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Early-Stage Assessment of a Flexible Aircraft Simulation Framework in a Pilot-in-the-Loop Environment

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Accurate prediction of the interactions between aeroelastic effects, flight control, and flight dynamics is essential for evaluating the handling qualities and safety of future aircraft concepts. This paper reports on the development of an advanced modelling and simulation framework for assessing the impact of airframe flexibility on flight dynamics within a real-time pilot-in-the-loop environment. As part of this, a series of shakedown trials were conducted using a model of a Saab 340B to test system integration, pilot interaction, and dynamic response through open-loop manoeuvres. These tests were supported by subjective fidelity ratings using the Simulation Fidelity Rating (SFR) scale to evaluate the framework's readiness for formal handling qualities assessments. Pilot feedback confirmed the general suitability for such evaluations, while also identifying perceptual and modelling limitations. This research demonstrates the feasibility and value of integrating multidisciplinary modelling tools with piloted simulation and establishes a foundation for the forthcoming handling qualities evaluation campaign.

I. Introduction

To mitigate the environmental impact of the aviation industry, aircraft designers are focusing on developing new technologies to create novel and more efficient aircraft configurations. This shift has led to a more integrated approach to designing the various components of an aircraft, enabling the development of advanced multidisciplinary design tools and expertise necessary to attain revolutionary configurations. Consequently, aircraft design disciplines that were traditionally treated independently, such as aeroelasticity and flight dynamics, must now be integrated. Concepts such as high aspect ratio wings (HARWs) improve aerodynamic efficiency and reduce aircraft weight through the use of new lightweight materials. However, the increased structural flexibility associated with these configurations introduces significant interactions between flight dynamics and aeroelasticity. Additionally, the interaction between the flight control system, aeroelastic system, and the flexible body motion of the aircraft can result in degraded handling qualities, excessive actuator control, and fatigue issues. The literature[1–4] highlights the significant impact on handling qualities of large transport aircraft with highly flexible wings when compared to rigid aircraft models. Identifying these interactions is crucial for enabling future pilots to anticipate the behavior of novel aircraft, which may not be fully understood or observable through purely numerical metrics.

Anticipating these interactions early in the aircraft design process is becoming increasingly critical to avoid costly redesigns at later stages. However, this design phase is typically characterised by limited availability of experimental data, while reliance on empirical approximations may fail to capture the complex behaviour of novel configurations. Consequently, accurate modelling and simulation environments are essential. These environments must be capable of capturing coupled aeroelastic and flight dynamic interactions, while also supporting real-time execution for pilot-in-the-loop evaluations and enabling the multidisciplinary analyses required in current design workflows.

The Cranfield Accelerated Aeroplane Loads Model[5–7] (CA^{2}LM) is a physics-based simulation framework developed to address this need. It enables aeroelastic flight dynamic modelling of flexible aircraft through the integration of structural dynamics, unsteady aerodynamics, and flight control modeling. This comprehensive modeling and simulation framework facilitates an integrated multidisciplinary approach enables the assessment of handling qualities, the development of flight control systems, and pilot-in-the-loop simulations. This capability has been envisioned in

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such way that CA^{2}LM will be able to contribute to a broader rapid-design environment for accelerated design flow and innovation by incorporating stability and handling qualities design considerations back into the design workflow.

The aim of this paper is to present the advancements on the integration of CA^{2}LM with Cranfield University's EFS500 engineering flight simulator to provide a unified simulation environment capable of supporting real-time, pilot-driven evaluations. More specifically, it presents the first stage in a broader research effort aimed at validating the fidelity of handling qualities assessments of flexible aircraft configurations through the proposed integrated capability. As the full simulation campaign is still in development, this paper documents a set of initial shakedown trials conducted to assess the readiness of the environment, the functionality of the interface, and the overall suitability of the setup for handling qualities assessment.

These shakedown trials involved a series of manoeuvres flown by a test pilot using an aircraft model based on the National Flying Laboratory Centre's (NFLC) Saab 340B. The primary objective was to test the methodology and identify limitations in the setup, including cueing fidelity, input device calibration, and pilot workload. This configuration was selected due to the availability of a comprehensive flight test dataset NFLC, enabling validation of the simulation model and overall integration approach. The trials also explored the use of a proposed Simulation Fidelity Rating (SFR) scale[8] as a means of capturing subjective assessments of simulation fidelity during early integration stages.

This paper begins with a brief overview of the physics-based methods used to integrate aerodynamics, structural dynamics, and flexible equations of motion within a unified modular simulation framework, and introduces its real-time simulation capabilities and integration architecture. This is followed by a description of the experimental setup and a presentation of the outcomes of the shakedown trials, including detailed observations on pilot feedback and system performance. The use of the SFR scale for subjective fidelity evaluation is also discussed, along with its applicability to fixed-wing piloted simulations. Finally, the implications of the findings for future fidelity and handling qualities assessments are discussed, and the next steps in the ongoing research programme are outlined.

II. Theoretical Background

CA^{2}LM is a novel numerical simulation environment developed in MATLAB/Simulink, designed for modelling aeroelastic aircraft and providing real-time analysis of aeroservoelasticity and flight dynamics. This framework serves as a reduced-fidelity, physics-based simulation tool that predicts the impact of airframe flexibility on handling qualities. Figure 1 illustrates the overall architecture of the framework, highlighting the essential components required for constructing a simulation environment specifically designed for flight dynamics modelling of flexible aircraft.

