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Aircraft Pitch Control Via Parametric Identification and PID Optimization

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Conflicts of interest
The author declares that there is no conflict of interest.

Abstract. A comprehensive methodology for designing an aircraft pitch angle control system is proposed, combining mathematical modeling, aerodynamic parameter identification, and controller optimization. A comparative study was conducted on the accuracy of the Euler and 4th-order Runge-Kutta methods for numerical integration of longitudinal short period motion equations in identification tasks. It was established that the Runge-Kutta method provides higher accuracy for estimating aerodynamic force coefficients, while the Euler method is preferable for moment analysis, defining the criteria for algorithm selection during data generation. Automated tuning of the PID controller in Simulink achieved record dynamic system performance characteristics (without considering the actuator): rise time — 0.0709 s, overshoot — 11.6%, which is 20–30% superior to results from known counterparts. The developed approach demonstrates the possibility of replacing labor-intensive flight tests with digital models while maintaining accuracy, thereby reducing design time. The results confirm that the integration of numerical modeling, parametric identification, and optimization forms a new standard for preliminary studies in aviation technology, aligning with the digitalization trends in the aerospace industry.

Keywords: approximate modeling, accuracy of estimates, estimates of coefficients, Euler method, Runge — Kutta method, control system synthesis, auto-tunning

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Управление самолетом по тангажу с помощью параметрической идентификации и ПИД-оптимизации

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Заявление о конфликте интересов

Автор заявляет об отсутствии конфликта интересов.

Аннотация. Предложена комплексная методология проектирования системы управления углом тангажа самолета, сочетающая математическое моделирование, идентификацию аэродинамических параметров и оптимизацию регуляторов. Проведено сравнительное исследование точности методов Эйлера и Рунге — Кутты 4-го порядка при численном интегрировании уравнений короткопериодического движения для задач идентификации. Установлено, что метод Рунге — Кутты обеспечивает повышенную точность оценки аэродинамических коэффициентов силы, а метод Эйлера предпочтителен для анализа моментов, что определяет критерии выбора алгоритмов при генерации данных. Автоматизированная настройка ПИД-регулятора в Simulink позволила достичь рекордных динамических характеристик системы без учета рулевого привода: время нарастания — 0,0709 с, перерегулирование — 11,6 %, что на 20–30 % превосходит результаты известных аналогов. Разработанный подход демонстрирует возможность замены трудоемких натурных экспериментов цифровыми моделями с сохранением точности, сокращая сроки проектирования. Результаты подтверждают, что интеграция численного моделирования, параметрической идентификации и оптимизации формирует новый стандарт для предварительных исследований в сфере авиационной техники, соответствующий тенденциям цифровизации аэрокосмической отрасли.

Ключевые слова: приближенное моделирование, точность оценок, оценки коэффициентов, метод Эйлера, метод Рунге — Кутты, синтез системы управления, автонастройка

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Introduction

Contemporary aviation technology demands enhanced safety, stability, and controllability [1]. The precise characterization of aircraft short-period motion, defined by the coupled dynamics of the angle of attack, pitch rate, and normal load factor, is fundamental to achieving these objectives [2; 3]. Accurate modeling of aerodynamic phenomena, including the transitional states of complex configurations, is essential [3]. Traditional analytical methods have limitations when addressing nonlinear dynamics and stochastic disturbances [4]. Consequently, numerical integration techniques critically influence simulation fidelity and computational efficiency [4; 5]. Euler's method offers advantages for real-time applications in onboard flight control computers [6], whereas Runge — Kutta methods enable higher-fidelity aircraft motion modeling [7].

The relevance of this study is the need to improve the accuracy of short-period motion models, particularly under nonlinear dynamics and stochastic disturbances. Traditional analytical modeling methods described in studies on flight dynamics are often limited to simple cases, whereas modern computational approaches, such as Runge — Kutta and Euler methods, allow solving complex problems with controlled error. The reliable estimation of aerodynamic parameters from flight data underpins effective system identification [8; 9]. Parametric identification methods, including the least-squares method (LSM) and neural network algorithms, remain key tools for minimizing errors in estimating aerodynamic coefficients. Experimental data processing methods, such as noise filtering and error estimation, also play an important role, which is particularly important for complex aerodynamic systems. The estimated coefficients enable a robust flight control design in which PID controllers are universally employed for aircraft attitude regulation[1] [10–12]. Computational aero-dynamic modeling provides the foundation for flight dynamics simulation [13], although validation against experimental data remains imperative [14]. PID synthesis leverages transfer function fitting [5], optimization techniques [10], and specialized approaches for nonlinear systems [13]. Adaptive control strategies [14; 15] and delay-compensation methods [16] address practical implementation constraints, whereas rotor dynamics simulations [17] and director algorithms for landing [18] further demonstrate the dependency on precise models. PID tuning methodologies [19] complete this essential framework.

