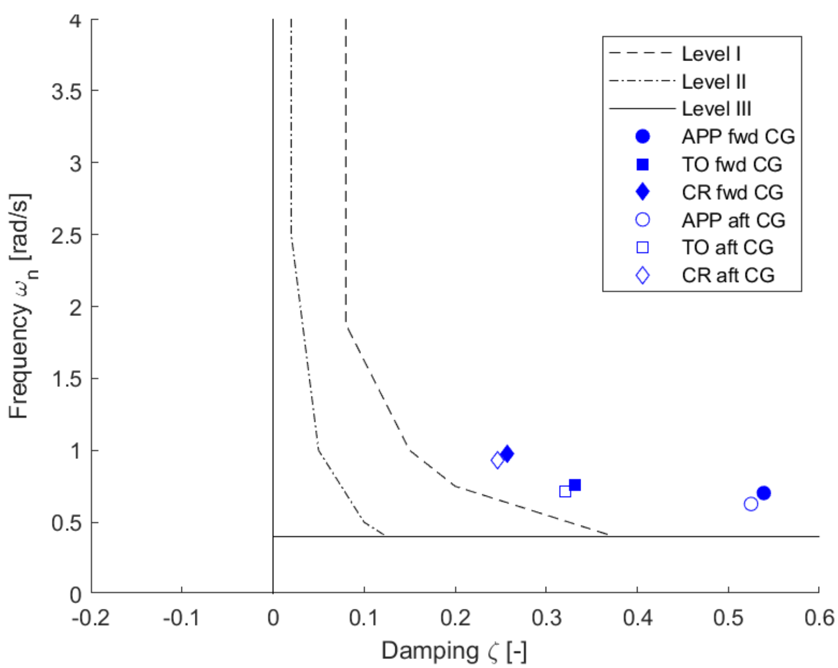


Fig. 6 Dutch Roll parameters of analytical handling quality assessment with SAS-2 implemented.

2. Piloted assessment results

The piloted assessment also was repeated with the prototype flight control system implemented, and the requirement compliance with each tested maneuver was obtained. Analogous to the bare-airframe analysis, the experimental requirement compliance was compared to the analytically hypothesized requirement compliance. The maneuvers with a mismatch to the hypothesized outcome are shown in Table 14.

From the feedback retrieved from the pilots after each experiment run, several trends were obtained regarding the aircraft with flight control system *SAS-2* implemented:

Table 14 Flight control system SAS-2 experimental analysis, mismatches with analytical assessment.

Requirement	Predicted Compliance	Experimental Compliance	Cond.	CG	Pilot
TTB	Failed	Passed	APP	fwd	P2, P3
TTB	Failed	Passed	TO	fwd	P1, P2
OEI-T	Failed	Passed	APP	fwd	P2, P3, P4

1) The implementation of the flight control system considerably improved the experienced handling qualities.
2) The Dutch Roll was positively damped and pleasant to fly, no pilot-compensation was required.
3) Insufficient pitch control authority was still reported in approach conditions.
4) When control surfaces saturated, the control allocation yielded adverse axis-coupling.
5) Lateral Pilot Induced Oscillations occurred when arresting the roll rate in the Time to Bank roll maneuver.
6) The lack of cross control required during a Steady Heading Sideslip maneuver was considered unconventional.
7) The flight control system was considered excessive in an engine failure situation, by keeping the pilot out of the loop.
8) Similar to the bare-airframe, the thrust effect was found unconventional, specifically the low thrust value required in trim and high value required for acceleration of the aircraft.

The maneuvers with a mismatch between the analytically hypothesized result and experimental result, shown in Table 14, required further assessment. All showed requirement compliance, whereas analytically no requirement compliance was hypothesized. Hence, the logged experiment data was further assessed.

The pilot inputs of the (unexpectedly) passed Time to Bank maneuvers showed use of the rudder pedals to roll the aircraft, both for the approach and take-off flight conditions. Since pedal use was not included in the analytical assessment of the roll maneuver, an increased roll capability was available to the pilots when using these rudder pedals. This is attributed to having caused the requirement compliance where non-compliance was hypothesized.