A. Global Overview of CA^{2}LM

CA^{2}LM solves a set of extended six-degree-of-freedom equations of motion that incorporate not only the rigid-body translational and rotational dynamics, but also the contributions from structural flexibility and unsteady aerodynamic loads. These equations are formulated to dynamically couple the aircraft's motion with modal structural deformations and spanwise-resolved aerodynamic forces, enabling time-accurate prediction of aeroelastic effects within a unified simulation framework. This method overcomes the limitations of traditional aerodynamic derivative-based formulations, which are typically limited to rigid-body assumptions and cannot adequately capture the complex interactions between structural deformation and aerodynamic flow dynamics. The equations are expressed about the body-axis centre rather than the instantaneous centre of gravity (CG). This approach avoids the nonlinearities that arise in flexible aircraft, where modal deformation leads to continuous shifts in mass distribution and CG location. With this approach, CA^{2}LM ensures consistent coupling between structural modes and flight dynamics, and simplifies the treatment of inertial and aerodynamic force integrations across the flexible structure. The ability to resolve these coupled effects in real time is particularly relevant for piloted simulation, where accurate prediction of the aircraft dynamic response is essential for assessing simulation fidelity.

Local unsteady lift and pitching moment coefficients are calculated using indicial aerodynamic theory, incorporating both circulatory and non-circulatory contributions. This methodology allows capture of the unsteady buildup of lift due to changes in angle of attack and airspeed as state-space representation. The framework employs a general two-pole approximation of the Wagner function to model this behaviour, corrected for compressibility effects using the Prandtl-Glauert coefficient[5, 9, 10]. This approach, enables accurate representation of aerodynamic forces during structural deformations and dynamic flight conditions, crucial for flexible aircraft simulation. An extended lifting line theory is implemented[11, 12] to resolve of the three-dimensional lift, induced drag and pitching moment distributions by incorporating the mutual interference between spanwise stations and allowing for arbitrary wing planforms, sweep angles, and twist distributions.

Aerodynamic and gravitational forces are mapped to modal forces through a modal transformation matrix, with displacements, velocities, and accelerations determined via structural equations of motion following a linear beam-element formulation. The structure modal peoperties can be initialised using an interfaced external solver of varying fidelities[13, 14], depending on the availability and format of the mass data. With this, CA^{2}LM assumes linearly varying beam properties and is valid primarily for small deformations, typically wingtip deflections of less than 10% of the wing semi-span. Additionally, CA^{2}LM incorporates atmospheric disturbance models to simulate gusts and turbulence. Flight control dynamics and actuation models for various surfaces are integrated to enable exploration of optimal control strategies and load alleviation laws. Further details on the theoretical foundations underlying the framework are available in references[4–6].

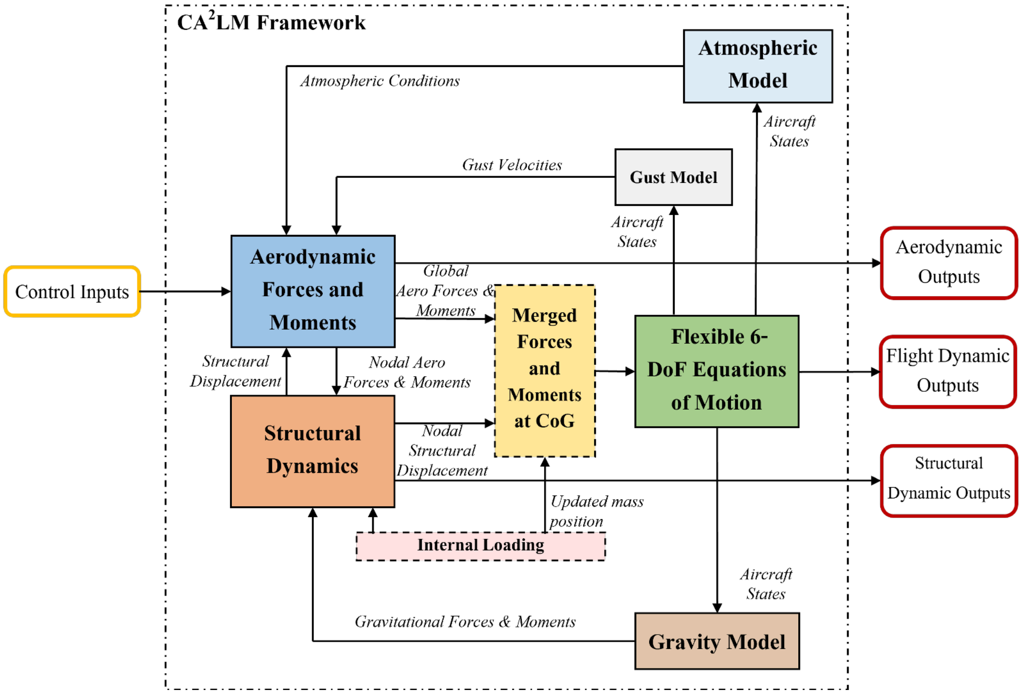

Fig. 1 General architectural diagram of the CA^{2}LM framework.

B. Flight simulation framework

The demand for real-time simulation of flexible aircraft stems from concerns that low-frequency aeroelastic modes may interact with rigid-body modes, such as the aircraft's short-period pitch oscillation, leading to undesirable aircraft-pilot coupling and diminished handling qualities. Moreover, emerging concepts for future aircraft, such as blended-wing-body configurations, necessitate comprehensive stability and control analysis early in the design phase. Consequently, a real-time pilot-in-the-loop simulation environment is imperative to detect and address handling qualities issues.

CA^{2}LM has been integrated with Cranfield University's EFS500[15, 16], a single-pilot engineering flight simulator, shown in Figure 2, to enable pilot-in-the-loop simulation[4, 17–19]. This integration provides a platform for the pilot to interact with the CA^{2}LM framework, enabling to capture subjective qualitative feedback on real-time simulation-based investigations into handling qualities of flexible aircraft.

