Design of aircraft flight performance analysis and simulation software

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Abstract: Considering design of flight control system in the early stage of aircraft design is the development trend of aircraft design, which improves the design quality and reduces the cost, and the analysis of aircraft dynamic characteristics is its foundation. The aircraft flight performance analysis and simulation software is designed and developed by C++ language according to the flight dynamics principle of fixed-wing aircraft with conventional layout, combined with control law and simulation algorithm, which can be used to analyze the stability of aircraft, estimate the flight performance, preliminarily design the flight control system and carry out real-time flight simulation. The numerical example shows that the software can accurately analyze and calculate the flight performance of the aircraft, and achieve good attitude maintenance and maneuver control in the simulation. The comparison of results verifies the accuracy of the software.

1. Introduction

In traditional aircraft design, aircraft dynamic characteristics are usually analyzed when the design is at a relatively mature stage. Once the dynamic characteristics cannot meet requirements, the design scheme may be significantly modified, and the design cost will increase. Meanwhile, it is difficult to obtain optimal scheme through multidisciplinary optimization. On the other hand, the design of flight control system also needs the accurate description of the aircraft dynamic characteristics. Therefore, in order to reasonably design the flight control system and ensure the dynamic characteristics of aircraft, it is necessary to introduce aircraft dynamic characteristics analysis in the process of aircraft design as early as possible [1].

CFD methods have been widely used in flow field simulation calculation, which can generate high precision aerodynamic data models, making it possible to introduce dynamic characteristics analysis in the early stage of aircraft design [2-3]. In the multidisciplinary numerical optimization, combining aerodynamic, structural, strength and stability analysis, and taking requirement of dynamic characteristics specification as constraint conditions, the aircraft design scheme satisfying given conditions can be solved efficiently through parallel iterative calculation [4]. As an important part of the aircraft, the flight control system becomes more and more important with the increase of performance requirements. To a large extent, the advantage of the aircraft depends on the quality of the flight control law. Flight simulation technology, which can analyze and evaluate the whole process of the development, production and use of aircraft, has obvious advantages of low cost, quick results, safety, reliability and reusability. For the flight stability and flight control system of aircraft, more importantly, it can improve the safety of system test [5].

At present, the aircraft design software, such as AAA, Piano, Pacelab and CAESIOM, mostly focus...
on the design of parameters [6-8]. Different research institutions and universities have independently
developed software platforms for control law design and simulation under the Matlab/Simulink
environment, which are often poor in generality and seldom combined with parameter design and
stability analysis [9-10].

In order to combine stability analysis, control system design and flight simulation, thus improve the
design efficiency and reduce the design errors in the conceptual design stage, the aircraft flight
performance analysis and real-time flight simulation (AFPAS) software for fixed wing aircraft with
conventional configuration is designed. AFPAS can analyze the static and dynamic stability and the
flight performance of the aircraft based on the aircraft database, and carry out the preliminary design of
the flight control system and real-time flight simulation.

2. Overall software design

2.1. Software functions

AFPAS is designed using C++ language and Qt platform and runs on an ordinary computer. The
functions include: flexible and convenient data entry and project management; static and dynamic
stability analysis; flight performance estimation; linear quadratic regulator (LQR) controller and
nonlinear dynamic inverse (NDI) controller design; real-time flight simulation and data review.

2.2. Software structure

According to the functional requirements, AFPAS can be divided into three layers, interaction layer,
function layer and data layer, and five function modules, including project management module, stability
analysis module, flight performance module, flight control system module and flight simulation module.
The data layer is composed of aircraft database, aerodynamic database, environment database and
simulation database [11]. Fig. 1 shows the structure of AFPAS.

The project management module is used for action on the project, including creation, opening and
closing, and data file browsing and editing. The stability analysis module can analyze the dynamic and
static stability of the aircraft model respectively, and provide the changing curve of state of the aircraft
model after being disturbed. The flight performance module is used for calculating the maneuverability
parameters of the aircraft, such as flight envelope, range, endurance, overload characteristic curve and
hover performance. The flight control system module is used for analyzing and setting the parameters of LQR and NDI controllers. The flight simulation module can set the flight parameters, carry out real-time flight simulation and review the simulation data.