The One Engine Inoperative Trim maneuver in approach flight conditions was unexpectedly passed by multiple pilots. The logged aircraft state data showed the margins around the velocity and attitude targets were used to dynamically reach the 10 seconds required for maneuver requirement compliance. It is expected that further maintainability was not attainable with the set margins.

Of the pilot comments, the tendency for pilot induced oscillations while ending the Time to Bank roll maneuver was assessed further. The logged experiment data showed roll oscillations and lateral sidestick-input oscillations at the end of these maneuvers. Further assessment showed these oscillations to occur during control surface deflection-rate saturation. Since deflection-rate saturation is a known cause for (Category 2) pilot induced oscillations [42], it is attributed to have caused this tendency, and confirmed the trend in pilot comments.

C. Prototype Flight Control Systems *SAS-1* and *SAS-2 ext.* Implementation Results

Next to the results presented in the previous sections, two extra research questions were further explored. First, the effect of excluding the roll damping from the prototype flight control system, yielding *SAS-1*. Second, augmenting the control authority by extending the maximum allowed control surface deflections linearly, yielding *SAS-2 ext.*. The analytical assessment of these was of limited interest: the analysis with *SAS-1* yielded similar results to *SAS-2*, and no analytical assessment with *SAS-2 ext.* was performed. The extended control authority was expected to yield full requirement compliance, hence only required further piloted assessment. Table 15 shows the maneuvers with a mismatch to the hypothesized outcome for the piloted assessment with *SAS-1* and *SAS-2 ext.*. The unexpected pass of the Time to Bank maneuver is again likely to be caused by rudder-pedal use; the unexpected failed compliance with the Coordinated Turn Capability requirement is discussed later in this section.

Table 15 Flight control systems *SAS-1* & *SAS-2 Ext.* mismatches experimental with analytical assessment.

Requirement	Predicted Compliance	Experimental Compliance	Condition	CG	SAS	Pilot
TTB	Failed	Passed	TO	fwd	SAS-1	P1, P2
CTC	Passed	Failed	CR	aft	SAS-2 ext.	P3

The Cooper-Harper rating scale was used to assess the pilot-subjective handling qualities of using *SAS-1* and *SAS-2* to attain the adequate and desired performance as previously shown in Table 4. Table 16 shows the obtained

Cooper-Harper ratings by Pilots 1 and 2 for the maneuvers chosen to compare *SAS-1* and *SAS-2* on.

Table 16 Cooper-Harper rating results for *SAS-1* and *SAS-2* comparison.

Pilot	Condition	Engine	Requirement	SAS 1	SAS 2
P1	APP	OEI	SHS	8	10
P1	APP	AEO	TTB	8	10
P1	TO	OEI	SHS	1	5
P1	TO	OEI	TTB	2	3
P1	CR	OEI	SHS	1	1
P1	CR	AEO	TTB	2	1
P2	APP	OEI	SHS	7	10
P2	APP	AEO	TTB	10	9
P2	TO	OEI	SHS	2	2
P2	TO	OEI	TTB	5	5
P2	CR	OEI	SHS	3	2
P2	CR	AEO	TTB	5	5

Pilot feedback on the comparison of the aircraft with flight control system *SAS-1* and *SAS-2* yielded multiple distinctive comments. Amongst others, Pilot 2 commented that *SAS-1* required logical inputs, and had a pleasant cross-control mix of pedal and lateral stick control. Besides, the pilot noted the use of *SAS-2* to be unconventional and peculiar, since the roll damping reduces the lateral stick input required during, e.g., a sideslip maneuver. Pilot 1 commented similarly, by stating *SAS-1* was more predictable than *SAS-2*. To assess if the pilot comments favoring *SAS-1* can be confirmed statistically significant from the obtained Cooper-Harper ratings, a Related-Samples Wilcoxon Signed Rank Test was used. A difference in median of the Cooper-Harper ratings given to SAS-1 and SAS-2 was tested, yielding a statistic significance of a difference in median of 0.090, larger than the set significance level of 0.050 thus considered not statistically significant.

