Research on Approximate Real-time Model Technology for Complex Off-line Model of Civil Aircraft Hydraulic System

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Abstract. Analysis on the performance of the aircraft hydraulic system needs to be extremely accurate, which results in a large amount of calculation and wastes much CPU compute resources. The complex model can only be used for offline simulation and cannot be used in the hardware-in-the-loop environment. This paper introduces some techniques and methods for real-time simplification model of hydraulic system: use active index, energy analysis tool or linear frequency tool to modified the original complex offline model; appropriate order-reduction model based on test data, increased the step size of the model operation under the premise; split complex model into multiple subtasks and processed in parallel to improve the computational power of real-time simulation hardware. Through the real-time simulation tests, the real-time simulation results show that the simplified real-time model can replace the complex offline model of hydraulic system for hardware-in-the-loop platform, engineering simulator, etc.

1. Introduction
The civil aircraft hydraulic system is an important power system of the aircraft to support the safe flight, guidance and approach. The design level of the hydraulic system is an important indicator of the advanced level of the aircraft, which deeply affects the safety and economy of the aircraft. The aircraft hydraulic system usually provides hydraulic energy for users such as landing gear retracting, front wheel turning, wheel braking, wing extending. In order to meet the flight safety requirements, modern aircraft hydraulic systems generally adopt redundant design that is multiple hydraulic systems, which are mutual independent and mutual backup.

At present, with the gradual improvement of digital simulation technology, model-based designing analysis has become an effective method to develop complex system products. The complex simulation model of the civil aircraft hydraulic system can be established to realize the function validation, performance test, design evaluation and optimization, cross-linking interface confirmation between hydraulic system and other systems.

However, the high-precision model of the performance characteristics of civil aircraft hydraulic system generally solves a large amount of calculation, but cannot solve in real time. The calculation time is much longer than the real-world running time of the hydraulic system. Therefore, it is necessary to perform real-time processing on the basis of complex offline models to meet the requirements of real-time solution for specific scenarios. However, real-time hydraulic system is relatively difficult without significantly reducing the accuracy, the method of real-time model processing to replace the complex offline model of hydraulic system with equivalent is researched. [1-3]
2. Description of complex offline model of hydraulic system

According to the component-subsystem-system development and integration process, strictly correspondence between the model combination structure and the actual composition of the physical system, the complex offline model of a certain type of civil aircraft hydraulic system is completed. The model architecture is shown in Figure 1.

![Figure 1. Complex offline model architecture of a civil aircraft hydraulic system.](image1)

Part of the hydraulic system model developed and integrated is shown in Figure 2. It contains numerous hydraulic system component models: hydraulic pumps, fuel tanks, accumulators, energy conversion devices, various valves, hydraulic conduits, actuators, and oil media. The interface with the hydraulic system users and the flight environment need to be considered.

The subsystem composition of the model is too complicated. Although the calculation accuracy is very high, the execution simulation calculation cycle is too long. The simulation step size of the simulator solver is generally set to the offline simulation of the variable step size calculation. When the simulator solver is set to fixed step size calculation, the calculation process cannot be completed, causing the simulation tool to report the error and interrupt simulation. Obviously, complex high-precision model cannot be used in real-time environments such as hydraulic system control unit in loop testing and engineering simulator which focuses on evaluates flight quality.

![Figure 2. Schematic diagram of part of system mod.](image2)

3. Real-time processing method

The difference between real-time simulation and off-line simulation is that the real-time simulation calculation must use a fixed-step integrator solution, and the calculation amount of each step must be less than the maximum computational load capacity of the calculation platform. Usually in order to reduce the hardware resource consumption, a very simplified mathematical model is used instead of the original model in real-time simulation. However, the simple mathematical model does not reflect the full characteristics of the hydraulic system, which causes model calculations to be inaccurate or even incorrect. For example, considering the hydraulic pump model as a simple hydraulic on-off switch, the amount of calculation can be greatly reduced, but the characteristics of the pressure establishment process and pressure pulsation of the hydraulic system cannot be reflected, which affects the dynamic performance simulation of the model system. Therefore, on the basis of retaining the hydraulic system model as much as possible to simulate the real system characteristics, the model...
is moderately simplified. Meanwhile, the computational load requirement for the real-time simulation platform is reduced, and the accuracy of the calculation result is guaranteed to be within tolerable range.