3. Aircraft model
To realize flight performance analysis and simulation, the aircraft, control law and turbulence should be modeled firstly, and then the program is designed according to the model.

3.1. Aircraft kinematic model
The model adopts the European-American coordinate system, and the equation of motion of the center of mass and the rotation equation of the plane as a rigid body can be written as [12-13]:

\[
\begin{align*}
\mathbf{m} \left( \frac{\delta \mathbf{V}}{\delta t} + \mathbf{\omega} \times \mathbf{V} \right) &= \mathbf{P} + \mathbf{F}_B + \mathbf{G}_B \\
\mathbf{\delta K} + \mathbf{\omega} \times \mathbf{K} &= \mathbf{M} + \mathbf{M}_P 
\end{align*}
\]

(1)

where \( \mathbf{V} \) is the velocity vector in the body shafting, \( \mathbf{\omega} \) is the angular velocity vector of aircraft rotation around the center of mass, \( \mathbf{P} \) is the thrust vector, \( \mathbf{F}_B \) is the projection of aerodynamic force vector in the body shafting, \( \mathbf{G}_B \) is the projection of gravity vector in the body shafting, \( \mathbf{K} \) is the moment of momentum vector, which is composed of aircraft and turbojet engine, \( \mathbf{J} = \mathbf{J} \mathbf{\omega} + \mathbf{K}_P \), \( \mathbf{J} \) is the moment of inertia matrix, \( \mathbf{K}_P \) is the moment of momentum vector of the turbojet engine, \( \mathbf{M} \) is the aerodynamic moment vector and \( \mathbf{M}_P \) is the thrust moment vector.

Quaternion is introduced into kinematic equation to optimize the kinematic equation to avoid singularity when the traditional Euler Angle is used in flight with large angle of pitch [14].

3.2. Control surface model and engine model
In order to reflect the changing process of the control surface and engine output, control surface and engine are modeled. The first-order transfer function is adopted for the design of the control surface model. The transfer function \( G_s(s) \) and the time model \( f_s(t) \) of the control surface designed according to the transfer function are respectively:

\[
\begin{align*}
G_s(s) &= \frac{1}{\tau_s s + 1} \\
f_s(t) &= A_{sn} + B_{sn} e^{-\frac{t-t_n}{\tau_s}} (t \geq t_n)
\end{align*}
\]

(2)

where \( A_{sn} \) and \( B_{sn} \) are model parameters of control surface when \( t \geq t_n \).

The engine model adopts the second-order transfer function, and the transfer function \( G_e(s) \) and the designed engine time model \( f_e(t) \) are respectively:

\[
\begin{align*}
G_e(s) &= \frac{1}{(\tau_{e1} s + 1)(\tau_{e2} s + 1)} \\
f_e(t) &= A_{en} + B_{en} e^{-\frac{t-t_n}{\tau_{e1}}} + C_{en} e^{-\frac{t-t_n}{\tau_{e2}}} (t \geq t_n)
\end{align*}
\]

(3)

where \( A_{en} \), \( B_{en} \) and \( C_{en} \) are model parameters of engine when \( t \geq t_n \).

3.3. Control law model
Advanced control methods include optimal control, fuzzy logic control, multi-step pushback adaptive control, synovial variable structure control, nonlinear dynamic inverse control and many other methods [15]. LQR is a common form of optimal control with good robustness, damping and steady-state characteristics [16]. NDI is the most widely studied feedback linearization method, which can ensure the aircraft to maintain good stability performance under various flight conditions [17]. In the design of the control system module, the two control methods and the direct control from control mechanism to the control surface are taken as the design objects.
3.3.1. LQR controller
The research object of LQR is the state space in modern control theory, and the key problem is to design a state feedback \( u = -Kx \), \( K \in \mathbb{R}^{m \times n} \), so that the state space closed-loop system performance can meet the expectations. The feedback matrix \( K \) is obtained by solving the Riccati equation of the state space:

\[
\begin{align*}
PKR^{-1}B^TP - PA - A^TP - Q &= 0 \\
K &= R^{-1}B^TP
\end{align*}
\]

where \( A \) is the state matrix, \( B \) is the control matrix, \( Q \) is the state weighting matrix, \( R \) is the control weighting matrix. In this module, the matrix sign function method is used for solving the equation [18].