The scientific novelty of this work consists of the integration of Runge — Kutta methods of the 4th order and adaptive LSM for joint modeling of aircraft dynamics and parameter identification in conditions of nonlinear disturbances, the development of an algorithm for automatic adjustment of the PID controller, taking into account the relationship between aerodynamic coefficients and transient characteristics of the system, and the creation of a universal methodology for parametric studies in MATLAB/Simulink. This study systematically evaluates how numerical integration errors propagate into aerodynamic coefficient estimation and subsequently affect PID controller performance. This analysis provides critical insights into aviation systems that require balanced computational efficiency and control fidelity.

1. Problem Statement

In aircraft dynamics, the short-period mode of the aircraft motion refers to pitch motion in which the aircraft rotates around its lateral axis. This motion includes changes in the pitch angle, pitch rate, and airspeed. In this short-period mode, the aircraft experiences rapid pitch angle fluctuations owing to interference, such as turbulence or pilot actions. The stability and controllability characteristics of the aircraft in this mode are crucial for flight safety and efficiency.

The aim of this study is to develop an integrated approach to model the short-period motion of aircraft, combining numerical methods for solving differential equations (Euler and Runge — Kutta methods), algorithms for parametric identification, and optimization of control systems based on PID controllers. This study solves the following tasks: comparative analysis of the accuracy of the Euler and Runge — Kutta methods, identification of aerodynamic coefficients using LSM, and Repetition. Revision required synthesis and automatic adjustment of the PID controller in the Simulink environment to improve the stability of the pitch control system. Presents an integrated methodology comprising: Dynamics simulation of short-period motion using Euler and Runge — Kutta methods, Aerodynamic parameter identification, and Automatic PID controller tuning for pitch control. The methodological basis of the study includes a three-stage approach: dynamics modeling using Euler and Runge — Kutta methods to solve a system of nonlinear differential equations, para-

[1] Kryuchkov AN, Ermilov MA, Vidyaskina AN. *Synthesis of PID controller using frequency response: Guidelines.* Samara: Samara University Publ.; 2021. (In Russ.)

meter identification using LSM based on experimental data, as well as control optimization through automatic adjustment of the PID controller.

2. Modeling of Aircraft Short Period Motion

This study employed numerical modeling to simulate the aircraft's short-period longitudinal motion, specifically capturing the coupled dynamics of the angle of attack (AoA), pitch rate, and normal load factor. This approach minimizes the costs and risks associated with traditional methods that rely on wind tunnel experiments or flight tests.

Elevator deflection served as the input excitation, while the outputs such as AoA, pitch rate, and normal load factor were selected as standard parameters defining the short-period mode for longitudinal dynamics analysis.

The governing system of nonlinear differential equations was solved using two numerical integration techniques: the explicit Euler method and the 4th-order Runge-Kutta (RK4) method. The choice of the numerical method critically influences the solution stability and local error magnitude, particularly under nonlinear aerodynamic conditions, as established in prior research.

2.1. Euler Method

This is the most elementary numerical method for solving systems of ordinary differential equations (ODEs). It was first described by Leonhard Euler in 1768 in his work "Institutiones Calculi Integralis". The Euler method is an explicit single-step first-order accuracy scheme. It approximates the solution curve with a piecewise linear function termed the Euler polygon.

Moreover, it represents the simplest numerical technique for solving first-order ODEs. This method is employed for the approximate solution of the initial value problems (Cauchy problems) and determines the values of a function defined by a differential equation on a specified point grid.