In order to assure that sufficient control authority was available for full requirement compliance with *SAS-2 ext.*, the new control surface deflection limits allowed for excess deflection with respect to the analytically obtained surface deflections required. Next, the actual deflections used by the pilots were obtained, to be used as an approximate figure for future control surface design in this flight condition. Table 17 shows the (pilot-averaged) maximum control surface deflections used per control surface, for each maneuver separately. All maximum control surface deflections occurred while performing the maneuvers in approach flight conditions.

Table 17 Pilot-averaged maximum control surface deflections used with *SAS-2 ext.*.

	Nominal limit	CTC	TTB	OEI-T	SHS
C1 [deg]	37.0	44.2	121.8	26.2	85.1
C2 [deg]	30.0	38.4	84.5	27.8	68.9
C3 [deg]	30.0	67.8	130.9	53.0	97.2
C4 [deg]	30.0	87.2	91.0	43.2	42.4
C5 [deg]	30.0	54.1	51.3	29.3	35.4
C6 [deg]	37.0	45.5	124.5	28.7	82.4

From the pilot feedback on flying the aircraft with *SAS-2 ext.*, it was obtained that the controls were found sufficient most often when compared to other configurations. Still, the pitch control authority in the Coordinated Turn Capability maneuver was found insufficient. Further research showed this to have occurred due to the gain tuning of the aircraft. While the control authority was extended by allowing increased maximum control servo deflections, the gain tuning was not altered to make full use of this new limit. Hence, the pitch control authority was found to be limited by the (input) gain tuning, and requirement compliance was found difficult to attain in approach flight conditions. This lack of pitch control authority is expected to have caused the failed requirement compliance of the Coordinated Turn Capability maneuver, shown in Table 15. Further pilot comments on *SAS-2 ext.* were analogous to those given on the stability and (unconventional) control of *SAS-2*.

V. Discussion

A. Bare-Airframe Handling Qualities

The bare-airframe handling quality analysis as presented in Section IV.A yields several results. First, the analytical assessment shows the control authority in pitch, roll, and yaw to be insufficient in approach flight conditions, and the control authority in roll to be insufficient in take-off flight conditions. The control deflections analytically found required to perform the critical maneuvers violate the set limits, to the largest extent in the approach flight conditions. In take-off flight conditions the control surface deflection limits were also violated, but only during the Steady Heading Sideslip maneuver, and only around the roll axis.

The analytically found lack of control authority was validated by the piloted-experiment results: the runs hypothesized as not possible due to a lack of control authority were not passed by the pilots. Moreover, the pilot feedback shows a trend regarding a lack of pitch control authority, and at times a lack of roll control authority. Similar as analytically found, the pitch control authority was mainly reported insufficient in the approach flight conditions. The at times stated insufficient roll control authority of the bare-airframe Flying-V was not limited to a single flight condition. It stood out most for the Steady Heading Sideslip maneuver in approach and take-off flight conditions, where the roll control authority was insufficient to keep the aircraft wings level at larger angles of sideslip. Contributing to this effect is the large sweep angle of the Flying-V, which yields a large roll moment when a sideslip angle occurs, i.e., possesses a large C_{l_β} [19]. This roll moment in sideslip was found too large to be compensated by the available roll control surfaces.

Next to the limited control authority, the analytical assessment showed mainly an unstable (and for one flight condition, marginally stable) Dutch Roll in the different flight conditions. Pilot feedback shows this to be of considerable influence on the experienced handling qualities of the aircraft. The Dutch Roll was stated to be unstable in approach, and although stated controllable in take-off and cruise, it was found to interfere with the performance in numerous maneuvers throughout the different flight conditions. The Dutch Roll was found to be difficult to compensate with the rudder pedals and frequently showed a build-up throughout a maneuver, leading to lateral-directional oscillations preventing state maintainability. Suppression of the Dutch Roll with lateral stick input was reported to be easier than through the pedals.