3.3.2. NDI controller
The study object of NDI is the nonlinear characteristics of the system, which can be described as [19]:

\[
\begin{align*}
\dot{x} &= f(x) + g(x)u \\
y &= h(x)
\end{align*}
\]

where \( x \in \mathbb{R}^n \) is the system state vector, \( u \in \mathbb{R}^p \) is the system input, \( y \in \mathbb{R}^m \) is the system output, \( f(x) \) is the nonlinear dynamic function, \( g(x) \) is the nonlinear control distribution function, \( h(x) \) is the m-dimensional vector function.

If \( g(x) \) is reversible for all the values of \( x \), then the needed control input can be solved using algebraic inverting according to the desired \( \dot{x} \), namely:

\[
u = g(x)^{-1}(\dot{x} - f(x))
\]

The nonlinear dynamic inverse control needs to decompose the system state variables into several decoupled subsystems. According to the singular perturbation theory, the time scale separation is performed according to the speed of the state variables: 1. fast state, includes \( p, q, r \); 2. slow state, includes \( \alpha, \beta, \mu \); 3. very slow state, includes \( V, \theta, \Psi \); 4. slowest state, includes \( x, y, z \).

In this module, NDI controller is designed by combining LESO observer, fast loop control of fast state and slow loop control of slow state [20].

3.4. Turbulence model
Turbulence is one of the important environmental factors affecting aircraft flight. The turbulence model adopts Dryden model to simulate turbulence changes by generating random signals and passing through a filter. The transfer functions of filters in three directions are:

\[
\begin{align*}
\sigma_u &\sqrt{\frac{2L_u}{\pi V}} \cdot \frac{1}{1 + \frac{L_u}{V^2} s} \\
\sigma_{vw} &\sqrt{\frac{2L_{vw}}{\pi V}} \cdot \frac{1 + \frac{2\sqrt{3}L_{vw}}{V s}}{\left(1 + \frac{2L_{vw}}{V s}\right)^2}
\end{align*}
\]

where \( \sigma_u \) and \( \sigma_{vw} \) are root mean square turbulence intensity, \( L_u \) and \( L_{vw} \) are the characteristic length, and \( V \) is the velocity [21].

The longitudinal turbulence transfer function is similar to the control surface model, hence the time model of the same form can be designed. The turbulence time model in lateral and vertical directions \( f_{vw}(t) \) can be designed to:

\[
f_{vw}(t) = A_{vw} + B_{vw} \cdot (t - t_n) e^{-\frac{t - t_n}{\tau_{vw}}} + C_{vw} e^{-\frac{t - t_n}{\tau_{vw}}} (t \geq t_n)
\]

where \( A_{vw}, B_{vw} \) and \( C_{vw} \) are the turbulence model parameters when \( t \geq t_n \).
4. Module interface

4.1. Project management module
Project management module is designed to create new project, read selected project, browse data files in two forms and close project. Two ways are designed for data entry in this module: interactive interface input and text file fast import. The aircraft database is composed of basic data, control data, engine data and aerodynamic coefficient data, and the data file is stored in .txt format. The format of aerodynamic data file supports up to 4 custom parameter, so as to establish a more complete aerodynamic database. The data entry dialog is shown in Fig. 2.

4.2 Stability analysis module
In the static stability analysis, the longitudinal static stability margin, overload static stability and velocity static stability are selected to calculate. The dynamic stability analysis is carried out by solving eigenvalues of aircraft state matrix, which is generated according to the linearization theory and the small disturbance theory. The eigenvalues are obtained through QR decomposition. In addition, flight quality evaluation is given according to the flight quality specification of manned aircraft [22]. Fig. 3 shows the interface of dynamic stability analysis.