The development of such a simulation environment necessitates specialised hardware to accelerate the model and achieve real-time performance suitable for pilot-in-the-loop operation. The EFS500 hardware includes a cockpit environment, featuring a generic single-seat cockpit layout, shown in Figure 2, equipped with an artificial loading system, enabling force feedback response to the central stick and rudder pedals. It includes two touchscreen displays for the primary flight display (PFD) and another for the electronic horizontal situation indicator (EHSI), illustrated in Figure 3. The legacy computer system comprises seven units, each dedicated to specific functions, including running

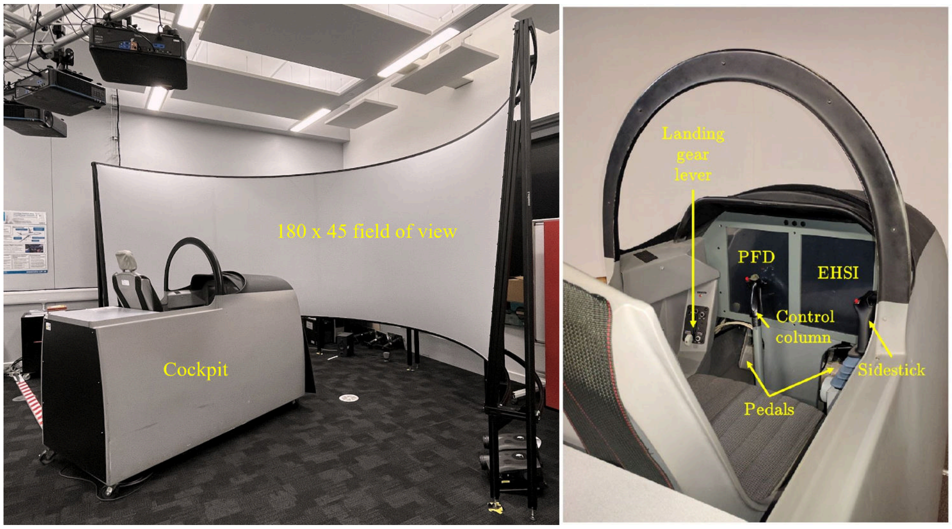

Fig. 2 Overall setup (left) and cockpit environment (right) of the EFS500 flight simulator.

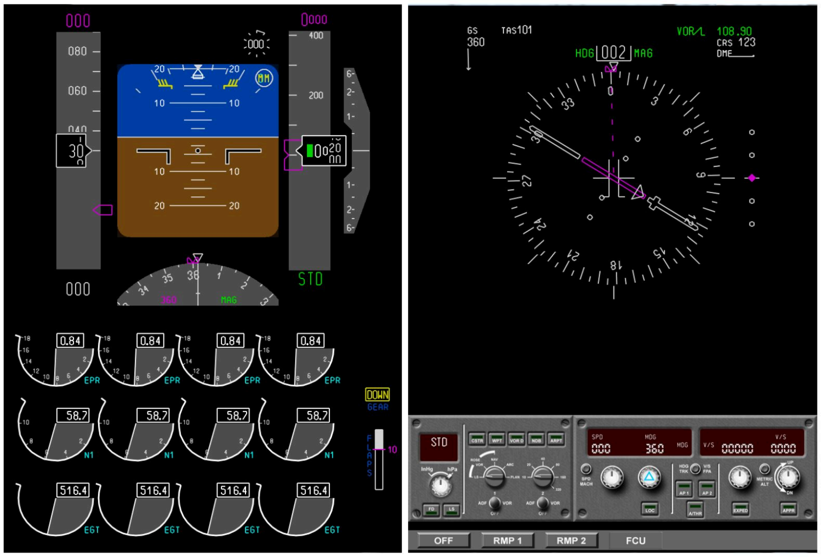

Fig. 3 PFD and EHSI displays in EFS500 flight simulator cockpit for a B747-type aircraft.

the flight dynamics model, managing cockpit displays, avionics, the instructor operating station, and image generation. An I/O system computer, based on a Raspberry Pi, serves as the interface between the simulator's analogue and digital control inputs from the cockpit and the computer system.

Furthermore, an additional development computer provides an interface between the simulator and CA^{2}LM by deploying the MATLAB/Simulink model through a real-time target machine. In this setup, a Speedgoat performance real-time target machine is employed, which enables robust execution of high-fidelity simulations with low latency, ensuring accurate and synchronised communication between the simulator and the CA^{2}LM framework at the EFS native 50Hz rate.

All computers within the simulator communicate via UDP over a designated local network, with a secondary local network reserved for the integration of the Simulink real-time workflow. Figure 4 shows the general architectural diagram of the real-time interface via hardware and network communication between CA^{2}LM and the EFS500.

Additionally, the EFS500 is equipped with a sound generation system, capable of generating environmental and warning sounds, as well as an image generation system, which comprises three projectors and a conical screen, providing a 180° × 45° field of view as shown in Figure 2.