The combination of lack of control authority at low speeds, and unstable, difficult to compensate Dutch Roll is expected to yield the pilot-declared difficult and inadequate flight characteristics of the bare-airframe Flying-V.

B. Flight Control System implementation effect

The implementation of the prototype flight control system, consisting of the adapted control allocation and stability augmentation system *SAS-2*, considerably improved the handling qualities, bringing them to an acceptable level.

The adapted control allocation showed by analytical assessment to increase overall control effectiveness, and decreased the required maximum control surface deflection in most maneuvers. This decrease was sufficient to eliminate the take-off flight conditions (M 0.3) as critical. The increase in control effectiveness however was insufficient for requirement compliance in approach flight conditions (M 0.2). The analytical findings were validated with the results of the experimental analysis and were confirmed by trends in the pilot feedback. Pilot feedback confirmed the increase in overall control effectiveness, but also confirmed the pitch axis control authority to still be insufficient in the slow approach flight conditions. The latter to the extent of negatively influencing the lateral-directional requirement compliance in these flight conditions.

Despite the positive effect on overall control effectiveness, the adapted control allocation still yielded adverse axis-coupling when control surfaces saturated. When pitch control surfaces saturated and a roll input was given simultaneously, the control allocation cannibalized the pitching moment to obtain a rolling moment. This yielded nose-down behavior when rolling while in pitch saturation, which occurred most in approach flight conditions. Pilot feedback showed this to severely influence the experienced handling qualities of the aircraft in approach flight conditions.

The Dutch Roll damping was increased by the implementation of the stability augmentation system, which can be seen when comparing Figure 5 and Figure 6. This analytically found improvement was validated in the piloted experiment. The pilots confirmed the Dutch Roll to be positively damped and pleasant to fly. Moreover, no Dutch Roll eigenmode interference with other maneuvers was reported.

The implementation of the stability augmentation system showed to not only influence the Dutch Roll characteristics of the aircraft. Pilot feedback yielded multiple trends on unconventional behavior of the aircraft with flight control system *SAS-2*. First, Pilot Induced Oscillations occurred when the roll maneuver of the Time to Bank was arrested, and were determined to be caused by servo rate-limit saturation. Second, the stability augmentation led to only small deviations in attitude where pilots expected larger compensation to be necessary. Mainly during a Steady Heading Sideslip, where lateral stick deflection is expected to be necessary to compensate for the rudder induced roll moment. Similarly, during an engine failure situation, tested in the One Engine Inoperative Trim maneuver, only very limited lateral-directional attitude changes occurred due to compensation of the stability augmentation system. This yielded a trend in feedback on the pilot feeling kept out of the loop in an engine failure situation, which was deemed unsafe.

The positive effects of the control allocation and stability augmentation system are expected to have caused the trend in pilot feedback of the flight control system considerably improving the handling qualities compared to the bare airframe. This despite the prototype flight control system introducing side-effects, such as the adverse axis-coupling when control surfaces saturated, a tendency for pilot induced oscillations and unconventional controls required.

C. Roll Damping Experiment

As discussed in Section IV.C, pilot feedback favored *SAS-1* (without artificial roll damping) over *SAS-2*. Since the effect on the handling qualities of including a roll damper was found pilot subjective in previous research [9], it was decided a difference should be proven statistically significant instead of only be based on verbal pilot feedback. SAS-1 was expected to yield better (i.e., lower) Cooper-Harper ratings. Since the Cooper-Harper rating scale yields ordinal data, a difference in median should be proven significant. The Related-Samples Wilcoxon Signed Rank Test was used to compare the medians of the Cooper-Harper ratings given to SAS-1 and SAS-2. The test statistic significance was found to be larger than the set significance level. Hence, for this experiment no statistically significant difference in median could be used to confirm the pilot comments, and no conclusion on the use of the roll damper is drawn.

