Comprehensive Analysis of Aircraft Dynamics Stability with SCSim: Integration and Assessment

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Abstract: *This research presents a comprehensive analysis of the dynamic stability of aircraft using modules of the software named SCSim (Stability and Control Simulation Tool), which is dedicated to the analysis of aircraft stability and control. The stability of an aircraft can be examined in two directions: longitudinal and lateral. The ability to determine an aircraft's limits and handling qualities depends on its stability. This study report demonstrates a complete dynamic stability analysis using SCSim with aerodynamic input data from the commercial software Advanced Aircraft Analysis (AAA). SCSim is implemented within a common framework in MATLAB, adapted from a MATHCAD script, providing an easier way to enter user-defined input data, and introducing a set of new features. The study is divided into three main parts, each based on an analysis of stability. First, static stability is examined to understand how the system behaves when it is in equilibrium. Then, dynamic stability is assessed to understand how the system reacts to perturbations and disturbances. Finally, handling qualities systematically assess the dynamic modes of the aircraft's behavior and establish the levels of handling qualities. In this paper, a generic model of a propeller-driven aircraft is used for the study due to the availability of flight parameters, geometric, and aerodynamic data. The obtained results demonstrate the capabilities of the Stability and Control Simulation Tool (SCSim) in designing and analysing an aircraft's stability under various flight conditions and configurations, with validation using AAA.*

Key Words: *lateral stability, longitudinal stability, dynamic modes, handling qualities*

1. INTRODUCTION

Due to the inherent uncertainties associated with flight, the assessment of stability holds a prominent role in ensuring flight safety. Stability plays a vital role in the design, control, and safety of aircraft and other flying vehicles [1]. It is an essential consideration for all types of aircraft. However, the approach to handling stability needs to be tailored to the specific characteristics of the aircraft under investigation. For instance, commercial aircraft generally require a higher degree of stability compared to military aircraft. This distinction arises from the fact that military aircraft are designed to execute rapid manoeuvres in line with their operational objectives. This paper focuses on the assessment of stability by using the INCAS developed tool *SCSim* (Stability and Control Simulation Tool) and comparing the results with the commercial tool *AAA* (Advanced Aircraft Analysis) [2].

SCSim is a flexible MATLAB application created for assessing the stability and control attributes of a system within a range of different types of aircraft configuration. This software offers a wide range of analysis features, encompassing the examination of static stability, dynamic stability, and an assessment of handling qualities. The tool was developed and adapted after the mathematical model that was used in the paper [3]. The tool is equipped to perform static stability analysis, examining the behaviour of the system in equilibrium. It assesses parameters such as trim points, stability derivatives, and neutral point to determine the system's inherent static stability characteristics. The tool's dynamic stability analysis module evaluates the system's response to perturbations and disturbances. It computes eigenvalues of the system's state-space representation, providing valuable insights into modes of stability, including oscillatory, divergent, or neutral behaviours [4]. The handling qualities assessment feature within *SCSim* tool extends its capabilities by incorporating the well-established criteria outlined in MIL-STD (Military Standard) documents [5]. This feature systematically evaluates the dynamic modes of an aircraft's behaviour and determines their respective handling qualities levels, allowing the user to gain a comprehensive understanding of the aircraft's control characteristics.

In this paper the main objective is the stability analysis of a generic aircraft model defined at INCAS using the Advanced Aircraft Analysis software. The generic aircraft aerodynamic and geometric data defined and generated using *AAA* is an input for *SCSim*. *AAA* is suitable for conceptual and preliminary design phases of both conventional and unconventional fixed wings aircraft configurations. *AAA* allows for multi-fidelity analyses, combining classical and fast semi-empirical methodologies with physics-based methods. In addition, a graphic user interface provides for the required user-friendliness.

The primary focus of this study is to perform stability and handling qualities assessment on a generic aircraft model and subsequently compare and validate the output obtained from the *SCSim* tool with that of the *AAA* software, thereby ensuring the accuracy and reliability of *SCSim's* stability analysis results.

2. METHODOLOGY

SCSim is a versatile tool designed to evaluate the stability and control characteristics of a given system in the field of aerospace engineering. This tool provides a comprehensive suite of analysis capabilities, including static stability assessment, dynamic stability analysis, and an evaluation of handling qualities.