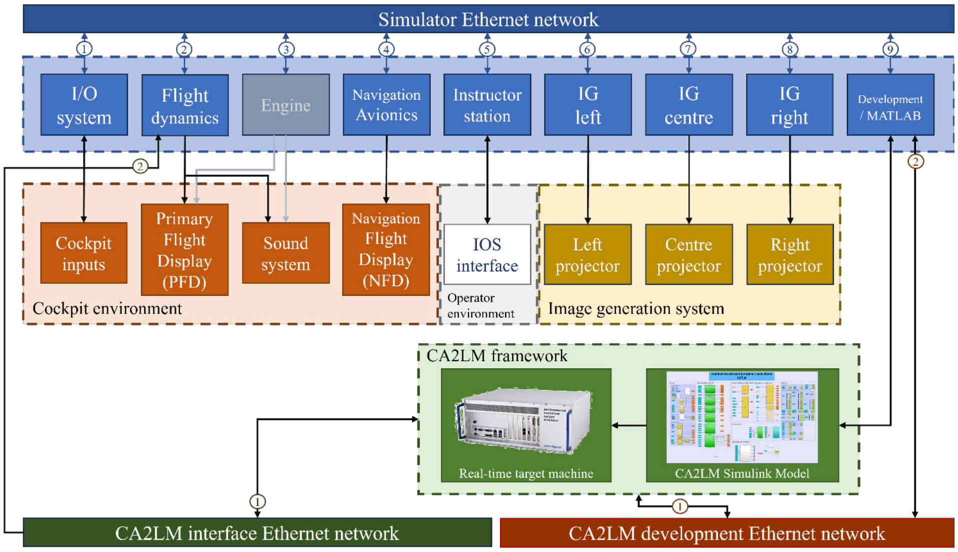

Fig. 4 General architectural diagram of the real-time interface between CA^{2}LM and the EFS500.

The simulator operates on custom-coded software, primarily developed in the C programming language, distributed across the multiple computers to facilitate straightforward modifications to individual applications. The image generation machines utilise C++ to interface with OpenSceneGraph graphics library. All C and C++ applications across the nodes are compiled using the 'gcc' compiler. Consistent with the modular design philosophy of CA^{2}LM, the EFS500 software is architected for flexibility, where modifications to the aircraft model are confined to a single node to ensure that changes do not disrupt the functionality of other systems.

III. Trial Design

A shakedown trial was conducted as a preliminary evaluation of this integrated piloted-simulation framework, with the objective of evaluating model fidelity, system performance, and pilot observations, and therefore to establish the readiness of the system for handling qualities assessments. This experimental approach focused on a set of longitudinal manoeuvres selected to demonstrate key dynamic characteristics of the model, while maintaining consistency with available flight test data from the Saab 340B aircraft.

The pilot was briefed on a series of planned tasks designed to be open-loop in nature, in which the pilot was instructed to apply control inputs and observe the aircraft response, without tracking tasks with strict accuracy requirements or following strict performance criteria. This allowed to minimise pilot workload and to reduce the influence of control compensation, thereby allowing a clearer observation of the aircraft's intrinsic dynamic response characteristics.

Three manoeuvres were performed across the trials:

- Short-period pitching oscillation (SPPO) response, characterised by small-amplitude pitch stick doublets.
- Long-period (Phugoid) response, initiated through sustained pitch attitude changes.
- Longitudinal static stability (LSS) assessment, involving controls-fixed trimmed flight at varying speeds.

Each of these manoeuvres was executed under five distinct mass configurations, which involved variations in both passenger loading and fuel quantity. The test sequence was structured such that each mass configuration was flown across all manoeuvres, rather than holding a fixed manoeuvre and cycling through configurations. This approach facilitated a more realistic and progressive pilot workload and enabled qualitative comparisons of aircraft response across different loading cases. All manoeuvres were initiated from a trimmed flight condition at speeds close to 160 KIAS at various altitudes, with the throttle input communicated to the pilot prior to each run to ensure that the thrust matched the trim setting. These conditions and configurations were selected to correspond with those from the flight tests performed by the NFLC and facilitate validation. The specific mass, centre of gravity, and flight condition configurations tested during the trials are summarised in Table 1.

After each test point, the simulation was paused to allow the pilot to complete a subjective evaluation using the Simulation Fidelity Rating (SFR) scale, shown in Figure 9. This facilitated immediate, task-specific assessments while the experience was still fresh. In parallel, all relevant data were logged by the CA^{2}LM framework, including control inputs, aircraft states, as well as aircraft forces and moments. Voice recordings were also collected throughout the trials to capture the pilot's real-time observations, qualitative feedback, and contextual comments for later analysis.

A. Test Configuration

Cranfield University's Saab 340B[20] will be used to validate both modelling and flight simulation environments. The Saab 340B, Figure 5 is a twin-turboprop transport aircraft designed to seat 30-36 passengers, which has been adapted to operate as a flying laboratory for educational and research purposes. Flight test data for this study are readily available, obtained from the instrumentation onboard the NFLC Saab 340B. The aircraft is extensively equipped to support detailed analyses, including two cabin cameras positioned to view through a starboard-side window, facilitating image-based aeroelasticity analysis and non-intrusive measurements. Additional instrumentation includes an Inertial Measurement Unit (IMU), a Touchscreen Flight Navigator, and a data acquisition system. The data acquisition unit logs critical onboard parameters, such as control surface deflections, control stick positions, and outputs from Saab 340B instruments.

Fig. 5 NFLC and Cranfield Univeristy's Saab 340B[20].

The flight tests, operated by the NFLC, are carried out for various manoeuvres to excite flight dynamics modes at different flight and mass conditions. Flight test data is collected at predefined trim points, with thrust forces and moments obtained using the propeller efficiency map provided by the manufacturer. Furthermore, experimental data is supplemented by a numerical database generated through the application of system identification methodologies to extract aerodynamic characteristics from the flight test data[21, 22].

To support these trials, the SAAB 340B is being modelled within CA^{2}LM. While CA^{2}LM includes interface tools for mass estimation, a detailed mass model developed specifically for the SAAB platform is being leveraged. This existing model offers significantly higher fidelity and accuracy, making it a more suitable choice for this application. Additionally, a wing-propeller interaction model is being incorporated into the framework. Initially, this model will utilise a reduced-order approach based on ESDU methods. Further development of the interaction model is planned for the following year, aiming to enhance both its fidelity and the broader modelling capabilities of the CA^{2}LM framework. It is important to note that, while the model includes structural flexibility, the Saab 340B is, in practice, a relatively rigid aircraft, therefore, these trials were not intended to investigate the impact of airframe flexibility on flight dynamics.

