Development of a Modularized Virtual Flight Simulator based on Multiple Discipline Coupled Method

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Abstract. The problem of aircraft control involves multiple subjects and has always been extremely complicated in mechanics modelling. Virtual flight simulation was put forward in order to reduce the cost of full-scale airplane flying test and wind tunnel experiment. A typical virtual flight simulator includes a computational fluid dynamics (CFD) solver, a structure dynamics (FD) function, and a flight controller. However, existed virtual flight solver usually ignores the universal modelling of dynamics for complex aircraft configuration and the modularization of CFD, FD and flight controller module, which makes it very inconvenient for many in-house virtual flight codes for engineering application and commercial software development. A new framework of virtual flight simulation platform is established with a parallel Reynolds Averaged Navier-Stokes (RANS) solver, a structured moving overlapping grid function, a generic multiple body dynamics (MBD) solver, and a plug-in type flight controller platform. A universal data exchange interface between MBD and flight controller is presented. An X-wing missile flying forward and pitching-up maneuvering validation case is conducted with the current virtual flight simulator, the result is compared with Matlab Simulink solver based on steady aerodynamic database and good agreement is obtained.

1. Introduction

The mechanism of aircraft flying is a typical multiple discipline problem involving aerodynamics, rigid body dynamics, structure dynamics and control theory. Traditional methodology is based on static aircraft analysis, from which the control system is designed, validated and optimized by long-term and expensive flying tests and wind tunnel experiments. The control law of aircraft developed in such method is usually conservative, which will suppress the flying and maneuvering performance of aircraft.

As the prosperous development of computational fluid dynamics (CFD) and high performance computer (HPC), it is possible to run a numerical flying model including unsteady Navier-Stokes equations solver, flight dynamics and control law calculator in first principles. A numerical “virtual flight” simulator can provide detailed aerodynamic characteristics, fluid-structure coupling effect and control law validation by fewer expense and shorter period than full-scale flying test in traditional way.

The US army research laboratories (ARL) firstly conducted the coupling of rigid body dynamics and unsteady CFD to solve the attitude of flight vehicle during its ballistic trajectory[1]. In 2007, the software
program of CREATE (Computational Research and Engineering Acquisition Tools and Environment) by US Department of Defence is presented, in which the “Kestrel” software is a typical numerical virtual flight tool for fixed wing aircraft. Kestrel aims at combining multiple discipline including unsteady CFD, aircraft control, aeroelastics, propulsion and six-degree of freedom (6-dof) rigid dynamics in flight simulation[2]. DLR has achieved fluid-structure coupling for X-31 airplane for its angle of attack maintenance and rolling maneuvering in inviscid flow[3]. Zhang et al[4] from China Aerodynamic Research and Development Center (CARDC) presented a numerical virtual flight solver based on unsteady unstructured RANS solver, a pitching-up missile with closed-loop attitude control is verified by wind tunnel flight test.

A new numerical virtual flight software framework is presented in this paper, which has improvements over existing method in four following aspects:

- The CFD solver, flight/structure dynamics solver and flight controller is completely modularized independently in different code packs and is easy to be substituted. Between each module minimum necessary data is exchanged to improve efficiency.
- The traditional 6-dof rigid body dynamics is replaced by a multiple body dynamics (MBD) solver. The latter can automatically build complex aircraft with unconventional control surfaces such as tailless 6-generation fighter and new VTOL aircraft (figure 1 and figure 2).
- A generic data interface format is designed for rigid body motion data and flight control feedback, which is capable in multiple aircrafts, control channels and control surfaces.
- A plug-in type flight controller platform is presented. Different flight control code can be quickly introduced as static library.

2. Computational methodology of modularized virtual flight simulator

2.1. Modularized software framework of virtual flight simulator

The virtual flight simulator is composed of three major modules: a parallel URANS CFD solver with structured moving overlapping grid function, a serial MBD solver and a serial flight controller platform. Time-accurate iteration steps are conducted after system initialization. In each iteration step, the multiple disciplines coupled computation is as follows (figure 3):

- Step 1. In time step $t_n$, aircraft/control surface aerodynamic load data $F_N$ is transmitted from URANS solver to MBD solver, MBD solves system dynamic equations and obtains motion data $M_{n0}$;
- Step 2. $M_{n0}$ and $F_N$ are then transmitted from MBD to flight controller through an adaptor of universal data interface as in figure 4. MBD and flight controller is able to deal with multiple aircrafts, multiple control channels in single aircraft, and multiple control surfaces in single control channel;
- Step 3. Flight controller choose the corresponding control law for each aircraft/channel, control feedback $C_N$ data is solved and then sent to MBD, which updates $M_{n0}$ to $M_{n1}$ as the final motion data in this time step;
• Step 4. MBD send MN1 to URANS solver to change the moving overlapping grid, in which CFD solver computes unsteady flow field. Aerodynamic load FN+1 for tN+1 is computed. Recycle this iteration and return to step 1.

Figure 3 Modularization of Virtual Flight Simulator.

Figure 4 MBD and control law data exchange interface.