D. Extended Control Authority Experiment

An experimental analysis with (augmented) extended control authority was performed, as introduced in Section III.C.3. It was expected that by extending the control authority sufficiently, full requirement compliance would be attained by each pilot. As shown in Table 15, it was not attained by one pilot out of four. The pitch control authority was found to be limited by the (input) gain tuning, and requirement compliance was found difficult to be attained in approach flight conditions.

Generally, augmenting the increased control authority allowed for requirement compliance in flight conditions where previous configurations did not. As introduced in Section IV.C, the new control surface deflection limits allowed for excess deflection with respect to the analytically obtained surface deflections required. The deflections used by the pilots can be interpreted as approximation for future control surface design, when assuming the pilots used approximately the amount of control surface deflection required for favorable handling qualities. As shown in Table 17, the maximum rudder deflection was up to 124.5 degrees, more than three times the current limit set. The maximum elevon deflection was up to 130.9 degrees, more than four times the current limit set. This shows a large challenge for future control surface design of the Flying-V, since the control effectiveness, maximum control surface deflections or both have to be drastically increased for requirement compliance at the tested flight conditions. Increasing the landing speed to avoid the problematic 0.2 M flight condition would seem to be a more feasible solution.

E. Remaining Challenges in Handling Qualities for the Flying-V

As discussed in Section V.A and Section V.B, implementing the prototype flight control system with the adapted control allocation and stability augmentation system showed to be a first improvement of the handling qualities of the Flying-V. Nevertheless, a challenge remains in improving the handling qualities of the Flying-V further, in order to obtain compliance with the handling quality requirements for conventional aircraft.

The analytical and experimental assessment of the Flying-V with the prototype flight control system implemented showed the handling qualities to still be insufficient at low speed. Foremost, even after adapting the control allocation, the control authority in pitch was insufficient for requirement compliance. Although the study focused on the lateral-directional handling qualities of the Flying-V, the lack of pitch authority at low speeds severely influenced the lateral-directional requirement compliance. Hence, if the approach velocity tested will be part of the Flying-V flight envelope, it is recommended to redesign the control surfaces to allow for more control authority in pitch.

Next to the pitch control authority, the roll control authority showed to, mainly, be insufficient for requirement compliance in sideslip maneuvers in approach flight conditions. Analogous to the pitch control authority, servo saturation severely influenced the pilot-experienced handling qualities, and it is recommended to assess redesigning the control surfaces to allow for more control authority in roll and yaw.

The control authority around all axes could benefit from introducing new control surfaces, or from adapting the six control surfaces of the current design. New control surfaces could, e.g., consist of spoilers asymmetrically dumping lift for roll control [43]. The control surfaces of the current design could be adapted to unconventional control surface designs, such as split flaps or split rudders for roll or yaw control [44].

Next to the control surface design changes, it is recommended to re-assess the low speed handling qualities at velocities between the tested 0.2 and 0.3 Mach. Since the analysis showed increasing speed to be beneficial to the handling qualities, an approach speed with sufficient control authority could be found. If this speed is a feasible landing speed, no or fewer design changes would be required if the flight envelope of the Flying-V is altered.

Finally, it is recommended to further develop the prototype flight control system. Amongst others, the effect of including or excluding a roll damper requires further research before the implementation can be decided on. Moreover, the simple feedback systems currently tested should be enhanced further before being able to comply with current fly-by-wire system standards. Amongst others, attitude hold, auto-throttle and turn coordination were noted to be missing by multiple pilots performing the experiment. Besides, the gain tuning of a stability augmentation system can yield pilot subjective results, such as for the (highly) augmented prototype flight control system, *SAS-2*, being at times stated to be excessive.

