

## LONGITUDINAL FLYING QUALITY ANALYSIS FOR A SMALL FIXED-WING UAV MODEL

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### Abstract

This article presents a detailed analysis of the longitudinal flying qualities of a small fixed-wing unmanned aerial vehicle (UAV). The UAV model is developed using MATLAB/Simulink, supported by the Aerospace Blockset for six-degree-of-freedom dynamic modeling. Aerodynamic coefficients are obtained from Digital DATCOM based on the UAV's geometry and operating conditions. A trimmed flight state is determined, and the nonlinear model is linearized to extract longitudinal dynamics. The short-period and phugoid modes are analyzed according to MIL-STD-1797A criteria. Results indicate that the UAV meets Level 1 requirements for both modes, with the short-period damping ratio near the lower limit and the natural frequency well above the minimum threshold. These findings clarify the UAV's inherent dynamic behavior and provide a foundation for future control system development and flight performance optimization.

**Keywords:** Flight dynamics; UAV; flying quality.

### 1. Introduction

Unmanned Aerial Vehicles (UAVs), especially small fixed-wing platforms, have gained increasing importance in a wide range of civilian and military applications due to their flexibility, low cost, and ease of deployment [1]. Despite advancements in hardware and control systems, ensuring desirable flying qualities remains a critical challenge, particularly in the longitudinal axis, which directly affects flight stability, pilot workload, and autopilot performance.

Flying qualities refer to the aircraft's dynamic response to control inputs and disturbances, and they are crucial for ensuring controllability, stability, and autopilot performance. For manned aircraft, standards such as MIL-F-8785C and the more modern MIL-STD-1797A define these qualities through damping ratios, natural frequencies, and mode classifications [2]. However, no dedicated flying quality standard currently exists for UAVs, and current research often relies on manned aircraft

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DOI: 10.56651/lqdtu.jst.v21.n1.994

standards as substitutes, despite inherent differences in size, speed, mass properties, and the absence of a human pilot for real-time evaluation.

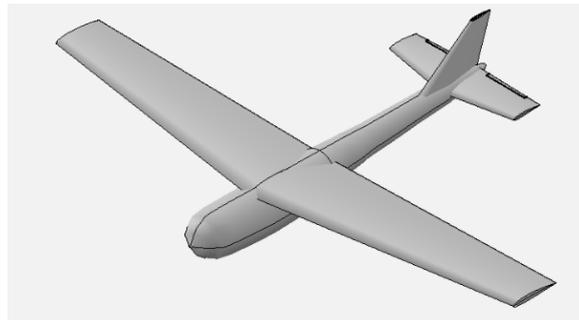
Several studies have explored the applicability of classical criteria to UAVs. Peters and Andrisani [3] found that lightweight UAVs required significantly faster short-period dynamics compared to full-scale aircraft to maintain acceptable flying qualities. Meanwhile, Lesiário and Hagström [4] conducted parametric studies to link design variables with flying quality metrics and highlighted the lack of generalizable standards for UAVs, despite the utility of classical models. Li *et al.* [5] also highlighted the role of stability modes in the context of autopilot design for small aerial vehicles.

Although many studies have applied manned-aircraft flying quality criteria to UAVs, there is still a lack of dedicated standards that account for the unique aerodynamic and dynamic features of small fixed-wing platforms. The integration of high-fidelity aerodynamic coefficient estimation with dynamic simulation and standardized flying quality evaluation remains limited in UAV research. This study develops a comprehensive analysis framework that combines aerodynamic modeling using Digital DATCOM, six-degree-of-freedom dynamic simulation in MATLAB/Simulink, and linear stability assessment against MIL-STD-1797A criteria. After identifying a trimmed flight condition, the longitudinal dynamics are isolated and linearized to analyze the short-period and phugoid modes. These modes are then evaluated against MIL-STD-1797A criteria to determine the UAV's flying quality level and stability characteristics.