Under the premise of ensuring the accuracy of the model, the simulation speed of the model can be accelerated as much as possible. The following three aspects of real-time processing techniques are used to analyze and modify the original complex offline model.

1) Moderately simplified model
Using the active index and energy analysis tool and linear frequency analysis tool together, modify the original model appropriately.

The active index and energy analysis can quickly determine the energy changes of each sub-component during system operation, and find the sub-model of the least active component. Linear frequency analysis can obtain the natural frequency of each sub-component of the system. The combination of the two ways of analysis can identify sub-models that have little impact on the system and have a large impact on the fixed-step solver. By modifying these models, computational work can be reduced greatly.

2) Model order-reduction
The Model based on real system has high precision, but it often requires accurate characteristic data and complicate algorithm, which takes much long time to calculate. The data preprocessing is used to preprocess the key components. According to the characteristics of the experimental data of the key components, the high-order model is reduced in order to avoid the local complex calculations dragging the calculation speed of the overall system.

3) Complex model split
Many real-time computing simulation platforms, such as Concurrent iHawk or RT-LAB, support the splitting of complex models into multiple subtasks that can be executed in parallel, and assign these tasks to multiple target nodes in the whole compute network. These nodes work together to perform distributed parallel computing. The split models are separately processed by the simulation hardware for multi-platform parallel processing, which can also reduce the computational load of a single platform.

4. Real-time processing example

4.1 Model simplification example
AMESim, a commonly used modeling and simulation tool for hydraulic systems, provides an activity index and energy analysis tool that automatically calculates the activity index, and also provides a linear frequency analysis tool that performs frequency analysis. After analyzing the complex offline model of a certain type of aircraft hydraulic system, the simplified component models can be roughly divided into two categories:

The first type is the pressure calculation model of the cavity. Calculated the pressure unit in AMESim by calling the integral solver. The cavity pressure calculation model allows the individual sub-models in the liquid model to be solved independently by numerical integration, which solves the algebraic loop problem that is difficult to process in computer simulation. In order to make the cavity model not affect the real dynamic characteristics of hydraulic system, the volume parameters of these cavity models are designed to be very small, thus adding a state variable with high frequency characteristics to the system. In order not to solve the problem of algebraic loop, a large number of cavity sub models cannot be deleted in simulation calculations, but the natural frequency can be reduced by increasing the flow resistance model, which reduces the amount of calculation correspondingly.

The second type is the mass model of the valve core and the actuator of the hydraulic valve. Since the weight is lighter and the moving distance is small, the activity energy of the mass has a small proportion of the active energy of the entire system, which can be ignored. The massless sub-model is used instead of the original mass sub-model to reduce the number of system states, and the reduction
in the number of states also reduces some of the computational work correspondingly. [4-5]

The above two classification model simplification methods complement each other and jointly complete the simplification task of the partial offline model, as shown in Fig. 3, which is a load model of the hydraulic system. The original model can only operate normally in less than 100us in the fixed step mode, and the modified model can be correctly calculated by adjusting the fixed step size to about 600us. Therefore, through model simplification, it can be solved in real time with a large step size integrator, which greatly reduces the performance requirements for real-time simulation hardware.

4.2 Model order-reduction example

For components with a large amount of experimental measured data, the model can be reduced in order to simplify processing. For example, as shown in Figure 4, it is a mathematical model established according to the structural principle of the electro-hydraulic servo valve, which considers various factors such as the valve core structure, the mass, the cavity, the damping, the spool speed/displacement and the fluid, etc.