The Euler method approximates the solution at each step using local linearization. At each iteration, a new function value y_{n+1} is computed based on the current value y_n and its derivative. The integration step is denoted as h. At every step, the x-value increments by h, whereas the y-value is updated according to the following formula:

$$y_{n+1} = y_n + hf\left(x_n, y_n\right), \tag{1}$$

where y_n is the current function value; y_{n+1} is the next function value; $f\left(x_n, y_n\right)$ is the derivative at a point $\left(x_n, y_n\right)$; h is the integration step.

The process is repeated for each step until the endpoint of the integration interval is reached.

2.2. Runge-Kutta Method

The Runge — Kutta method represents one of the numerical techniques used for solving ordinary differential equations (ODEs). The most widely adopted variant is the fourth-order Runge — Kutta method (RK4), which delivers a high accuracy and is extensively utilized in practice.

The RK4 method employs four intermediate points to compute the slope (derivative) at each integration step. This approach enables a significantly more accurate solution approximation compared to the Euler method. The integration step is denoted as h. At each iteration, the x-value increments by h, whereas the y-value is updated as follows:

$$y_{n+1} = y_n + \frac{1}{6}\left(k_1, 2k_2, 2k_3, 3k_4\right), \tag{2}$$

where k_1, k_2, k_3, k_4 are intermediate coefficients calculated at each step.

The intermediate coefficients are calculated as follows:

$$k_1 = f\left(x_n, y_n\right);$$
$$k_2 = f\left(x_n + \frac{h}{2}, y_n + \frac{h}{2}k_1\right);$$
$$k_3 = f\left(x_n + \frac{h}{2}, y_n + \frac{h}{2}k_2\right);$$
$$k_4 = f\left(x_n + h, y_n + hk_3\right). \tag{3}$$

The new value y_{n+1} is calculated as a weighted sum of these coefficients.

2.3. Modeling the Dynamics of the Angular Motion of an Aircraft as a Control Object

The presented system of ordinary differential equations describes the dynamics of the angular motion of the aircraft in the longitudinal channel, considering it as an object of control.

$$\Delta\dot{v} = \overline{X}^{v}\Delta v + \overline{X}^{\alpha}\Delta\alpha + \overline{X}^{\theta}\Delta\theta + \overline{X}^{\delta_B}\Delta\delta_B + \overline{X}^{\rho}\Delta\rho_{ctrl};$$

$$\Delta\dot{\alpha} = \Delta\omega_z - \overline{Y}^{v}\Delta v - \overline{Y}^{\alpha}\Delta\alpha - \overline{Y}^{\delta_B}\Delta\delta_B - \overline{Y}^{\rho}\Delta\rho_{упр} + \frac{g}{v_0}\sin\theta\Delta\theta;$$

$$\Delta\dot{\omega}_z = \overline{M_z}^{\alpha}\Delta\alpha + \overline{M_z}^{\omega_z}\Delta\omega_z + \overline{M_z}^{\dot{\alpha}}\Delta\dot{\alpha} + \overline{M_z}^{v}\Delta v + \overline{M_z}^{\delta_B}\Delta\delta_B + \overline{M_z}^{\rho}\Delta\rho_{crtl};$$

$$\Delta\dot{\vartheta} = \Delta\omega_z;$$

$$\Delta\dot{H} = \frac{v_0}{57.3}\Delta\theta; \quad \Delta\theta = \Delta\vartheta - \Delta\alpha;$$

$$\Delta\dot{\theta} = \omega_z - \Delta\dot{\alpha};$$

$$\Delta n_y = \frac{v_0}{57.3g}\Delta\dot{\theta} = \frac{v_0}{57.3g}\left(\omega_z - \Delta\dot{\alpha}\right). \qquad (4)$$

In short-period motion, the change in the airspeed of the aircraft can be negligible, and in this flight mode, $\Delta v = 0$, $\rho_{ctrl} = 0$ and $\theta_0 = 0$. Then, the mathematical model of the aircraft can be described as follows:

$$\Delta\dot{\alpha} = \Delta\omega_z - \overline{Y}^{\alpha}\Delta\alpha - \overline{Y}^{\delta_B}\Delta\delta_B;$$

$$\Delta\dot{\omega}_z = \overline{M_z}^{\alpha}\Delta\alpha + \overline{M_z}^{\omega_z}\Delta\omega_z + \overline{M_z}^{\dot{\alpha}}\Delta\dot{\alpha} + \overline{M_z}^{\delta_B}\Delta\delta_B;$$

$$\Delta\dot{\vartheta} = \Delta\omega_z; \; \Delta\theta = \Delta\vartheta - \Delta\alpha; \; \Delta\dot{\theta} = \Delta\omega_z - \Delta\dot{\alpha}. \qquad (5)$$

Simulations in the presence of a stepwise input signal of the angle of attack and pitch rate were performed using the Euler method and the fourth-order Runge — Kutta method. The processing time was 10*s*, in increments of 0.01. The simulation results of the short-period motion of the aircraft in the longitudinal channel are shown in Figures 1, 2, and 3.