## **2. Methodology**

### **2.1. UAV model**

In this study, the UAV model is developed based on the general configuration and performance characteristics of the Russian Orlan-10 UAV. This UAV represents a conventional fixed-wing reconnaissance platform with a standard aerodynamic layout. The three-dimensional representation of the UAV model is shown in Fig. 1.



*Fig. 1. 3D model of the UAV.*

The primary geometric and performance specifications of the UAV are summarized in Tab. 1.

Tab. 1. Key characteristics of the UAV model

No.	Parameter	Unit	Value
1	Wingspan	m	3.1
2	Fuselage length	m	1.8
3	Takeoff weight	kg	18.6
4	Range	km	600
5	Speed range	km/h	70-150
6	Altitude range	m	300-5000

## 2.2. Calculation of aerodynamic coefficients

The aerodynamic coefficients of the UAV were computed using the open-source software Digital DATCOM. Digital DATCOM [6] is a tool developed by the United States Air Force for estimating the aerodynamic and stability derivatives of flight vehicles with conventional configurations. The software is written in the FORTRAN programming language. DATCOM utilizes a semi-empirical methodology, combining analytical equations with empirical correction factors obtained from wind tunnel experiments and flight test data. This approach allows for reasonably accurate estimation of aerodynamic properties while maintaining computational efficiency.