B. Trial Procedure and Manoeuvres

The pilot first familiarised with the simulator environment and the aircraft model, allowing time to adjust to the control feel, visual cues, and dynamic response. Following this familiarisation phase, the predefined set of manoeuvres were performed.

1. Longitudinal Static Stability

This task aims to measure how the elevator deflection required for trimmed flight varies with airspeed, under controls-fixed conditions, in which the elevator position is held constant by the pilot instead of balanced with the trim tab

Table 1 Summary of mass, centre of gravity, and flight condition configurations tested.

Mass configuration	Manoeuvre	Total Mass (kg)	CG (% MAC)	Altitude (ft)	Trim Speed (KIAS)
A1	SPPO	12051	17	7175	154
A2	Phugoid	12051	17	7175	154
A3	LSS	12163	17	3196	156
B1	SPPO	11626	12	7546	158
B2	Phugoid	11636	12	7920	173
B3	LSS	11744	13	6601	157
C1	SPPO	12118	28	6834	156
C2	Phugoid	12129	28	7116	157
C3	LSS	12286	28	7500	160
D1	SPPO	11498	22	8068	157
D2	Phugoid	11509	22	8199	167
D3	LSS	11668	23	7500	160
E1	SPPO	11973	23	5915	160
E2	Phugoid	11984	23	5902	178
E3	LSS	12189	23	7500	160

to float freely. Additionally, when repeated across multiple CG positions, this flight test is used to estimate the aircraft's static margin, providing insight into longitudinal static stability and helping to define the aft CG limit for safe operation.

The manoeuvre began from a trimmed condition at approximately 160 KIAS. The pilot then gradually decelerated and accelerated in steps of ±15 knots, covering an airspeed range from 130 KIAS to 190 KIAS. At each speed increment, the aircraft was allowed to stabilise, and the elevator deflection required to maintain trimmed flight was recorded.

2. SPPO

To excite the short-period pitch mode, the pilot applied a rapid elevator doublet input, consisting of a brief back-and-forth pulse on the stick executed over approximately one to two seconds. This standard flight-test technique is commonly used to initiate short-period oscillations and assess the corresponding dynamic response of the aircraft.

3. Phugoid

The pilot excited the long-period pitch oscillation by performing a gentle elevator pull-up and then releasing the control, a standard method to disturb the trim airspeed. Specifically, the pilot would pitch up and hold for the few seconds to reduce airspeed by 20 knots, and then release the stick to let the aircraft oscillate freely.

C. Simulation Fidelity Assessment

The SFR scale, as proposed by Perfect et al.[8], provides a structured method for capturing a pilot's subjective assessment of how faithfully a simulator replicates real aircraft behaviour for a given task. In a HQ evaluation campaign, the SFR scale can be systematically employed alongside traditional Cooper-Harper ratings to provide an additional layer of fidelity monitoring. The rational for this dual assessment approach is that SFR ratings offer a repeatable, task-specific measure of perceptual fidelity, complementing more quantitative metrics. Therefore, it balances engineering fidelity, which measures quantitative agreement with flight data, and perceptual fidelity, which seeks the pilot's subjective impression of the real aircraft. This ensures that HQ conclusions are drawn from a simulation environment that pilots themselves deem sufficiently representative of real-world flight conditions.

For critical manoeuvres, SFR scores Fidelity Level in the range of 1 to 3, where 1 indicates excellent fidelity. Ratings outside this range may indicate perceptible discrepancies and may prompt further investigation into simulator fidelity before accepting associated HQ findings. Additionally, the SFR methodology allows for the identification of specific weaknesses in the simulation by correlating fidelity ratings with particular flight phases or dynamic responses, thus helping to define the boundaries within which the simulator remains valid.

Table 2 Summary of SFR results.

Manouevre	Fidelity Rating	Fidelity Level
SPPO	3	2
Phugoid	2	1
LSS	2	2

A limitation of the SFR methodology is its dependence on pilot familiarity with the reference aircraft, particularly in the context of HQ evaluations. Ideally, pilots providing SFR assessments should have conducted Cooper-Harper ratings on the real aircraft, enabling a meaningful comparison between simulated and actual handling. However, this is not always feasible in research environments, and was a constraining factor in the present shakedown trials: while the test pilot had flown a closely related turboprop aircraft, the pilot had not performed HQ evaluations on the Saab 340B itself. Furthermore, the manoeuvres conducted in this early phase were open-loop in nature, focused on characterising system response rather than tracking tasks. As such, they were not suitable for full Cooper-Harper or formal SFR assessments.

Nonetheless, the SFR framework was informally introduced and proved useful in framing pilot observations. Its structured application will be integrated into the upcoming HQ evaluation campaign, where representative closed-loop tasks will allow for more rigorous fidelity monitoring.

IV. Outcomes from Shakedown Trials

This section presents the pilot's qualitative evaluation of the simulation fidelity during the shakedown trials, based on both general observations and task-specific feedback. An important objective of this assessment was to determine whether the simulator could be trusted for HQ evaluation tasks, and whether any modelling or interface limitations would compromise the pilot's ability to perform meaningful assessments. The pilot's feedback was structured around the SFR scale, shown in Figure 9, alongside additional comments and observations.