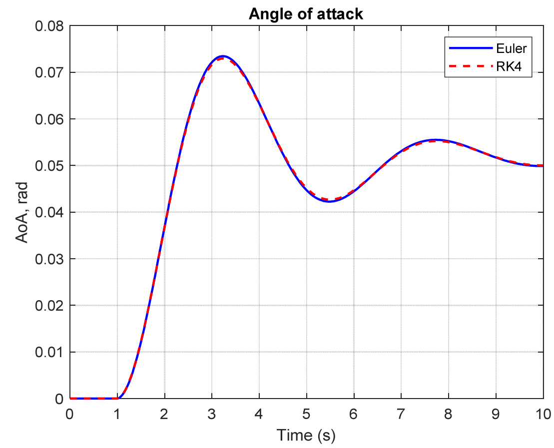

Figure 1. Angle of attack
Source: by San Lin Aung in MATLAB

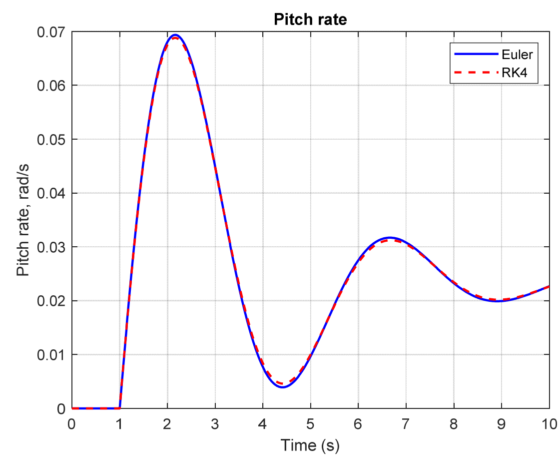

Figure 2. Pitch rate
Source: by San Lin Aung in MATLAB

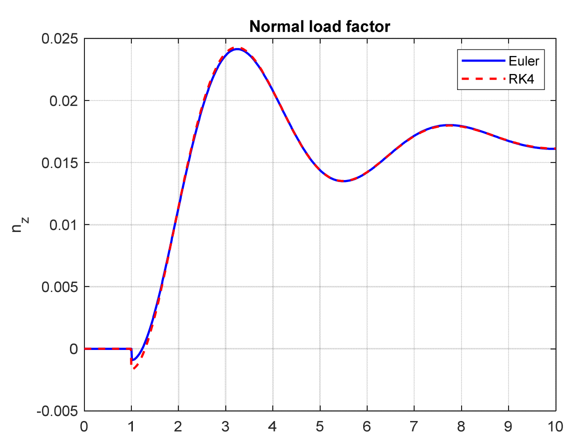

Figure 3. Normal load factor
Source: by San Lin Aung in MATLAB

A key feature of this approach is the utilization of simulated data instead of experimental data for the subsequent parametric identification. This enables the estimation of aerodynamic coefficients via the Least Squares Method (LSM) under controlled conditions, eliminating the influence of external noise and measurement inaccuracies

The simulation results demonstrate that the Runge — Kutta method yields a reduced discretizetion error compared to the Euler method, which is critical for identifying high-frequency flight regimes. The accuracy of the numerical method is crucial for analyzing short-duration dynamic modes. The obtained data provides a foundation for developing digital twins of aerodynamic systems corresponding to trends in aviation engineering digitalization.

Thus, combining Euler and Runge — Kutta methods in simulation frameworks not only reproduces short-period motion, but also evaluates the applicability boundaries of each method for specific problem classes. This contributes to the advancement of aviation system design methodologies.