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1 CASEID ORLAN10
2 $FLTCN WT=150.0,NMACH=1.0,RNNUB(1)=7.57E4,LOOP=2.0
3 MACH(1)=0.09,NALT=1.0,ALT(1)=1500.0,NALPHA=15.0,
4 ALSCHD(1)=-7.0,-5.0,-3.0,-1.0,0.0,3.0,5.0,6.0,7.0,
5 8.0,9.0,10.0,11.0,12.0,13.0$
6 $OPTINS SREF=1.23,CBARR=0.33,BLREF=3.1,ROUGFC=0.25E-3,$
7 $SYNTHS XCG=0.56,ZCG=0,
8 XW=0.43,ZW=0.036,ALIW=2.0,
9 XH=1.75,ZH=-0.019,ALIH=-7.0,
10 XV=1.41,ZV=0.026,$
11 $BODY NX=7.0,BNOSE=1.0,BLN=0.145,BTAIL=1.0,BLA=0.022,
12 X(1)=0.0,0.041,0.098,0.145,1.016,1.978,2.0,
13 R(1)=0.04,0.08,0.11,0.121,0.105,0.04,0.0,
14 ZU(1)=0.036,0.036,0.036,0.036,0.036,0.026,0.026,
15 ZL(1)=-0.062,-0.152,-0.195,-0.208,-0.208,-0.05,-0.034,$
16 NACA-W-4-2412
17 $WGFLNF CHRDR=0.51,CHRTP=0.29,SSPN=1.55,DHDADI=4.0,
18 TYPE=1.0,SSPNE=1.43,SAVSI=8.0,CHSTAT=0.0,TWISTA=0.0,$
19 NACA-H-4-2412
20 $HTPLNF CHRDR=0.25,CHRTP=0.18,SSPN=0.41,SSPNE=0.385,SAVSI=7.0,
21 CHSTAT=0.0,TWISTA=0.0,DHDADI=4.0,TYPE=1.0,$
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23 $VTPLNF CHRDR=0.59,CHRTP=0.22,SSPN=0.39,SSPNE=0.38,
24 SAVSI=45.0,CHSTAT=0.0,TWISTA=0.0,DHDADI=0.0,TYPE=1.0,$

```

Fig. 2. Input configuration for the UAV in Digital DATCOM.

Input data for DATCOM is provided in the form of structured text files composed of *namelist* and *control card* sections, which define the aircraft geometry, flight conditions, and reference parameters. The input configuration used for the UAV model is shown in Fig. 2.

### 2.3. Dynamic model of the UAV

#### 2.3.1. Equations of motion

The motion of the UAV is governed by a set of six coupled nonlinear differential equations, consisting of three translational force equations and three rotational moment equations, expressed in the body-fixed reference frame [7]:

$$\begin{aligned}
 \dot{U} &= RV - WQ - g \sin \theta + \frac{1}{m}(-D + T \cos \alpha) \\
 \dot{V} &= -UR + WP + g \sin \phi \cos \theta + \frac{1}{m}(Y + T \cos \alpha \sin \beta) \\
 \dot{W} &= UQ - VP + g \cos \phi \cos \theta + \frac{1}{m}(-L - T \sin \alpha) \\
 \dot{P} &= (c_1 R + c_2 P)Q + c_3 L_A + c_4 N_A \\
 \dot{Q} &= c_5 PR + c_6 (P^2 - R^2) + c_7 M_A \\
 \dot{R} &= (c_8 P - c_2 R)Q + c_4 L_A + c_9 N_A
 \end{aligned} \tag{1}$$

In these equations,  $U$ ,  $V$ , and  $W$  represent the components of the translational velocity in the body-axis system, while  $P$ ,  $Q$ , and  $R$  denote the angular velocity components about the roll, pitch, and yaw axes, respectively. The terms  $D$ ,  $Y$ , and  $L$  correspond to the drag, lateral force, and lift. The aerodynamic moments in roll, pitch, and yaw are represented by  $L_A$ ,  $M_A$ , and  $N_A$ , respectively.  $T$  denotes the thrust. The angles  $\alpha$ ,  $\beta$ ,  $\phi$ , and  $\theta$  refer to the angle of attack, sideslip angle, roll angle, and pitch angle. The coefficients  $c_i$  are functions of the UAV's principal moments of inertia and can be computed as outlined in [8].