SCSim tool was developed using a mathematical model from the paper [3] based on [4]. The mathematical model was developed initially as a MATHCAD file, but it was migrated to the MATLAB software, because it has a series of advantages regarding user-friendliness, possibility of creating user-defined input and output in different file formats and easier to implement conventional and non-conventional aircraft configurations.

In this study the dynamic model is created by using the minor disturbances model for the longitudinal and lateral directional motions.

The equations are derived from the linearization and simplification of the equations of motion.

The fundamental assumption made here is that the aircraft's motion is characterized by slight deviations from a stable and symmetrical reference flight [4].

The formal representation of the dynamic system governing longitudinal and lateral-directional motion is encapsulated in the equation (1):

$$\dot{\mathrm{x}} = \mathrm{Ax} \tag{1}$$

2.1 Input model

The input data for aircraft (A/C) geometry, aerodynamic characteristics, mass/inertia properties, and stability derivatives were obtained from *AAA* as input in *SCSim*. The aircraft model employed for stability analysis is a generic propeller-driven aircraft model developed by INCAS through AAA software. The INCAS Generic A/C (*Fig. 1*) model was utilised to furnish the necessary data for SCSim. This model serves a dual purpose: to offer essential input for SCSim and to function as a high-fidelity benchmark for evaluating the stability parameters calculated by SCSim, thereby validating its capability in computing these parameters.

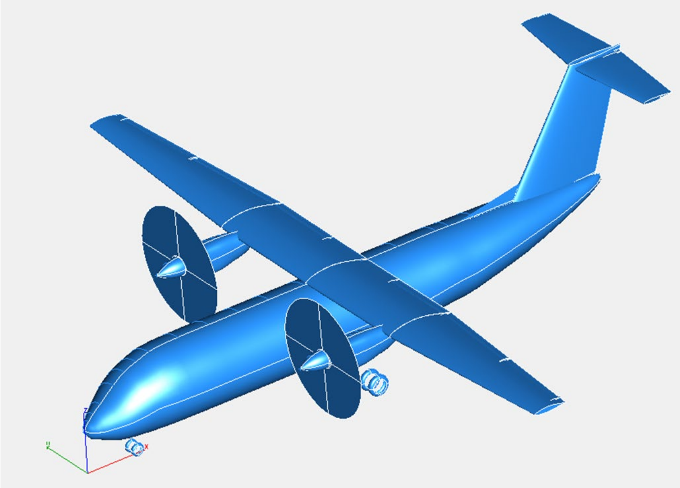


Fig. 1 INCAS Generic A/C

The aerodynamic characteristics of the model, including the drag polar, lift polar and pitch at the cruise flight condition, can be observed in the following figures.