4.3 Flight performance module
Flight performance is a number of parameters describing the law of motion of an aircraft, including speed, altitude, range, endurance, ceiling, take off, landing and maneuvering flight (such as somersault, hover, combat turn, etc.). The flight performance module provides the calculation and analysis of level flight envelope, range, endurance, overload characteristics and horizontal hover performance. The
module calculates the performance data and draws the graph with the corresponding algorithm for different performance based on the aircraft database. Fig. 4 shows the analysis interface of the level flight envelope and theoretical ceiling.

![Fig. 3. Dynamic stability analysis interface](image1)

![Fig. 4. Flight performance calculation interface](image2)

### 4.4 Flight control system module

This module includes two sub-modules, LQR controller module and NDI controller module. Each module carries out the preliminary simulation of the control system according to the parameters set, and gives the simulation curve. The control system parameters set in the module will be used in flight simulation module. Fig. 5 shows the operation interface of two controller.
### 4.5 Flight simulation module

The flight simulation module contains three contents, one is flight condition setting, the other is flight simulator, and the third is simulation data review.

Flight condition setting is used for setting the aircraft flight parameters, atmospheric environment conditions and flight control system parameters before simulation. Considering the error among the aerodynamic data calculated by CFD, the wind tunnel test data and the actual flight test data as well as the deviation of the control signal, the design of error setting of aerodynamic coefficient and control signal is introduced in the flight simulation to test the control effect of the control system in the simulation. Interface of flight control system parameters setting is shown in Fig. 6.

![Fig. 6. Flight condition setting interface](image)

The simulator consists of status data bar, auxiliary device button, multi-function display module, simulator controller, control law options, throttle and control surface data bar, throttle module and stick module. The operation interface is shown in Fig. 7.
In order to provide better simulation control, the program provides keyboard and mouse operation modes. The parameters controlled by keys in different control modes are shown in Table 1.

**Table 1: Keyboard and mouse settings for operation mode**

| Key          | Direct control | NDI fast loop control | NDI slow loop control |
|--------------|----------------|-----------------------|-----------------------|
| H/K Mouse horizontal moving | Aileron | Angular velocity p | Angle of speed roll |
| U/J Mouse vertical moving | Elevator | Angular velocity q | Angle of attack |
| A/D Rudder | Rudder | Throttle | Angle of sideslip |

The key of real-time flight simulation is the solution of aircraft differential motion equations. Program uses fourth-order Runge-Kutta method to solve the equation. The trigger will run `time_out()` function per step to calculate the state of aircraft of next step. The data flow of the simulator among interactive interface, functions and database is shown in Fig. 8.

After each simulation is completed, the simulator saves the simulation data to the project data file for subsequent data reference. The stored data file is shown in Fig. 9.
5. Validation
Each software, and in particular simulation tools, need to be validated. In this case, the best way of verifying analysis result is to compare the calculation result of SDSA and AFPAS. For verifying the simulation precision, it’s necessary to compare the simulation result and theoretical value. Assessment of effectiveness of controllers needs to compare the control effect of different controllers. And analyze simulation running performance by checking simulation frames per second.

5.1. Modal characteristics analysis of Dutch roll
In stability analysis, Dutch roll modes were selected for comparison. The flight conditions are sea level and the speed ranges from 80 m/s to 260 m/s. The dynamic characteristics are compared as shown in Fig. 10. The comparison shows that the error between AFPAS and SDSA is the largest when velocity equal to 80 m/s, and the calculation results of other conditions are in good agreement.

(a) Damping ratio  (b) Undamped natural frequency
Fig. 10. Comparison of modal characteristics of Dutch roll

5.2. Range and endurance performance
The performance analysis selects the range and endurance in the calculation mode of constant Mach number and altitude for comparison, as shown in. The calculation results show that the deviation between the analysis results of AFPAS and SDSA at high Mach number is large. The max deviation is about 7%, and the deviation of other calculation points is small.

(a) Range  (b) Endurance
Fig. 11. Calculation results and comparison

5.3. Simulation precision
The precision of the simulation system is verified through the simulation of the circling motion on given flight conditions and comparing the circling radius and circling period with the theoretical values. The flight conditions are given as follows: 1000 m for flight altitude; aircraft mass is constant and equals to 9299 kg; 160 m/s for flight speed; 30° for angle of speed roll; simulation step is set as 50 ms. Table 2 shows the hovering radius and period data.