The aerodynamic forces and moments are computed from aerodynamic coefficients using the following relationships [7]:

$$\begin{aligned}
 D &= \bar{q} S C_D, Y = \bar{q} S C_y, L = \bar{q} S C_L, \\
 L_A &= \bar{q} S C_l b, M_A = \bar{q} S C_m c, N_A = \bar{q} S C_n b,
 \end{aligned} \tag{2}$$

where  $\bar{q} = \frac{1}{2} \rho V^2$  is the dynamic pressure,  $S$  is the reference wing area,  $c$  is the mean aerodynamic chord, and  $b$  is the wingspan.

The aerodynamic force and moment coefficients are expressed as linearized

functions of state variables and control inputs, based on the small disturbance theory [7]:

$$\begin{aligned}
 C_D &= C_{D_0} + C_{D_\alpha} \alpha + C_{D_q} Q \frac{c}{2U_1} + C_{D_{\dot{\alpha}}} \dot{\alpha} \frac{c}{2U_1} + C_{D_{\delta_e}} \delta_e \\
 C_y &= C_{y_\beta} \beta + C_{y_p} P \frac{b}{2U_1} + C_{y_r} R \frac{b}{2U_1} + C_{y_{\delta_a}} \delta_a + C_{y_{\delta_r}} \delta_r \\
 C_L &= C_{L_0} + C_{L_\alpha} \alpha + C_{L_q} Q \frac{c}{2U_1} + C_{L_{\dot{\alpha}}} \dot{\alpha} \frac{c}{2U_1} + C_{L_{\delta_e}} \delta_e \\
 C_l &= C_{l_\beta} \beta + C_{l_p} P \frac{b}{2U_1} + C_{l_r} R \frac{b}{2U_1} + C_{l_{\delta_a}} \delta_a + C_{l_{\delta_r}} \delta_r \\
 C_m &= C_{m_0} + C_{m_\alpha} \alpha + C_{m_q} Q \frac{c}{2U_1} + C_{m_{\dot{\alpha}}} \dot{\alpha} \frac{c}{2U_1} + C_{m_{\delta_e}} \delta_e \\
 C_n &= C_{n_\beta} \beta + C_{n_p} P \frac{b}{2U_1} + C_{n_r} R \frac{b}{2U_1} + C_{n_{\delta_a}} \delta_a + C_{n_{\delta_r}} \delta_r
 \end{aligned} \tag{3}$$

In these equations,  $\delta_e$ ,  $\delta_a$ ,  $\delta_r$  are the deflections of the elevator, aileron, and rudder, respectively;  $U_1$  is the steady-state flight speed used for linearization; the coefficients  $C_{xi}$  represent the partial derivatives of the aerodynamic forces and moments with respect to the state or control variables. All aerodynamic coefficients used in this model were calculated using Digital DATCOM based on the UAV's geometry and flight condition inputs. These coefficients are listed in the Tab. 2.

Tab. 2. Aerodynamic coefficients and derivatives

Coefficient	Value	Coefficient	Value	Coefficient	Value
$C_{D_0}$	0.028	$C_{D_q}$	0.0	$C_{D_{\delta_e}}$	-0.008
$C_{D_\alpha}$	0.2521	$C_{D_{\dot{\alpha}}}$	0.0	$C_{L_{\delta_e}}$	0.212
$C_{L_0}$	0.228	$C_{L_q}$	8.288	$C_{m_{\delta_e}}$	-0.5272
$C_{L_\alpha}$	4.971	$C_{L_{\dot{\alpha}}}$	1.539	$C_{y_{\delta_a}}$	0.0
$C_{m_0}$	0.0133	$C_{m_q}$	-1.883	$C_{y_{\delta_r}}$	0.2076
$C_{m_\alpha}$	-2.197	$C_{m_{\dot{\alpha}}}$	-4.882	$C_{l_{\delta_a}}$	0.3145
$C_{y_\beta}$	-0.293	$C_{y_p}$	-0.09	$C_{l_{\delta_r}}$	-0.038
$C_{l_\beta}$	-0.081	$C_{y_r}$	0.0	$C_{n_{\delta_a}}$	-0.0102
$C_{n_\beta}$	0.052	$C_{n_p}$	-0.019	$C_{n_{\delta_r}}$	-0.05
$C_{n_r}$	-0.049	$C_{l_p}$	-0.437	$C_{l_r}$	0.078