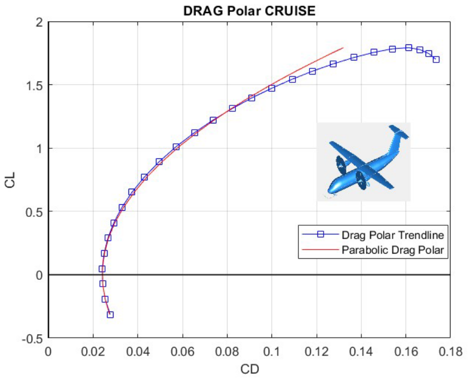


Fig. 2 Drag polar at cruise flight condition

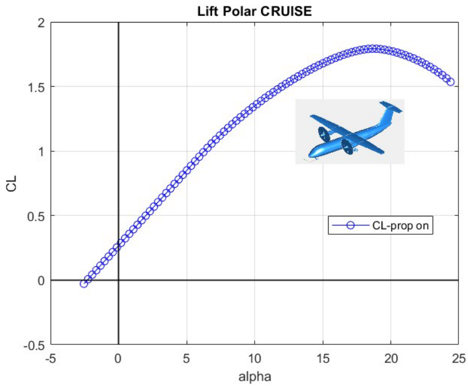


Fig. 3 Lift polar at cruise flight condition

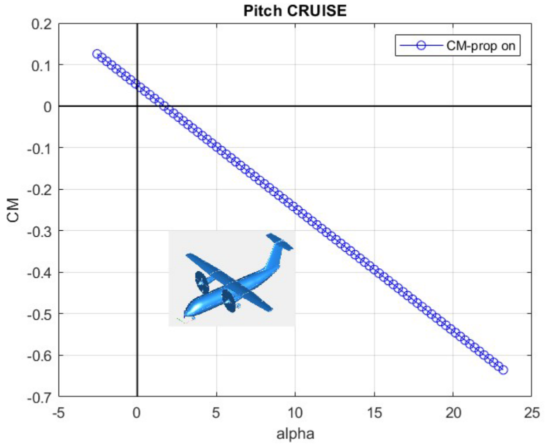


Fig. 4 Pitch at cruise flight condition

The parabolic drag polar is plotted at $MRe = 26$, with the drag polar type $C_D = C_{D_0} + kC_L{}^2$, where $C_{D_0} = 0.0241,\ e = 0.79,\ k = 0.0336$ provided by the INCAS evaluation of the Generic A/C 2020_R using *AAA*.

Table 1 INCAS Generic A/C Geometric data

INCAS Generic A/C Geometric data	
Wingspan (m)	29.66
Wing area (m^2)	73.31
MAC (m)	2.46
Mass (kg)	27384.208
Moment of inertia:	433832.8
Moment of inertia:	473574.3
Moment of inertia:	878677.9
Moment of inertia:	446.9

Table 2 INCAS Generic A/C Flight conditions - Cruise

INCAS Generic A/C Flight conditions - Cruise	
Altitude (m)	0
ΔT (deg C)	0
$U_1 (m/s)$	151
$\alpha\ (deg)$	-0.02
β (deg)	0
$\rho\ (kg/m^3)$	1.225

To validate the results of *SCSim*, the stability characteristics are compared with results obtained in *AAA* for the generic aircraft model. The steady straight cruise flight is assumed to be the reference condition for both tools.

2.2 SCSim workflow

SCSim basically computes the stability parameters [4] by using input data from *AAA* to calculate the coefficients of the polynomial characteristic equation. The dynamic behaviour is analysed by studying the eigenvalues of the polynomial characteristic. The nature of the eigenvalues gives information about the aircraft's dynamic stability:

- Real and Negative: Stable non-oscillatory mode.
- Real and Positive: Unstable non-oscillatory mode.
- Complex with Negative Real Part: Damped oscillatory mode.
- Complex with Positive Real Part: Unstable oscillatory mode.

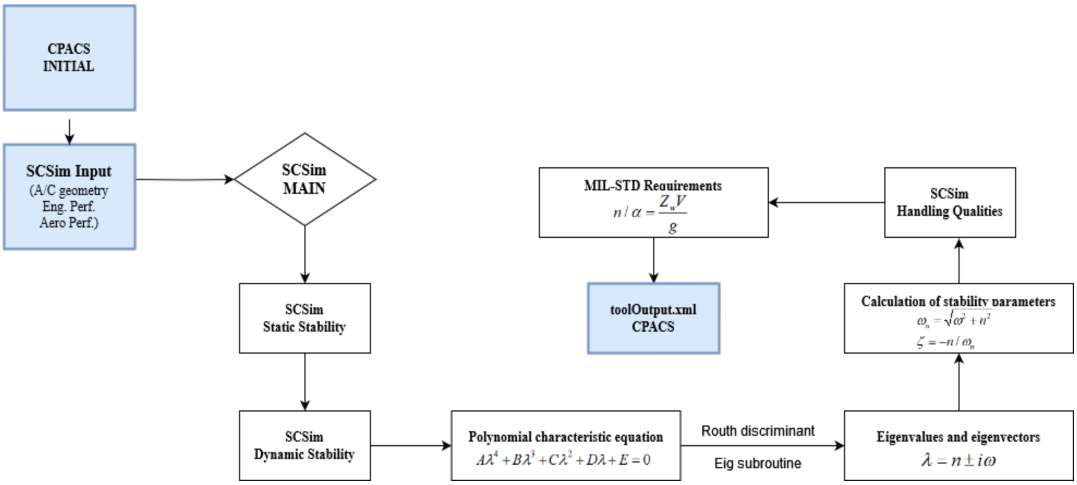


Fig. 5 SCSim flowchart configuration

All the numerical examples and the computation of the eigenvalues and eigenvectors in this paper were done using the MATLAB software package [6].