The flow rate calculation formula of port A of the solenoid valve is:

\[ q_A = C_{q_{\text{max}}} \times A \times \sqrt{\frac{2 \times \Delta P}{\rho}} \times \tanh \left( \frac{2 \times \text{diam} \times \frac{2 \times \Delta P}{\rho}}{\gamma \times \tau_c} \right) \]  (1)

where:
- \( q_A \) — the flow rate of port A of the valve;
- \( \Delta P \) — Pressure difference between port A and port P of the valve;
- \( A \) — the flow area of the valve hole;
- \( \text{diam} \) — valve hole diameter;
- \( C_{q_{\text{max}}} \) — the maximum flow coefficient;
- \( \rho \) — oil density;
- \( \gamma \) — oil viscosity coefficient;
- \( \tau_c \) — critical flow rate.

Through the large amount of measured test data of the electro-hydraulic servo valve, the dynamic characteristic interpolation of the electro-hydraulic servo valve is reduced to a linear system model. The flow rate of port A is affected by the opening area of the electro-hydraulic servo valve. The model can be expressed by a simple formula:

\[ q_A = a \times A^2 + b \times A + c \]  (2)

a, b, c are the constant values set by the measured data, and the flow calculation result after the reduced order can be approximated to the measured data value, which is greatly reduced compared
with the theoretical formula. After the model is reduced, local complex calculations can be avoided to drag the calculation speed of the overall system.

4.3 Model split example
The data of real-time parallel computing affects each other, requiring the calculation results of each node to be absolutely correct and synchronized in time. Therefore, the principle of model splitting is to analyze the coupling of the system model and find the part with relatively strong and low coupling in the system. Split the entire system into several tasks with relatively small coupling, and the part with strong coupling as a computing task, which minimizes the data transmission between distributed computing nodes and ensures that the computing load of each node is relatively average.

After analyzed the flight control actuator model of a certain aircraft hydraulic system, the original model can be divided into three relatively low-coupling parts, as shown in Figure 5. Part ① is the normal actuator unit model, and part ② is the backup operation, and part ③ is the hydraulic source.

Through the split processing, the interface module is added in three parts, to transmit the data of flow, pressure, displacement of the actuator, as shown in Figure 6. The three models are divided into three emulation download computer nodes, which connect with high-speed network.

5. Real-time model verification and application

5.1 Model verification
After real-time processing, the hydraulic system model can run normally with a fixed step length of 600us. The real-time calculation results are compared with the offline simulation results to verify whether the real-time model meets the application requirements, as shown in Figure 7.
Figure 7. Comparison of simulation results.

The green curve is the offline simulation solenoid valve outlet flow, and the red curve is the real-time simulated solenoid valve outlet flow. It is obviously that the offline simulation is more accurate than the real-time simulation, which is more in line with the actual situation. But the result curve of real-time simulation is also similar to offline simulation in trend. Therefore, there is no doubt that the real-time model can be applied to some real-time environments with low precision requirements.

5.2 Hardware-in-the-loop test

The hardware-in-the-loop test platform is constructed by Real-time simulation computers loading real-time model, a hydraulic system controller, a host computer, and visualization system, as shown in Figure 8. The user inputs the control command using the host computer, and the real-time simulation model provides the hydraulic system status signal to the hydraulic system controller through the real-time simulation computer and receives the feedback signal of the hydraulic system controller, then the HIL platform can test the function and performance of the hydraulic system controller.

5.3 Engineering simulator application

Engineering simulator, which is important equipment for aircraft testing, typically requires loading different systems' models for flight simulation testing and pilot training. The model accuracy of aircraft system directly affects the effect of the engineering simulator on real aircraft. The hydraulic system is often extremely simplified to run in the engineering simulator, directly affecting the flight experience of the engineering simulator. Downloading the equivalent real-time model code of the hydraulic system which retains certain dynamic characteristics and realizes the approximation effect of the offline model to the engineering simulator, it can run successfully.

Figure 8. Hydraulic system controller in the ring test.

Figure 9. Application in engineering simulator.
6. Conclusion
Researched the real-time model processing method, which simplifies the calculation of the complex off-line model of the hydraulic system by means of model simplification, model order-reduction, model split parallel calculation, etc., and verifies by real-time simulation results of the example. The model simulation speed is fast after real-time processing, and the calculation result is similar to the simulation result of the original model. It can be used instead of the offline model to apply to the hardware system in-loop test, engineering simulator and other platforms that require high real-time operating environment.

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