### 2.3.2. Simulation model

The dynamic simulation model of the UAV was implemented in MATLAB/Simulink, utilizing components primarily from the Aerospace Blockset. This specialized toolbox provides a comprehensive suite of blocks and tools for modeling, simulating, and analyzing aerospace systems. It enables the integration of flight environment models, aerodynamic force computation, coordinate transformations, and numerical solutions of motion equations.

As shown in Fig. 3, the UAV dynamic model comprises several core subsystems. The central block, "UAV Airframe", is responsible for calculating the external forces acting on the UAV, including aerodynamic forces, engine thrust, and gravity. These forces are then used to solve the six-degree-of-freedom (6-DOF) equations of motion to determine the UAV's attitude and position over time (Fig. 4).

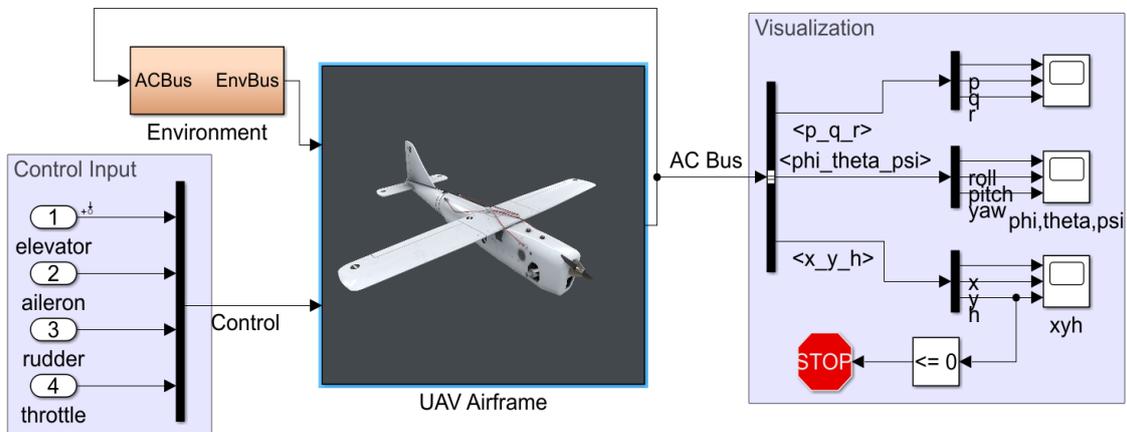


Fig. 3. Schematic of the UAV dynamic model in Simulink.

The "Control Input" block provides control surface deflections and propulsion inputs, such as elevator, aileron, and rudder angles, as well as engine thrust. The "Environment" block computes atmospheric parameters, including air density, wind speed, and gravitational acceleration, based on the UAV's altitude, position, attitude, and velocity. Finally, the "Visualization" subsystem generates graphical outputs of key flight parameters, including attitude, position, and angular velocity, allowing for post-simulation analysis of UAV behavior under various flight conditions.

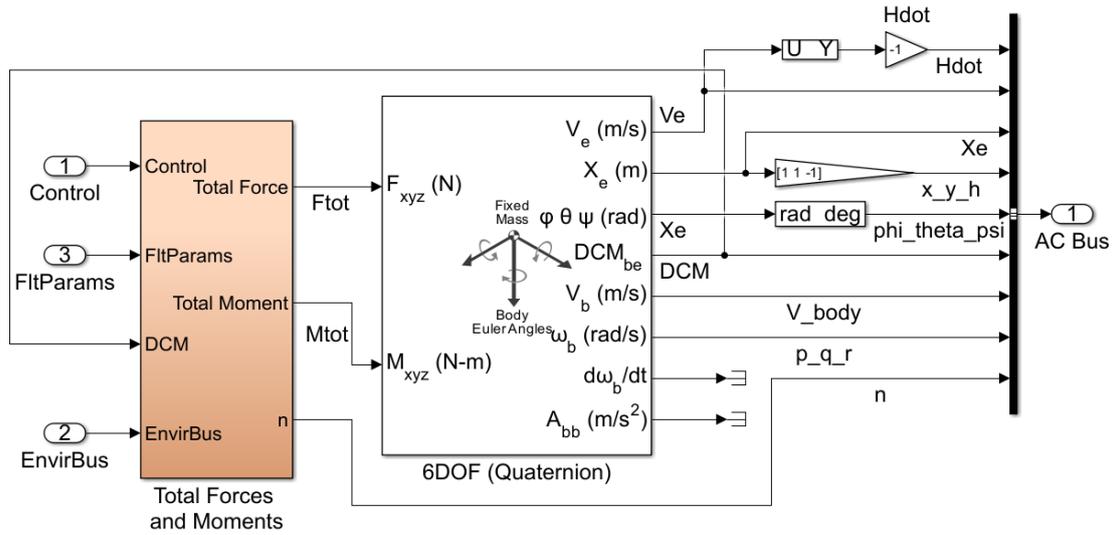


Fig. 4. Subsystem for computing and integrating the equations of motion.

### 3. Flight quality analysis

#### 3.1. Linearization of the longitudinal model

Accurately analyzing the stability of a nonlinear flight dynamic system can be challenging and time-consuming due to the complexity of its behavior. However, since fixed-wing UAVs typically operate within relatively small deviations from a trimmed flight condition, their behavior can be well-approximated using linearization techniques. According to the small disturbance theory [9], linearizing the nonlinear equations of motion around a steady-level flight trim point provides a reasonable and efficient method for analyzing flight dynamics.

In this study, the trimmed flight condition is computed using the “*findop*” function from the Simulink Control Design toolbox. The operating point corresponds to a steady, level flight at an airspeed of 30 m/s and an altitude of 1500 m. The computed trim solution (Fig. 5) yields an elevator deflection angle of  $-0.0318$  radians (approximately  $-1.8$  degrees).

Once the trim condition is obtained, the nonlinear Simulink model is linearized around this point using the *linearizeAirframe* function. Since the focus of this analysis is on longitudinal flying qualities, only the longitudinal motion is extracted from the full 6-DOF system for simplicity. A perturbation input is applied to the elevator command input port  $\delta_e$ , and the outputs are taken as the pitch angle ( $\theta$ ) and pitch rate ( $q$ ).