Also, before solving the polynomial characteristic it is verified using Routh's criteria for stability.

The criterion is applied to the equation's coefficients and the requirement is that every function of the following form must be positive:

$$R = D(BC - AD) - B^2 E > 0 \tag{2}$$

The main stability parameters calculated by SCSim are the natural frequency, damping, number of oscillations, the period, time to half/double and the number of cycles for the time to half/double.

All this information is fed to the handling qualities module of the tool, where all the data is handled and rated using the MIL-STD Requirements evaluating the level of flying qualities for each dynamic mode.

3. STATIC STABILITY ANALYSIS

The neutral point is typically used to express the need for static longitudinal stability. The neutral point is a specific location of the aircraft's centre of gravity (CG). It is the line that separates stable and unstable centre of gravity positions in a limited sense. Static lateral stability is typically required in very small amounts.

It just means that, in the event of a divergence, the spiral mode will have a time to double that of a specified minimum.

The equilibrium position is that only when the resulting moment of the centre of gravity and the resulting external force disappear can an aircraft continue in steady, unaccelerated flight. Specifically, this demands that there be no pitching moment. This is the longitudinal balance state [4]. Static Stability has 3 categories of stability:

- Stable: A system is said to be stable if it can be disturbed and then returns to its equilibrium position. With time, any departures from the equilibrium position become less noticeable.
- Neutral: When the system stays in its new position after being moved, it is said to be in a neutral equilibrium. Minor agitations do not result in additional movement.
- Unstable: When perturbed, an unstable system deviates from its equilibrium position, with the deviations growing with time.

The results of the comparison between *AAA* and *SCSim,* demonstrate a similar position of the neutral point, the model being stable regarding the static stability criteria mentioned earlier.

4. DYNAMIC STABILITY ANALYSIS

Ensuring dynamic stability is a primary concern in aircraft design, so to validate *SCSim* regarding dynamic stability parameters, it is important to compare the outputs of the tool with the *AAA* commercial software*,* to ensure its reliability.

4.1 Longitudinal dynamics results and comparison

In an aircraft, motion around the lateral axis (from wingtip-to-wingtip) is referred to as longitudinal motion. Changes in pitch angle, angle of attack, and forward speed are all included in this motion. Because it impacts both passenger comfort and the aircraft's controllability, longitudinal dynamic stability is crucial. The two dynamic modes of the longitudinal motion are the short period and the phugoid.

Short period mode is a faster oscillation involving pitch rate and angle of attack changes. It is typically well-damped in most aircraft designs. Phugoid mode is a long-duration, low-frequency oscillation involving the exchange of kinetic and potential energy (speed and altitude) [6].

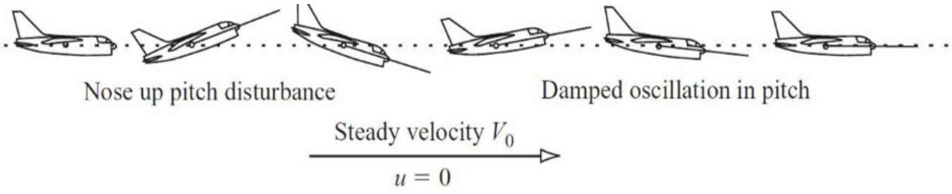


Fig. 6 Short period mode [7]

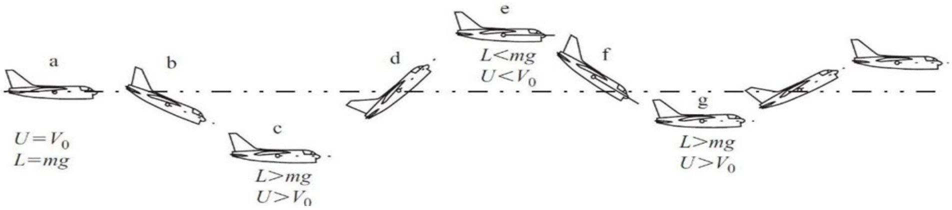


Fig. 7 Phugoid mode [7]