2.2. Parallel unsteady RANS solver and grid overlapping module

The parallel unsteady RANS solver is based on Arbitrary Euler-Lagrangian (ALE) which allows arbitrary motion and deformation structured grid.

\[
\frac{d}{dt} \iiint_{V} Q dV + \iint_{S} \left( \vec{H}^{I} - Q \vec{V}_{\text{grid}} \right) \cdot \vec{n} dS = \iint_{S} \vec{H}^{F} \cdot \vec{n} dS
\]  

(1)

The grid splitting technique is optimized to satisfy the requirement of average load balance and low grid fragmentation. The overlapping grid module is able to automatically identify hole-cutting boundaries in parallel processes and split grid blocks.
2.3. Multiple body dynamics solver

By replacing traditional flight dynamics with multiple body dynamics method[5], a generic modeling and simulation framework is established in solving complex aircraft control surface motion, time-variant constraints and rigid/flexible body system dynamics. The MBD equations are differential-algebraic equations (DAEs) in Cartesian description as

\[ \phi(z)_{t-e^{\omega t}} = \left[ \begin{array}{c} E \\ C \end{array} \right] = \left[ \begin{array}{c} M\ddot{q} + C_\theta \lambda + Q \\ C(q,\dot{q},t) \end{array} \right]^{+1} = 0 \]  

in which \( E \) are dynamic differential equations and \( C \) are algebraic constraint equations.

3. Computational and validation: flying missile control with large angle of attack

An X-tail missile pitching-up maneuvering control process is simulated by the current virtual flight platform (Figure 5). By rotating each tail rudder around an axis on the missile fuselage by a controlled angle (Figure 6), the change of the aerodynamic force on the control surface makes the whole missile pitch up as its angle of attack (included angle between mass center velocity and missile axis) raise from 0 degree to 30 degree. The missile is pushed by engine thrust force and flies forward and upward. The computation parameters are listed in Table 1. The CFD structured grid is about 9.6 million and parallel computation is applied using 128 ARM V64 CPU cores. Figure 7 exhibits the overlapping grid effect between tail rudder grid blocks and background grid blocks, where clear interpolation boundaries are observed.

| Table 1 | Missile virtual flight computation parameters. |
|---------|-----------------------------------------------|
| Missile mass | 60kg                        |
| Pitching momentum of inertia | 63.5kg·m²                   |
| Missile diameter | 0.16m                   |
| Engine thrust | 200N                          |
Initial flight altitude 1000m
Initial inflow velocity 150m/s
Initial angle of attack 0 degree
Angle of attack of control objectives 30 degree
Reynolds number $1.5 \times 10^6$

In large angle of attack flight, the linear control law based on small disturbance assumption cannot consider the nonlinearity of aerodynamic force and motion. A nonlinear full-state feedback dynamic inversion (DI) control law is developed[6], in which each of the four tail rudders has the same control channel. The control law is firstly developed on the Matlab/Simulink, a C code version is then realized and functions as static library in control law platform in figure 4.

Figure 8 displays the missile attitude animation in an inertial reference frame of which the coordinate origin is at missile mass center and coordinate direction is the same with ground reference frame. The current results is compared with a Matlab/Simulink solver based on the steady aerodynamic database in Figure 9~Figure 15. It can be seen that the two results are fundamentally in good agreement. The differences are mainly caused by unsteady aerodynamics effects and dynamic nonlinearity.

The missile travels about 1000m forward (figure 9) and 450m upward in altitude (figure 10) during 15s simulation. The kinetics of missile transform into gravitational potential energy, which cause decrease in velocity magnitude (figure 11). The velocity inclination angle, defined as the angle between mass center velocity vector and x direction in ground reference frame, reaches a maximum value of 42°at $t=8s$ and decrease to nearly zero at $t=15s$ (figure 12). The angle of attack, as the control objective, quickly raise to 37°at $t=2.5s$ and gradually decrease to 30°(figure 13). The pitching angular velocity firstly reaches 0.6rad/s and reduces to -0.2rad/s at the end of simulation (figure 14). Figure 15 shows the rudder deflection angle results, the leading edge of the control surface pitch downward to 14°at $t=2.5s$ and adjust itself from 12°~13°afterward. It can be seen in figure 15 that after $t=10s$, an oscillation in rudder deflection angle is emerging. Large angular velocity of the control surface leads to highly aerodynamic load, which may cause aircraft attitude divergence. Virtual flight simulator based on unsteady CFD solver shows significant advantage in predicting oscillation attitude effect.

![Missile Attitude Animation](image)
Figure 8 Attitude and aerodynamic pressure coefficient contour of missile

(a) $t=9.51\text{s}$  (b) $t=12.68\text{s}$  (c) $t=14.27\text{s}$

Figure 9 $X$ displacement of missile.

Figure 10 Altitude $h$ of missile mass center.

Figure 11 Velocity magnitude of missile.

Figure 12 Velocity inclination angle
4. Conclusion
A modularized virtual flight simulator based on multiple discipline coupling is developed. With the help of unsteady parallel CFD solver, MBD methodology and plug-in controller platform, the current simulator has the ability to solve complex aerodynamic-dynamic-control problems. A typical pitching-up flight missile control case is computed and validated, in which unsteady and nonlinearity effect is observed. Based on this virtual flight framework, a commercial software can be developed by adding functions and static and dynamic link library. Multiple UAV close formation control problem, automatic air-refuelling flight control, and new VTOL concept aircraft control can be simulated to improve aircraft design and safety.

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