F. Reflection on Analytical and Experimental Analysis

Reflecting on the analytical and experimental analysis yields remarks on modeling the aircraft, and remarks on the difference between the analytical and experimental analysis. Two remarks can be made on the aerodynamic model used for the analysis. First, the control deflection force and moment contributions had to be linearly extrapolated based on only one deflection to force or moment output slope. A higher fidelity control deflection model would be preferred for future research, since non-linear force and moment outputs are expected from a linearly increasing control surface deflection. Second, the VLM method only simulated lift-induced drag, thus no parasitic (i.e., skin friction) drag was modeled. This yields a low drag in trim, and reduces the fidelity of engine-modeling.

Next to the modeling remarks, remarks can be made on differences between the analytical and experimental analysis. First, it was found that the analytical state-attainability did not always correctly predict the experimental outcome: reaching and maintaining a state in a piloted experiment can differ from the analytical state-attainability. Although the vast majority of the analytically found hypotheses were experimentally validated, factors such as interfering Dutch Roll eigenmotion and operating at the edge of the aircraft control authority did at times result in insufficient handling qualities for requirement compliance. Second, differences in analytically hypothesized and experimentally obtained requirement compliance occurred due to the set state-limit margins on the flight conditions in the experiment. Whereas the analytical assessment uses exact flight conditions to assess state-attainability, the piloted experiment allowed for deviations around the flight conditions to increase the feasibility of performing the maneuvers. This led to pilots using the margin around the target state to dynamically comply with a trim-state requirement.

VI. Conclusion

Analytical and experimental assessment showed the lateral-directional handling qualities of the bare-airframe Flying-V model studied to be insufficient for compliance with set requirements, due to a lack of pitch, roll and yaw control authority in low-speed flight conditions, and an insufficiently stable Dutch Roll eigenmode. The Dutch Roll eigenmode not only failed to comply with the Dutch Roll Stability requirement assessed, but also interfered with piloted requirement compliance of other maneuvers tested. The prototype flight control system, consisting of an adapted control allocation and stability augmentation system, showed to both analytically and experimentally improve the control authority, stability, and handling qualities of the Flying-V considerably. While the effect on the lateral-directional stability was sufficient for compliance with the Dutch Roll Stability requirement, the control authority could not be sufficiently increased for compliance with all manoeuvrability requirements and flight conditions. Thus, a challenge remains in improving the handling qualities of the Flying-V at low speeds. If the 0.2 M flight condition is to remain part of the flight envelope, a four-fold increase in control surface authority would be called for. In that light, an increase in approach and landing speed towards the tested 0.3 M speed would seem a more feasible option.

Appendix

Table 18 Input variables and ranges of the Airbus Flying-V VLM model.

Variable	Description	Range	Unit
CG	Centre of Gravity	[45, 51.5, 57.5]	%MAC
M	A/C velocity in Mach	[0.2, 0.225, 0.25, 0.275, 0.3, 0.85]	-
α	Angle of Attack	[-5, 0, 5, 10, 12.5, 15, 16.5, 18, 20]	Degrees
β	Sideslip Angle	[-1, 0, 1]	Degrees
p^*	Normalized roll rate	[-1, 0, 1]	Radians
q^*	Normalized pitch rate	[-1, 0, 1]	Radians
r^*	Normalized yaw rate	[-1, 0, 1]	Radians
δ_{c1}	Deflection of left rudder	[-1, 0, 1]	Degrees
δ_{c2}	Deflection of left outboard elevon	[-1, 0, 1]	Degrees
δ_{c3}	Deflection of left inboard elevon	[-1, 0, 1]	Degrees
δ_{c4}	Deflection of right inboard elevon	[-1, 0, 1]	Degrees
δ_{c5}	Deflection of right outboard elevon	[-1, 0, 1]	Degrees
δ_{c6}	Deflection of right rudder	[-1, 0, 1]	Degrees

Table 19 Gain tuning of stability augmentation systems SAS-1 and SAS-2.