Table 3 Comparison between AAA and SCSim for the longitudinal dynamics results

SCSim						
No.	**Mode**	$\omega_n(rad/s)$	ζ	**Period** (s)	$t_{half}(s)$	$N_{half}(cycles$
1	Phugoid	0.0879	0.0954	71.8339	82.7072	1.1514
2	Short-Period	3.4403	0.5692	2.2213	0.3539	0.1593

AAA						
No.	**Mode**	$\omega_n(rad/s)$	ζ	**Period** (s)	$t_{half}(s)$	$N_{half}(cycles$
1	Phugoid	0.1001	0.0934	125.47	74.0728	1.172
2	Short-Period	3.7759	0.5432	1.63	0.3378	0.170

As evident in Table 3, many of the parameters compared have similar values exhibiting very low error between the reference data in *AAA* and *SCSim.*

Notably, damping, a crucial factor in discussions about dynamic stability, demonstrates satisfactory values for SCSim in this case. The transient representations of the short period and phugoid are shown in the Fig. 8 and Fig. 9.

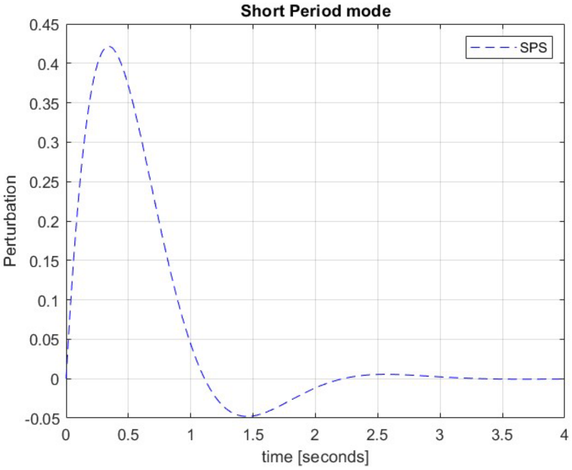


Fig. 8 Short period mode transient representation in SCSim

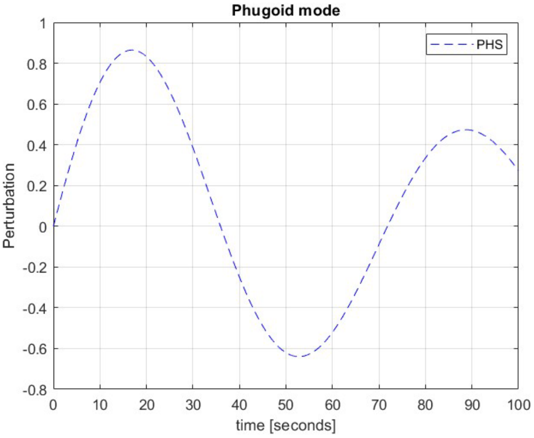


Fig. 9 Phugoid mode transient representation in SCSim

4.2 Lateral dynamics results and comparison

The lateral dynamic modes under investigation within this paper include the dutch roll mode, roll mode, and spiral mode. The dutch roll mode is characterized by a combination of yaw and roll oscillations, wherein the aircraft yaws and rolls in a somewhat synchronized manner. The comfort level experienced by passengers during this mode depends on its frequency and damping. The roll subsidence mode illustrates the decay of the roll rate following a roll disturbance (such as an aileron input). Typically, this mode is rapid and exhibits strong damping. In the non-oscillatory spiral mode, if an initial roll disturbance remains uncorrected, the aircraft may enter a progressively tightening spiral. The stability of this mode, either converging or diverging, depends on the specific design of the aircraft.