3. Identification of Aerodynamic Coefficients Based on Numerically Simulated Data

The identification of aerodynamic parameters constitutes a critical stage in the design and analysis of aircraft, as the accuracy of determining these parameters directly impacts the effectiveness and reliability of control systems. The obtained coefficient estimates were utilized for developing and tuning automatic control systems that ensure aircraft motion stabilization and control. Consequently, the accurate determination of aerodynamic characteristics plays a pivotal role in creating safe and high-performance control systems capable of adapting to various flight regimes and external conditions.

3.1. Estimation of Aerodynamic Coefficients Using the Least Squares Method

To estimate the aerodynamic coefficients, the traditional least-squares method was used in this work. The least-squares method is undeniably more effective for linear systems. The mathematical model of an object can be described as:

$$y_{(t)} = \hat{a}^T x_{(t)}, \tag{6}$$

where $y(t)$ is the output vector; $x(t)$ is the vector of regressors or state vector; $\hat{a}$ is the vector of unknown parameters to be estimated.

In this case, $Y = [y_1, y_2, y_3 ... y_N]^{\mathrm{T}}$ is of $N \times 1$ dimension and X is of $N \times 1$ dimension:

$$X = \begin{pmatrix} 1 & x_{1t(1)} & x_{2t(1)} & x_{3t(1)} \\ 1 & x_{1t(2)} & x_{2t(2)} & x_{3t(2)} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{1t(N)} & x_{2t(N)} & x_{3t(N)} \end{pmatrix}.$$

Unlike maximum likelihood, when using the least squares method, the parameters to be estimated must occur in expressions for the average values of observations. When the parameters are displayed linearly in these expressions, the least-squares estimation problem can be solved in a closed form, and it is relatively simple to obtain statistical properties for the resulting parameter estimates. The least-squares method is described as:

$$\hat{a} = \left(X^{\mathrm{T}} X\right)^{-1} X^{\mathrm{T}} Y, \tag{7}$$

where $\hat{a}$ — the vector of unknown parameters to be estimated; X — the object model matrix; Y — the output vector.

3.2. Estimation of Aerodynamic Coefficients Based on Numerically Simulated Data

This study presents the estimation of two force coefficients and four moment coefficients associated with the angle of attack, pitch rate, and normal load factor. To estimate the two force coefficients, the normal load factor is required to form the output signal vector. The object model matrix incorporates angle of attack and elevator deflection.

To estimate the four moment coefficients, a derivative of the pitch rate is required to form the output signal vector. The object model matrix incorporates the angle of attack, pitch rate, derivative of the angle of attack, and the elevator deflection.

Thus, the object model matrices, output signal vectors, and unknown parameter vectors take the following form:

For the estimation of two force coefficients $\overline{Y}^{\alpha}$ and $\overline{Y}^{\delta_B}$

$$X=\begin{pmatrix}\alpha_{t(1)} & \delta_{t(1)}\\ \alpha_{t(2)} & \delta_{t(2)}\\ \vdots & \vdots\\ \alpha_{t(N)} & \delta_{t(N)}\end{pmatrix},\quad Y=\begin{bmatrix}n_{y(1)}\\ n_{y(2)}\\ \vdots\\ n_{y(N)}\end{bmatrix},\quad \hat{a}=\left[\overline{Y}^{\alpha}\,\overline{Y}^{\delta_B}\right]^{T}.$$

For the estimation of four moment coefficients $\overline{M_z}^{\alpha}, \overline{M_z}^{\omega_z}, \overline{M_z}^{\dot{\alpha}}$ and $\overline{M_z}^{\delta}$.

$$X=\begin{pmatrix}1 & \alpha_{t(1)} & \omega_{z_{t(1)}} & \dot{\alpha}_{t(1)} & \delta_{t(1)}\\ 1 & \alpha_{t(2)} & \omega_{z_{t(2)}} & \dot{\alpha}_{t(2)} & \delta_{t(2)}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ 1 & \alpha_{t(N)} & \omega_{z_{t(N)}} & \dot{\alpha}_{t(N)} & \delta_{t(N)}\end{pmatrix},\quad Y=\begin{bmatrix}\dfrac{d\omega_{z(1)}}{dt}\\ \dfrac{d\omega_{z(2)}}{dt}\\ \vdots\\ \dfrac{d\omega_{z(N)}}{dt}\end{bmatrix},$$

$$\hat{a}=\left[\overline{M_z}^{\alpha}\,\overline{M_z}^{\omega_z}\,\overline{M_z}^{\dot{\alpha}}\,\overline{M_z}^{\delta_B}\right]^{T}.$$