Operating point search report for the Model uav\_sim.  
(Time-Varying Components Evaluated at time t=0)

Operating point specifications were successfully met.  
States:

						Inputs:			
						Min	u	Max	
	Min	x	Max	dxMin	dx	dxMax	(1.) <a href="#">uav_sim/elevator</a>		
(18.) $\underline{u}$	30.1	30.1	30.1	0	8.3716e-08	0	-Inf	-0.031875	Inf
(19.) $\underline{v}$	-Inf	-2.6129e-08	Inf	0	5.8609e-15	0	(2.) <a href="#">uav_sim/aileron</a>		
(20.) $\underline{w}$	-Inf	0.41247	Inf	0	-1.1873e-08	0	-Inf	-3.2456e-10	Inf
(21.) $\underline{X_e}$	-Inf	-1.1852e-15	Inf	-Inf	30.1028	Inf	(3.) <a href="#">uav_sim/rudder</a>		
(22.) $\underline{Y_e}$	-Inf	-2.0884e-13	Inf	0	-1.2745e-14	0	-Inf	-8.3597e-10	Inf
(23.) $\underline{Z_e}$	-1500	-1500	-1500	0	-2.6263e-10	0	(4.) <a href="#">uav_sim/throttle</a>		
							-Inf	19.3079	Inf

Fig. 5. Trimmed operating point of the UAV.

The linearization process in MATLAB directly returns the state-space representation of the longitudinal dynamics, in which the system matrices **A** and **B** are computed numerically from the trimmed operating point. The resulting model has the form:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\delta_e, \quad (4)$$

where the state vector is  $\mathbf{x} = [U, W, Q, \theta]^T$ , and the matrices **A** and **B** are given as:

$$\mathbf{A} = \begin{bmatrix} -0.064 & 0.118 & 0.3602 & -9.801 \\ -0.574 & -5.628 & 26.28 & -0.134 \\ 0.071 & -5.168 & -1.816 & 0.0 \\ 0.0 & 0.0 & 1.0 & 0.0 \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0.369 \\ -7.166 \\ -37.33 \\ 0.0 \end{bmatrix} \quad (5)$$

The roots of the system matrix **A** are:

$$\lambda_{1,2} = -3.724 \pm 11.49i, \lambda_{3,4} = -0.03 \pm 0.47i \quad (6)$$

As shown in Fig. 6, all poles of the system lie in the left half of the complex plane, meaning all real parts are negative. This confirms that the UAV exhibits longitudinal static stability at the trimmed flight condition.

The system exhibits two pairs of complex conjugate poles. The pair with higher frequency  $\lambda_{1,2}$  corresponds to the short-period mode, which primarily governs the UAV's pitch attitude and angular rate. The pair with lower frequency  $\lambda_{3,4}$  represents the long-period or phugoid mode, which characterizes the coupled variation of pitch attitude, airspeed, and altitude. This mode involves alternating

exchanges between kinetic and potential energy around a steady flight level, typically with negligible change in angle of attack.

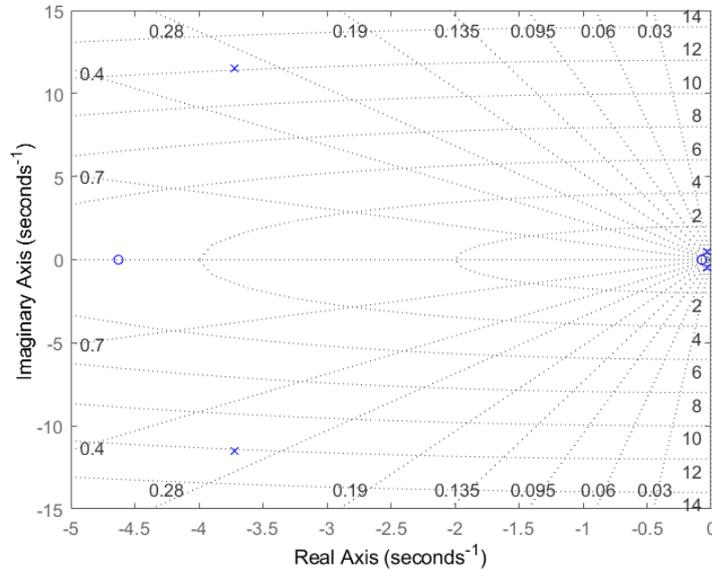


Fig. 6. Pole-zero map of the longitudinal state-space model.

### 3.2. Flying quality analysis

In this section, the longitudinal flying qualities of the UAV are evaluated based on the MIL-STD-1797A standard [10]. Although no specific flying quality standard currently exists exclusively for UAVs, MIL-STD-1797A offers a comprehensive framework that extends and modernizes the criteria from earlier standards (such as MIL-F-8785C), including considerations for digital flight control systems and a wider range of aircraft configurations. Therefore, it is commonly adopted in research and design evaluations for small UAVs in the absence of a dedicated UAV-specific standard.