Table 4 Comparison between AAA and SCSim for the longitudinal dynamics results

SCSim						
No.	**Mode**	$\boldsymbol{\omega_n(rad/s)}$	ζ	**Period(s)/ Time constant**	$\boldsymbol{t_{half}(s)}$	$\boldsymbol{N_{half}(cycles)}$
1	Dutch Roll	2.3606	0.1945	2.7135	1.5094	0.5548
2	Roll	-	-	0.2276	0.1578	-
3	Spiral	-	-	283.847	127.433	-
AAA						
No.	**Mode**	$\boldsymbol{\omega_n(rad/s)}$	ζ	**Period** $\boldsymbol{(s)}$	$\boldsymbol{t_{half}(s)}$	$\boldsymbol{N_{half}(cycles)}$
1	Dutch Roll	2.4653	0.1959	2.547	1.434	0.551
2	Roll	-	-	0.2291	0.1588	-
3	Spiral	-	-	306.126	212.191	-

The results in the Table 4 show that for each mode the transient characteristic obtained is in conformity with the expectancies. The dutch roll mode is well-damped and in comparison with *AAA,* the actual value of the damping factor has a low error margin. Fig. 10 represents the oscillatory transient characteristic of the dutch roll mode in *SCSim.*

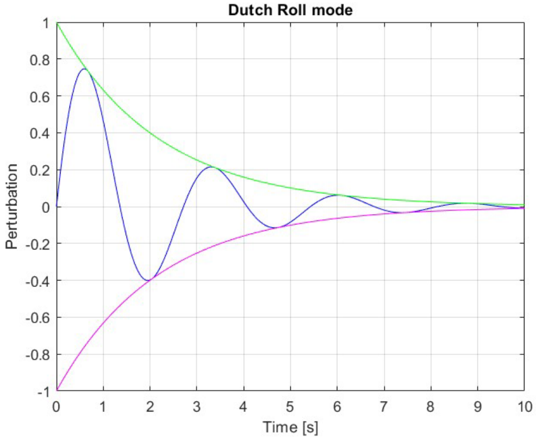


Fig. 10 Dutch roll mode transient characteristic in SCSim

Roll and spiral, as non-oscillatory behaviours, are distinguished by their time constants and notably by their time-to-double/half characteristics. A discrepancy is noticeable in the time constant values between SCSim and AAA. Despite this variance in values, both tools ultimately demonstrate satisfactory flight quality levels for both roll and spiral modes. In SCSim, the representation depicts the transient behaviour of the stable (converging) roll subsidence mode is shown in Fig. 11.

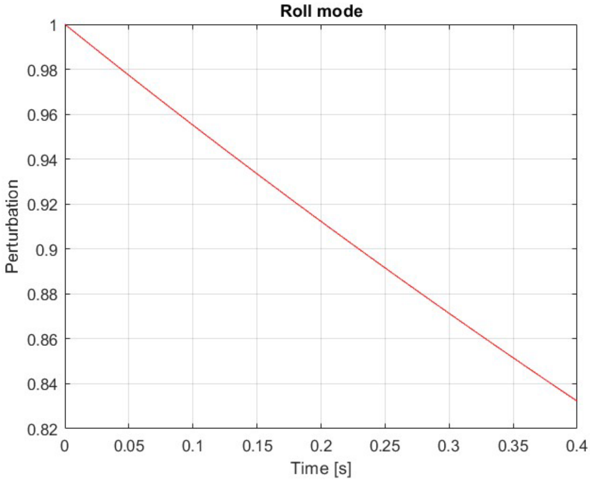


Fig. 11 Roll mode transient characteristic in SCSim

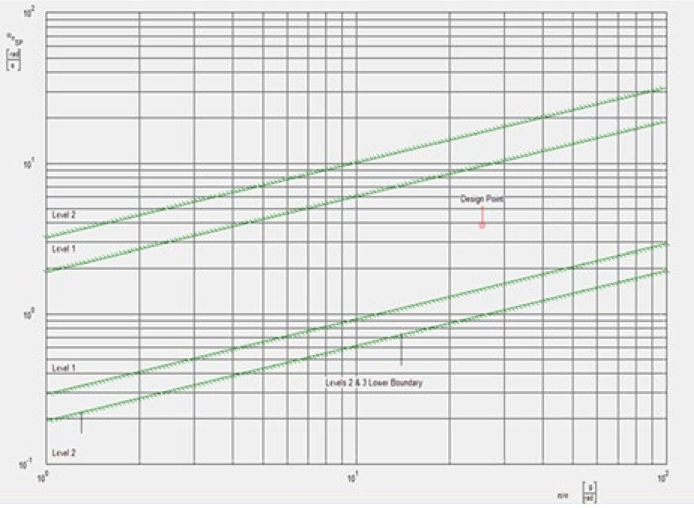
5. HANDLING QUALITIES ASSESSMENT

Aircraft handling qualities are defined and evaluated according to established standards such as MIL-STD (Military Standard) [5]. These standards provide a framework for assessing and rating handling qualities based on various flight conditions, including stability, controllability, manoeuvrability, and pilot workload.