To analyze the efficacy and stability of the Least Squares Method (LSM) for estimating aerodynamic coefficients, a numerical experiment was conducted with varying measurement noise levels. Measurement noise was modeled using random variables with normal distribution, characterized by zero mean and different standard deviation values (σ = 0.01, 0.02, 0.03). The quantitative results of the aerodynamic coefficient estimation, reflecting the error dependence on measurement noise intensity, are presented in Figures 4 and 5.

The research results demonstrate that the data obtained using the Runge — Kutta method provide significantly higher accuracy for estimating aerodynamic force coefficients, whereas Euler method-derived data yield superior accuracy for estimating aerodynamic moment coefficients across various measurement noise levels. These findings underscore the critical importance of selecting appropri ate numerical methods for aerodynamic modeling, as they directly impact parameter estimation reliability and, consequently, control system design.

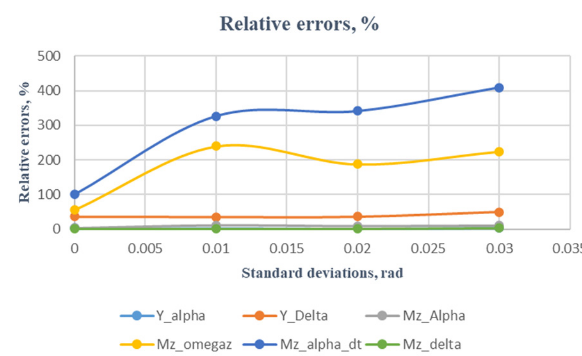

Figure 4. The results of the estimation of aerodynamic coefficients using data modeled by the Euler method
S o u r c e: by San Lin Aung in Excel

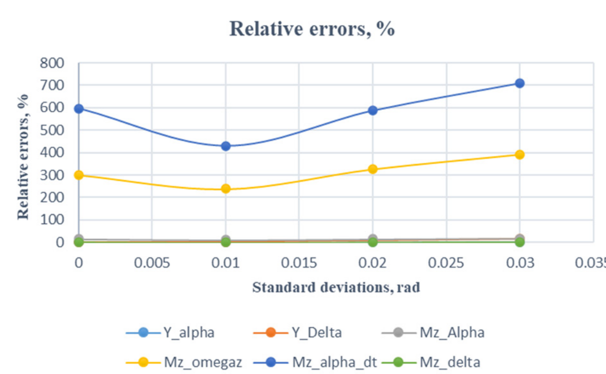

Figure 5. The results of the evaluation of aerodynamic coefficients using the data modeled by the Runge Kutta method
S o u r c e: by San Lin Aung in Excel

4. Aircraft Pitch Control System Using PID Controller

The aerodynamic coefficients were estimated using the Least Squares Method (LSM), which enabled the acquisition of the necessary parameters for designing an automatic pitch angle control system. The obtained coefficients are utilized to derive the transfer function relating the pitch rate to the elevator deflection, which represents a critical stage in control system development. This transfer function is derived from equations describing the angle of attack (α) and pitch rate, establishing a mathematical relationship that quantifies how changes in elevator deflection (δ) affect the pitch dynamics (Figure 6). This phase is essential for creating a reliable and precise control system that ensures effective regulation of aircraft angular motion.

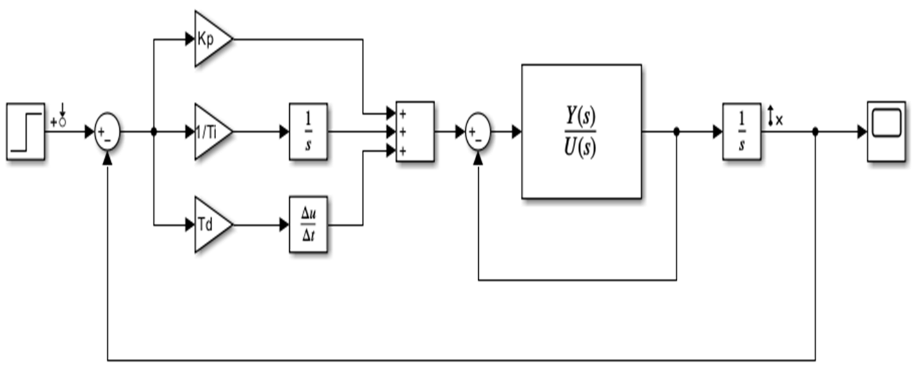

Figure 6. Structure diagram of the aircraft's automatic pitch control system
S o u r c e: by San Lin Aung in Simulink