The pilot's confidence in the simulator's dynamic response and control characteristics was generally positive, and the simulation was considered adequate for proceeding to HQ evaluations, provided that certain perceptual and calibration issues were addressed. Table 2 summarises the fidelity ratings provided by the pilot for each key manoeuvre, following the corresponding fidelity level as defined in the SFR methodology.

A. Short-Period Response Characterisation

To evaluate the short-period pitch dynamics of the aircraft model, the pilot initially applied a series of elevator doublets based on estimation. While most of the attempts produced acceptable responses, one of them was judged ineffective, with the pilot noting that the nose-down phase was too slow relative to the aircraft's natural short-period frequency. This resulted in insufficient excitation of the mode. To refine the procedure, the pilot employed a classic frequency sweep technique, in which the oscillation rate of the stick is progressively increased to identify the natural frequency of the short-period mode. This method exploits the phase relationship between input and aircraft response: at low frequencies, the aircraft closely follows the control input, and at high frequencies, the response will lag. When the aircraft begins to respond in phase with the stick, the short-period mode is effectively excited. Once this resonance point was identified, the pilot executed a properly tuned doublet at that frequency. This approach ensured the input was neither too slow to risk contamination by the phugoid, nor too fast to excite a meaningful aircraft response.

The pilot observed a clean short-period response, characterised by a damped pitch oscillation with one to two overshoots before settling. This behaviour corresponds to an estimated damping ratio in the range of 0.5 to 0.7, which indicates a moderately damped and stable mode, consistent with Level 1 flying qualities for most categories under MIL-STD-1797A[23]. The frequency of the response was qualitatively estimated to be near 1 Hz, a typical value for general regional-class aircraft. The mode behaved as a classical second-order system, and was readily identifiable through pilot-driven excitation. These findings suggest that the dynamic characteristics of the CA^{2}LM-EFS500 simulation are well-aligned with expected short-period behaviour. Any significant discrepancies, such as unrealistic damping, timing, or control sensitivity, would have likely been immediately perceptible to an experienced pilot.

B. Limitations Due to Lack of Motion Cueing

During the short-period evaluations, the pilot noted the absence of motion cueing as a perceptual limitation. In real flight, pitch oscillations of this type are accompanied by distinct normal acceleration cues that can be physically felt through the seat and body. In the fixed-base EFS500 simulator, these g-force cues were absent, requiring the pilot to rely solely on visual and instrument feedback, such as the attitude indicator, airspeed trends, and the preferred one, cockpit visual markers used for pitch awareness against the horizon, in order to interpret the aircraft's response. The lack of g-force feedback also meant that typical sensations associated with the aircraft loading up during pitch were missing, which made it more difficult to instinctively judge the magnitude of control inputs required.

Despite these limitations, the pilot was able to adapt effectively by shifting attention to available visual cues, and successful short-period excitations were still achieved. However, the pilot noted that the absence of normal acceleration cues made it significantly more difficult to assess the manoeuvre with confidence. Its absence limited the pilot's ability to intuitively judge the aircraft's response. As a result, this manoeuvre received a SFR of 3, downgrading it to Level 2.

This outcome highlights a known constraint of fixed-base simulators and reinforces the importance of motion cues in certain dynamic evaluations. It also highlights the need for careful interpretation of pilot feedback in manoeuvres where perceptual limitations may mask or distort the aircraft's dynamic qualities and workload perception, even when the underlying model is accurate.

C. Phugoid Response Observations

During the assessment of the phugoid mode, the pilot noted that the simulated response exhibited slightly divergent behaviour in some of the mass configurations, deviating from the expected weakly damped or neutral phugoid typically experienced in real aircraft of this class.

A divergent trend in the simulation may suggest either a modelling deficiency, such as underestimation of aerodynamic damping or tailplane contribution, or a configuration-related issue, such as an aft centre-of-gravity, or operation near minimum drag speed, where phugoid damping is naturally reduced. The pilot hypothesised that the aircraft may have been trimmed near this minimum drag condition, which would reduce the exchange of kinetic and potential energy, thereby contributing to the observed weak damping. This can be observed in Figure 7.

Although the pilot was able to complete the evaluation, the phugoid behaviour flagged a potential deficiency in the aeroservoelastic model's representation of low-frequency dynamics. This is an instructive case of how subjective pilot feedback, even during open-loop tasks, can help uncover modelling mismatches that may not be immediately apparent from quantitative parameters alone. As a result of these findings, future iterations of the simulation model will need to review the implementation of pitch damping and centre-of-gravity location.

D. Aileron Bias Due to Stick Miscalibration

During initial runs, the pilot reported a persistent right-wing-down tendency despite the stick being held at its nominal neutral position. Investigation revealed a calibration bias in the control stick, which introduced a significant unintended aileron deflection of approximately 3° due to an offset in the aileron channel. To correct this, a quick software patch was applied that subtracted the measured bias from the input signal. Following this adjustment, the aircraft remained level when the stick was released, with only a minor residual reading. The offset was refined throughout the trial to ensure it was always zeroed, and the control response was deemed acceptable for the remainder of the trials. This hardware issue is currently being investigated further to ensure it is permanently resolved ahead of the main simulation campaign.

E. Environment Fidelity

A critical point of interest was system latency. The simulator, operating at a 50Hz sample rate via the Speedgoat real-time target, demonstrated no noticeable lag between control input and response. The pilot confirmed that any latency present was imperceptible and did not affect handling feel. This suggests that the simulator's real-time integration was performing within acceptable thresholds for pilot-in-the-loop tasks.