The MIL-STD outlines specific criteria and levels to rate handling qualities, ranging from excellent to unacceptable, providing a standardized method for quantifying and comparing an aircraft's performance across different phases of flight.

Understanding these metrics is fundamental in ensuring that an aircraft meets the necessary criteria for safe and efficient operation, contributing to pilot confidence and overall flight safety.

For the INCAS Generic A/C the handling qualities level achieved in *AAA* for the short period mode is Level 1. *SCSim* achieved Level 1 handling qualities for the short period mode with the factor $n/\alpha = 25.3623$, while in the *AAA* model the factor is $n/\alpha = 25.406$.



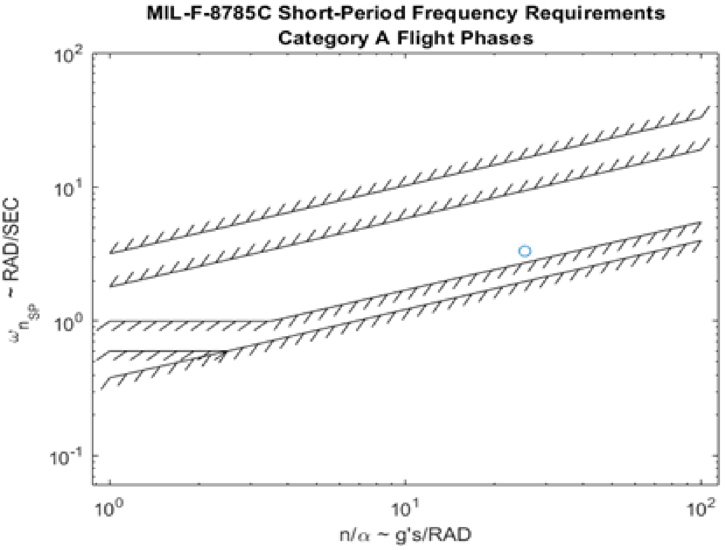


Fig. 12 Short period frequency requirements in AAA (upper image) and SCSim (lower image)

Table 5 Flying qualities level comparison

Mode	Name	AAA	SCSim
1	Phugoid	Level 1	Level 1
2	Short-Period	Level 1	Level 1
3	Dutch Roll	Level 1	Level 1
4	Roll	Level 1	Level 1
5	Spiral	Level 1	Level 2-3

The comparison of flying qualities levels between *AAA* and *SCSim* software reveals an overall alignment in the assessment of the flight modes. Phugoid, Short-Period, Dutch Roll, and Roll modes demonstrate consistent evaluations, both rated at Level 1 in both software analyses. However, notable divergence arises in the evaluation of the Spiral mode, where *AAA* rates it at Level 1, while *SCSim* depicts a rating between Level 2 and 3. This error can be rationalized on the difference between the methodologies that both tools approach ([6], [4]) and in the way they solve the mathematical equations. Also, *SCSim* is still in development and is yet to reach high precision results.

6. CONCLUSIONS

In conclusion, this study offers valuable insights into the comparison between *SCSim* and AAA for stability analysis, highlighting *SCSim* as a dependable alternative with low error rates in computed parameters when compared to *AAA*. The use of the INCAS Generic A/C model in both *AAA* and *SCSim* simulations further reinforces its reliability for stability analysis. Notably, the divergence in results between the two simulations can be attributed to the distinct approaches in solving Ordinary Differential Equations (ODEs) and because of the difference between the methodologies utilised by the two tools. The *SCSim* mathematical model is based on the B. Etkin methodology [4], while *AAA* software is based on J.Roskam [8]. It is important to note that while *SCSim* demonstrates promising reliability, its fidelity remains a work in progress, with further refinements necessary to attain the full maturity of results. The future work for this research involves enhancing the dynamic control analysis module within *SCSim*.

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