To evaluate the longitudinal flying qualities of the UAV, the stability characteristics of short-period and phugoid modes must be determined. The roots of a second-order dynamic mode are given by [9]:

$$\lambda = \zeta\omega_n \pm i\omega_n\sqrt{1-\zeta^2}, \quad (7)$$

where  $\zeta$  is the damping ratio and  $\omega_n$  is the undamped natural frequency.

From this, we extract:

$$\zeta = \frac{1}{\sqrt{1 + \frac{\text{Im}(\lambda)}{\text{Re}(\lambda)}}}, \omega_n = \frac{\text{Re}(\lambda)}{\zeta} \quad (8)$$

The calculated stability characteristics of short-period and phugoid modes are shown in Tab. 3.

Tab. 3. Longitudinal stability characteristics

	Short-period	Phugoid
<b>Eigenvalues</b>	$\lambda_{1,2} = -3.724 \pm 11.49i$	$\lambda_{3,4} = -0.03 \pm 0.47i$
<b>Damping ratio</b>	$\zeta_{sp} = 0.308$	$\zeta_{ph} = 0.063$
<b>Undamped natural frequency</b>	$\omega_{nsp} = 12.08 \text{ rad/s}$	$\omega_{nph} = 0.475 \text{ rad/s}$
<b>Requirements per MIL-STD-1797A</b>	$\zeta_{sp} > 0.3$ and $\omega_{nsp} > 1.0 \text{ rad/s}$	$\zeta_{ph} > 0.04$

For the short-period mode ( $\lambda_{1,2} = -3.724 \pm 11.49i$ ), the calculated damping ratio is  $\zeta_{sp} = 0.308$ , and the undamped natural frequency is  $\omega_{nsp} = 12.08 \text{ rad/s}$ . According to MIL-STD-1797A, for Level 1 flying qualities in Phase B (typical of cruise, climb, descent, and loiter), the short-period mode must have a damping ratio of at least 0.3 and an undamped natural frequency of no less than 1.0 rad/s. The UAV meets these criteria: the damping ratio is marginally above the minimum threshold, while the natural frequency significantly exceeds the lower limit, indicating a highly responsive short-period dynamic.

The high frequency ( $12.08 \text{ rad/s} \approx 1.92 \text{ Hz}$ ) suggests a fast pitch attitude response to control inputs, which is typical of small UAVs with low inertia and relatively high control authority. However, such a high frequency also implies that the system must be supported by a sufficiently fast actuator and sensor bandwidth to avoid phase lag or instability in closed-loop operation. Moreover, the fact that the damping ratio is only slightly above the Level 1 threshold may pose concerns regarding pilot or autopilot workload, especially in turbulent or high-speed conditions. A lightly damped response in the short-period mode can lead to noticeable oscillations and reduced precision in pitch control unless carefully managed.