Visual scene fidelity was also discussed. While the EFS500 simulator provides an external visual display, the pilot noted that for the types of stability and response tests conducted, a highly detailed visual environment was not essential. Instrument references, primarily the airspeed and attitude indicators, along with a stable horizon line would be sufficient for task execution. The pilot suggested that a minimal visual scene (e.g., a simple solid sky and ground) would be adequate and potentially more effective, as added visual complexity did not contribute meaningfully to his evaluation of the aircraft's handling qualities. This observation offers flexibility for future trials, where visual rendering resources could be traded for computational efficiency if necessary, without compromising the quality of pilot assessments for basic dynamic tasks.

Finally, the one caveat consistently acknowledged throughout the trials was the absence of motion cueing, as aforementioned. As a fixed-base simulator, the EFS500 does not provide physical g-force feedback. The pilot commented that while this limitation was manageable for small perturbation manoeuvres, it remained a point of caution, given that in the absence of acceleration cues, there is a risk of unintentionally exceeding realistic load factors by over-controlling based on instrument readings alone, which can be observed in Figure 6. The team discussed the value of monitoring load factor data in real time or introducing visual or auditory g-load cues to prevent excursions beyond the expected flight envelope.

In summary, the simulator's technical performance, considering its real-time responsiveness, control feel, and visual feedback, was found to meet the requirements for tasks conducted, with the exception of the uncalibrated central stick, which introduced a minor aileron offset. Despite this, the pilot was generally able to focus fully on the evaluation tasks without undue interference from the simulation environment. The low latency met the thresholds required for meaningful handling qualities assessment, and the overall performance provides a robust foundation for future, more demanding evaluations—such as pilot-in-the-loop control tasks or disturbance rejection tests—assuming the stick calibration issue is resolved.

Time histories of selected variables for the short-period pitch oscillation (SPPO), phugoid, and longitudinal static stability (LSS) manoeuvres are presented in Figures 6, 7, and 8, respectively. These examples illustrate key variables of the simulated dynamic response. However, a comprehensive quantitative analysis and comparison against corresponding flight test data is still required to fully validate the simulation model and assess its accuracy across configurations.

V. Conclusion and Path Forward

The initial shakedown trial has demonstrated that the integrated CA^{2}LM–EFS500 simulation environment can credibly reproduce key dynamic behaviors of a flexible aircraft, laying the groundwork for formal handling-qualities studies. Pilot feedback on the simulator's dynamic response and control feel was generally positive, indicating that the system behavior closely mimics the real aircraft characteristics. Using the SFR scale, the pilot evaluated the simulator's fidelity across a range of maneuvers and found the overall performance acceptable for proceeding to HQ evaluations, provided certain issues are resolved. The aircraft model will be refined to address the identified aeroservoelastic deficiencies. In particular, the phugoid dynamics will be revisited to verify the slight divergence observed in the current model, as well as the high frequencies observed in the SPPO. Furthermore, the calibration issue in the control hardware is being investigated to ensure it is fully resolved before the coming trials. Effectively, the insights from this shakedown have directly informed of enhancements to the simulation framework moving forward.

Finally, the next phase of this research will involve formal pilot-in-the-loop evaluations using pilots from Cranfield's NFLC who have a Saab 340B Type Rating. These pilots will conduct a series of standardised manoeuvres in the CA^{2}LM–EFS500 simulation environment that again will replicate flight tests, in order to systematically assess its fidelity and the handling qualities of the aircraft model. The SFR scale will be used in these trials to capture quantitative fidelity ratings. The outcomes of these evaluations will not only verify that the simulator can deliver sufficient fidelity for credible HQ assessments at the early stages of the design process, but also will provide further insights to refine the model if needed.

Altogether, this work advances the development of a simulation environment aimed at supporting the generation and evaluation of optimal aircraft designs. In this context, accurate prediction of the interactions between aeroelasticity, flight control and flight dynamics is critical for the evaluation of handling qualities and safety of future aircraft concepts. For this reason, CA^{2}LM is being envisioned to facilitate the assessment of the impact of airframe flexibility, unconventional layouts and other emerging systems on the aircraft dynamics, handling qualities and control, and therefore on safety. The ability to conduct these evaluations early in the design process, involving not just quantitative analysis but also incorporating a pilot-in-the-loop providing expert feedback, is particularly crucial for unprecedented concepts. Furthermore, this approach enables any identified design modifications to be incorporated back into the design loop for revision, thereby assessing and mitigating risks associated with such configurations with more confidence. Similarly, developing such capabilities can pave the way for simulation-based certification processes.

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A. Appendix

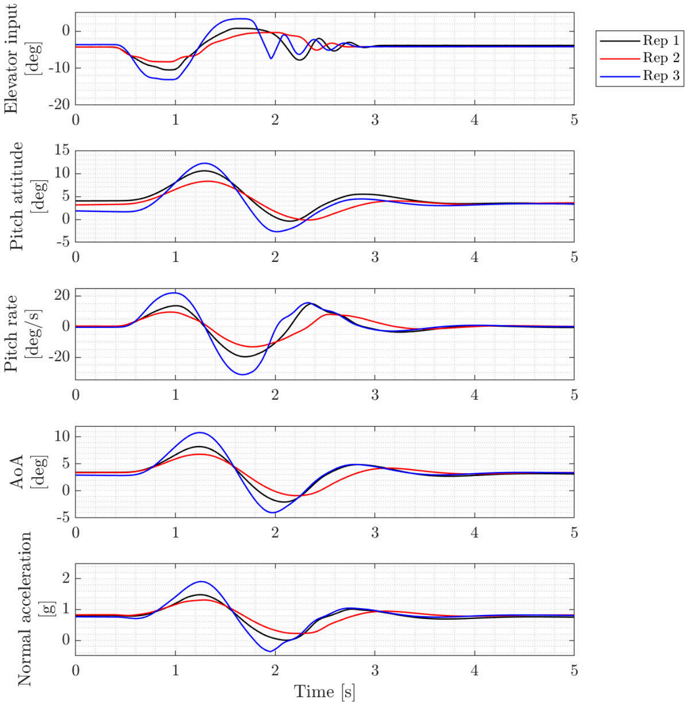

Fig. 6 Time histories of the SPPO response for configuration A1.