	SAS-1			SAS-2		
	Approach	Take-Off	Cruise	Approach	Take-Off	Cruise
K_r	-1000	-400	-200	-700	-200	-150
K_V	10	2	1	5	2	1
$K_{V_{input}}$	40	31.2	31.2	40	31.2	31.2
K_p	n/a	n/a	n/a	2000	900	400
$K_{p_{input}}$	30	30	30	0.3	0.3	0.3
K_q	-100	-55	-65	-100	-55	-65
$K_{q_{input}}$	0.2	0.2	0.2	0.2	0.2	0.2

Table 20 Trimmed control outputs of analytically critical requirements of bare-airframe Flying-V. [18]

Maneuver	CTC	TTB		OEI-T	SHS						
Condition	APP	APP		APP	APP				TO		
Engine	AEO	AEO		OEI	AEO		OEI		AEO	OEI	
CG	fwd	fwd	aft	fwd	fwd	aft	fwd	aft	fwd	fwd	aft
C1 [deg]	7.0	23.1	**90.6**	26.7	**-66.7**	**-41.5**	**-51.7**	-24.8	-10.9	-7.8	-5.8
C2 [deg]	-17.3	**-90.4**	**-99.5**	5.0	**-78.5**	**-71.3**	**-80.9**	**-74.0**	**-33.2**	**-33.7**	**-30.1**
C3 [deg]	**-52.9**	**-51.6**	-15.1	**-41.8**	**-36.5**	-7.5	**-36.6**	-7.5	-15.4	-15.4	-1.4
C4 [deg]	**-52.9**	**-51.6**	-15.1	**-41.8**	**-36.5**	-7.5	**-36.6**	-7.5	-15.4	-15.4	-1.4
C5 [deg]	17.3	**90.4**	**99.5**	-5.0	**78.5**	**71.3**	**80.9**	**74.0**	**33.2**	**33.7**	**30.1**
C6 [deg]	-7.0	-23.1	**-90.6**	-26.7	**66.7**	**41.5**	**51.7**	24.8	10.9	7.8	5.8
T1 [kN]	108.2	64.1	79.7	113.0	50.0	53.1	98.1	105.8	27.8	55.6	60.9
T2 [kN]	108.2	64.1	79.7	0.0	50.0	53.1	0.0	0.0	27.8	0.0	0.0

Table 21 Trimmed control outputs of previous and new critical maneuvers, SAS-2 analytical handling quality assessment. [18]

Maneuver	CTC	TTB			OEI-T	SHS						
Condition	APP	APP		TO	APP	APP				TO		
Engine	AEO	AEO		OEI	OEI	AEO		OEI		AEO	OEI	
CG	fwd	fwd	aft	fwd	fwd	fwd	aft	fwd	aft	fwd	fwd	aft
C1 [deg]	4.0	**79.6**	**81.0**	19.8	4.9	**-68.3**	**-45.2**	**-52.8**	-28.7	-14.3	-11.1	-8.5
C2 [deg]	-26.2	**-62.6**	**-41.7**	-24.0	-20.8	**-50.0**	**-31.7**	**-47.9**	-29.4	-18.3	-17.9	-10.5
C3 [deg]	**-46.0**	**-101**	**-72.1**	**-33.1**	**-37.2**	**-54.0**	**-32.9**	**-57.1**	**-36.1**	-24.3	-24.9	-13.6
C4 [deg]	-28.4	**41.5**	**58.8**	-13.3	-21.8	2.4	22.3	5.4	25.5	2.2	2.8	11.6
C5 [deg]	-18.5	26.2	**32.4**	-11.8	-14.6	19.0	25.3	16.9	23.0	5.0	4.6	9.3
C6 [deg]	-7.4	**-82.4**	**-81.6**	-20.4	-7.6	**65.9**	**44.7**	**50.5**	28.2	13.3	10.1	8.4
T1 [kN]	113	61.0	67.0	74.9	122	52.3	53.9	105	107	29.6	59.1	61.8
T2 [kN]	113	61.0	67.0	0.0	0.0	52.3	53.9	0.0	0.0	29.6	0.0	0.0

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