In contrast, the phugoid mode shows a much slower oscillation, with eigenvalues at  $\lambda_{3,4} = -0.03 \pm 0.47i$ , corresponding to a damping ratio of  $\zeta_{ph} = 0.063$ , and a natural frequency of  $\omega_{nph} = 0.475 \text{ rad/s}$ . These values are well within Level 1 requirements under MIL-STD-1797A, which specify a minimum damping ratio of 0.04 for the phugoid mode. The UAV, therefore, comfortably satisfies the criteria for this mode.

## 4. Conclusion

This study has presented a comprehensive analysis of the longitudinal flying qualities of a small fixed-wing UAV by integrating aerodynamic modeling, dynamic simulation, and linear stability evaluation into a unified framework. The authors computed aerodynamic coefficients using Digital DATCOM and seamlessly incorporated them into a six-degree-of-freedom UAV model developed in MATLAB/Simulink with the Aerospace Blockset. This integration allowed an accurate representation of aerodynamic characteristics in the dynamic simulation environment, enabling precise analysis of the UAV's longitudinal modes.

Linearization around a trimmed flight condition enabled the identification of short-period and phugoid modes, which were assessed against MIL-STD-1797A criteria. The results confirm that the UAV meets Level 1 flying quality requirements for both modes. The short-period mode exhibits a damping ratio marginally above the lower limit and a natural frequency significantly exceeding the minimum, while the phugoid mode demonstrates stable, slow oscillations.

These findings provide a valuable reference for controller design, system tuning, and potential aerodynamic refinements to enhance flight stability and performance in autonomous UAV operations.

## Acknowledgment

This research is funded by Le Quy Don Technical University Research Fund under the grant number 25.01.32.

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## PHÂN TÍCH CHẤT LƯỢNG BAY KÊNH DỌC CHO MÔ HÌNH UAV CÁNH BẰNG CỖ NHỎ

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**Tóm tắt:** Bài báo phân tích chi tiết về chất lượng bay kênh dọc của một mô hình UAV cánh bằng cỡ nhỏ. Mô hình UAV được xây dựng trong phần mềm MATLAB/Simulink kết hợp với mô đun Aerospace Blockset để mô phỏng động học sáu bậc tự do. Các hệ số khí động được tính toán bằng phần mềm Digital DATCOM dựa trên hình dạng hình học và điều kiện bay đặc trưng của UAV. Sau khi xác định trạng thái bay bằng, mô hình phi tuyến được tuyến tính hóa để tính toán các đặc trưng động học kênh dọc. Các mode dao động dọc, bao gồm chu kỳ ngắn và phugoid, được phân tích và đánh giá theo tiêu chuẩn MIL-STD-1797A. Kết quả cho thấy UAV đáp ứng yêu cầu mức 1 đối với cả hai mode dao động dọc, trong đó hệ số tắt dần của chu kỳ ngắn nằm sát cận dưới, còn tần số riêng cao hơn đáng kể so với mức yêu cầu tối thiểu. Những kết quả này có thể dùng làm cơ sở cho các nghiên cứu tiếp theo về thiết kế hệ thống điều khiển và tối ưu hóa hiệu suất bay.

**Từ khóa:** Động lực học bay; UAV; chất lượng bay.

Received: 27/06/2025; Revised: 24/09/2025; Accepted for publication: 27/01/2026