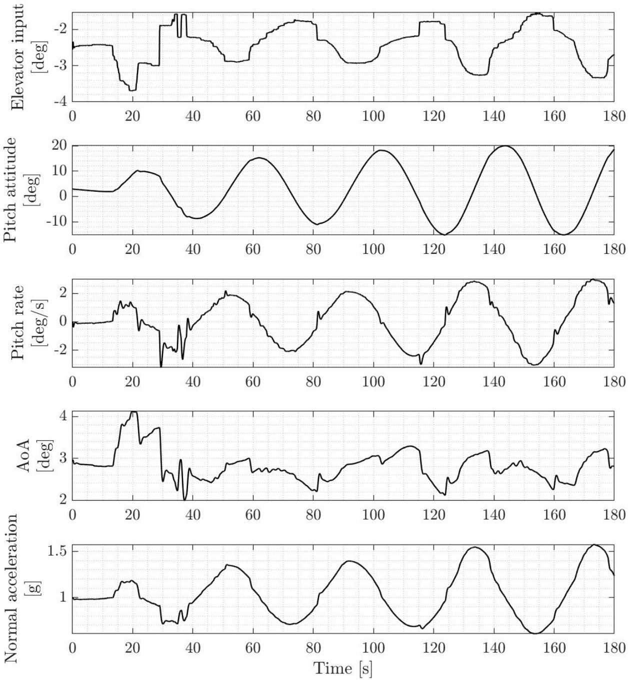

Fig. 7 Time histories of the phugoid response for configuration C2.

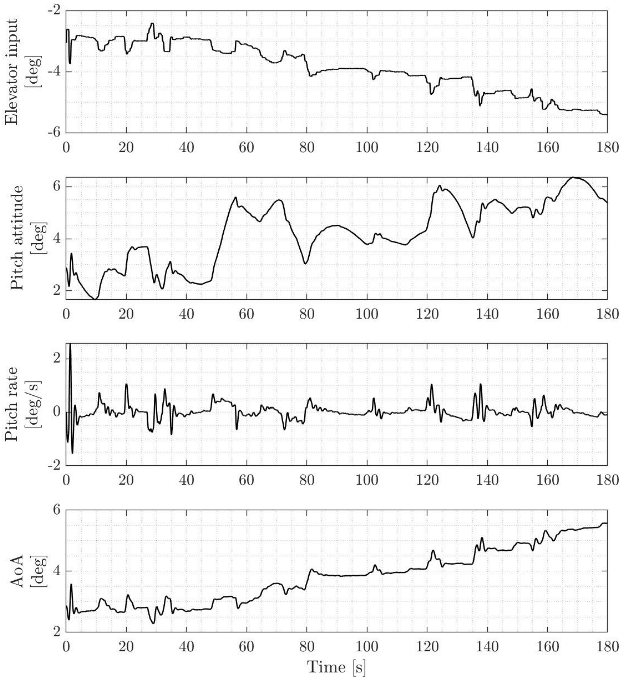

Fig. 8 Time histories of the LSS for configuration E3.

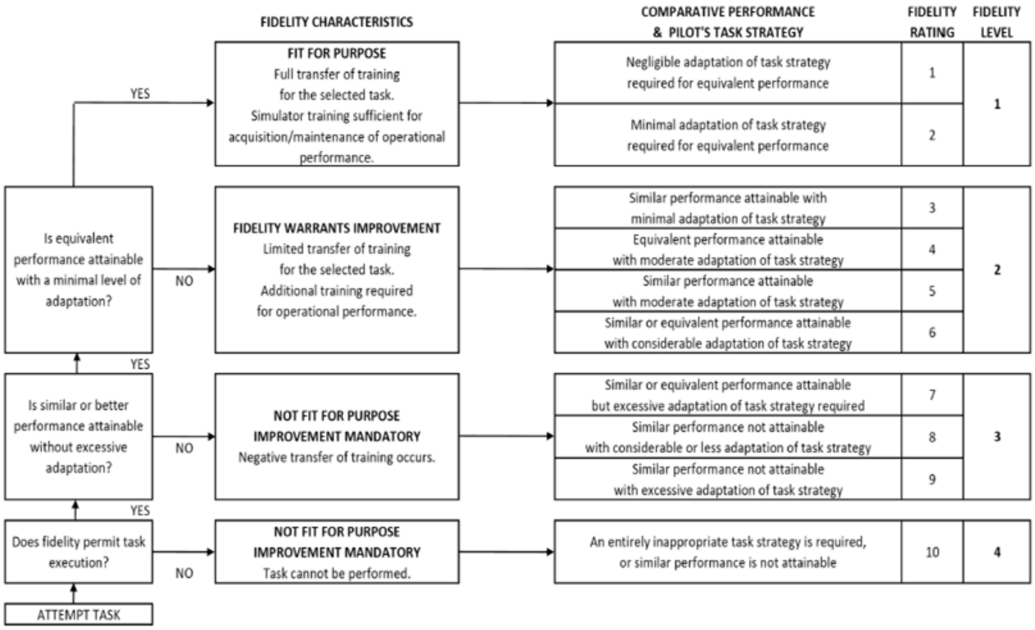

Fig. 9 Simulation Fidelity Rating Scale[8].

Early-stage assessment of a flexible aircraft simulation framework in a pilot-in-the-loop environment

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