Aircraft transfer functions via Laplace transformation can be expressed as:

$$\left(s-\overline{M}_z^{\omega_z}\right)W_{\omega_z}^{\delta_{\text{В}}}(s)+\left(-\overline{M}_z^{\dot{\alpha}}s-\overline{M}_z^{\alpha}\right)W_{\alpha}^{\delta_{\text{В}}}(s)=\overline{M}_z^{\delta_{\text{В}}};$$

$$-W_{\omega_z}^{\delta_{\text{В}}}(s)+\left(s+\overline{Y}^{\alpha}\right)W_{\alpha}^{\delta_{\text{В}}}(s)=-\overline{Y}^{\delta_{\text{В}}};$$

$$W_{\delta_{\text{В}}}^{\omega_z}(s)=\frac{\Delta\omega_z(s)}{\Delta\delta_{\text{В}}(s)}=$$

$$=\frac{\left(\overline{M}_z^{\delta_{\text{В}}}-\overline{Y}^{\delta_{\text{В}}}\overline{M}_z^{\dot{\alpha}}\right)s+\overline{M}_z^{\delta_{\text{В}}}\overline{Y}^{\alpha}-\overline{Y}^{\delta_{\text{В}}}\overline{M}_z^{\alpha}}{s^2+2\xi_{\alpha}\omega_{\alpha}s+\omega_{\alpha}^2};$$

$$W_{\delta_{\text{В}}}^{n_y}(s)\Big|_{\overline{Y}^{\delta\text{В}=0}}=\frac{v_0}{57{,}3g}\frac{\overline{M}_z^{\delta_{\text{В}}}\overline{Y}^{\alpha}}{s^2+2\xi_{\alpha}\omega_{\alpha}s+\omega_{\alpha}^2}.$$

In this study, a model that does not consider the elevator lift is used as a mathematical model of the first approximation.

$$\Delta\dot{\alpha}=\Delta\omega_z-\overline{Y}^{\alpha}\Delta\alpha$$

$$\Delta\dot{\omega}_z=\overline{M}_z^{\alpha}\Delta\alpha+\overline{M}_z^{\omega_z}\Delta\omega_z+\overline{M}_z^{\dot{\alpha}}\Delta\dot{\alpha}+\overline{M}_z^{\delta_{\text{В}}}\Delta\delta_{\text{В}}. \quad (8)$$

The transfer function from the elevator to the pitch rate through the Laplace transform $W_{\delta_{\text{В}}}^{\omega_z}(s)$ can be written as:

$$W_{\delta_{\text{В}}}^{\omega_z}(s)=\frac{\Delta\omega_z(s)}{\Delta\delta_{\text{В}}(s)}=\frac{\left(\overline{M}_z^{\delta_{\text{В}}}\right)\left(s+\overline{Y}^{\alpha}\right)}{s^2+2\xi_{\alpha}\omega_{\alpha}s+\omega_{\alpha}^2} \quad (9)$$

The initial PID controller coefficients were set empirically, followed by a linear analysis of the transient response of the system to step elevator deflection (Figure 7). The investigation results revealed the following dynamic performance indicators:

- Overshoot σ = 22.9%, indicating pronounced oscillatory components during the transients;
- Rise time $t_{rise}=1.53s$, reflecting high initial responsiveness;
- Settling time $t_{set}=10.9s$, demonstrating insufficient damping in the initial controller configuration resulting in prolonged stabilization within the 2% tolerance band.

To address these deficiencies, automatic parametric optimization of the PID controller was implemented using gradient descent algorithms in Simulink, targeting settling-time minimization while maintaining acceptable overshoot levels. These findings underscore the necessity of adaptive approaches to tuning controllers in dynamically complex aerospace systems.