The comparison between the simulation data and the theoretical values shows that the real-time flight simulation module of AFPAS has excellent stability and simulation precision.
Table 2 Hovering data

| Circle No. | Circle radius/m | Theoretical radius/m | Radius relative error/% | Circle period/m | Theoretical period/s | Period relative error/% |
|------------|------------------|-----------------------|-------------------------|-----------------|----------------------|------------------------|
| 1          | 4538.8            | 4522.9                | 0.352                   | 178.2           | 177.6                | 0.338                  |
| 2          | 4538.5            | 4522.9                | 0.345                   | 178.2           | 177.6                | 0.338                  |
| 3          | 4538.3            | 4522.9                | 0.340                   | 178.2           | 177.6                | 0.338                  |

5.4. NDI fast loop command response

NDI fast loop controls the angular velocity. 10% aerodynamic coefficient perturbation and -5% operation signal noise are introduced into the simulation. The response curves of angular velocity $\dot{\theta}$ under the influence of different conditions are shown in Fig. 12, in which T represents turbulence, P represents perturbation and N represents signal noise.

![Fig. 12. NDI fast loop response curve](image)

Comparison shows that under the condition of no control signal noise, NDI fast loop control has good aircraft angular velocity control and anti-interference ability. For aerodynamic coefficient perturbation from CFD and wind tunnel test, by introducing LESO observer, NDI controller can ensure good control of the angular velocity, improve the robustness of the system.

5.5. Angle of attack stability

This section compares the ability of aircraft to maintain stable angle of attack under the influence of turbulence when the four control methods are used respectively. The flight conditions are 1000 m for height, 160 m/s for speed, high turbulence intensity, and 0.1 s for turbulence adjustment period. The system simulation step is 50 ms, and the simulation time is 20 s. The variation of the angle of attack is shown in Fig. 13.

Under such flight conditions, the convergent short-period mode of the aircraft model and the NDI slow loop control on angle of attack can maintain the angle. Under the influence of turbulence which shows a normal distribution, the NDI fast loop control keeping the angular velocity basically unchanged is able to keep angle of attack near the reference value. While the LQR controller, due to the maneuverability of its control characteristics, will make the angle of attack change greatly, which is consistent with the variation characteristics of angle of attack in LQR controller design module.

5.6 Simulation system performance

The key to realize real-time flight simulation is to ensure that the calculation frequency in the solution process is not less than 24 Hz, that is, the average simulation computing time should be less than 41.67 ms. Fig. 14, the statistical results of simulation computing time of simulation in Section 5.4, shows that the maximum computing time in the simulation process is about 49ms. Except for a few data, most simulation computing time is less than 42 ms, and the average computing time in the simulation process is 22 ms. Therefore AFPAS simulation module can be considered to have excellent simulation efficiency and satisfy the real-time simulation requirements.
6. Conclusion

The aircraft flight performance analysis and simulation software is designed by using C++ language and Qt platform in this paper. By comparing the analysis result of AFPAS and SDSA, and simulation data with the theoretical value, the accuracy of analysis module of AFPAS is verified. The angle of attack stability curves, angular velocity command response curves and time-consuming data verify the validity of simulation module and controller module of AFPAS.

AFPAS can achieve well dynamic and static stability analysis and aircraft flight performance prediction, and carry out flight simulation with high precision and performance. The project file is established through the project management module, which is not restricted by strict data file format and has good universality. Design of the model of control surface, engine and turbulence improves the authenticity of the simulation system, which is more conducive to evaluating the stability of aircraft and the performance of flight control system.

AFPAS can be used for assisting the stability analysis and the preliminary design of the control system in the early stage of aircraft design, which is beneficial to improve the quality of aircraft design and reduce the design cost. Running the real-time simulation module contributes to understanding the stability and maneuverability of the aircraft more intuitively.

According to the requirements of the control system, the control law options of the control system can be updated by adding the control system module, which has certain expansibility.

The software can be used to build the next generation integrated aircraft design platform.

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