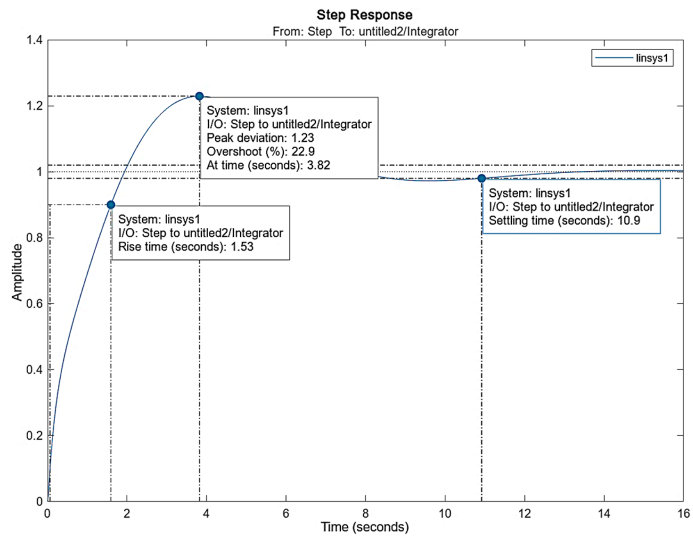

Figure 7. Transient function of the aircraft's automatic pitch control system using a PID controller at preset coefficient values

Source: by San Lin Aung in Simulink

The initial PID controller coefficients were adjusted using an automatic tuning algorithm implemented in Simulink (Figure 8). For the simplified mathematical model, excluding the actuator dynamics and physical constraints, the transient characteristics demonstrate high controller efficacy:

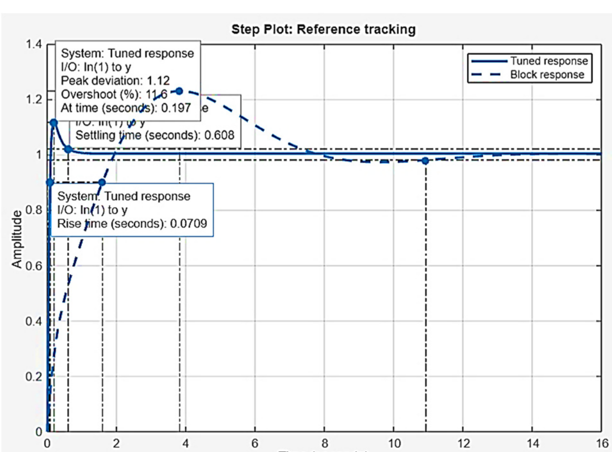

Figure 8. Transient function of the aircraft's automatic pitch control system using a PID controller with automatic tuning coefficient values

Source: by San Lin Aung in Simulink

- Overshoot $\sigma = 11.6\%$, reflecting moderate oscillatory components during transients within acceptable limits for aviation systems;
- Rise time $t_{rise} = 0.0709s$, indicating minimal system inertia when responding to control inputs;
- Settling time $t_{set} = 0.608s$, confirming the rapid attainment of steady state within the 2% tolerance band.

These parameters demonstrate the high system responsiveness and stability achieved through gradient-based optimization methods. However, the model limitations stemming from neglected actuator dynamics and real operational constraints necessitate further research for validation under near-physical conditions. These results establish a foundation for developing adaptive algorithms that account for nonlinear effects and external disturbance characteristics of aircraft control systems.

Conclusion

This study confirms the efficacy of integrating Euler and Runge — Kutta methods for solving aerodynamic modeling, parametric identification, and pitch control system synthesis tasks. It was established that the Runge — Kutta method provides enhanced accuracy for estimating aerodynamic force coefficients, whereas the Euler method demonstrates advantages for estimating moment coefficients under distinct measurement noise con-ditions. The developed pitch angle PID controller, characterized by a rise time of 0.0709 s, overshoot σ = 11.6%, and settling time of 0.608 s, validates the feasibility of achieving high-quality control despite noise disturbances in systems neglecting actuator dynamics.

The proposed methodology integrating numerical simulation, parameter identification, and adaptive controller synthesis demonstrates the potential for creating digital twins and their application in preliminary design stages, notwithstanding simplifications in the aerodynamic model. These results underscore the critical role of numerical method selection, which directly impacts estimation credibility and designed system reliability.

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